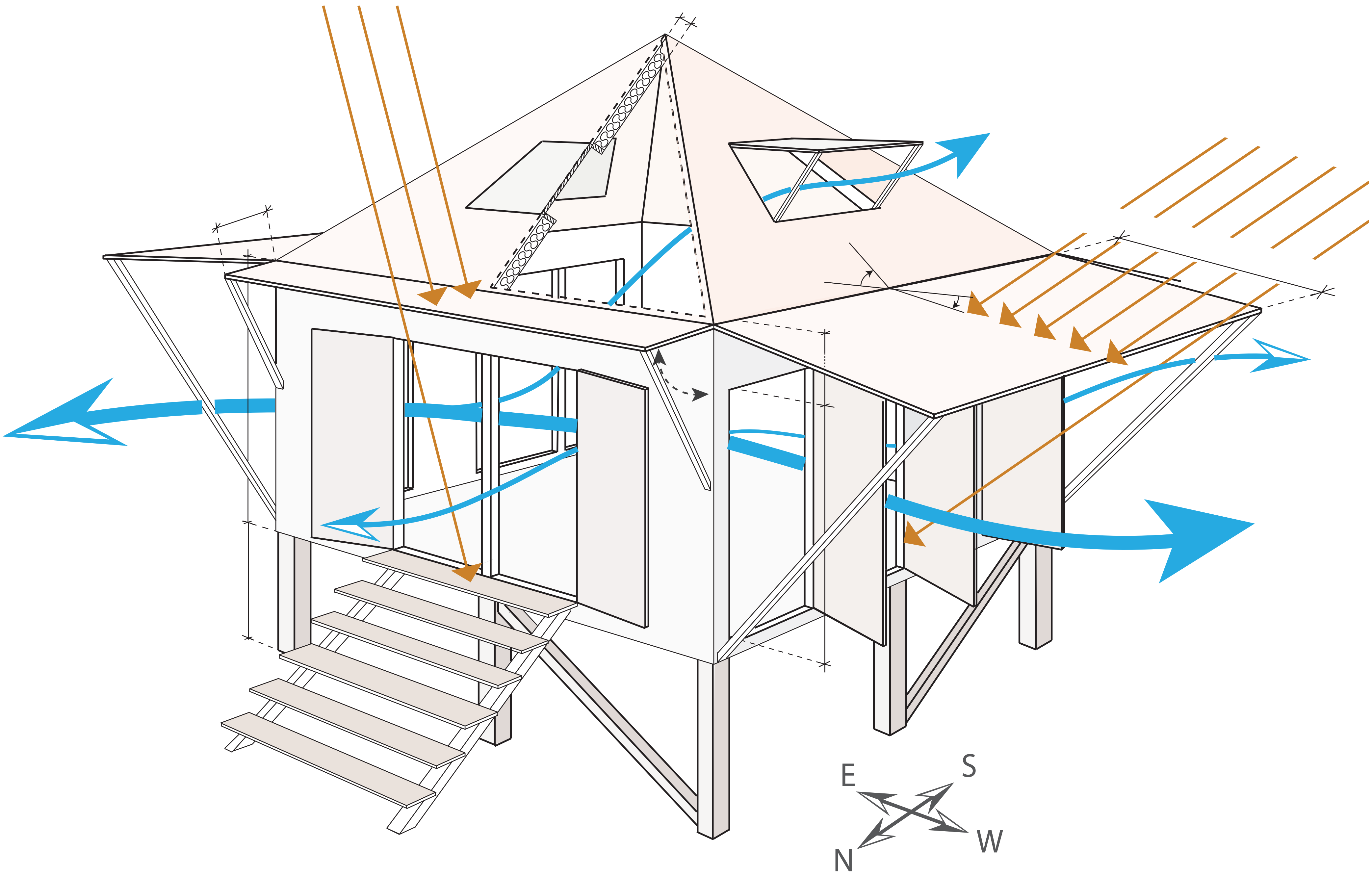
Passive design guidelines for Philippine housing based on the bahay kubo

Thermal comfort analyses and conceptual implementation of vernacular design strategies

R. Spittka



Passive design guidelines for Philippine housing based on the bahay kubo

Thermal comfort analyses and conceptual implementation of vernacular design strategies

by Rubin Spittka

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Wednesday August 14, 2019 at 15:30.

Student number:	4065093	
Project duration:	July 2018 - August 2019	
Thesis committee:		
Chair	Prof. dr. ir. R. Nijsse,	TU Delft,
Daily supervisor	ir. P. H. Ham,	TU Delft,
Supervisor	ir. E. R. van den Ham,	TU Delft,
Supervisor	ir. J. Spiegeler,	OMRT

An electronic version of this thesis is available at `http://repository.tudelft.nl/`.

TU Delft

Preface

Before you lies the master thesis, *"Passive design guidelines for Philippine housing based on the bahay kubo. - Thermal comfort analyses and conceptual implementation of vernacular design strategies."* It has been written to fulfil the graduation requirements of the master Civil Engineering, track Building Engineering at the TU Delft. This research is performed in collaboration with OMRT from July 2018 until August 2019.

Mr. Ham and OMRT initiated the topic of this research. The idea was to study how thermal comfort of the Finch Floating Homes project could be improved based on the bahay kubo, using high-tech engineering simulations to improve low-tech architecture. While I was inexperienced in the topic of comfort and thermal performance, it gave me great pleasure to work on because of its graspability. Making a trip to the Philippines sparked the enthusiasm further by experiencing the local conditions and challenges first hand. The various nature of the subject, collaboration and method made it enjoyable until the end. The biggest challenge in the process for me was to find the balance in enthusiasm to study many topics and also deliver the desired quality.

I would like to thank my supervisors for their guidance and availability to assist when needed. This made me feel like I was not doing this research on my own, which I appreciate greatly. Personally I want to thank Mr. Ham for his patience in our many sessions and pushing the level of this study, Mr. Spiegeler for his willingness to think along any problem I had, Mr. van den Ham for his readiness to share his expertise and Mr. Nijsse to guard the overall goal of this thesis.

To the people that helped me in the Philippines, I would like to thank you for your willingness to help unquestionably and making me feel welcome. In special, I would like to thank Mr. Ravina and colleagues from San Carlos University for their guidance and support in our shared field trip trough the Philippines. It was a wonderful experience to be able to do this trip together. I would also like to thank Ms. Ylagen-Funk from the St. Benilde University and Mr. Germar from University of the Philippines Diliman for receiving me at their universities, and helping me where possible. Finally, I would like to thank the Finch Floating Homes team for letting me be a part of the team for a week and letting me help constructing the first Finch Floating Home.

Delft, August 2019

Abstract

Philippine low-income housing is uncomfortable since it is not built to deal with the hot and humid climate in a passive way. Since local vernacular architecture is known to have a good climatic responsive performance, the aim of this research is to learn how Philippine vernacular design strategies can improve thermal comfort for low-lying, sub-urban and rural, low-income housing. The strategies studied are openings, eaves, stilts, orientation, roof insulation and roof angle.

Two-day in-situ thermal measurements are used to study the comfort performance of the housing typology. To study the influence of the strategies or combinations of them on comfort, numerical predictions are used consisting of energy and CFD, wind-driven simulations. The numerical models are validated before the strategies are varied on a general case or a case study. The average exceeding temperature (AET) in Kelvin is used to assess comfort. It is calculated by accumulating for every hour of the year the exceeding temperature in Kelvin and divide this by the amount of hours that could be uncomfortable. A conceptual implementation study is performed to take disaster resilient and practical considerations into account.

The impact of varying the strategies on the case study resulted in a reduction in AET of about 5 K for openings, 0.7 K for orientation, 0.6 K for eaves, 0.5 K for stilts and 0.1 K for roof insulation. On this basis, it can concluded that applying the guidelines as stated below, comfort increases significantly. More impact can be obtained if the strategies are implemented and combined as described by the passive design guidelines below.

- To increase wind driven ventilation in wind direction, openings should be made on the wind- and leeward facade until ground floor, have an opening height (O_h) based on the facade height F_h by the rule of thumb: $O_h[m] = 0.85 \cdot F_h[m]$, include a leeward roof opening and include openings on the remaining facades.
- Dependent on the wind direction, the openings should be opened accordingly. If no wind is present, all roof openings should be opened. During typhoons, they should be closed.
- As much open area on facades in the main monsoon wind direction is advised. The openings on the other facades should be placed in the middle of the width to increase the performance with wind coming from the other directions.
- Hinged eaves with a 15° and length calculated by the rule of thumb: $E_{l,15°}[m] = 0.6 \cdot F_h[m]$ should be used. During typhoons they should be folded in to decrease the related pressures.
- Increasing stilts height increases comfort by an exponential decay. To determine the height, a comfort increase of about 0.17 K for 1 meter, 0.30 K for 2 meter and 0.40 K for 3 meter in AET reduction are obtained. Braced, wooden stilts are advised to protect against floods and increase earthquake resilient behaviour.
- A roof insulation with an Rc-value of 1 m^2K/W is advised to gain about 0.2 K AET.

Further research is needed on buoyancy driven ventilation to improve the provided design guidelines.

Contents

1 Introduction

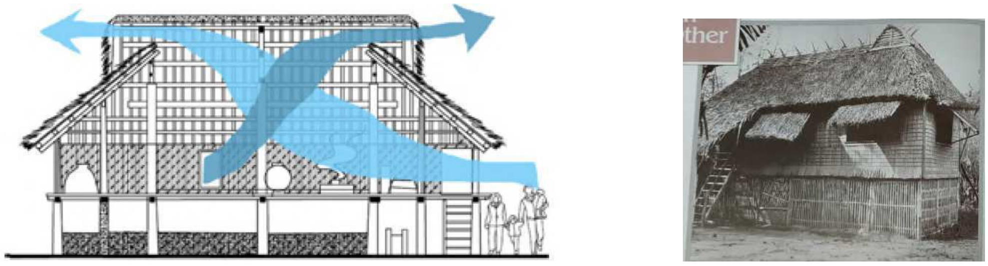
In this chapter, the subject and framework of this research is introduced. First, the relevance is discussed. The objective with corresponding research questions, terminology and delimitations are discussed next. The methodology that is adopted to answer the research question is discussed in the third section. The chapter is concluded with the outline of this report.

1.1. Relevance

The high temperatures and high humidities found in the Philippines result in severe difficulties in achieving thermal comfort in a passive way [19]. Since low-income housing households lack the means to use active design solutions, they suffer from undesirable thermal comfort conditions. These conditions are the worst in low-lying areas, because they are subject to the highest temperatures. Therefore, applicable passive climate design knowledge for low-income and low-lying households is necessary.

The housing typologies found in cities show a large variety in terms of scale and surroundings. In sub-urban and rural areas however, the typologies found are observed to have similar scales and surroundings. In addition, heat can dissipate easily in these areas compared to dense cities. Therefore, providing passive design knowledge for sub-urban and rural housing is widely applicable with a greater potential. As a benefit of passive design knowledge, the need for air conditioning decreases. Since air conditioning is a significant portion of the energy use of the Philippines, this can contribute to reducing the energy use which is in line with our global aim to reduce energy consumption.

Vernacular architecture is known to be well adapted to the climatic and social conditions of its location [20]. Studies in countries with similar conditions like Vietnam [25] and Malaysia [19], showed the potential of vernacular passive design solutions (or strategies) to improve thermal comfort. Figure 1.1a illustrates a qualitative analyses of the used vernacular design strategies found in Vietnam. Philippine vernacular architecture is also known for its climate responsive behaviour and similar to the intended housing typology. Several architectural analyses expressed the qualities, distilled several climate responsive design strategies [21] [28] or performed an implementation step of the strategies to modern mass housing [12]. However, thermal comfort performance of Philippine vernacular architecture is not studied and translations to applicable solutions are missing. Therefore, studying Philippine vernacular architecture has high potential to provide applicable climatic design knowledge. The figure below (1.1b), illustrates an example of Philippine vernacular architecture.



(a) Vernacular design strategy of attic and cross ventilation [25]. (b) A bahay kuboAn example of Philippine vernacular architecture, [33].

Figure 1.1: Analyses of Vietnamese vernacular architecture and an example of Philippine vernacular architecture.

Since the Philippines is also one of the most disaster prone countries of the world, focussing on climatic principles only is not durable. The table in figure 1.2, illustrates the impact of the top three disasters in the last 117 years. To reduce this impact, disaster resilient behaviour should be taken into account when design guidelines are provided. However, quite some research is already performed on the influence of these strategies on disaster resilient design. Applicable recommendations and guidelines on shape, materials, foundation systems and methods [43] [11] [2] are available to use when providing design guidelines.

Disaster type	Disaster subtype	Events count	Total deaths	Total affected	Total damage ('000 US$)
Storm	Tropical cyclone	322	48369	164830872	21414349
Floods	Coastal, flash and riverine	150	3668	33510034	3811363
Earthquake	Ground movement	31	9943	5857237	603516

Figure 1.2: Total damages by top 3 recorded natural disaster types in the Philippines (1901-2018):EM-DAT: The Emergency Events Database - Université catholique de Louvain (UCL) - CRED, D. Guha-Sapir - www.emdat.be, Brussels, Belgium

1.2. Objective, research questions and delimitations

The objective is defined first in this section. The research question is derived next, which is then narrowed down by the scope. It is ended by a further definition of the used concepts.

1.2.1. Objective definition
Based on the relevance of this issue as stated in section 1.1, the following objective can be defined:

"To provide passive design guidelines to improve indoor thermal comfort for low-lying, sub-urban and rural, low-income housing in the Philippines."

1.2.2. Research questions
The objective translates to the following main research question.

"How can Philippine vernacular climate responsive design strategies improve thermal comfort for low-lying, sub-urban and rural, low-income housing in the Philippines?"

From the main question the sub-questions stated below can be derived. By answering the sub-research questions, the main question is answered. The sub-questions are as follows:

Ch. 3 *What is the thermal comfort performance of this housing type?*

Ch. 4 *Which design strategies should be studied in this research to improve thermal comfort of this housing type?*

Ch. 5 *How do the design strategies influence thermal comfort parameters?*

Ch. 6 *How do the design strategies influence thermal comfort performance?*

Ch. 7 *How could the design strategies be implemented in this housing type to improve thermal comfort?*

1.2.3. Delimitations
The following delimitations are used.

Strategy selection Since many Philippine vernacular design strategies can be used to improve thermal comfort, a selection must be made. In chapter 4, a selection is performed based on the potential to improve thermal comfort and applicability. Materials are not considered as a design strategy to study because the aspects are too extensive to study within the given time frame.

Housing typology While the housing typologies knows different shapes and dimensions, a general square shape is used. Windows are defined at mid-height. Their with is half the length of the facade and their height is half the facade height. Single-story buildings are considered with a hipped roof of 45°. The length and width considered are 4.8 m by 4.8 m to house a single family. The house can consist of a single room or multiple rooms.

1.2.4. Definition of concepts
The terms below are often used in this research. To avoid misinterpretations, the definitions used are elaborated.

- **Vernacular architecture** - Architecture or housing that has originated in the course of centuries through an evolutionary process. It is based on availability of local materials, techniques and social conditions. It can be considered optimized to the needs and traditions.
- **Passive design** - Design that takes advantage of the climate to maintain a comfortable temperature range in the home.
- **Design strategy** - An architectural feature or design solution, to reach a certain goal or principle. For example, an eave is a climate responsive design strategy for the climatic responsive principle, solar shading.
- **Climate responsive principle** - A principle to use one of the climatic features to its advantage or protect against it, also called passive design principle. For example, solar shading or natural ventilation.
- **Low-income housing** - Single-family housing of one story with a value between 300.000 to 500.000 pesos in the Philippine context. In euros this would be roughly 5000 to 9000 euros.
- **Sub-urban and rural** - Areas with low density population compared to urban cities. The places where singular free standing low-rise buildings are found.

- **Thermal comfort** - Describing the state of mind related to thermal sensations like hot and cold.
- **Low-lying** - Areas close to sea level.
- **Flow** - A description for the stream of air through a building including its velocity.
- **Flow pattern** - A description for the stream of air through a building but not indicating its velocity.

1.3. Methodology

In this section the methodology to answer the research questions is discussed.

1.3.1. Research steps

Per sub-question, a step is defined and corresponding method discussed. The last step concludes the findings. The flow chart of figure 1.3 shows an overview of the method per step.

Step 1 To answer the first sub-research question, in-situ thermal comfort measurements are performed on a building of the intended housing type. Thermal measurements are a well known and used [19] [25] method to obtain reliable thermal comfort performance. Since several vernacular design strategies are used in this building, their influence can be evaluated.

Step 2 To answer the second sub-research question, Philippine vernacular architecture is analysed by literature study to distil the used climate responsive design strategies. A selection is made on potential to increase comfort and applicability for the housing typology. Step two is concluded by a literature review on the state of the art of the selected strategies.

Step 3 To study the influence of the design strategies on thermal comfort parameters, computational simulations are performed. The development of computational simulations allows the extensive analyses per strategy or combination of strategies on their comfort parameter. It has shown to be a valuable tool for analyses of these kind of strategies in vernacular architecture by Nguyen [25]. To avoid influence of specific design features, general dimensions related to the housing typology are used.

Step 4 To obtain a realistic influence of the strategies on comfort performance, a case study is used. Certain influences found in specific designs are thereby taken into account. Computational simulations are used in extension of step three to be able to do extensive simulations.

Step 5 To be able to provide applicable design guidelines to improve comfort, a conceptual implementation study is performed. An explorative case study design is used to discover the relevant considerations in implementation of the strategies.

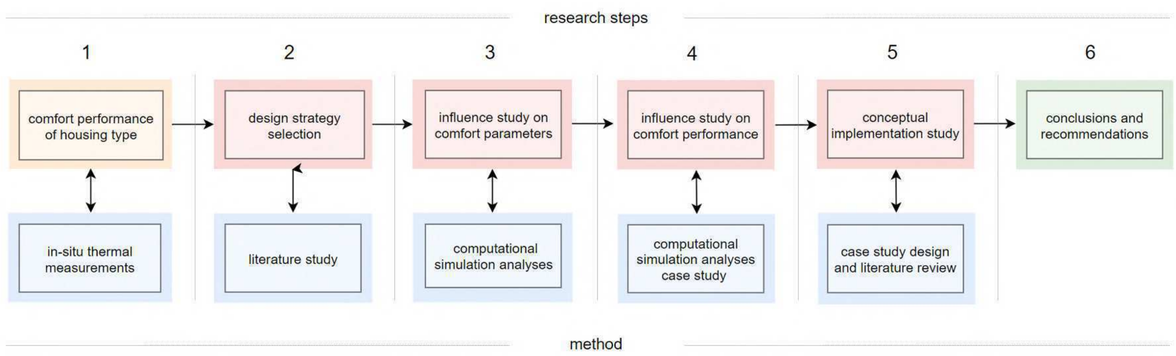


Figure 1.3: Research steps and their corresponding method.

Step 6 After an evaluation of all the results the conclusions and answer to the main question can be formulated.

1.4. Report outline

The following outline is used in this report. First, the theoretical framework is discussed in chapter 2. This includes the analyses of Philippine vernacular architecture and its design strategies. From chapter three to chapter seven, a sub-question is answered by the method defined in section 1.3. The research questions and corresponding chapter numbers are used as presented in section 1.2. The outline for these chapters is as follows. First, the method is further defined and discussed. Then, the results are shown and evaluated, followed by the conclusions. Chapter 8 answers the main research question. The findings of each chapter are used in the following chapters.

2
Theoretical framework

In this chapter the theoretical framework used to answer the research questions is elaborated. First, thermal comfort will be discussed. Then, studying air velocity is addressed. It is followed by Philippine vernacular architecture and its use of design strategies before the chapter is ended with a summary of the conclusions.

2.1. Thermal comfort in the Philippines

To be able to study the influence on thermal comfort of design strategies, the concept of thermal comfort is discussed. First, the theory is elaborated. Then, the Philippine climate is addressed. The section is concluded with a discussion of the comfort model.

2.1.1. Thermal comfort theory

The term thermal comfort is used in general for describing the state of mind related to its thermal environment. This state of mind is influenced by thermal sensations, psychological and physiological parameters. Thermal sensations are influenced by the heat balance of the body. It aims for thermal neutrality (equilibrium) between the heat produced (or gained) and heat loss of the body. Psychological parameters deal with aspects like expectations. The physiological parameters are defined by the response of the body to the environment, i.e., if it can adapt naturally. To understand the mechanisms influencing the conditions related to thermal sensations, these are discussed first. The psychological and physiological parameters are incorporated in the comfort model.

Heat exchange mechanisms

Two types of parameters influence the heat balance of the body. These are personal and ambient parameters[9]. The ambient parameters are temperatures, air velocity and relative humidity. These are the parameters that can be controlled in a building. The personal parameters are clothing insulation and metabolic heart rate. On a more specific level; age, food and gender could also taken into account. If these are not in equilibrium, we heat up or we cool down which causes discomfort [9].

The four laws of thermodynamics provide the basis to relate heat and temperature to energy and work, exchange and equilibrium. The main mechanisms regarding heat exchange are elaborated below. While they have different characteristics, they often occur at the same time and influence each other.

- **Thermal convection** - Heat transfer by carrying it along the flow of matter, is called thermal convection. This flow can be caused by external or internal processes like buoyancy forces when the thermal energy expands the fluid.
- **Thermal conduction** - Also called thermal diffusion, is the heat transfer by exchanging kinetic energy of particles by collisions. This takes place within bodies, matter or the boundary of two systems. The heat flows to reach equilibrium between the particles or bodies in that system.
- **Thermal radiation** - The transfer or energy by photons in electromagnetic waves due to thermal motion of matter. This transfer occurs through any transparent medium like fluids, gas or solid and does not need matter to travel. The amount of heat emitted of a material is dependent on its temperature and the property called the emissivity factor. For most materials this is around 0.9. An example of an exception is shiny materials, with a factor of 0.05.
- **Phase change** - When a material changes its phase, energy is needed while the temperature stays constant. This energy is needed to change the bond between the molecules.

Ambient thermal comfort parameters

Several expressions are used to describe ambient thermal comfort parameters or a combination, influencing heat mechanism and the heat balance of the human body. The primary parameters are elaborated below.

- **Dry-bulb temperature** - Dry-bulb temperature is considered the true temperature of the air. It is measured by a thermometer which is exposed to air but shielded from radiation and moisture. The dry-bulb air temperature is influenced by thermal conduction of heat by exchanging it to the human body and environment. It is also influenced by convection which transports heat away or to the object.
- **Mean radiant temperature** - The mean radiant temperature describes the influence of thermal energy or heat radiated by matter. It uses the weighted average of the radiant surface temperatures enclosing a zone in steady state conditions [9]. Since the human skin is very perceptible to radiant heat, the radiant temperature has a significant influence.
- **Operative temperature** -To establish a better indication of the temperature that is experienced, the operative temperature is defined. It knows multiple definitions. The most straight forward one uses the average of the mean radiant temperature and the dry-bulb temperature in a zone.
- **Relative Humidity** - A way for humans to lose heat is by the evaporation (phase change) of sweat. For this process to happen, the air should be able to absorb the vapour. The relative humidity expresses

the amount of water vapour in the air, compared to the maximum amount of water vapour that the air can absorb. Since the latter is dependent on air temperature, relative humidity is influenced by temperature. To indicate the total mass of water vapour present in a volume of air, the absolute humidity is used. It is the mass of the water vapour, divided by the volume or air and water vapour mixture. This value is more constant compared to the daily drops and rises in temperature.

- **Air velocity** - Is the rate of air movement to a given distance over time. An increase of air velocity increases the process of thermal conduction or sweat evaporation from the human body and building surfaces to the air. It also increases the thermal convection from outdoor to the indoor environment for example.

2.1.2. Philippine climate

The Philippine climate is shortly elaborated and related to the housing type and area. In appendix A, more information is provided regarding the climate data used later in this thesis. The national Meteorological and Hydrological Services of the Philippines [32] is used for the climatic review.

Classification and seasons The Philippine climate can be classified by tropical and maritime. It is characterized by relatively high temperature, high humidity and abundant rainfall [32]. Based on distribution of rainfall, four climate types are recognized. The climate can be divided into two major seasons, based on rainfall and temperature. One, the rainy season from June to November. And two, the dry season from December to May [32]. The dry season can be divided into a cool dry season from December to February, and a hot dry season from March to May. The latter is considered as summer and experienced as the most uncomfortable [32].

Humidity Due to the high temperature and its location being surround by water, the Philippines has a high relative humidity. The monthly average lies between 85 percent in September and 71 percent in March. The combination of a high temperature and relative humidity in the Philippines results in the climate being experienced as very hot [32].

Typhoons Typhoons influence a significant portion of the rainfall, humidity and cloudiness of the Philippines. They originate around the Marianas and Caroline islands. They follow a path Northwest, sparing the island of Mindanao mostly. The recorded paths per month of the typhoons are illustrated in figure A.3.

Monsoon The Philippines are subject to the climate phenomenon of the monsoon. It describes seasonal changes in atmospheric circulation and precipitation. The monsoon is caused by unsymmetrical heating of air by the warm seas in the south and cooler lands in the north. The summer monsoon from late April to October is coming from the west and south-west. The warm, sea air filled with water vapour cools down when it goes north over land. As a result, precipitation increases. The winter monsoon comes from east or north-east direction from late October to April [12]. It is formed over Siberia and northern China. The wind is cooler and precipitation decreases.

Temperature At or near sea level, the annual temperature is observed to be generally the same in the Philippines. Even in the most northern and southern stations, the differences found are insignificant [32]. Significant differences are only found when a difference in altitude is present. As a rule of thumb: with every 1000m of elevation the temperature decreases with 6 to 10 degrees. For low-lying areas therefore, an example set of temperatures is applicable.

Wind direction The monsoon causes the wind to have two main directions which are in opposite direction. The wind is coming from the east or north-east and west or south-west. Figure 2.1 shows an example of wind speed, frequency and direction from Manila. As can be seen, the wind is coming from east and west for the majority of the hours. However, a considerable smaller portion comes from the other directions with a relatively evenly spread. The wind direction is influenced by obstacles like mountains or buildings [43]. However, these influences are location specific and should be taken into account when relevant.

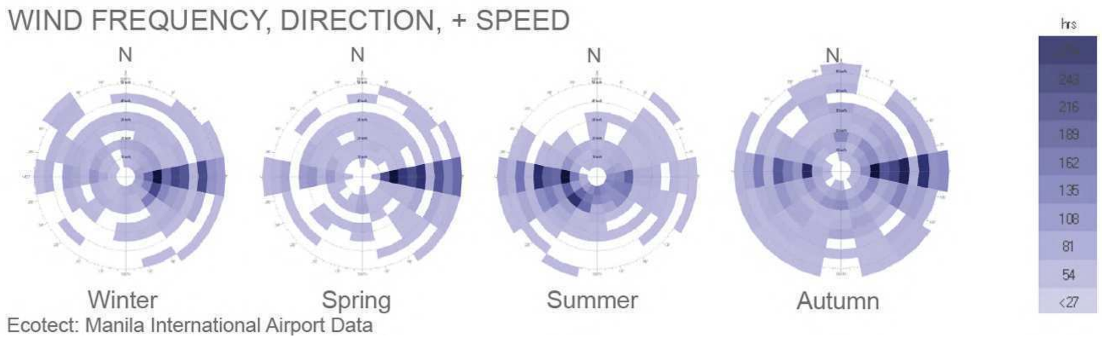


Figure 2.1: Wind frequency, direction and speed of Manila [5].

Climate conclusion

The climate of the Philippines can be characterized by high temperatures, high humidity and abundant rainfall. The temperatures found in low-lying Philippine areas are the same and therefore generally applicable. Two main wind direction are caused by the monsoon. These are winds coming from east or north-east and south-west or west and depend on the time of the year. Evenly spread, smaller amounts of wind comes from the other directions, these are considerable as well. Location based influences like mountains can change the main directions of the wind, and should be taken into account when relevant.

2.1.3. Comfort model

In order to assess thermal comfort, multiple models have been developed. They are introduces first, before they are discussed and a selection is made.

The predicted mean vote model

The first extensively studied thermal comfort model is the predicted mean vote (PMV) model. It is based on experiments involving over a thousand subjects being exposed to well-controlled environments [29] [10]. It showed that comfort appreciation is predictable by a function of activity, clothing and the four classical thermal environmental parameters: air temperature, mean radiant temperature, air velocity and humidity. The comfort appreciation is indicated by a description and numerical value, illustrated in figure 2.2. Since comfort appreciation is different per person, a percentage of people dissatisfied (PPD) is used. This is 5 percent for a neutral appreciation.

Description	Numerical value
Hot	3
Warm	2
Slightly warm	1
Neutral	0
Slightly cool	−1
Cool	−2
Cold	−3

Figure 2.2: PMV comfort scale used in ASHRAE

The PMV model has been an international standard since 1980. However, several studies [26] showed that the PMV model does not give correct predictions compared to field studies in several climates and buildings. This resulted in the development of improved PMV models or alternative models.

For naturally ventilated buildings in hot climates the extended PMV model (ePMV) has been introduced by Fanger and Tofum [29]. This model takes into account an expectancy factor e_p by a multiplication of the PMV. The expectancy factor is based on local climate and popularity of mechanical conditioning. By defining an e_p value per situation or country, the ePMV has shown to agree well with available quality field studies [29]. It has to be noted that a decimal change in the expectancy value has a tangible result on comfort, resulting in strong over- or underestimations [9].

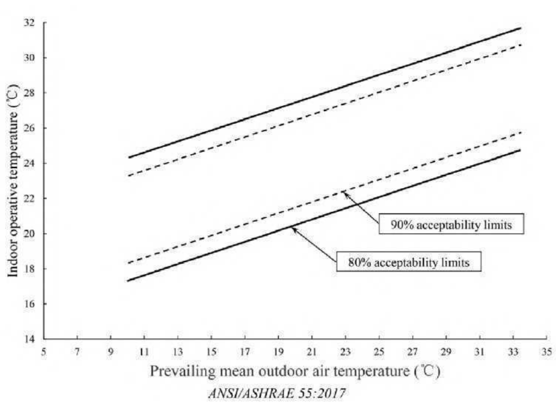
$$ePMV = e_p \cdot PMV$$

The PMV en ePMV model have limitations regarding comfort in naturally ventilated buildings in hot climates. Since they are based on a steady state balance approach in stable controlled environments, they do not take the adaptability of people into account. For example, if it is hotter, people tend to slow down their activities and the estimated metabolic rate in the PMV model is not correct. While this is just one example of adaptability, their accumulation has shown to influence comfort significantly [26]. This adaptive idea, led to the adaptive thermal comfort approach.

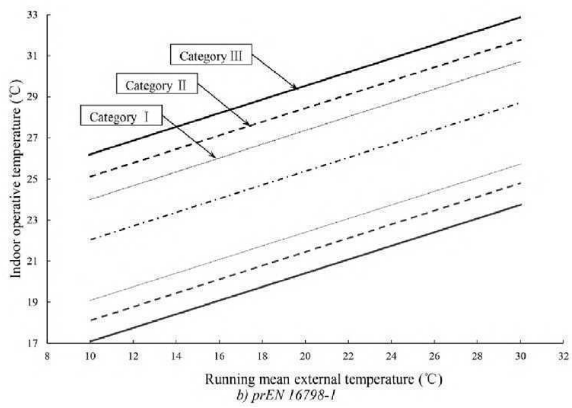
The adaptive thermal comfort model

The fundamental assumption of the adaptive approach is as follows. If a change occurs that produces discomfort, people react in ways which tend to restore their comfort. As a result, the acceptable comfort range is widened.

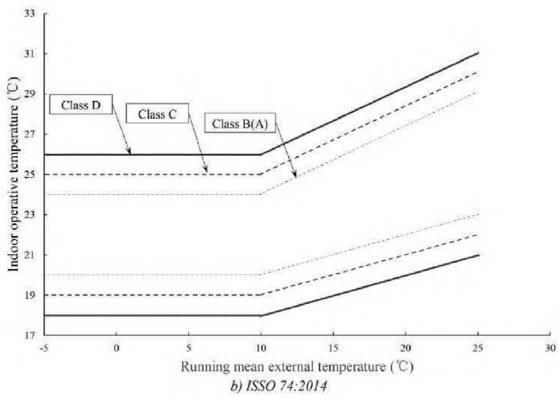
Based on field studies, it was found that the neutral temperature is related to the mean average of the outdoor temperature with a comfortable range of +/- 2 °C. It uses dry-bulb temperature, radiant temperature and air velocity. If the building gives control to change the conditions, this range can be increased up to 4 degrees. Figure 2.3b illustrates an example of the adaptive thermal comfort model with the neutral temperature and comfort ranges. Humidity is not taken into account in the adaptive thermal comfort model. It is taken into account by adjusting the model for humid climate types as will be discussed later.



(a) ANSI/ASHRAE adaptive comfort chart [6].



(b) European 16798-1 comfort [6].



(c) Dutch model, ISSO 74:2015 [6].

Figure 2.3: Comfort models illustrated as charts in the different codes [6].

Adoption in building codes The adaptive thermal comfort model gained momentum since its development. This resulted in adoption of the model in multiple building codes. Several examples are illustrated in figure 2.3. The comfortable range of indoor operative temperatures is plotted over the horizontal mean outdoor temperature. As can be seen, different comfortable ranges are used based on applicability for building types, use classes or acceptable percentage limits. Since these models are intended for different source regions and based on data of different field studies, difference in approximate equations are found. However, the different models result in roughly the same adaptive temperatures. This reinforces the robustness of the theory and regulatory documents [6]. However, the adaptive thermal model is also being criticised. It is stated that the approach is too simplified or needs more research. In addition, several studies [44] [47] [27] and [26] state that the model should be adapted to comply with field studies for hot and humid climates.

Adaptive model for hot and humid climates Toe [44] studied how the adaptive thermal comfort model should be adapted for hot and humid climates. The conclusions are presented in the list below. Figure 2.5 shows the field study results used and relevant neutral lines. The outdoor average temperature range of the Philippines is indicated in red.

- The neutral line for hot and humid climates is based on the field study results for hot and humid climates. Figure 2.5 illustrates this line.
- The upper comfortable limit is defined by the neutral temperature minus 0.7 °C for an 80% comfort vote.
- No lower comfortable temperature limit is observed in hot and humid climates.
- With an indoor air velocity of: v > 0.65 [m/s], the upper comfortable limit can be increased above the neutral operative temperature.

Many studies showed the significant contribution of indoor air velocity to increase the comfort range in hot climates [26] [44]. For example, Nicol [26] showed that an air velocity of 0.45 m/s in hot climates increases the comfortable temperature by 2 °C. From a theoretical analyses and assuming a constant air velocity, the allowance is raised by the relation depicted in the graph of 2.4 [26]. The EN15251 comfort model uses the same approach and values. The ASHRAE uses several steps to increase comfort by wind speed.

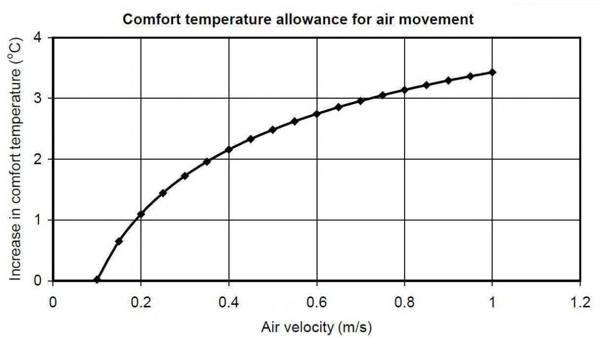


Figure 2.4: Increase in comfort temperature with air velocity [26].

Comfort model selection

Since the PMV and the adaptive thermal comfort models comply with field studies, the idea behind the models is compared to align with the living conditions in the intended housing typology. The PMV model is intended for controlled environments while the adaptive model is intended for adaption to the outdoor environment. Since living and working in low-income and sub-urban and rural areas is usually not done in controlled environments, the adaptive comfort model is selected.

If the available adaptive comfort models are compared to the adoptions for hot and humid climates, the EN15251 model shows representative results with a slight overestimation of comfort. This is illustrated in figure 2.6. The EN15251 upper comfortable limit is plotted over the mean outdoor temperature of the Philippines. As can be seen the lines are almost identical. However, Toe [44] recommended to decrease this neutral temperature with 0.7 °C. Therefore, comfort is deemed slightly overestimated. To take air velocity into account, a continuous relation of the comfort range to air velocity is deemed more realistic than a step wise function. Since the EN15251 model shows representative results and uses a continuous relation to air velocity, it is selected for this study.

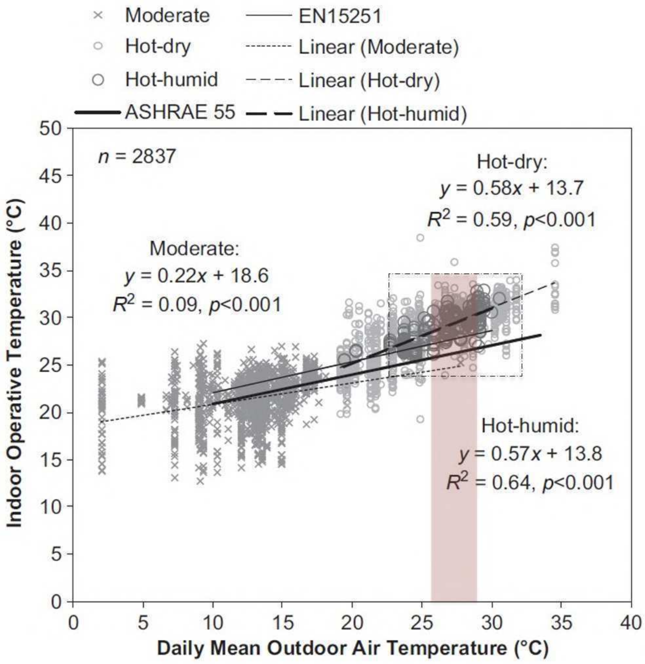


Figure 2.5: Results and neutral line per climate type [6]. The red area indicates the mean outdoor temperature range of the Philippines.

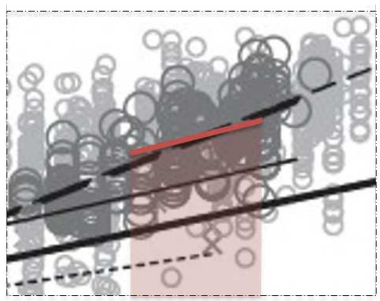


Figure 2.6: The EN15251 80% upper comfortable limit temperature [°C] plotted as a red line over the outdoor temperature range of the Philippine.

Conclusion comfort model

Thermal comfort knows several concepts to assess the state of mind to its thermal environment. The adaptive approach is selected because it complies with field studies and is in line with the living conditions of the studied housing typology. The adaptive model relates a +/- 2 °C comfortable range to the mean average of the outdoor temperature. If the adoptions for hot and humid climates are taken into account, the EN15251 adaptive thermal comfort model shows representative but slightly overestimated comfort indications. In addition, the lower comfortable limit is removed.

2.2. Studying air velocity

In this section, knowledge necessary to study air velocity and flow patterns in buildings is addressed. First, aerodynamics and its principles is introduced. Then, the use of computational fluid dynamics (CFD) is discussed.

2.2.1. Aerodynamics

Aerodynamics is a branch of fluid dynamics and studies the movement of gasses. If the movement of gasses in buildings is studied, the continuum assumption is used. This assumption neglects the discrete behaviour of molecules and allows properties as density and flow velocity to be defined. These properties can then be used in the dynamics conservations laws of mass, momentum and energy. When the flow is much lower everywhere then the speed of sound, an incompressible flow can be used. This means the density does not change in the flow and allows a simplified version of the differential equations to be solved.

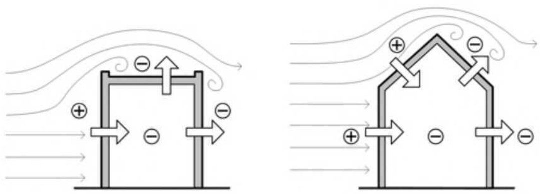
- **Laminar or turbulent flow** - A laminar flow is characterized by the flow following smooth paths in layers with little or no mixing. Turbulent flow is in contrast with the laminar flow. It is a rough flow with adjacent layers mixing and chaotic changes in pressure and flow velocity.
- **Reynolds number** - The Reynolds number, describes the relation between the inertia force versus the shearing force. E.i. the speed of the flow relative to the viscosity. It relates the speed of the flow to the occurrence of laminar or turbulence flow [4].
- **Boundary layer** - The boundary layer concept refers to the layer close to the boundary. In this layer, the effects of viscosity are significant. It describes the different flow in this region compared to the undisturbed free flow stream. It is defined by the particles reaching 99% of the free stream velocity.

- **Aerodynamic forces** - Air flowing around and past the surfaces of a body, exert a force on it. Drag is the force in parallel direction to the wind while lift is the force in perpendicular direction. Drag force is proportional to the velocity for a laminar flow, and is proportional to the squared velocity for a turbulent flow.

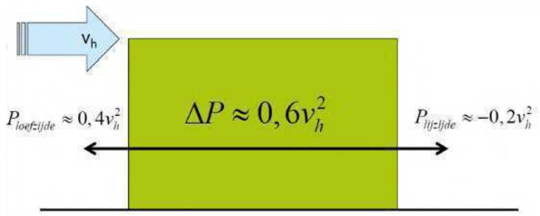
2.2.2. Indoor air velocity

To provide an air flow, a pressure difference and a path to solve it are required. Two natural ways are used to provide this pressure difference. These are wind driven ventilation and buoyancy driven ventilation.

Wind driven ventilation Since the building forms an obstacle for wind, a higher pressure is created on the windward side and a lower pressure is created at the leeward side. This is illustrated in figure 2.7a. The pressure difference is found to be relatable to the squared wind speed at the roof edge as illustrated in figure 2.7b. To estimate the volume of air going in through the openings based on this pressure difference, Bernoulli's equation can be used. Bernoulli uses the concept of conservation of energy and mass along a streamline to relate the pressure, the potential and kinetic energy of the flow through the area. An incompressible flow is used without viscous forces. Applying these equations to the building and simplifying, resolves in the equation written below. This is known to result in good estimates of volumes of air for simple cases. However, the flow is not defined and eaves, orientation and roof angle are not taken into account



(a) Pressure development on facades due to wind [41].



(b) The pressure difference related to wind speed at roof height [45].

Figure 2.7: Pressure development and difference related to a reference wind speed at roof height.

$$V \approx v_h \cdot C_d \cdot A_e$$

Where

V = Air volume $[m^3/s]$
v_h = Wind speed at roof edge $[m/s]$
A_e = Equivalent opening area defined as $1/A_e^2 = 1/A_1^2 + 1/A_2^2$
C_d = Discharge coefficient between 0.65 and 0.8

Buoyancy driven ventilation Buoyancy driven ventilation is also called stack effect. It is caused by differences in indoor and outdoor temperatures which create pressure differences. When the indoor temperature is higher than outside, the higher pressure will cause it to rise and exit the building. It is then replaced by cooler, denser air from below creating the so called stack effect. The stack effect is dominant during periods of low wind speeds [1]. It was found that the difference in temperature and vertical distance between in and outlet determine the efficiency of stack ventilation [1]. Since in tropical regions no substantial differences between in and outdoor environments are present, studies agreed that cross ventilation is a more effective approach than stack ventilation [13] [3]. In addition, our single-story housing provides little vertical distance and the velocity should be above 0.2 m/s to increase the comfortable limit. Therefore, no significant contribution of stack effect to air velocity is expected. Initiating air movement however does contribute to heat dissipation and therefore still contributes to increase comfort. Especially when no wind is present this effect

2.2.3. Computational fluid dynamics analyses

To study the flow of air through a building computational fluid dynamics (CFD) analyses can be used. In CFD, modelling assumptions influence the result significantly. Validation of the results to wind tunnels test is therefore necessary.

2.3. Philippine vernacular architecture and its design strategies

In this section, Philippine vernacular climate responsive design strategies are reviewed by a literature study. The Philippine vernacular buildings are introduced first. It is followed by a list of the used strategies.

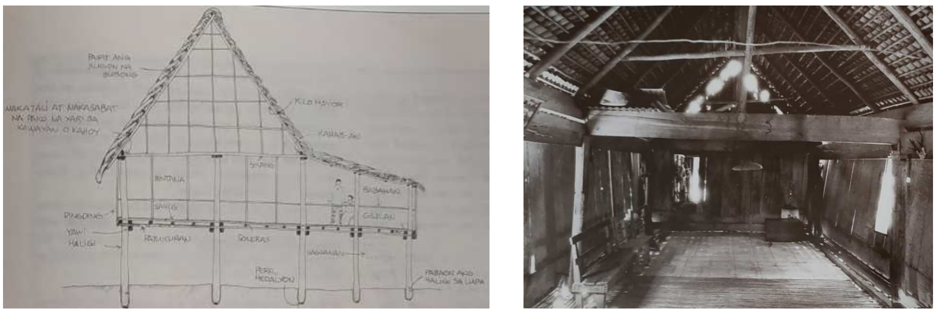
2.3.1. Philippine vernacular buildings

The bamboo hut

One main vernacular building was found everywhere in the archipelago [33]. Perez [33] used the term "bamboo hut" to describe the following similar characteristics of this building type. It was a hut constructed of wood, bamboo and thatch. It used a single room as depicted in figure 2.9b. It rested on stilts and was covered by a steep roof. The roof could be hipped, pyramidal or gable shaped and continued in eaves. Although having many similarities, further distinction is made based on location and other characteristics [33]. For example, the bahay kubo (cube house), mountain dwellings and island dwellings [33]. These are illustrated in figure 2.8. Figure 2.9a shows a section of the bahay kubo.

(a) A mountain dwelling found in Cordillera [33]. (b) A bahay kubo found in Panay [33]. (c) An island dwelling found in Sulu [33].

Figure 2.8: Several bamboo hut types as recognised by Perez [33].



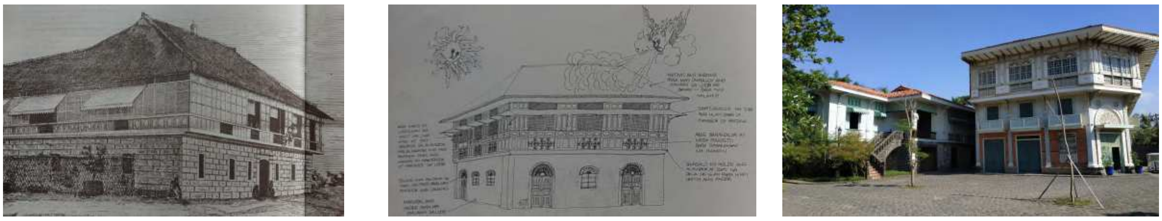
(a) Section of a bahay kubo [33]. (b) Room of a bahay kubo [33].

Figure 2.9: Bamboo hut section drawing and picture of a room [33].

The bahay na bato

The bahay na bato is the product of evolution of the bahay kubo with a mixture of Spanish architecture. Due to the Spanish influences, it is up to debate if it can be considered real vernacular architecture. However, it also went through an evolutionary process of hundreds of years, mainly used local materials and is known for its passive design performance. It is therefore also reviewed for its use of design strategies.

It is characterised by a hipped roof, elevated living quarters, a post and lintel construction and a stone facade on ground level. The introduction of stone to the building went through an evolutionary process. Stone was introduced to increase fire safety but comfortability and earthquake behaviour limited its use to the first floor height. The houses were mostly designed in a town setting for the rich. Abundant space, rooms for servants and multiple prestige rooms were therefore provided. Through time it has known many shapes and forms. Figure 2.10 illustrates several of its appearances.



(a) A typical early form of a bahay na bato [49]. (b) The all weather bahay na bato [49]. (c) A preserved bahay na bato in urban setting.

Figure 2.10: Several bahay na bato appearances.

2.3.2. Philippine vernacular design strategies

Several design strategies are mentioned by scientific studies regarding Philippine vernacular architecture [21] [28] [12]. More elaborate analyses were found in architectural books [33] [49]. The found climate responsive strategies are presented below.

- Facade openings for natural ventilation and lighting. Sometimes in the form of a removable wall panel
- Permeability of floor, wall and roof to provide natural ventilation.
- Material permeability to cool air.
- Eaves to provide solar shading and rainwater discharge.
- Building on stilts to increase natural ventilation and prevent flood damages.
- The callados concept (walls not to ceiling) to enhance natural ventilation.
- Building orientation and location for natural ventilation and solar shading.
- Hipped and high pitched roof for protection against solar radiation and providing stack effect.
- Light building materials to have a light thermal mass.
- Evaporative cooling for passive cooling.
- Light colour use for passive cooling.
- Courtyard induced ventilation for natural ventilation.
- Roof insulation by a thick thatch roof to decrease solar gain.
- Using orientation and location for solar shading and natural ventilation.
- Adjustable openings like jealousies for natural ventilation and lighting.
- High ceiling, no ceiling or permeable ceiling to increase natural ventilation.
- Big openings between rooms in houses for natural ventilation.
- A volada (balcony with facades) for solar shading, thermal insulation by design and dust and noise protection.
- A corridor for solar shading and thermal insulation by design.
- An opening between the facade and roof for natural ventilation and natural lighting.

2.4. Conclusions

To assess comfort, the European adaptive thermal comfort model (EN15251) without lower comfortable limit is selected. It is shown to be representative with a slight overestimation for the hot and humid climate of the Philippines. It uses an operative comfortable temperature range around a neutral temperature. The operative temperature is the average of the dry-bulb temperature and the mean radiant temperature. The neutral temperature is related to the mean outdoor temperature. The range is increased by air velocity.

The climate of the Philippines can be characterized by high temperatures, high humidity and abundant rainfall. The temperatures found in low-lying Philippine areas are the same and therefore generally applicable in these areas. An opposite sided main wind direction is caused by the monsoon. The winds are coming from east or north-east and south-west or west and depend on the time of the year. A considerable evenly spread smaller amount comes from the other directions.

Wind driven ventilation mode is selected to study air velocity. Buoyancy driven ventilation is not expected to significantly contribute to air velocity, but should be provided to enhance heat dissipation.

3

Comfort performance of housing type

In this chapter the comfort performance of low-income, sub-urban and rural housing is discussed. The following sub-research question is thereby answered: *"What is the thermal comfort performance of this housing type?"* To answer this question thermal measurement are performed on a house in San Remigio, Cebu, the Philippines. In section one the method is discussed and the hypotheses formulated. The results are discussed in section two. The findings of this chapter are concluded in section three.

3.1. Method

To study the thermal comfort performance, in-situ measurements are performed. First the performed measurement are introduced. The measurement variables and equipment are addressed next. The measurement plan is defined in sub-section three. The section is concluded by definition of the hypotheses.

3.1.1. Introduction measurements

The house measured is depicted below in figure 3.1. Information about duration and location of the measurements is presented in the table of figure 3.2. The duration addresses two day and night cycles. The building is regarded as an example of sub-urban and rural, low-lying and low-income housing for the following reasons: it is located in a low-lying and rural area, the dimensions are close to our intended housing typology, and its materials and construction method is low-income based. Air velocity is measured in a half-hour time window at multiple locations in the building.

Figure 3.1: Measurement object of housing type.

duration	location	start date	start time	end time
48 hours	San Remigio, Cebu Island, Php	02/11/2018	17:00	17:00

Figure 3.2: Measurement specifications of the object.

Additional measurement objects

In addition to the previous object, a bahay na bato and a bamboo hut in a resort were measured. They were selected on their use of vernacular design strategies, resemblance to Philippine vernacular architecture and availability. The buildings are illustrated in fig 3.3 and their measurement specifications in the table of figure 3.4. Since their results did not significantly contribute to the conclusions, the results of these measurements are shown in appendix B. The air velocity measurements of the bahay na bato are most relevant and discussed more elaborately in appendix B.2.2.

(a) Bahay na bato.

(b) Bamboo resort hut.

Figure 3.3: Additional measurement objects. The results are shown in appendix B.

building	duration	location	start date	start time	end time
bahay na bato	3 hours	Las Casas du Acuzar, Bataan, Php	13/10/2018	14:00	17:00
bambuu hut resort	15 hours	Bagac, Bataan, Php	12/10/2018	17:00	08:00

Figure 3.4: Measurement specifications of additional measurement objects.

3.1.2. Measurement variables and equipment

As explained in section 2.1, the relevant comfort parameters are dry-bulb temperature, radiant temperature and air velocity. The equipment, the variable(s), the range, interval and accuracy are shown in the table of figure 3.5. Relative humidity is also measured since it indicates a thermal sensation and is inversely related to the dry-bulb temperature. A 10-minute interval is used to obtain a representative indication of the performance over time.

amount	Machine	Measures	Range	Accuracy	interval	brand	type
4	Hobo	Temperature [C°] and RH [%]	-20 to 70 [C°] and 5 - 95 [%]	+/- 0.35 [C°] +/- 2.5 [%]	10 min	Hobo	U12-012
10	I-button	Temperature	- 15 to 46 [C°]	+/- 1.0 [C°]	10 min	I-button	Thermochron DS192
1	Infrared T	Surface radiation temperature [C°]	- 50 to 380 [C°]	+/- 2 [C°]	10 min	Infinite	EAN 0644221184288
1	Aimometer	Wind speed [m/s]	0.8 - 30 [m/s]	+/- 5 %	1 min duration	Aimometer	MS6252A
1	Anemometer	Wind speed [m/s]	0.2 - 25 [m/s]	+/- 5 %	1 min duration	Extech	SDL350

Figure 3.5: Specifications measurement machines and logging

Test measurement A test measurement of dry-bulb temperature is performed to validate the accuracy of the equipment. The observed accuracy is +/- 0.7 °C for the I-buttons except one. The result of this I-button are therefore calibrated to the mean of the other temperatures by adding 1.2 °C.

Radiant temperature By placing the I-buttons with their sensors against the material surface, the surface temperature can be measured. The radiant temperature can then be determined by taking into account the emissivity factor (usually 0.9). For rough or curved surfaces, it is expected to be less accurate due to the surfaces not being in direct contact. As a result, the air in between can be replaced by fresh air, underestimating the results during hot periods.

Air velocity Based on availability, the Aimometer is used to measure the air velocity. However, the range of the Aimometer might not be sensitive enough (v > 0.8 m/s) to measure the expected indoor wind speeds. Since it measures a one-dimensional direction of the velocity, multiple directions per location are measured.

3.1.3. Measurement plan

In this section, the building is elaborated and the measurement plan discussed.

The object

The building is illustrated in the pictures of figure 3.6. Its surroundings are indicated in figure 3.7. As can be seen, the building uses modern galvanised iron (GI) roof panels, three layers hollow core cement blocks stacked on the ground floor and sawali mats (woven bamboo slats) for the facades. The use of GI roof panels and sawali mats makes it a lightweight building. The floor is made of cement. More information about the building and choices for the materials is provided in appendix section B.1.

The following design characteristics and strategies are recognised. An operable opening and a door on the front north-east facade, a hipped roof of 30 degrees, eaves of 0.8m with a 30 degree angle and permeable facades. Between the roof and facade, a 30cm opening is present all around the building as illustrated in figures 3.6f and 3.6g. The location is close to sea but on higher ground. The rural setting and orientation is illustrated in figure 3.7. As can be seen, the building is not protected by shading of the surroundings during the day. The kitchen is located outside. The electrical appliances are a speaker set and a small tv. A family consisting of two parents and two children inhabits the building.

Measurement plan

The measurement plan is depicted in figure 3.8, using the equipment and intervals depicted in figure 3.5. The locations of the loggers are discussed below.

Placing equipment To measure the dry-bulb temperature in every room, at least one meter is placed per room. They are situated away from appliances generating heat to avoid disturbances. In the rooms that are used for sleeping, the height is adjusted to sleeping level. In the living zone, meters on multiple height are used to see if the temperature is influenced by height. To determine the radiant temperature a temperature logger is placed on the surface of every roof panel and most of the facades. The directions of the panels are indicated by abbreviations. For example, s-e indicates the panel which faces the south-east direction. Multiple data loggers are placed outside to avoid location based influences.

(a) Front facade north-east. (b) South-west facade. (c) South-east facade.

(d) Interior. (e) Facade permeability. (f) Roof material and structure. (g) Opening between eave and wall.

Figure 3.6: Illustrations of the measurement building.

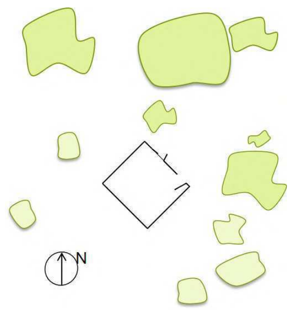
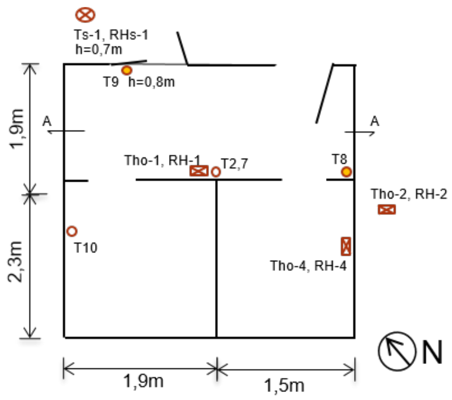
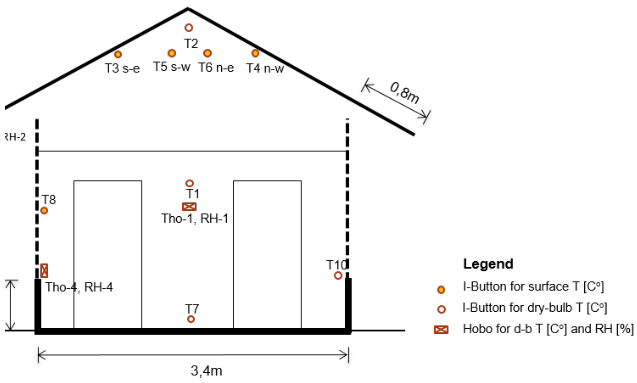


Figure 3.7: The surrounding of the measurement object. In green the trees. The height is indicated by the shade of green used. Only the trees in the north are higher than the building.



(a) Location of equipment in the floor plan.



(b) Location of equipment in the 'AA' cross-section.

Figure 3.8: Measurement plan in cross-section and floor plan.

Use of house The inhabitants occupied the house during the measurements. The inhabitants opened the openings during the day and closed them during the night. As observed, living during the day was mostly done outside.

3.1.4. Measurement plan air velocity

To obtain an indication of the air velocity and flow through the building, the speed at several openings and rooms is measured. A single half our measurement period is used per building because the outdoor wind speed and direction are known to be quite constant in this range. To have a realistic indication with only one measurement machine, per location the velocity is measured for 1 minute in the relevant direction. Afterwards, the average is taken to determine the air velocity.

3.1.5. Hypotheses

The basis which led to the hypotheses are shortly discussed before the hypotheses are presented in italic. A distinction of day and night is used to refer to the hours with or without sunlight. Based on the sunrise (05:50) and sunset hours (17:25), day indicates the time range from 05:30 to 17:45 and night indicates the hours in between.

- The building is a lightweight structure and has low insulation values of the facades and roof. In addition, a permanent opening between the roof and facade in combination with a considerable permeability, allows heat to dissipate during day and night. Consequently, the following hypothesis is formulated. *"The building is responsive to the outdoor temperature."*
- During the day, the heat load on the building can't dissipate as easy as outside since no constant wind driven flow is allowed by the openings. During the night, the extra heat generated by people and electrics, cause more heat to be inside than outside. *"The indoor dry-bulb temperatures are higher than the outdoor dry-bulb temperature."*
- Since the insulation values of the facades and roof are low, the inside surface temperature are expected to rise up significantly. They follow the solar radiation load and orientation. The GI roof panels are subject to the most solar radiation and are therefore expected to heat up most. *"The inside surface temperatures are expected to increase significantly, dependent on solar orientation and load."*
- The heat radiated to the direct environment by the inside surface temperatures is expected to influence the dry-bulb temperature of the rooms. The air temperature rises accordingly by conduction of the heat to the environment. *"The inside surface temperatures influence the dry-bulb temperatures of the room correspondingly."*
- The high solar radiation load emitted by the GI roof panels, the short eaves and lack of openings to increase the upper comfortable temperature by providing velocity, cause the living room to be uncomfortable during the major part of the day. Since it is a lightweight building where air can constantly dissipate through the permeable walls, the heat is released easily when the night arrives. Therefore, for the major parts of the day, it is expected to be uncomfortable. *"The building is uncomfortable during the major part of the day."*
- As explained in section 2.2, the openings in combination with the pressure difference, result in a flow through the openings and house. Since the area is the smallest at the opening, the highest speed is expected. The area increases in between the openings through the house, therefore decreasing the speed. *"The air velocities measured are maximum at the openings and lowest in the rooms."*

3.1.6. Conclusion method

The comfort performance is measured by in-situ measurements of dry-bulb temperature, radiant temperature and air velocity. Based on a test measurement, the accuracy of the temperature meters is determined within a range of 0.8 °C. The inside surface temperatures are expected to be underestimated when rough or curved surfaces are measured. Due to availability, the Aimometer is used to measure air velocity. Its range of ($v > 0.8$ m/s) might not be sensitive enough to measure the air velocity.

The measurement plan is designed as follows. In every room a dry-bulb temperature meter is placed. In the living room the temperature is measured at different heights. The inside surface temperature of the roof panels and two facades are measured to obtain the radiant temperature. The outdoor temperature is measured at several locations to obtain a more reliable result on the outdoor temperature. One-minute average air velocity measurements are used at multiple locations to generate an indication of the velocity and flow in the building.

3.2. Results

In this section, the thermal performance results of the two-day field measurements are presented and discussed respectively. The following hypotheses are tested.

- *"The building is responsive to the outdoor temperature."*
- *"The indoor dry-bulb temperatures are higher than the outdoor dry-bulb temperature."*
- *"The inside surface temperatures are expected to increase significantly, dependent on solar orientation and load."*
- *"The radiant temperatures influence the dry-bulb temperatures correspondingly."*
- *"The building is uncomfortable during the major part of the day."*
- *"The air velocities measured are maximum at the openings and lowest in the rooms."*

3.2.1. Results

All the temperature results and the monthly average are plotted in the graph of figure 3.9. The in and outside dry-bulb temperature results are plotted in figure 3.10. Figure 3.11 illustrates the thermal performance of the building and indicates the surface temperatures by dashed lines. In these graphs the horizontal axis indicates the time. The vertical axis indicates the temperatures. The outdoor temperature results are discussed first so it can be used for discussion of the other results.

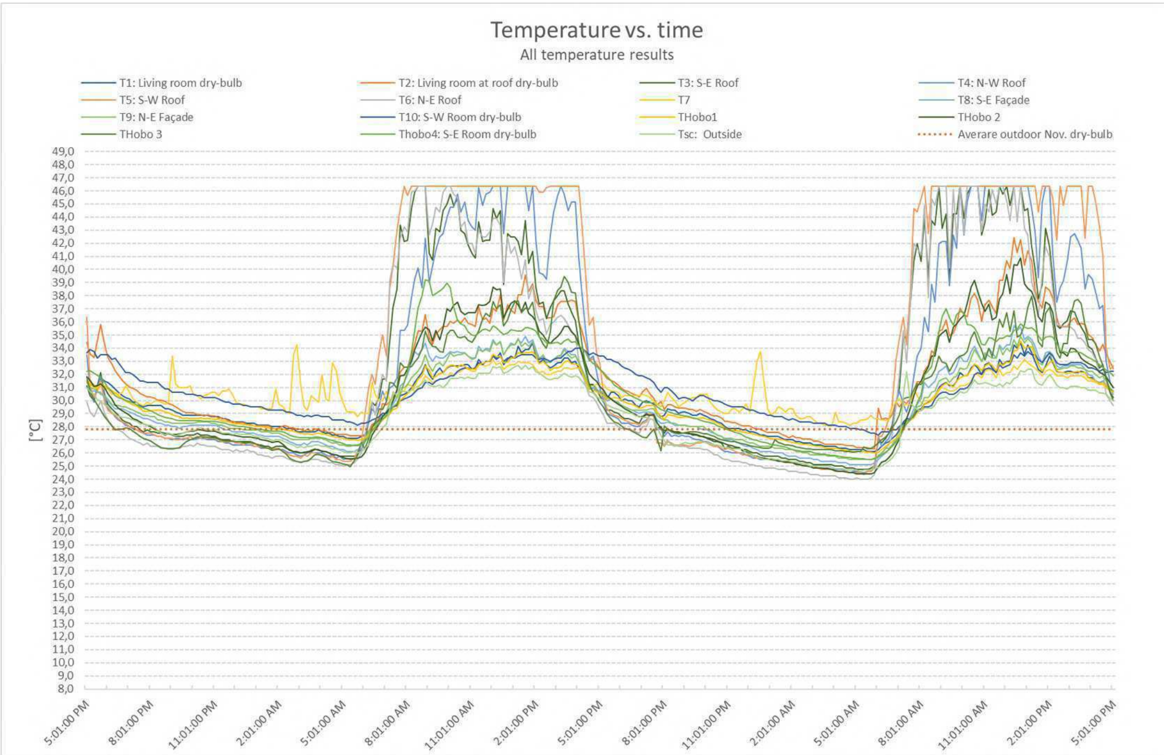


Figure 3.9: All temperature results plotted over time. The orange dashed line indicates the average temperature of the month November.

Outdoor temperature

Results The loggers T2, T3 and T San Carlos (Tsc) indicate the outside temperature. The outside temperatures are different during the day. E.g., T2 is significantly lower during the day than THobo 2 and THobo 3. TsanCarlos has lower values during the day than inside and than Thobo2 and Thobo1.

Discussion The unrealistic high outdoor dry-bulb temperatures during the day of Thobo3 and Thobo2 are explained by their location. Their attachment to GI panels covered it from rain but also caused it to heat up significantly due to the solar radiation. TsanCarlos was better protected versus solar radiation because it was placed under the kitchen under a cover. However, the cover is exposed to solar radiation coming from north east (in the morning) and heat by cooking. This explains the small peaks found in the morning. Since

TsanCarlos has the least influences from external factors which can be distinguished easily, it is used as the governing outdoor dry-bulb temperature.

Indoor environment results

Dry-bulb Temperature The inside dry-bulb temperatures, are indicated by T1, T2, T7, T10, THobo1 and THobo4. All the temperatures except T7 follow the same day and night pattern. They rise to a top during day and then cool down to their minimum point just after 5AM. T7 is the only temperature meter which performs fluctuating behaviour during the night with differences of 6 °C between peaks and troughs. During the night, the outside temperatures follow the same regression line as inside but about 2 °C lower. At 6 AM, the in and outside temperatures, start to increase again.

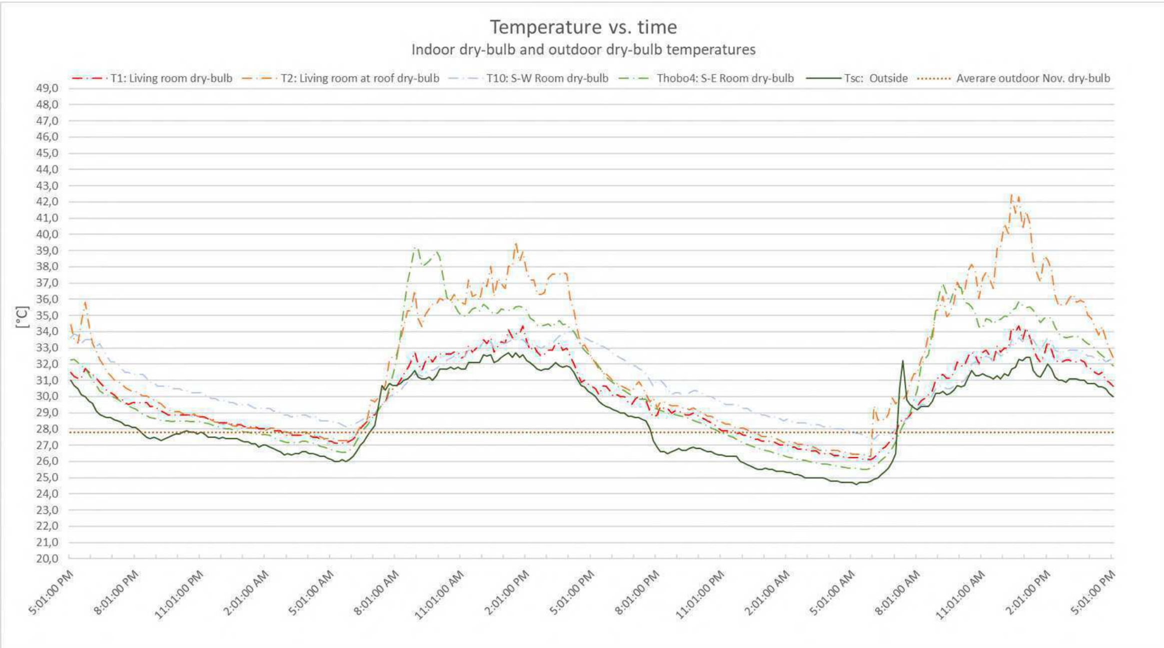


Figure 3.10: The plotted indoor and outdoor dry-bulb temperatures over time. The indoor temperatures are plotted as dashed lines and the outdoor temperature as the continuous green line.

During the day, the range between temperatures is several times greater than during the night. For example, T2, which is located just under the roof, is hotter with around 4 °C during the day. The range of the fluctuations is also greater than during the night. In night-time, the same regression line within a range of 1.5 °C is observed for all the temperatures except T7 and T10. T10 which is located in the west room is hotter than the other dry-bulb temperatures with about 1.5 °C.

Radiant temperature The radiant roof temperatures are indicated by T3 s-e, T4 n-w, T5 s-w and T6 n-e. They indicate the south east, north west, south west and north east roof temperatures. Logger T8 is from the south-east facade and T9 from the north east facade. All the temperatures follow the day and night pattern. They rise through the day to a maximum and than cool down to their lowest point in the early morning. The south-west and roof surface temperatures rise up to their maximum at 46.3 °C. During the day, the facade surface temperatures are significantly lower than the roof surface temperatures and are close to the indoor dry-bulb temperatures.

The peak of the south east roof panel is early in the day and at midday. The peak of the south west roof panel is during the whole day, and the peak of north west in the middle and end of the day. During morning and midday, the south east facade and north east facade show a temperature increase of one or several degrees Celsius more than the dry-bulb temperature increase.

Air velocity The air velocity measurement were all 0 m/s.

Thermal comfort performance In the graph of figure 3.11, the light green area indicates the comfort range of operative thermal comfort temperature for November. Since no air velocity is measured, this range is not increased by air velocity. As can be seen, at 8AM, all the indoor temperatures rise above the upper comfortable limit. The dry-bulb living room temperature (T1) increases with two to three degrees Celsius above the upper comfortable limit and is highest just after midday. All the surface temperatures are higher than the dry-bulb temperature of the living room.

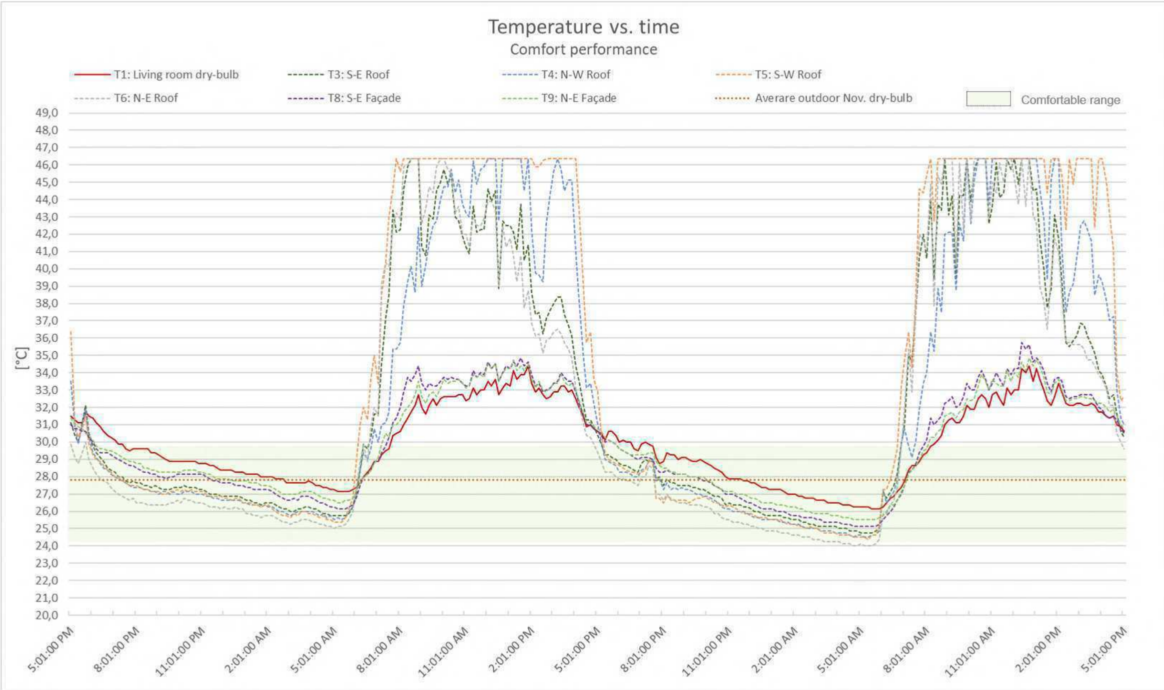


Figure 3.11: The comfort performance of the building. In light green, the comfortable temperature range. The surface temperatures are indicated by the dashed lines. The continuous line present the governing dry-bulb temperatures of the living room.

3.2.2. Discussion results

The results are discussed per hypothesis.

Building responsiveness to outdoor temperature The indoor dry-bulb temperature results show the same trend in rising and decreasing as outdoors except one. The short response time of less than half an hour is explained by its light weight structure and provision of natural ventilation. The fluctuating behaviour and increase of general temperature during the night of T7 can be explained by the uncontrolled environment of the measurement. It is placed close to the ground, making it susceptible to contact with animals or persons sleeping next to it. Another option would be that electrical appliances were moved. The hypotheses is therefore deemed as true.

Indoor dry-bulb temperatures higher than outdoor The hypotheses holds except for the small peaks. These are explained at the outside temperature discussion. Therefore, the hypotheses is tested as true.

The inside surface temperatures follow solar radiation The inside roof surface temperatures follow the orientation to the sun clearly. Several reached the limit of the equipment. The high temperature were also confirmed by indicative measurements using the infrared thermometer. The hypotheses is therefore tested as true for the roof panels.

The facade temperatures are both from the living room. They show a small increase in inside surface temperature which corresponds with the fluctuations of the living room dry-bulb temperature. It is expected that T8 did not increase significantly because the eave protected it from solar radiation. T9 did not because it was placed just underneath the opening. This shutter blocked the solar radiation.

The influence of radiant temperatures The heating up of T2 during the day can be explained by the role of the radiant temperature. Is it located close to the significantly hotter roof panels which emit a lot of radiant heat. In addition, the hotter rising air can not escape and is therefore trapped. As a result the temperature rises even more. Therefore, radiant temperatures influence the dry-bulb temperature significantly in the ridge.

The two facade temperatures measured don't increase significantly. However, the dry-bulb differences in temperatures of the room can be explained by their orientation and solar radiation. This indicates the influence of the inside surface temperatures on the dry-bulb temperatures. The rooms on the west show the highest temperatures in the afternoon and evening. The south east room show higher temperatures in the morning and midday and has a significant increase compared to the other rooms. The latter can be explained by its location close to the facade at a low height. This makes it susceptible for influence of solar radiation load. Based on the increase of temperatures inside the house on solar radiation and roof surface temperatures, the hypotheses is deemed true.

Air velocity No air velocity was measured. This is explained by the sensitivity of the Aimometer which is not sensitive enough to measure the low air velocities. However, the occurrence of a small breeze was experienced and observed by moving curtains due to wind during the measurements.

Comfort performance T1 is used as the governing temperature since it is in the living room and close to living height. The graph in figure 3.11 illustrates clearly the performance compared to the comfort range. As can be seen, the dry-bulb temperature is 3 to 4 °C higher than the upper comfortable limit temperature. Several roof surface temperatures are at least 16 °C higher than the upper comfortable limit temperature. Since the other surface temperatures are expected to be in the same range or higher than the indoor dry-bulb temperature, the house is uncomfortable during the day. It is most uncomfortable during midday when the dry-bulb temperatures and radiant temperatures are the highest. Since the level of discomfort is high and the days measured have average temperatures, its yearly performance is considered to be uncomfortable. The hypothesis is thereby tested as true with the specified addition.

3.2.3. Conclusion

The hypotheses were all tested as true with some small additions. The building has a short response time to the outdoor dry-bulb temperature and has a higher indoor temperature than outside. The inside surface temperatures follow solar radiation orientation except if they are blocked by eaves or shutters. The inside surface temperatures influence the dry-bulb temperatures of the rooms accordingly. They increase the temperatures during the day significantly. The high dry-bulb temperatures and radiant temperatures and the lack of air velocity, results in an uncomfortable building during the day and the least performance at midday.

3.3. Discussion

Two main principles are recognised in this building to increase comfort. These are providing natural ventilation and reducing heat absorption. Since no air velocity is measured, the upper comfortable limit is not raised. Furthermore, natural ventilation decreases the inside temperature to the outdoor temperature. Since the outdoor temperature also rises above the upper comfortable level, the necessity to increase the comfort limit is emphasized. The performance of the building is clearly influenced by solar radiation load. It increased the radiant and dry-bulb temperatures significantly. Reduction of heat absorption is therefore important to increase comfort.

Towards comfortable circumstances The dry-bulb living room temperature (T1) exceeds the upper comfortable limit with around 3 °C for most of the day. If the inside surfaces would be protected against solar radiation, the indoor surface temperature would be close to the dry-bulb temperature. To cover a 3 °C operative temperature exceedance, figure 2.4 shows an air velocity of 0.7 m/s to be necessary.

If the indoor environment would be the outdoor temperature. An air velocity of at least 0.5 m/s is necessary to cover the 2 °C exceedance during most of the day.

3.4. Conclusions

In this section, the findings op this chapter are concluded. The following question is thereby answered: *"What is the thermal comfort performance of this housing type?"*

The measurements on a house similar to our housing typology concluded to be uncomfortable during day time. Around midday the performance in indoor climate is at its lowest. Two phenomena influence this weak performance. These are too much heat absorption and too little ventilation. The indoor environment absorbs too much heat because the inside surfaces are not protected from solar radiation. This causes the inside surface temperatures to rise and the indoor environment to heat up significantly. Too little ventilation is recognised because the indoor temperature is several degrees Celsius higher than the upper comfortable limit. Providing air velocity is therefore expected to increase comfort significantly by raising the upper comfortable limit and allowing heat to dissipate. If the inside surface temperatures would be protected, an air velocity of 0.7 m/s is necessary to cover the exceeding 3 °C operative temperature.

4

Strategy selection and state of the art

This chapter answers the sub-research question: *"Which design strategies should be studied in this research to improve thermal comfort of this housing type?"*. Section one deals with selection of the design strategies for this study. Section two presents the state of the art of the selected strategies. Section three concludes the findings of this chapter.

4.1. Vernacular strategies selection

In this section, the selection process of the strategies is elaborated.

4.1.1. Criteria

Two criteria are used to select the strategies. The first criterium is based on the findings of chapter 3. It concluded that natural ventilation and heat reduction of solar radiation are the two phenomena to increase thermal comfort. The contribution of the strategies to these phenomena is therefore the first selection criteria. To provide useful design guidelines, applicability of the strategies on the housing typology is the second criterium. The housing typology is addressed in subsection 1.2.3.

4.1.2. Applying criteria

Using these criteria as a filter, the strategies stated in the list below remain. For example, using corridors for solar shading is not selected since the housing typology has too little space. The list found is similar to the strategies found by Gavieta [12] in his study for mass housing based on traditional design and indigenous materials using passive cooling techniques.

- Openings for natural ventilation
- Permeability of wall, floor and roof for natural ventilation and cooling of air.
- Building on stilts to increase wind speed.
- Orientation and location for natural ventilation and solar shading.
- Eaves for solar shading.
- Hipped and high pitched roof protection sun and rain and stack effect.
- The callados concept (walls not to ceiling) to enhance natural ventilation.
- Roof insulation by a thick thatch roof to decrease solar gain.

Since studying all these strategies is not feasible, further selection is necessary. Since the goal of this research is to improve comfort, their potential to increase comfort in the intended housing typology is the basis for further selection. Since few rooms are used and the dimensions are small, the influence of the callados concept is not deemed significant compared to the other strategies. To provide general applicable knowledge, using location specific elements is not possible. Location based influences are therefore not further studied. Permeability and openings both contribute to natural ventilation. However, the area which is open is much higher for openings than permeability. Its contribution to increase natural ventilation and thus comfort is therefore deemed significantly higher. After subtraction and translation of these, the following list remains for further study in this thesis. It should be noted that all the selected strategies were used in the bahay kubo. Thereby the title of this research is explained.

4.1.3. Selected strategies

- Openings
- Orientation
- Eaves
- Stilts
- Roof angle
- Roof insulation

4.2. State of the art of selected strategies

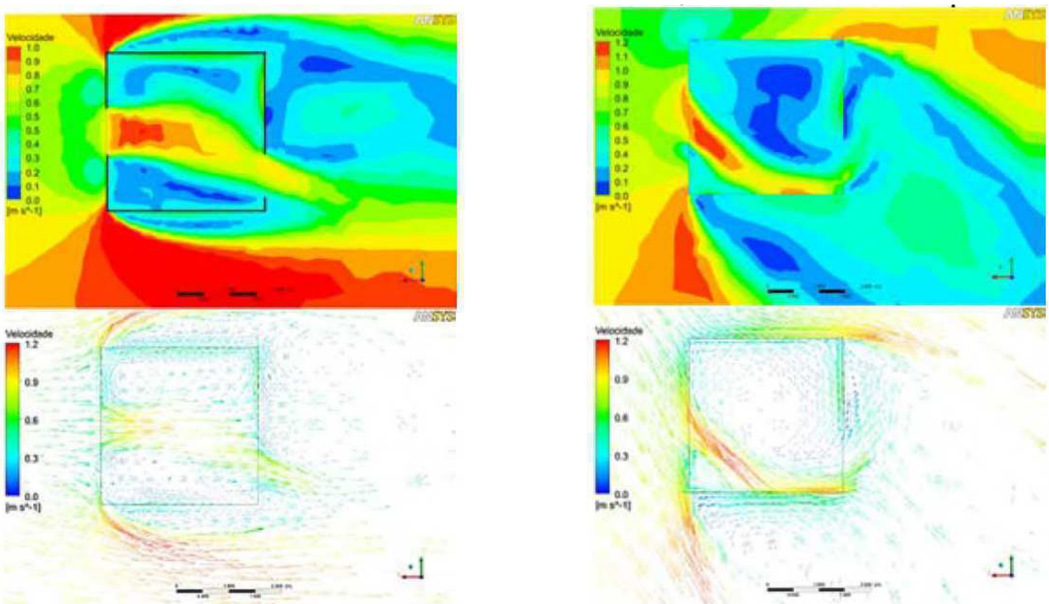
In this section the selected strategies and their relation to comfort parameters are studied by a literature review.

4.2.1. Openings

Openings influence the climate performance in three direct ways. They allow air to exchange between in- and outside, they increase air velocity and dry-bulb temperature exchange (convection), and they let solar radiation in (if no shading is present). Aflaki [1] concluded that natural ventilation is one of the two dominant passive design strategies in tropical climates. The effects of natural ventilation and openings have known quite some research by for example Omrani [31] [30], Sacht [39] and Aflaki [1]. Their important findings are addressed below. The solar radiation effect is often reduced by means of shading devices and therefore not separately addressed.

Configuration and location The configuration and number of openings influence the mode of ventilation used [22]. Using full-scale measurements, Omrani [31] concluded that cross ventilation contributes significantly to improve thermal comfort while single sided ventilation does not. Ma [22] also founded the significant this by full numerical investigations. Aflaki [1] found that the pressure discrepancies between the windward and leeward facade side in combination with perpendicular openings are significant variables regarding air velocity. Sacht [39] used numerical analyses to determine the flow through the building dependent on the opening configuration and location. Figure 4.1a illustrates cross ventilation flow from the windward opening (left side) to the leeward opening. The colours indicate the velocity distribution of the flow. As can be seen, both the configuration and location of the inlet and outlet openings determine the flow through the building.

Roof opening Section 2.2 concluded that the potential of stack effect to provide air velocity is not significant. However, providing roof openings is found to contribute significantly to heat mitigation, especially on wind still days. Significant reduction of indoor temperatures at ground level are found when roof openings are provided [40]. Multiple roof openings also allow heat to mitigate by wind driven ventilation because the speed inside is increased due to the pressure differences. In addition, this also decreases the inside surface temperatures of the roof [38].



(a) Incident angle of 0° [39]. (b) Incident angle of 45° [39]

Figure 4.1: Air velocity and direction (flow) results in buildings in horizontal section by [39].

Window size Sacht [39] concluded that the indoor air velocity is influenced by the size of windows. A larger opening allows the passage of air with less head loss due to the obstruction of the facade. The internal environment then benefits from greater air exchange rates per hour and higher air velocities.

4.2.2. Stilts

Using stilts influences air velocity in combination with openings and if the ground floor is in contact with the soil.

Air velocity When no stilts are used, it was found that air velocity is relatable to outdoor wind speed at a reference height [31]. Since wind speed increases with increasing height, this could increase indoor wind speed correspondingly. However, no literature was found describing this influence. The wind speed parallel to the ground surface can be described by the wind profile power law. For wind speed at a certain height, it uses the following relationship.

$$u(z) = u_r \left(\frac{z}{z_r}\right)^{\alpha}$$

The wind speed is defined by $u(z)$ [m/s] at height z [m], u_r is the known wind speed [m/s] at a reference height z_r [m]. The exponent α is the terrain roughness factor and takes the influence of the surroundings into account.

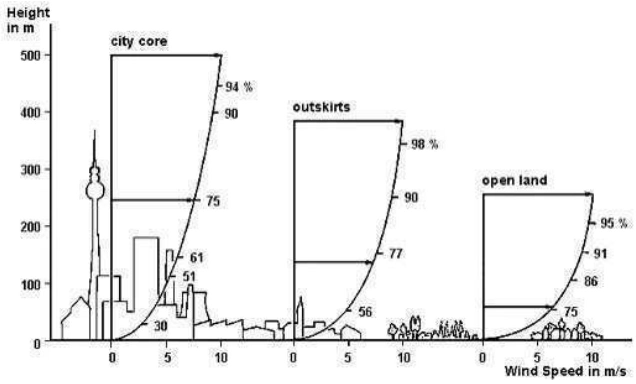


Figure 4.2: The profile power law wind speed distribution in different area types [14].

Ground contact Stilts with zero height could indicate contact between the ground floor and soil. This effect influences the surface temperature of the ground floor. Since this was often not the case in vernacular architecture and is not expected to contribute significantly to thermal comfort, this effect is not studied and contact with air is assumed.

4.2.3. Orientation

Orientation influences air velocity and solar radiation.

Air velocity by incident angle Sacht [39] concluded that the incident angle in combination with openings influence air exchange rates and indoor velocity significantly. The highest exchange rates per hour were recorded when the angle was between 0° and 45°. The lowest values for air exchange rates and indoor air velocity were found when the incident angle was parallel to the openings (90°). Fig 4.1 illustrates the influence of the angle on the flow through the building with its corresponding flow and direction properties.

Solar radiation The sun path determines the solar radiation load on the building by its incident angle towards the building. The shape of the building and orientation determines which area is subject to the solar radiation. Since the geometry of the building is not separately studied on shape, the influence of orientation is only studied in this research in combination with eaves.

4.2.4. Eaves

Eaves influence air velocity by obstructing wind and radiant temperature by protection versus solar radiation. They are addressed respectively.

Radiant temperature Eaves protect the facades versus solar radiation. As a result the inside surface temperatures decrease. The sun path of Manila is depicted in 4.3. It illustrates the orientation from the sun to the building. The values around the outer circle depict the horizontal angles. The circles from the mid-point to the outer circle illustrate the incident angle in vertical direction. As can be seen, in the east and west low incident angles of solar radiation are found. In the north a minimum angle of 70° is found and in the south a minimum of 40°. This indicates that to protect the facades, short eaves suffice for the north while longer eave lengths are necessary for the south west and east.

Air velocity Numerical analyses by Peren [34] on a sawtooth building with cross ventilation showed that air velocity is influenced by the eave length and angle. Figure 4.4 illustrates how increasing the eave angle influences the flow through the building.

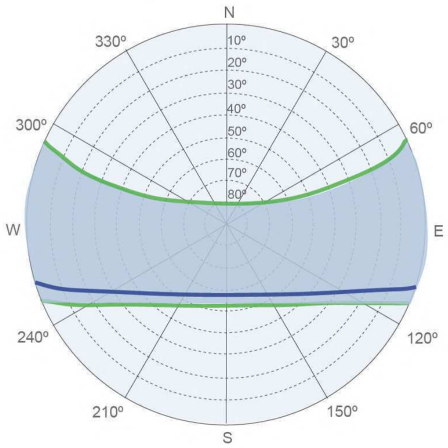


Figure 4.3: Sun path of Manila [5].

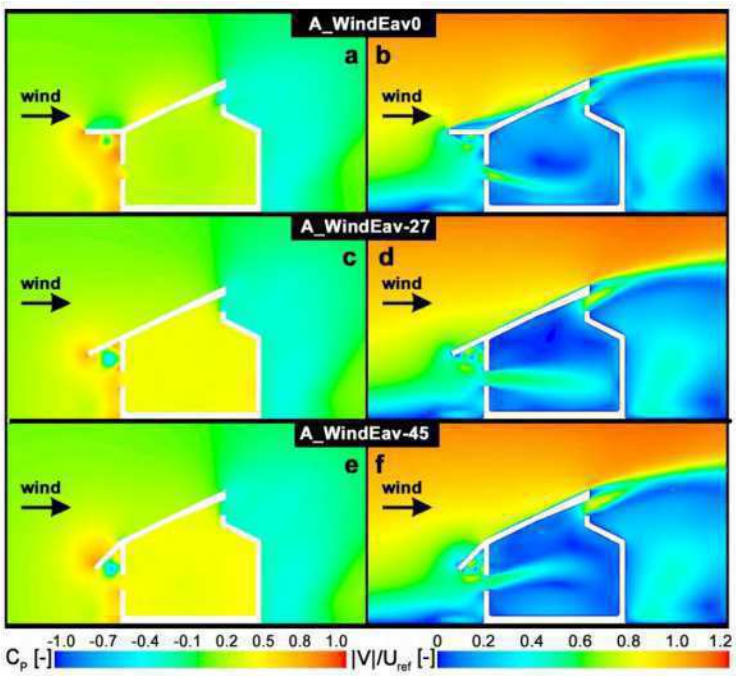


Figure 4.4: Influence of eave angle on air velocity, direction and pressures [34].

4.2.5. Roof insulation

Insulation influences radiant temperature by influencing the heat resistance of the building element. This means it protects the inside surface temperature from the solar radiation falling on the outside surface. It is about thermal conductivity $-k$ of the material(s) and is expressed in $[m^2K/W]$. Fourier's law for heat conduction is as follows.

$$q = -k\nabla T$$

Here ∇T is the temperature gradient in Kelvin. q is the heat flux in (W/m^2), i.e., the flow of energy per area. To describe the heat resistance of the roof, the Rc-value $[m^2K/W]$ is used. It indicates the resistance of all the materials used without the resistance between the materials and the in- and outside air.

4.2.6. Roof angle

The roof angle causes the radiant heat to be radiated by a different angle and the solar load to be subjected to a different surface area [35]. If steep angles are used, the area is perpendicular to the solar radiation in the mornings and afternoons. As a result, more heat is absorbed during these periods. During midday, the opposite effect is created by increasing the area subjected to the same amount of solar radiation. In terraced houses in Malaysia, it was found that the indoor dry-bulb temperatures decreases with 1.5 °C if the roof angle is decreased from 60 degrees to 0 degrees during midday [35]. In the morning and afternoons it increased with 0.5 °C [35].

4.2.7. Strategies relations to thermal comfort parameters

Although heat mechanisms often occur at the same time, the literature study showed the significant relations between the strategies and the comfort parameters. The direct relations are depicted below in the table of figure 4.5. As addressed in the literature study, the relations indicated in black are selected to study separately.

Strategy	Wind speed	Radiant temp	Db Temp
Openings	X	X	X
Stilts	X		
Orientation	X	X	
Eaves	X	X	
Roof insulation		X	

Figure 4.5: Strategies and corresponding comfort parameter. The black crosses indicate the relations separately studied in chapter 5.

4.3. Conclusion

Based on applicability and potential to increase comfort, the following climate responsive design strategies are selected to study in this research.

- Openings
- Orientation
- Eaves
- Stilts
- Roof angle
- Roof insulation

Based on a literature study, openings significantly influence air velocity by providing a flow and directing it through the building. Roof openings are found to increase heat mitigation significantly by stack effect during wind still times. Eave length and angle influence indoor wind speed in combination with openings and radiant temperature by protection from solar radiation. Orientation influences air velocity by the incident angle of the wind in combination with openings. Roof insulation influences radiant temperature by its thermal conductivity. Increasing roof angle influences radiant temperature positively during midday and negatively in mornings and afternoons. The table of figure 4.5 illustrates the relations that are further studied in this research.

5

Influence study on comfort parameters

In chapter 5, the sub-question *"How do the design strategies influence thermal comfort parameters?"* is answered. First, the method to answer the question is discussed. Section two addresses the validation of the computational models used in this chapter. Section three to section eight show the results, discussion and conclusions per strategy. In section nine, the conclusions of this chapter are summarized.

5.1. Method

In this section, the method to answer the sub-question is discussed. Per strategy, the comfort parameters that are studied are discussed first. The context and geometry used to test the strategies is discussed in subsection two. The assessment method is evaluated in the succeeding section. The section is concluded with formulation of the hypotheses.

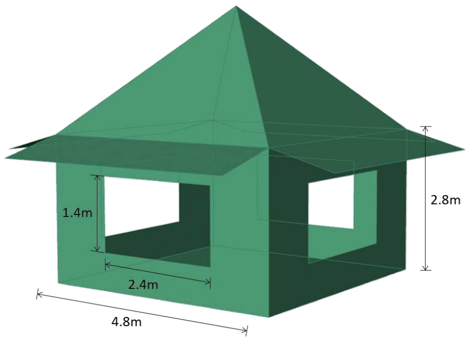
5.1.1. Geometry and climate

To study the influence of the strategies on the adaptive comfort parameters for the intended housing typology, a suitable, general geometry and climate are used.

Geometry and materials

According to the housing typology as described in section 1.2.3, a box geometry with a hipped roof is defined. Specific design features are avoided in order to increase the applicability and obtain clear associations between the strategies and results. The dimensions of the case study are used because they are representative in size to the intended typology. The geometry chosen is illustrated in figure 5.1a. The dimensions are 4.8 m in length and width and 2.8 m in height. A hipped roof of 40° is used. Openings are defined in the middle of the facade height as is common. The width of the window is 2.4 m and the height 1.4 m. The eaves are rectangular shaped in line with the case study. This results in openings on the corners.

Figure 5.1b shows the material properties and the conditions of the two hourly simulation steps used. To generate a building perceptive to the outdoor climate, thin wood siding for the facade, floor and roof is chosen with a relative low Rc-value and a high solar absorptance of 0.78.



(a) General geometry.

Wood siding material	Value
Roughness	MediumSmooth
Thickness [m]	0,01
Conductivity [W/m-K]	0,11
Density [kg/m3]	544,62
Specific Heat [J/kg-K]	1210
Thermal Absorptance	0,9
Solar Absorptance	0,78
Rc Value [m2K/W]	0,091

(b) Material properties of the facade, roof and floor elements.

Figure 5.1: The general geometry for this chapter with dimensions and material with corresponding properties.

Climate

The climate data of Manila is used for the simulations. As found in section 2.1.2, it is representable for the low-lying areas in the Philippines. In appendix figure A.1 the used dry-bulb temperature, the air velocity and the radiation load is graphically presented per hour.

5.1.2. Method per comfort parameter

In section 4.2, the relations of the design strategies to their comfort parameters are discussed. The black crosses in the table of figure 4.5 depict the relations studied in this chapter. As can be seen, radiant temperature and air velocity are studied. Their general method is addressed before by their assessment method is discussed.

Radiant temperature Radiant temperature is influenced by many aspects like the incident angle of solar radiation, geometry, material and climatic conditions. To take all these aspects into account, an energy performance simulation calculation is used. It determines the mean radiant temperature for every hour of the year. Since roof insulation is not dependent on all these factors, analytical calculations suffice to study the influence.

Air velocity Computational fluid dynamic simulations are used for two reasons. One, because it can provide detailed information on air velocity, direction and air inlet. Two, because it provides the possibility to study many alternatives in the available time.

Radiant temperature assessment method

A commonly used indication of the radiant temperature in a room or zone is the mean zonal radiant temperature (MRT) [9]. It is measured by an average of the radiant temperatures of the surfaces enclosing the zone weighted by their areas. The radiant temperature is calculated by the inside surface temperature times the thermal absorptance coefficient of the corresponding material (usually 0.9).

The influence of a strategy can be assessed on a yearly performance or on a specific time. For example, when eaves are considered, the geometry determines the influence on the comfort parameter per hour of the year. Consequently, the yearly average is used to give a representative result. The strategy roof insulation is not dependent on geometry. Therefore, a single time is sufficient to study its effect on reducing heat.

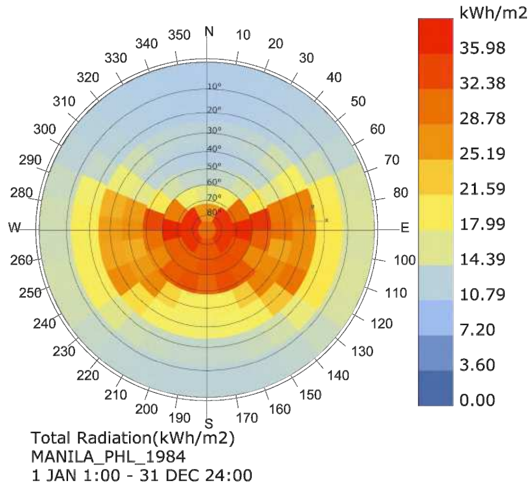
The yearly total radiation load per incident angle is depicted in figure 5.2a. The horizontal angles are indicated around the outer circle and the vertical angles are indicated by the inner circles. As can be seen, the main solar load follows the east-west path and is at its strongest from above.

Air velocity assessment method

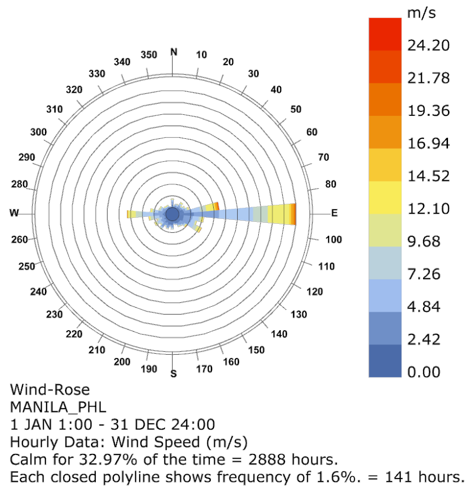
As explained in section 2.2, wind-driven flow is used to study air velocity. In this section, the conditions regarding wind are discussed first. The assumptions done to reduce the number of CFD simulations are discussed next. It is followed by definition of a comfort zone to obtain a representative indoor air velocity.

Wind conditions The yearly outdoor wind speed and direction distribution from Manila is used. It is depicted in the wind rose in figure 5.2b. The colours illustrate the speed. The numbers around the outer circle indicate the direction. The enclosure by a semi-circle indicates the occurrence of this direction. As can be seen, one main east wind direction and a secondary significantly smaller west direction is present. Figure 4.2 shows how the distribution is adjusted for sub-urban and rural housing. For the simulations, a reference speed of 6 m/s at 10 m height is used. This distribution is depicted in figure 5.3a.

Wind is available for 67% of the time of the year in this set. Figure A.1c illustrates the air velocity per hour of the year. It shows several months or weeks to have considerable more air velocity than others. 50.3% of the time of the year when wind is present, it is coming between 60° and 120° with the majority from 90°. On the opposite side between 240° and 300°, 22.5% of the total wind with the majority at 270 ° is present. If an opposite sided wind direction in east and west is used, it is representative for three-fifths of the total time of the directions.



(a) Solar radiation load per incident angle in degrees.



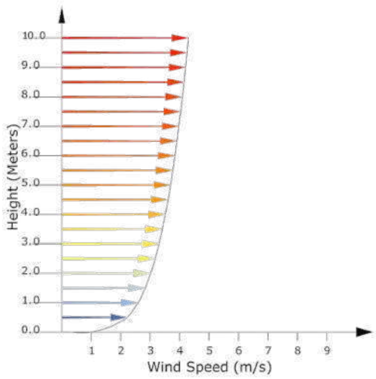
(b) Yearly outdoor wind speed and direction distribution.

Figure 5.2: Yearly solar radiation load and outdoor wind speed and direction distribution of Manila.

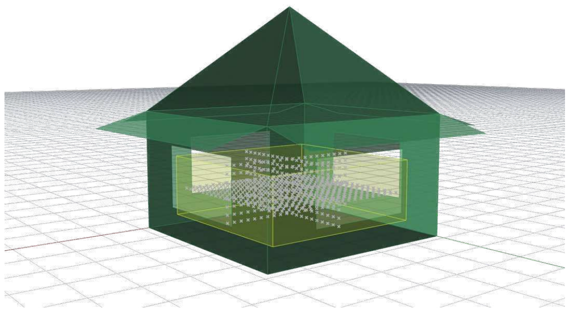
Assumptions To reduce the number of simulations necessary per variant studied, a single CFD from east direction is used. Since in most cases the building is symmetrical, it is also representative for wind coming from the west direction. As a result it is representative for three-fifths of the time as explained above. However, the remaining part is also still substantial. To take this into account, the influence of changing the orientation angle is also studied.

Comfort zone The actual velocity experienced in the building is dependent on the specific location in the building. However, the space used for living is often a zone. A singular measured point is therefore not representative. To achieve a representative air velocity, a zone is defined where people live in the building during the day. In this case, the comfort zone is defined to cover most of the space in the middle of the building at living height (from 0.3m until 1.8m). As a benefit of an average over an area compared to a single point, it provides a more representative indication of the amount of air going entering the building.

To define test points, this zone is cut by planes of points in the x-y, x-z and y-z directions. The average velocity of the points in the box is taken as the air velocity experienced. The building with comfort zone and test points is illustrated in figure 5.3b. In appendix section C.0.1, a result is used to analyse how representative the average is compared to the velocities measured. It is concluded that the average is representative.



(a) Air velocity distribution over the height for sub-urban and rural housing areas. A speed of 6 m/s at 10 m height is used.



(b) General geometry with comfort zone and test points for air velocity.

Figure 5.3: Air velocity distribution and geometry with comfort zone definition.

5.1.3. Influence study method

To study the influence of the strategy on the corresponding comfort parameter, the governing variable or parameter of the strategy is varied. This is referred to as the influence study or parameter study. Figure 5.4 illustrates the parameters of the strategies studied and the direction of their angles.

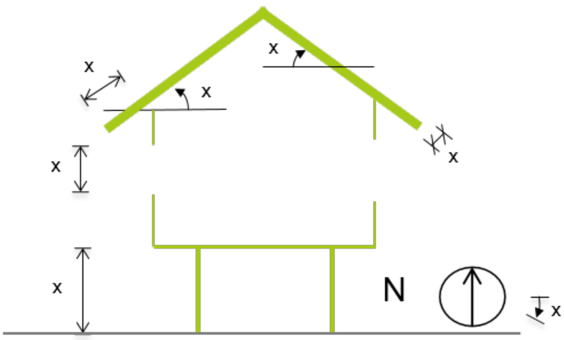
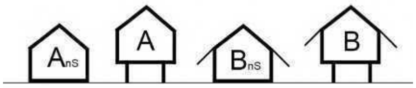


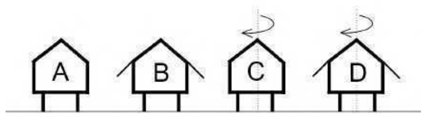
Figure 5.4: Illustrated influence study of the strategies and the direction of their angles.

Combining strategies However, the strategies that influence air velocity influence each other as a consequence. To generate a realistic amount of variants and still capture the influence of the parameter on air flow, a method with the following idea is used.

- *The strategy is varied using a set of relevant combinations of the other strategies. The relevant combinations are defined by the strategies which influence the air flow in the same plane. Consequently, the strategies are studied with the vertical and horizontal combinations as depicted in figure 5.5.*



(a) Relevant combinations of strategies in vertical direction.



(b) Relevant combinations of strategies in horizontal direction.

Figure 5.5: Relevant combinations of strategies in horizontal and vertical direction.

As a result, only the opening variations which change the flow in the corresponding plane need to be considered. The dimensions of the parameters used by these configurations are chosen to generate a clear influence on air velocity. The eaves are therefore defined by a inclination of 45° and 1.5 m length. An orientation angle of 45° and stilts of 1 m are used. Later it is shown that stilts do not significantly influence the flow qualitatively in the building. Since they lower the computation time significantly, the horizontal combinations are used with stilts.

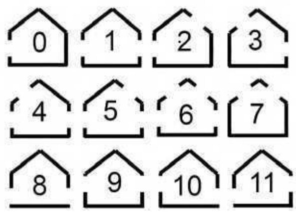
While this only yields results of the performance with that specific combination, it indicates the influence of the parameter with these strategies and provide thereby a basis for extrapolation of these results. Per strategy, the parameter study and relevant combinations are discussed below.

Openings parameter study

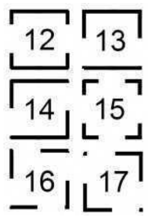
Defining opening variations Openings are studied on air velocity. The following parameters of openings can be defined that influence air velocity: the dimensions, the position on the facade and the configuration across the facades. If these were all used for generating variations, the amount generated would not be feasible to study in the limited time frame of this thesis. Therefore, assumptions are necessary to reduce the variations to a realistic number. However, they should still take the significant influence on air velocity and flow into account. The rules used for defining variations are presented after the discussion in italic.

- The findings of the literature study in section 3 and 2.2 concluded that the configuration of openings direct the flow through the building. It is therefore used as the main parameter to define opening variations. *The configuration of the openings is used as the main parameter to define opening variations.*
- The literature study in section 4.2.1 showed that by increasing the area of the opening, the volume of air entering through the opening increases. If it is assumed that air velocity is dependent on the volume of air entering, than increasing the size of the openings increases velocity and vice versa. The relation of opening size to air velocity is thereby assumed to be known. *Only one size of openings is used.*
- To further reduce the number of variations, the opening variant which change the flow in vertical direction are combined with the vertical combinations. And similarly for the horizontal opening variants with the horizontal combinations. *The variants that are expected to change the flow in horizontal plane are considered in the horizontal plane. The variants that change the flow in vertical plane are considered in the vertical plane.*
- The literature study in section 4.2.1 concluded that the position of the openings determine where the flow enters or leaves the building. Only the positions that are expected to have the biggest difference in results are therefore studied. For example, in the horizontal plane a position on the left, middle and right side of the facade is used. *In the horizontal plane, the opening positions studied are the left side, the middle and the right side. In the vertical plane the top, middle and bottom positions are studied.*
- If only a single opening is used per facade, the influence of the opening is better discernible. *A single opening per facade is used.*

Using these assumptions results in the opening variations depicted in figure 5.6. They are also referred to as configurations because that is essentially their main characteristic. Figure 5.6a illustrates the cross sections in the vertical plane. Figure 5.6b depicts the floor plans in the horizontal plane. It has to be noted that variant 1 and 12 are the same configurations.



(a) Vertical opening configurations. The cross section is at the middle of the building.



(b) Horizontal opening configurations as floor plans at 1.4 m height.

Figure 5.6: Opening configurations studied as cross sections on the right and floor plans on the left.

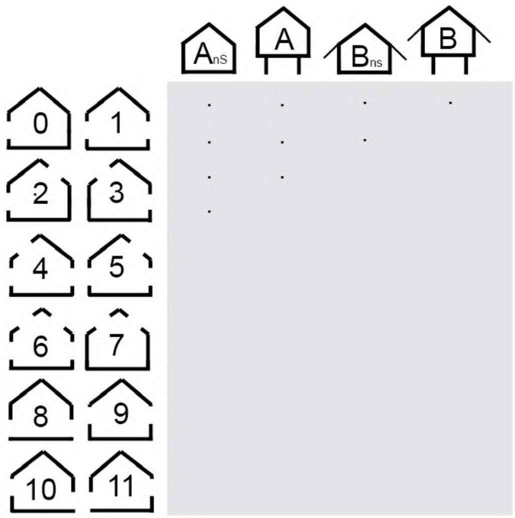


Figure 5.7: Openings influence study with vertical configurations and relevant vertical combinations.

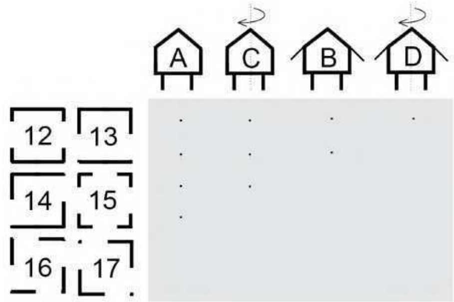
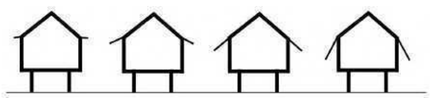


Figure 5.8: Openings influence study with horizontal configurations and relevant horizontal combinations.

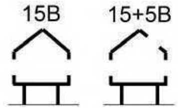
Combining openings and relevant strategies Following the idea of combinations, the opening configurations are studied with their relevant combinations. This is depicted in figure 5.7 and 5.8.

Eaves parameter study

The angle of the eaves and length are studied on air velocity and radiant temperature. Two opening configurations are studied. A standard case with facade openings on middle height and a case with addition of a leeward roof opening are studied. 15 and 15+5 respectively. Since applying stilts showed not to significantly influence the result, stilts are applied to reduce computation time.



(a) Varying eaves length and angle.



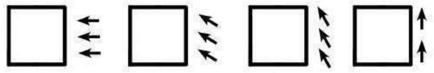
(b) The relevant combination of other strategies used.

Figure 5.9: Varying eaves length and angle on air velocity with relevant combinations of other strategies.

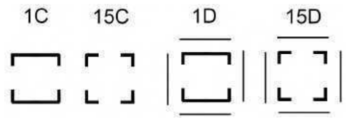
When radiant temperature is studied, the study geometry is used as a closed box to decrease the influence of other effects on the energy calculation. The yearly mean radiant temperature is used to assess the influence. Figure 5.10 illustrates this.

Orientation parameter study

The orientation angle is varied on air velocity with the relevant combinations C and D. The two opening configurations used are 1 and 15. The first has two openings across the facade while the latter has openings on all sides. This is illustrated in figure 5.10.



(a) Varying the orientation angle by changing the wind direction.

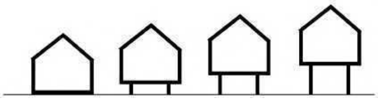


(b) The relevant combination of other strategies used.

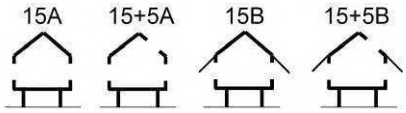
Figure 5.10: Varying the orientation angle by changing the wind direction with the relevant combinations of other strategies.

Stilts parameter study

The stilts height is varied on air velocity using two opening configurations. They are combined with the relevant vertical combinations A and B. It is tested with a standard configuration with openings in the middle of the facades at all sides (configuration 15). To study if this effect is influenced by a leeward roof opening, this is added to the configuration (indicated by 15+5). This process is illustrated in figure 5.11.



(a) Varying stilts height.



(b) The relevant combination of other strategies used.

Figure 5.11: Varying stilts height with the relevant combinations of other strategies.

Roof insulation parameter study

The Rc-value [m^2K/W] of the roof insulation is varied on the inside surface temperature.

Roof angle parameter study

The angle of the roof is varied on mean radiant temperature.

5.1.4. Hypotheses

In this section, the hypotheses are discussed. To avoid repeating text, the hypotheses are presented in the section of the corresponding strategy. The findings of the previous chapters are used. After the discussion,

- **Openings** As explained in chapter 2, the flow of air is determined by a pressure difference and a path to solve this pressure difference. If the flow is directed through the comfort zone, air velocity increases and vice versa. It is therefore expected that openings on the wind and leeward facade plus roof openings result in the highest air velocities for Ans, A, Bns and B. For combination C and D, this translated to openings on the corners to the wind and leeward direction.
- **Stilts** Since air velocity is often related to a reference outdoor wind speed on building height, it is expected that air velocity increases as wind speed increases.
- **Orientation** For combination C, if the orientation is used to direct the wind in alignment with the openings through the comfort zone, air velocity increases and vice versa. For combination D, the eaves are shaped to have openings on the corners. If these are placed in wind direction, the flow is not obstructed and benefits air velocity.
- **Eaves** Eaves influence air velocity and radiant temperature. The longer and more inclined the eaves are, the more solar radiation is blocked and wind obstructed. As a result the radiant temperature and air velocity decrease.
- **Roof insulation** Increasing the insulation value or Rc-Value of the roof increases the heat resistance of the material. As a result, the inside surface temperature reduces. However, the effect of increasing the insulation diminishes until at some it is only depended on the indoor temperatures.
- **Roof angle** As explained in section 4.2.6, increasing the roof angle decreases the yearly mean radiant temperature because it influences the peak hour temperatures significantly.

5.1.5. Computational simulation method

To be able to generate reliable results for the method proposed, the software chosen for the computational models is discussed. It is followed by addressing the validation steps necessary for this model.

Software

A modelling environment capable of running CFD and energy performance calculations is necessary. Furthermore, it must be capable of performing the multiple parameter studies. The parametric environment of Grasshopper-Rhino environment is capable of these simulations and is the most extensive parametric environment at this date. It uses EnergyPlus for the energy analyses. The link to EnergyPlus is executed by OpenStudio and the Honeybee and Ladybug plug-ins for Grasshopper. EnergyPlus is a renown program and used for many years in doing extensive energy simulations of the built environment. OpenFOAM is used to run the CFD analysis and is directed by the plug-in Butterfly. OpenFOAM is known as a very powerful and robust CFD solver with endless capabilities [8]. The software is therefore deemed appropriate for this study.

Computational models validation

In order to value the results and draw appropriate conclusions, the models need to be validated. They are addressed respectively.

CFD validation To validate a CFD model, using wind tunnel tests is the only option [16]. Since our geometry is fairly simple, wind tunnel tests with similar geometries are available to validate our model. Subsequently, the geometries can be extended and compared to see if the results make sense. This is a common procedure and done in many studies [34] [36], [15], [24].

Beforehand, the following actions can be taken to improve the result. The wind tunnel dimensions should be based on the object size exposed to wind [37] [48]. The height and width to both sides of the tunnel should be 5 times the object size, the leeward side 15 times and the windward side 5 times. The following meshing requirements are advised [17]. The refinement of the mesh should be built up gradually. The cells should be square-shaped and high refinement levels around edges should be used.

Energy model validation To make sure the model is built properly, it needs to be validated if it takes all the effects into account. To validate this, basic cases are defined by adding mechanisms and design strategies step by step. Consequently, it can be examined if they influence the result accordingly.

5.1.6. Method conclusion

The influence of the strategies on their corresponding comfort parameters is studied in this chapter. Air velocity and radiant temperature are studied by respectively CFD and energy simulations or analytical calculations. The computational models are validated so the results can be valued accordingly. A general design is used to increase the applicability and obtain clearer associations between the strategies and effects.

To study the influence per strategy, it is varied to to assess its effect on the corresponding comfort parameter. However, the combination of certain strategies also influences this comfort parameter. Hence, the strategy is varied using a set of relevant combinations of the other strategies. If this method is used, not every influence is captured because not every possible combination and variation is tried. However, it generates an indication about the effect of the combination with other strategies.

5.2. Computational model validation

In this section, the computational models used in this chapter are validated. The energy model will be addressed first, followed by the CFD model. The most relevant steps taken in the validation are elaborated here. The other steps are addressed in appendix C.

5.2.1. Energy model performance validation

First, the method is discussed. than, the results of the single-zone model and corresponding strategies are addressed, followed by the results of the multi-zone model and strategies.

Method

The energy model is validated by an empirical validation of the performance to a series of cases. This series is built up by adding step by step energy performance mechanisms or design strategies. The model conditions are elaborated first, before the cases are defined with corresponding hypotheses.

Model conditions Two simulation steps are used. They are a day and a night time with circumstances as depicted in figure 5.12. Case numbers followed with an index _N indicate the night time simulation step. The dimensions of the geometry are chosen according the dimensions of the case study.

Outdoor Climate	Day	Night
02/Jan		
Time	11AM	3AM
dbtemp [C°]	30,5	21
Windspeed [m/s]	3	2,5
wind direction	80	90
Cloud cover 0-10	5	0

Figure 5.12: Outdoor climate conditions of the day and night simulation step.

Single-zone cases definition and hypotheses A closed box is taken as the first basic case. This is expected to result in high temperatures compared to outside during the day because heat can't dissipate. Openings are added as case 2. This is expected to increase the temperature because solar radiation can enter the building. Adding air inlet as case 3 than decreases the lower zonal temperatures because heat can now dissipate. In the night cases temperatures like outside are expected. Increasing eaves length for case 4 and 5 results in decreasing mean radiant temperature because solar radiation is blocked by the eaves. Increasing the roof angle decreases the mean radiant roof temperature as explained earlier. The inside surface temperatures are expected to be higher in south east direction since they follow the solar radiation load.

Multi-zone cases definition and hypotheses First, the building including an inclined roof is studied as a single zone. than, it is considered as two zones split by a wooden floor. Since conduction is less efficient than convection in transferring heat through the zones, a clear separation in zonal temperatures is expected. Since it is not possible to create a virtual opening in a zone, the material "air wall" is used to fill this gap. This material has the insulation properties of an air film and exchanges air between zones. It is therefore expected that the temperatures equalize between the zones compared to the floor intersection. However, an air wall does not directly transmit radiation through as a normal opening would. Therefore, the mean radiant temperature of the living zone is deemed underestimated. Adding openings with air flow decreases the zonal temperatures of the living room to the outside temperature. As a consequence of the air exchange between the living zone and attic zone, this temperature also equalizes.

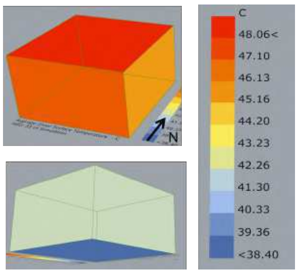
Results and discussion single-zone cases and strategies

In figure 5.13 the defined cases are described on the left side and the corresponding performance results on the right side. During night time the temperatures are lower than outside. When wind is added, the dry-bulb temperature increases close to the outside temperature. Figure 5.14b illustrates the inside surface temperatures of selected cases. It is observed that the facades on the south-east side are significantly hotter during the day than the north-east side.

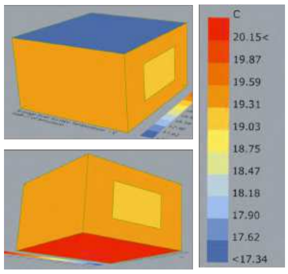
The results follow the hypotheses except during night time. In the night the temperatures are lower than outside. This is explained by the radiation emissivity to the surroundings. It causes the low surface temperatures. This effect is deemed slightly overestimated but is not significant since the comfort problems are expected during the day. The orientation is taken into account properly by heating up of the facades exposed to solar radiation. This can be seen in figure 5.14a.

Case		Performance	1	2	3	1_N	2_N	3_N		1	4	5		1	6	7
1	Box closed off	dbtemp zonal [°C]	43,0	44,2	29,4	18,1	18,1	21,4		43,0	40,5	38,7		43,0	42,7	42,5
2	Box with opening no airflow	radtemp zonal [°C]	43,5	44,8	40,1	18,1	18,1	18,9		43,5	41,1	39,1		43,5	43,4	42,9
3	Box with opening and airflow	operative temp [°C]	43,2	44,5	34,7	18,1	18,1	20,1		43,2	40.8	38,9		43,2	43,1	42,7
4	Box with eaves 0,75m at 30°	surf-temp inside [°C]														
5	Box with eaves 1,5m at 30°	air flow (inlet) [m3/s]			6,5			5,3								
6	Box with hipped roof 30°	air speed [m/s]			0,5			0,4								
7	Box with hipped roof 60°	mean radiant Temp. yearly average [C°]								30,6	30,1	29,8		30,6	30,6	30,6

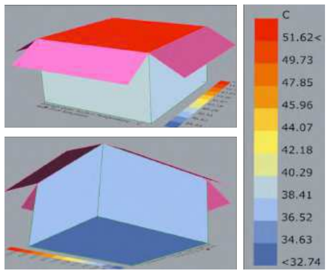
Figure 5.13: Cases and results of the single-zone model validation.



(a) Case 1.



(b) Case 3_N.



(c) Case 5.

Figure 5.14: Inside surface temperatures selected cases.

Results and discussion, multi-zone and strategies

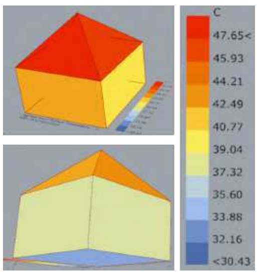
The cases for the multi-zone model and corresponding results are shown in figure 5.15. In the appendix in figure C.6 it is shown how the inter-zonal exchange rate of air in m3/s influence the temperatures in the house.

The results follow the hypotheses. The relation of the inter-zonal exchange rate to the results illustrate the added benefit of a corresponding CFD simulation to improve the accuracy of the simulation model.

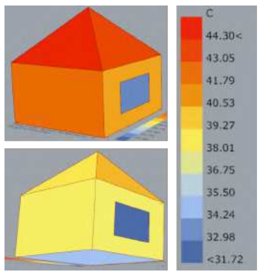
Case	
8	House single-zone
8b	House m-z floor intersection
8c	House m-z air-wall no mixture
8d	House m-z air-wall mixture
8e	House m-z air-wall mixture and opening with airflow

performance Zone living	8a	8b	8c	8d	8e
dbtemp zonal [°C]	42	35,2	40,6	34	29,4
radtemp zonal [°C]	42,4	35,6	40,9	38,2	37,1
operative temp [°C]	42,2	35,4	40,7	36,1	33,3
surf-temp inside [°C]					
air flow (inlet) [m3/s]					3,4
air speed horizontal [m/s]					0,25
Yearly average mean radiant T. [°C]	30,6	30,2	30,2	30,5	29,5
performance Zone Roof					
dbtemp zonal [°C]		42,5	43,9	34	29,6
radtemp zonal [°C]		42,8	44,2	40,8	39,5
operative temp [°C]		42,7	44	37,4	34,6
surf-temp inside [°C]					
Yearly average mean radiant T. [°C]		31,4	30,9	31,2	30
interzonal exchange [m3/s]		2,2	2,2	2,2	2,2

Figure 5.15: Cases and results of the multi-zone model validation.



(a) Case 8b.



(b) Case 8e.

Figure 5.16: Inside surface temperatures selected cases multi-zone.

Conclusion energy model validation

The performance of the model follows the hypotheses with two exceptions. One, the night time radiation emissivity is deemed slightly high. Consequently, the performance is overestimated. However, this is not deemed significant for the results since the difference is small and the focus of the model is during the day. Two, the radiant temperature of the living room in the multi-zone model is underestimated. This is caused by the air wall which does not directly transmit radiant heat through. Being aware of these exceptions, it can be concluded from the empirical validation to basic cases that the energy model takes the influences of the strategies and mechanisms into account properly.

5.2.2. Validation CFD simulation model

In this sub-section the CFD model is validated. First, the method is discussed. than, the validation results are considered and conclusions drawn.

Method

The method as explained in section 5.1.5 is used and further defined below. In appendix C additional analytical calculations results are presented to validate the results.

Model set-up The meshing is done using the recommendations provided in sub-section 2.2.3. To make sure the automatic meshing is done regarding the requirements, manual refinement regions are added. Based on the validation of the mesh to the results and computation time, the meshing settings illustrated in figure 5.17 are used. The green lines indicate the outlines of the manual refinement levels which are added.

Wind tunnel validation Since the geometry of this study is almost a box with openings, wind tunnel tests are available from literature. Three relevant tests are available from Ramponi [36]. They are shown in 5.21a, 5.20a and 5.18. All show a box with openings at different heights. The comparison to the wind tunnel tests are done in several steps. First, the wind tunnel tests are exactly copied. than, the geometry is changed to the dimensions of the geometry used in this chapter. It is followed by adding strategies and comparing their influence to the relevant wind tunnel test. Since no wind tunnel tests are available in the horizontal plane, the results are checked if they make sense and correspond to the other results.

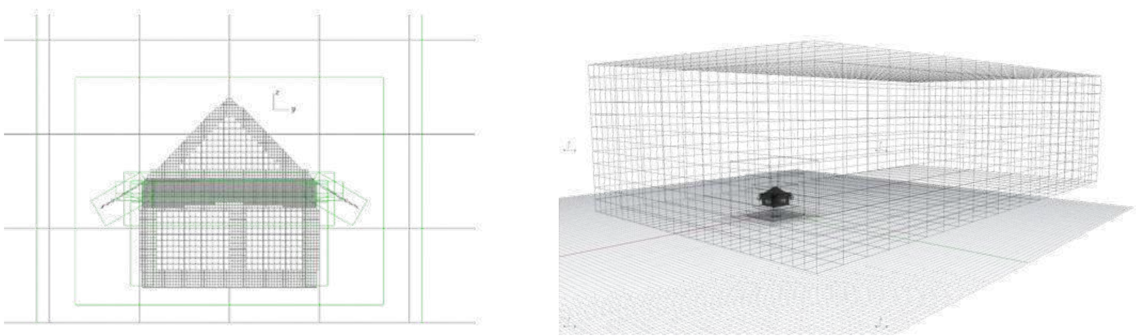


Figure 5.17: Manual mesh refinement levels displayed by green outlines on the left side and the wind tunnel set-up on the right side.

Results and discussion

Per paragraph, a step is addressed.

Wind tunnel copy In figure 5.18, the result of copying the wind tunnel test with openings at mid-height is shown. In appendix figure C.3 the results of copies of the other two wind tunnel tests are shown. As can be seen for al three, the same flow pattern and air velocity are observed. At the top left corner the CFD result shows less recirculation. However, this is not deemed to have a significant influence since the indoor flow is the same.

Study geometry In figure 5.19a the result is shown. The flow pattern and speed distribution observed follow the flow of the wind tunnel. It is spread more evenly than the wind tunnel and less circulation is observed.

The results to the changes in geometry behave as expected. Decreasing the height of the building and increasing the opening size results in a more evenly spread flow through the building. Correspondingly, the recirculation area and downward angle decrease compared to the wind tunnel.

Stilts and eaves In figures 5.19b and 5.19c, the results of adding stilts and eaves are shown respectively.

Since outdoor wind speed increases with height, the slight air velocity increase when stilts are added is explained. The indoor flow remains the same. This can be expected because the incident angle of the wind is not changed. The eaves split the flow before entering the building. It directs a major part above the building and the remaining flow underneath and upwards through the opening. This incident angle is maintained inside.

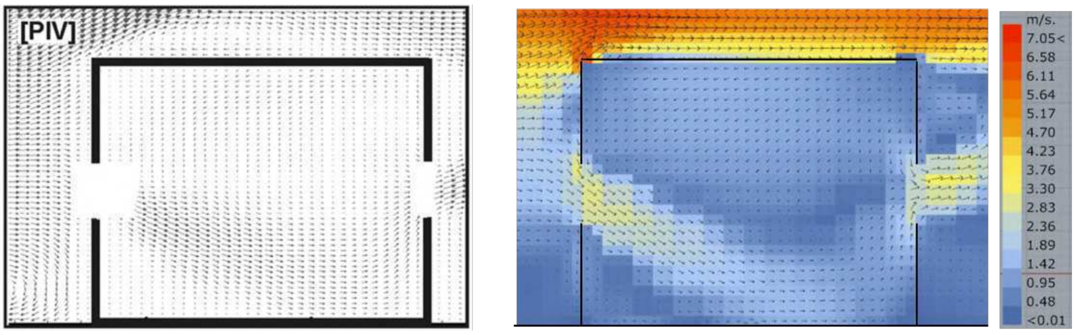
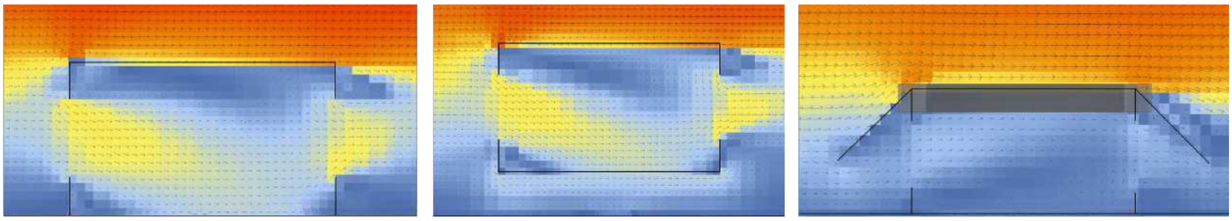


Figure 5.18: Wind tunnel test by PIV [36] with openings at middle height on the left and CFD result of the copied geometry on the right.

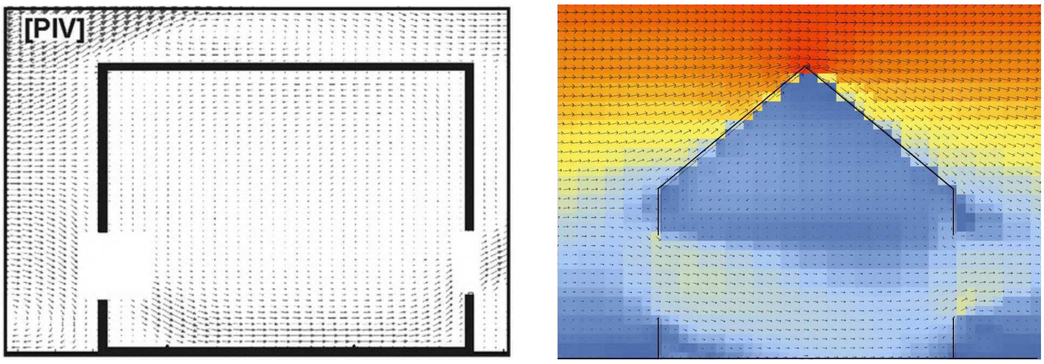


(a) Study geometry. (b) Adding stilts of 1 meter. (c) Adding eaves of 1.5 meter at 45°.

Figure 5.19: Validation of dimensions of the geometry, stilts and eaves by comparison.

Roof and roof openings In figure 5.20, the wind tunnel test with a low in and outlet is shown. It is compared to the geometry including a roof because it shares a large area above the openings. As can be seen, the same flow pattern in the building is observed. In figure 5.21 a leeward roof opening is added. It is compared to the wind tunnel test with a low inlet and high outlet opening. It shows a similar but wider spread flow and follows the floor and wall to reach the opening.

Both the CFD results follow the wind tunnel flow. While the hipped roof is different than the box, it does not influence the flow pattern inside significantly as is reasonable.

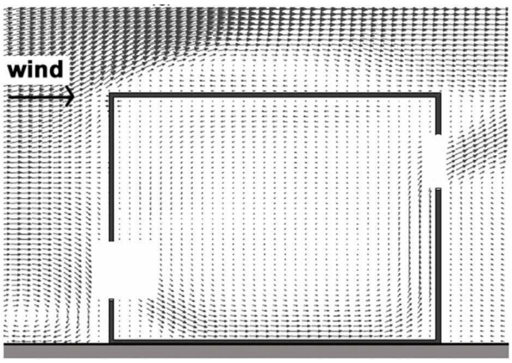


(a) Wind tunnel test by PIV with low openings [36]. (b) CFD result of adding a roof angle of 40°.

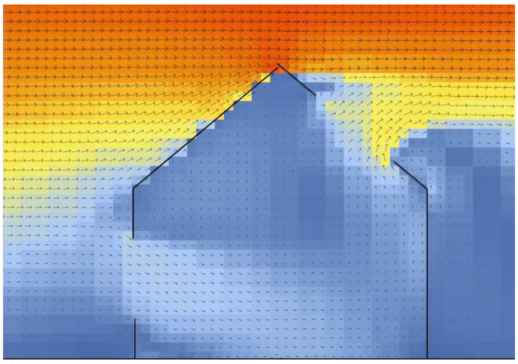
Figure 5.20: Validation of roof angle by comparison to a wind tunnel test.

Changing orientation In figure 5.22a, the horizontal flow pattern of the study geometry from figure 5.19a is shown. Figure 5.22b shows the result with an orientation angle of 45°. As observed, both flows follow the incident angle and decrease after entering. They increase again at the leeward opening. The flow of the changed orientation is obstructed by the wall. After the obstruction it is redirected to the leeward opening.

The decrease and increase of the speed in figure 5.22a corresponds to the vertical flow of figure 5.19a. Changing the orientation effects the incident angle of the wind. Consequently, it follows this direction until obstructed by the wall. The downward pattern is also observed. This makes sense because the incident angle in the vertical plane is not changed.

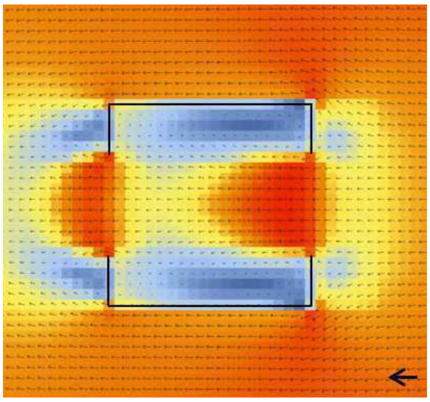


(a) Wind tunnel test by PIV with low inlet and high outlet opening [36].

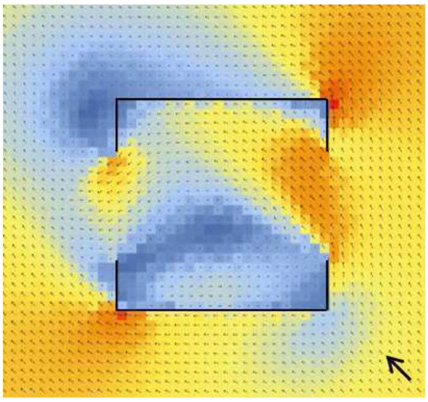


(b) CFD result of adding a leeward roof opening.

Figure 5.21: Validation of a leeward roof opening by comparison to a wind tunnel test.



(a) Orientation angle of 0°.



(b) Orientation angle of 45°.

Figure 5.22: Validation of a 0° and 45° orientation by comparison.

Conclusion CFD validation

Copying the wind tunnel tests showed accurate and representative results for the flow pattern and air velocity in the building. Changing the geometry and adding strategies showed logical results in the flow. Hence, it can be concluded that the CFD model generates representative flow pattern and velocity distribution results.

5.3. Openings

In this section, the results of openings on air velocity are studied. First, specific additions to the method are addressed. Then, all the results are presented and discussed per observation. The section is ended with the conclusions. The hypotheses stated below are tested in the discussion section.

- *"For combinations Ans, A, Bns and B openings on the wind, leeward facades and roof sides result in the highest air velocities."*
- *"For combinations C and D, openings on corners in wind and leeward direction plus roof openings result in the highest air velocities."*

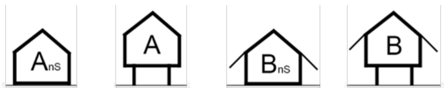
5.3.1. Method

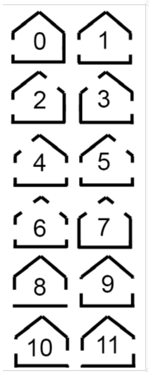
The method as addressed in 5.1 is used to evaluate the influence of the openings on air velocity.

- In the horizontal variants an eave length of 2.2 m instead of 1.5 m is applied to make the eave and influence visible in the horizontal flow results. As a result, differences in air velocity results for configuration 1 with combination 1D and 12D are expected.
- Different distances between the generated test points in the vertical and horizontal plane are used. This is done to make sure the solution is read out properly into the flow results. Consequently, small differences are expected between variant 1 and 12.

5.3.2. Results and discussion

The numeral air velocity results of the vertical configurations and combinations are presented in figure 5.23. The horizontal ones are presented in figure 5.24. Per combination, the best performing configurations are highlighted in green and the second best configurations in light green. In figures 5.26 and 5.25, the air velocity and direction (flow) results are shown. A selection is made of the results which contribute to the findings of this chapter.

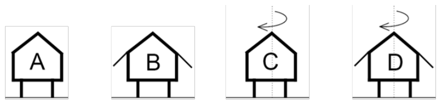


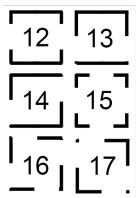


Open. Config.	AnS [m/s]	A [m/s]	BnS [m/s]	B [m/s]
0	0,07	0,18	0,07	0,10
1	1,15	1,27	0,96	1,13
2	0,84	0,74	0,67	0,82
3	0,47	0,56	0,48	0,54
4	0,82	1,07	0,60	0,80
5	1,48	1,63	1,16	1,39
6	1,17	1,47	0,81	1,15
7	0,47	0,49	0,44	0,49
8	0,75	0,84	0,96	1,40
9	1,02	1,33	0,45	0,56
10	1,05	1,36	0,41	0,50
11	0,70	0,65	0,71	0,92

Figure 5.23: Air velocity results of vertical configurations and combinations. Per combination, the best performing configurations are highlighted in green and second best in light green.

As can be seen in figures 5.23 and 5.24, the opening configurations which result in the highest air velocities are not the same in every combination. This shows the significant influence of the combinations. The results are elaborated and discussed per observation below.





Open. Config.	A [m/s]	B [m/s]	C 45° [m/s]	D 45° [m/s]
12	1,31	0,67	1,02	0,43
13	1,18	0,65	1,36	0,78
14	1,37	0,52	1,19	0,80
15	1,64	0,74	1,19	0,61
16	1,36	0,56	1,55	1,02
17	1,38	0,57	1,55	1,48

Figure 5.24: Air velocity results of horizontal configurations and combinations. Per combination, the best performing configurations are highlighted in green and second best in light green.

The air flow From observation of the flow, the results can be described as follows. The flow follows its initial direction through the opening until obstructed and redirected to the opening(s) on the leeward side. It shows a recirculation with low speeds in parts of the building were it is directed away from the leeward opening. A downward pattern at ground floor is observed when no eaves are used, and an upward pattern when the eaves are present.

These results follow the validation and theory. The flow can be described by the theory because it follows the pressure difference through the openings and around obstructions. If this flow is directed through the comfort zone, air velocity is benefited.

Applying stilts It is observed in figure 5.25 that adding stilts from AnS to A and BnS to B results in the the same flow pattern but not a proportional speed increase. For all configurations except 2 and 11, air velocity increases when stilts of 1 meter are used.

This can be explained by further studying the flow results. As can be seen, the incident angle of the outdoor wind is not changed. Since the lower pressure area on the leeward side does not change, the same flow pattern is explained. However, the space created by applying stilts under the building allows the pressure difference to be solved underneath also. If this path is shorter than the path through the building like in configuration 2, the area underneath is used for the major part of the flow. Hence, air velocity decreases.

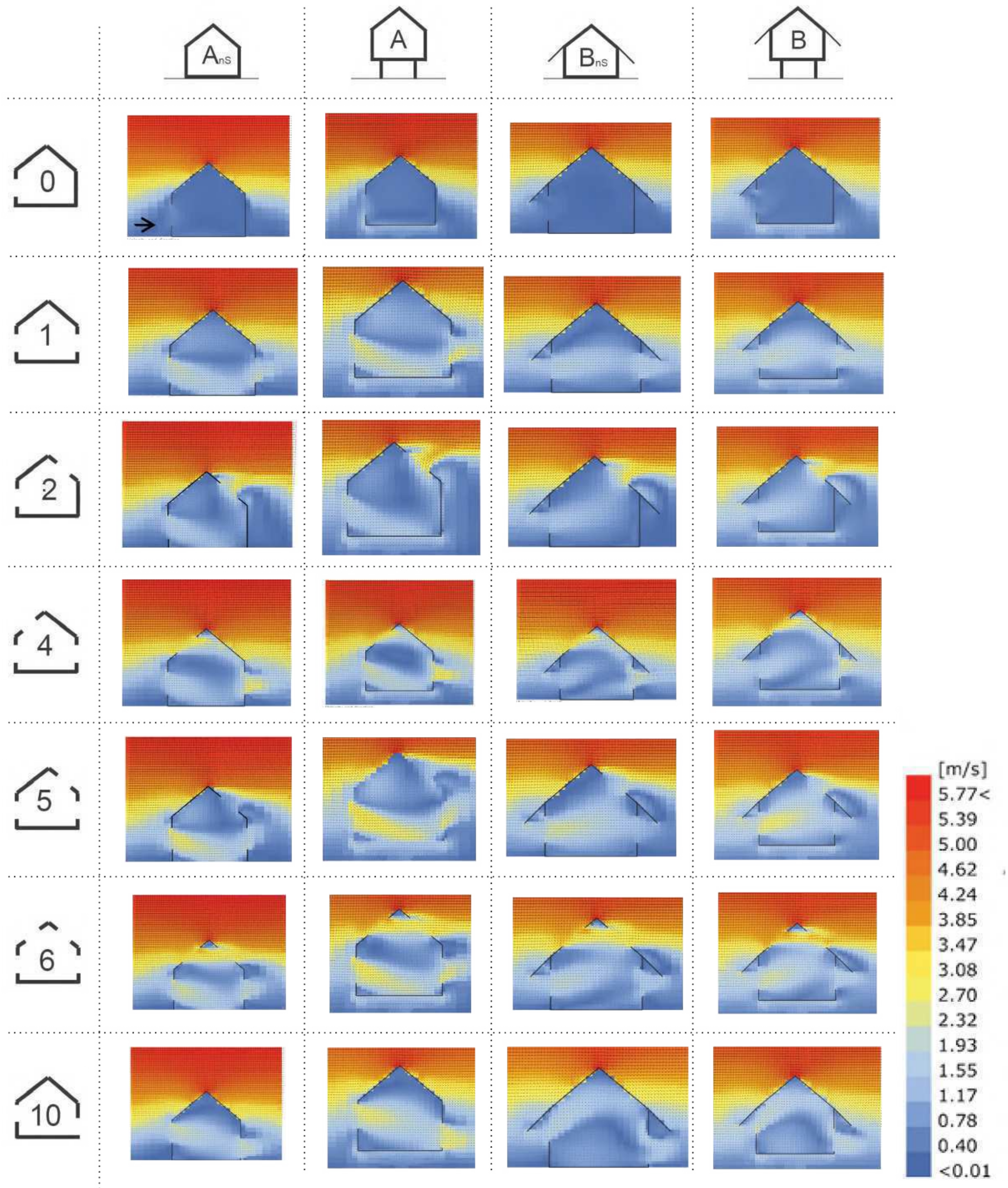


Figure 5.25: Air velocity and direction (flow) results for opening configurations with the relevant combinations in the vertical plane. The wind is directed from left to right as indicated in the combination 0Ans in the top left corner.

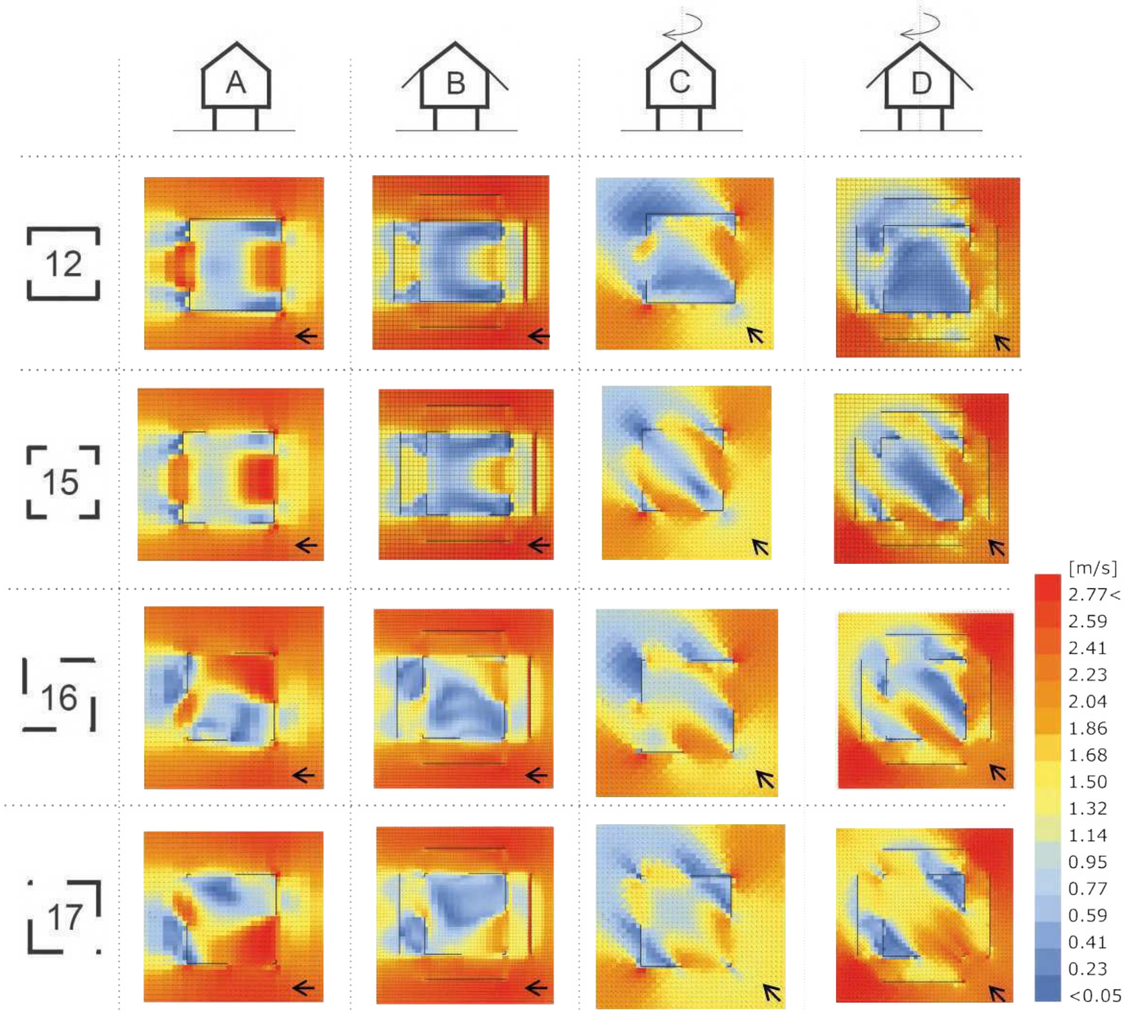


Figure 5.26: Flow results for opening configurations with the relevant combinations in the horizontal plane.

Using windward and leeward facade openings In the vertical plane, configurations with openings at both the windward and leeward facade side (1,4,5,6,8,9,10,11) score significantly better in all the combinations. The flow pattern illustrates this by directing the flow through the comfort zone. The configuration with a single opening (configuration zero), is observed to have an air velocity several times lower than the other configurations in every combination.

Providing an opening on the wind and leeward facade side increases the velocity because the pressure difference is solved through the comfort zone.

Aligning orientation and openings When the orientation is changed to 45°, configuration 16 and 17 in combination C result in the highest indoor air velocities. The alternating openings of configuration 16 illustrate the comfort zone to benefit from the redirection of the flow. Configuration 17 benefits from an unobstructed aligned flow through the comfort zone and building. The other configurations perform less compared to an orientation of 0°. The configuration with two openings performs the least. Configuration 15 with four openings results in two continuous flows directed around the comfort zone. Consequently, air velocity reduces.

In addition to the discussion on wind and leeward ward facade openings, the alignment of openings and comfort zone should be in direction of the wind to increase air velocity. Alternating openings can also be used to direct the flow through the comfort zone.

Leeward roof opening As can be observed in figure 5.23, the configuration with facade openings at middle height and a leeward roof opening (configuration 5) scores the best in every combination. This effect is illustrated by the flow pattern results. The flow is directed upwards through the comfort zone and the velocity increases at the inlet opening. If a roof opening is used on the wind and leeward side, two separate flows are observed. This increases the velocity slightly in the comfort zone.

A single roof opening on leeward side increases the velocity and influences the flow pattern by directing it upwards. This is explained by the increase in area of openings and its location. Since openings at mid height result in a downward flow pattern, adding a leeward roof openings increases velocity significantly by redirecting it upwards. Both hypotheses therefore need to be redefined to a leeward roof opening instead of roof openings.

Four-sided openings When the building is parallel to the wind direction, openings on all sides have higher air velocity than two-sides (configuration 12 and 15). In the flow results of combinations 15A and 15B in figure 5.26, it can be seen that the additional openings on the sides contribute to the total flow in the building and higher velocities in the comfort zone. If the openings are alternated like in configurations 16 and 17, having four sided openings also increases air velocity if they direct the flow through the comfort zone.

The increase in air velocity can be explained as follows. When the building is perpendicular to the wind direction, openings on the sides provide an additional path to solve the pressure difference. As a result, more air flows through the building and velocity increases.

Location of the opening As can be observed, the location of the openings on the facade significantly influences the flow pattern and air velocity. Since it is observed that the wind maintains its initial or downward direction in the building, the flow is for a major part determined by the inlet opening. For combination A, locations at middle or at the top of the facade benefit air velocity. For combination B, openings positioned at the middle or at the bottom of the facade perform well. For C and D, openings on the corners in wind direction are beneficial. These findings are illustrated by the flow results. The first part of the second hypothesis is thereby tested as true.

5.3.3. Conclusions

The conclusions of this section are presented below. It is followed by a discussion on the assumptions used to generate opening variants.

- Applying stilts of 1 meter does not change the flow pattern but does change the air velocity.
- The alignment of opening configuration and location with the comfort zone should be in direction of the wind to increase air velocity. Openings on the wind and leeward facade therefore benefit air velocity. Alternating openings also showed to perform well if their positions direct the flow through the comfort zone.
- To benefit air velocity, the location of the openings should be adjusted to the combination of other strategies and the comfort zone. For example, when the orientation is changed, the openings should be aligned on the corners in wind direction to increase air velocity. When eaves are used, lower positioned openings benefit air velocity because the flow is less obstructed by the eaves. When eaves are used in combination with a 45° orientation angle and opening on the corners, air velocity increases because the gap between the eaves does not obstruct the flow.
- A roof opening on leeward side influences the flow pattern by directing it upwards and increasing the velocity.
- Openings on all sides increase air velocity because they provide additional paths to solve the pressure difference. This is especially the case when the orientation angle is changed.

Discussion on air velocity assumptions As is illustrated by the flow pattern results, the configuration and location are significant to determine the flow and velocity through the house. The influence of the dimensions of the windows however is not as simple as assumed. Because the comfort zone does not benefit from a even spread flow through the building, increasing the size of the openings does not directly result in higher air velocities.

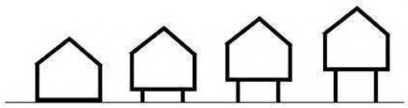
5.4. Stilts

In this section, stilts height is varied to study the influence on air velocity. The following hypotheses is thereby studied.

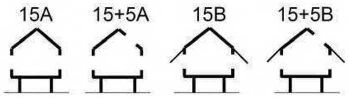
> *"Increasing stilts height increases air velocity with an exponential decay."*

5.4.1. Method

The method as discussed in 5.1.3 is used. Figure 5.27 illustrates the method.



(a) Varying stilts height.



(b) The relevant combination of other strategies used.

Figure 5.27: Varying stilts height with the relevant combinations of other strategies.

5.4.2. Results

In the graph of figure 5.28 the air velocity results are plotted over the stilts height. An general exponential decaying trend is observed with two exceptions. One, the trend observed is not very smooth. And two, for stilts height between 0m and 0.5m a decrease in air velocity is observed. The flow results in figure 5.29 illustrate the increase in velocity by increasing stilts height in the building. It can also be seen that the flow pattern does not change. It is observed that underneath the building, a faster flow is present than the outdoor wind speed at the same height.

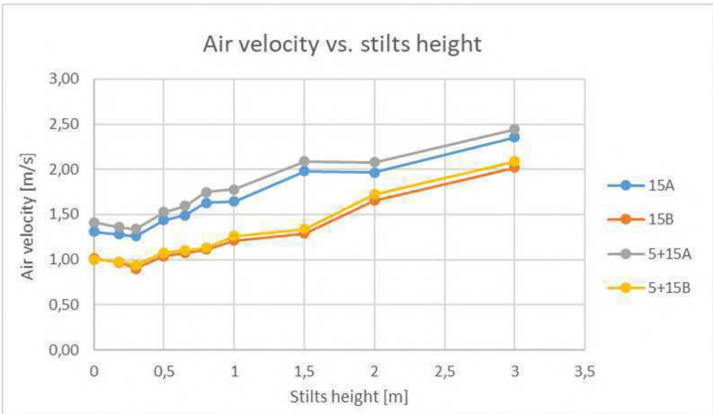
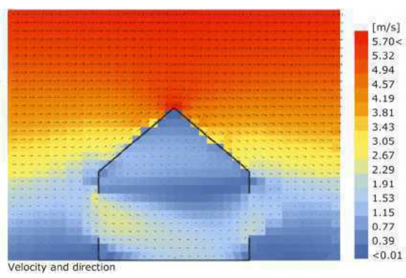
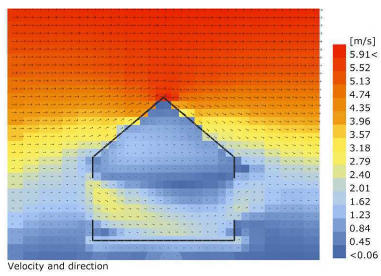


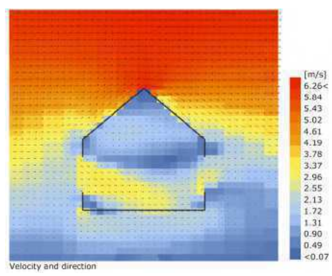
Figure 5.28: Air velocity versus stilts height for configuration 15A, 15B, 5+15A and 5+15B.



(a) 0 m stilts height.



(b) 0.6 m stilts height.



(c) 2 m stilts height.

Figure 5.29: Flow results for several stilts heights with combination 15A.

5.4.3. Discussion

The results are in line with the hypotheses with some exceptions. The decrease of air velocity at small stilts height can be explained by the pressure difference is also solved underneath the building. As a result, indoor air velocity decreases. The irregularities in the exponential decay could be caused by the relative large (0.22m) mesh settings used for reading the CFD solution. However, only a slight general decaying trend is still observed. If the hypotheses holds is therefore up to debate. To test the hypotheses, greater stilts height lengths should be studied. This will be done in the following chapter. In addition, a finer mesh setting will be used for reading the CFD solution.

5.4.4. Conclusion

Increasing stilt height influences air velocity but does not significantly influence the flow pattern in the building. The results showed that increasing stilts height increases air velocity. However, when inlet openings are used at middle height of the facade and stilts height below 0.5 m, a decrease in air velocity is obtained compared to stilts of 0 height. This is caused by the flow also going underneath the building. In the next chapter, larger stilt heights are studied to be able to test the hypothesis.

5.5. Eaves

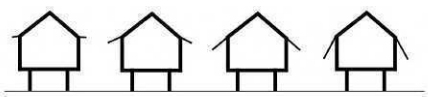
The results of the parameter study on eaves are elaborated in this section. First some specifications to the method are discussed. Then the result are discussed and concluded per comfort parameter. Mean radiant temperature is evaluated first and is followed by air velocity. The hypothesis defined below is thereby tested.

"Increasing the eaves length and angle decreases air velocity and mean radiant temperature.

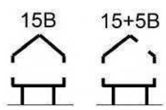
5.5.1. Method

The length and angle (to horizontal) of the eaves are studied on air velocity and mean radiant temperature as discussed in section 5.1. Figure 5.30 illustrates the variants studied for natural ventilation. For radiant temperature a box with eaves is used. The following additions are done.

- Five angles in combination with five lengths are defined to cover the significant part of the range of eaves and still have a realistic computation time.
- The same time step as in 5.2 is used for the inside surface temperature results. The specifications are depicted in figure 5.12.
- To accommodate hinged behaviour, the eaves are shaped as illustrated in figure 5.3b. As a result, there is a gap on the corners between the eaves. This gap does not block solar radiation and is therefore less effective than continuous eaves. The eaves are modelled as shading to block the radiation. As a result, they block the solar radiation but don't transmit heat. The effect is therefore slightly overestimated.



(a) Varying eaves length and angle.



(b) The relevant combination of other strategies used.

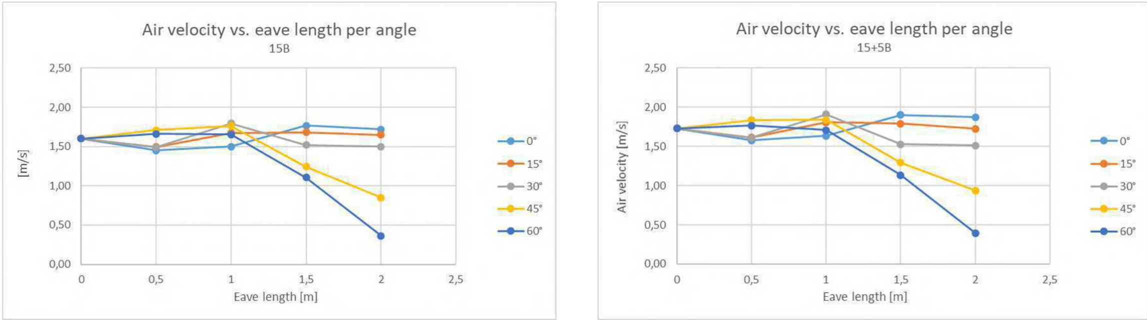
Figure 5.30: Varying eaves length and angle on air velocity with relevant combinations of other strategies.

5.5.2. Air velocity

Results

In the graphs of figure 5.31, the air velocity is plotted over the length for configuration 15 and configuration 15+5 respectively. Figures 5.32 show three selected flow results by varying the length. Figure 5.33 shows several results when the angle is varied. The same trends in air velocity are observed in both graphs. It can be seen that the results of configuration 5+15 are in general slightly higher.

For a 0°, 15° and 30° angle, varying the length results in small air velocity. For a 45° and 60° angle, increasing the eaves length decreases air velocity significantly. Increasing the eave length above 1 m shows a decrease in air velocity per angle increase and per length increase. For a 0° angle, no significant wind decrease and flow pattern change is observed. This can be seen in figure 5.33a.

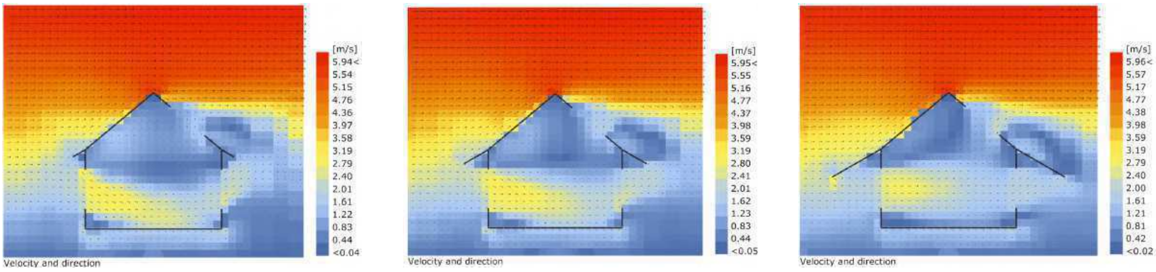


(a) Combination 15B.

(b) Combination 15+5B.

Figure 5.31: Air velocity inside over eave length per degrees angle to horizontal of eave for configuration 15+5B.

As is illustrated by the flow results, an upwards redirection of the flow inside the building is observed when the length or angle is increased. Increasing the angle of the eaves results in an enhancement of this effect and an occurrence with shorter eave lengths.

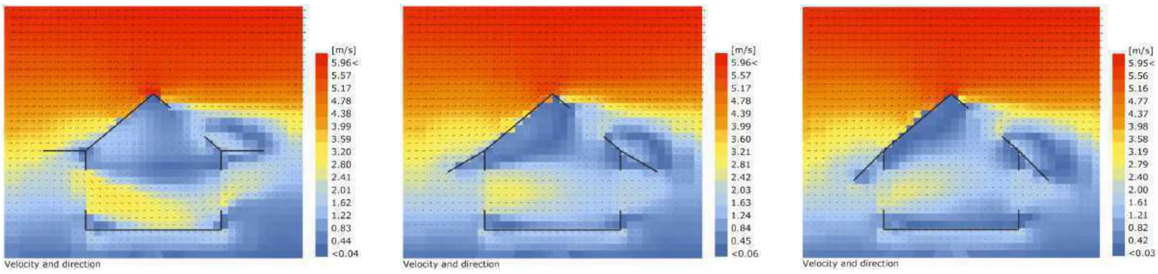


(a) Length of 0.5m.

(b) Length of 1m.

(c) Length of 2m.

Figure 5.32: Air velocity and direction results at increasing eave lengths with an angle of 30° at configuration 15+5B.



(a) Angle of 0°.

(b) Angle of 30°.

(c) Angle of 60°.

Figure 5.33: Air velocity and direction results at increasing eave angle in degrees with a length of 1.5 m for configuration 15+5B.

Discussion

Increasing the eave length for small angles, does not negatively direct the flow away from the comfort zone and therefore does not decrease the air velocity. It is even observed to benefit air velocity slightly. This can be explained by the air being forced through the opening since the eave blocks it from going upwards. The hypothesis is thereby tested as false.

Together with the inlet location of the opening and the opening configuration, the eaves influence the flow by changing the initial direction of the air. As can be seen in the flow results, long inclined eaves direct the flow upwards through the opening above the comfort zone. Short, strong inclined eaves or longer and slight inclined eaves direct the flow slightly upwards to benefit the velocity in the comfort zone. Adding a leeward roof opening to the configuration increases air velocity slightly in general. This support the conclusion made in section 5.3.

5.5.3. Mean radiant temperature

Results and discussion

In figure 5.34 the results are plotted. The graph shows per eave angle the mean radiant temperature over the length. A decreasing exponential decay in mean radiant temperature is observed by increasing the length of the eaves. This holds for every angle. The difference in mean radiant temperature per angle increase is about equal. The difference between a 0° and 60° angle at 2.5 m length is 0.7 °C and 1.3 °C respectively. Figure 5.35 shows the inside surface temperatures for two combinations of eave lengths and angles. The increasing length and angle results in lower inside temperatures of about 3 °C of the south and east facades. This is indicated by the light blue colour compared to the yellow colour of the shorter eaves.

The results follow the hypothesis. The relative slight decrease of 1.3 °C in yearly mean radiant temperature using maximum eave lengths is explained because it is a yearly average.

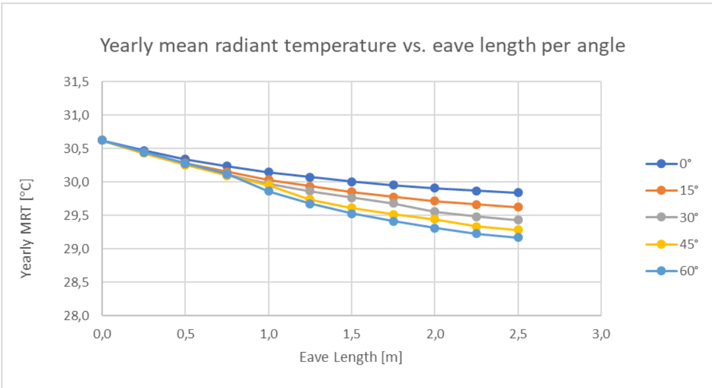
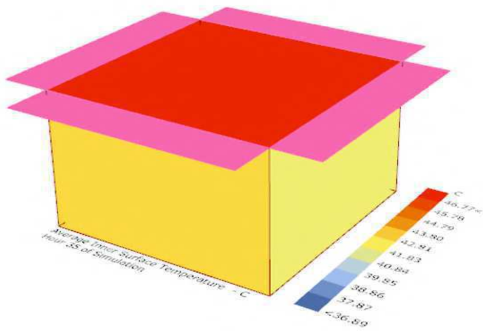
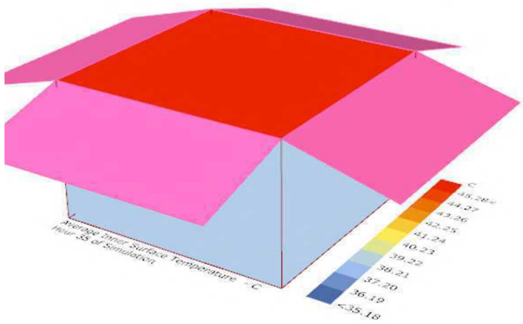


Figure 5.34: Plotted results of yearly mean radiant temperature over the length of the eaves per angle of the eaves.



(a) Eaves of 1 m and 0°.



(b) Eaves of 2.25 m and 15°.

Figure 5.35: Inside surface temperatures result at 11 AM.

5.5.4. Conclusion

An increase in eave length or eave angle decreases mean radiant temperature with a slight exponential decay.

Eaves length and angle in combination with the opening influence the flow pattern and velocity. Horizontal eaves and short eaves don't effect the velocity and flow significantly. Longer and inclined eaves change the initial direction of the flow before entering. As a result, the flow is directed upwards. For openings at middle facade height and small eave angles this can benefit velocity by counteracting the downward flow pattern. For larger angles and larger lengths, velocity decreases since a major part of the flow is guided around the building and the remaining part is directed above the comfort zone.

5.6. Orientation

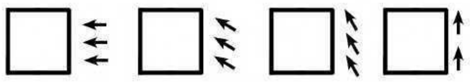
In this section, the result of changing the orientation angle on air velocity is studied. This is done in combination with eaves and without eaves. The latter is discussed first.

- *"For combination C, increasing the orientation angle increases air velocity when the incident angle of the wind is in alignment with the openings and comfort zone."*
- *"For combination D, using a 45° orientation angle benefits air velocity."*

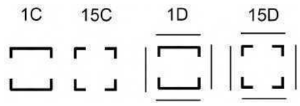
5.6.1. Method

The method as defined in section 5.1 is used. The following specifications to the method are made. Figure 5.27 illustrates this method.

- The eaves used are 2.2 m at an 45° angle so they are visible in the horizontal section of the flow results.
- Only angles from 0° to 90° are studied since they are representative due to symmetry.



(a) Varying the orientation angle by changing the wind direction.



(b) The relevant combination of other strategies used.

Figure 5.36: Varying the orientation angle by changing the wind direction with the relevant combinations of other strategies.

5.6.2. Combination C

In figure 5.37 the results per configuration and combination are plotted over the orientation angle. The velocity and direction results are shown in figure 5.38 for combination C and figure 5.39 for combination D.

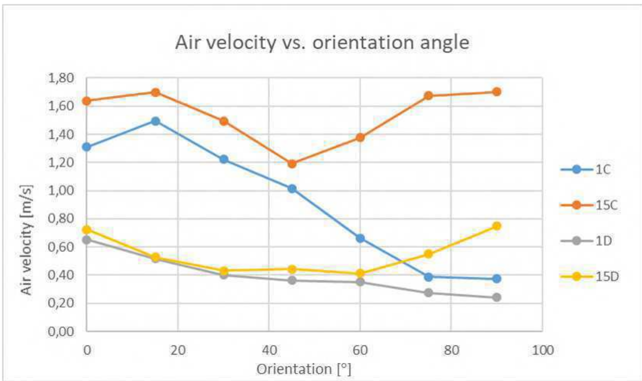


Figure 5.37: Results influence of orientation angle on air velocity.

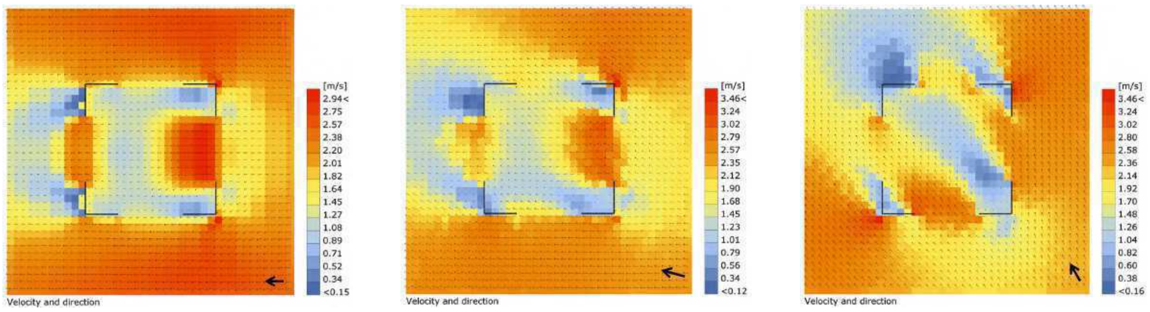
Results

Configuration 15 shows after a small increase at 15°, a declining trend to a minimum at 45°. It is followed by a reversed trend until 90°. Configuration 1 shows after an initial increase at 15°a declining air velocity with a minimum at 90°.

Figure 5.38 shows the flow to follow its incident angle. It is then redirected by obstructions to the other most aligned opening. It is observed in figure 5.38c that the flow is separated and partly guided around the comfort zone. In figures 5.38b and 5.38c it can be observed how the velocity is more continuous than at a 0 °angle.

Discussion

The hypotheses holds since it is observed that the wind follows its initial direction through the opening before being redirected by obstructions and other openings. Therefore, a direct alignment of wind direction with the



(a) Orientation of 0°. (b) Orientation of 15°. (c) Orientation of 60°.

Figure 5.38: Results air velocity and direction for changing the orientation for configuration 15C.

inlet opening, comfort zone and other openings benefit air velocity. Consequently, this explains why varying the orientation angle for configurations 1C and 15C does not benefit air velocity.

The more constant velocity observed can be explained as follows. If the orientation angle is varied, the distance between the openings in wind direction decreases. As a result the downward flow pattern has less distance to develop. Hence its effect decreases.

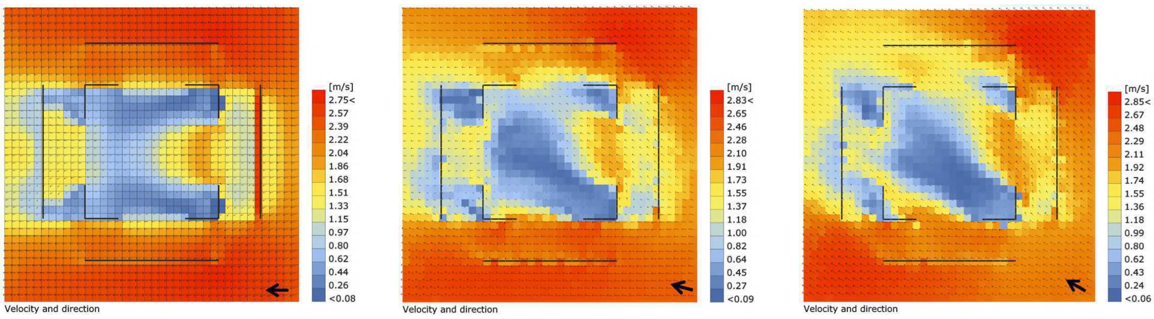
The small exceptions observed for configuration 1C at 15°and 15C at 15° and 75 °Can be explained the influence of the specific opening variants studied. The obstruction of the walls direct the flow more upwards through the comfort zone. This increases air velocity slightly but is not deemed significant since the difference is small and dependent on the variant tested.

Changing the orientation angle showed the significant influence of incident angle in combination with the openings. Using openings on all sides is shown to perform significantly better when the wind is not coming from the main directions. Therefore, openings on all sides are recognised to increase air velocity throughout the year significantly.

5.6.3. Combination D

Results

In figure 5.37 the parabolic symmetrical of configuration 15D can be seen. It has a constant part between 30° and 60°. For configuration 1D, varying the orientation decreases the air velocity. Figure 5.39 shows the flow to be directed outwards underneath the eave. It maintains this direction in the building.



(a) Orientation of 0°. (b) Orientation of 15°. (c) Orientation of 30°.

Figure 5.39: Flow results for changing the orientation angle of configuration 15D.

Discussion

The hypotheses does not hold. This can be explained by the role of the opening configuration. When varying the orientation angle, the gap between eaves and the openings are not aligned. Consequently, velocity decreases. The section of 5.3 showed that if they align, air velocity increases.

Conclusion

Based on the results and discussion, it can be concluded that the wind follows its initial direction through the opening before it is redirected to the other openings or obstructed. Therefore, varying the orientation angle to be in alignment with the inlet opening, comfort zone and outlet opening increases air velocity.

When the orientation angle is varied with long inclined eaves, the opening configurations determine how the air velocity is influenced. Openings aligned in wind direction on the corner then benefit air velocity. Openings in the middle of the facade increase air velocity when they are in normal direction to the wind.

Using openings on all sides increase air velocity significantly when the wind is not coming from the main wind directions.

5.7. Roof insulation

In this section, the influence of roof insulation on inside surface temperature is studied. The method is discussed first, before the results are evaluated and conclusions drawn. The hypothesis stated below as defined in section 5.1.4 is thereby verified.

"Increasing the Rc-Value m^2K/W of the roof decreases the inside surface temperature with an exponential decaying trend."

5.7.1. Method

The method as defined in section 5.1 is used. In figure 5.40a, the analytical calculation method is outlined by the formulas and values. It is based on the formula elaborated in section 4.2.5. An extreme case of a hot and sunny day without wind is used.

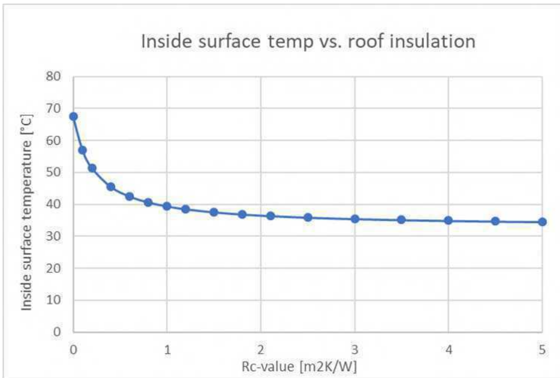
5.7.2. Results and discussion

In 5.40b, the result of the inside surface temperature over the Rc-value is plotted. An exponential decay is observed from 68 °C to 33 °C for Rc-Values of 0 m^2K/W to 5 m^2K/W.

The hypotheses holds. An Rc-value of 1 results in an inside surface temperature of 39 °C. This covers 83% of the total decrease possible. Since the decrease in temperature per increase in Rc-value is relative slow after Rc = 1, this is deemed the significant part. Using the warm conditions without wind causes the temperature to rise to 68 °C. As can be seen, increasing the insulation value converges the inside surface temperature to the inside climate.

Influence roof insulation (Rc) on indoor surface temp	
Tio = Ti + Rsi/(Rsi+Re+Rc)*(TSAT-Ti)	
TSAT = Te + Qsun/αe	
Warm day, clear sky, no wind	
Tio = inside surface temperature[C°]	
Ti = inside temperature [C°]	33
TSAT = Sol-air temperature	38,13
Rsi = Heatransfer resistance surface inside - air [m2K/W]	0,13
Rse = Heatransfer resistance surface exterior - air [m2K/W]	0,04
Rc = Heat transfer resistance roof [m2K/W]	x
Te = outside temperature [C°]	38
Qsun = Absorbed Irradiance sun load [W/m2]	560
qsun = Irradiance sun load [W/m2]	1120
αenw = wind factor outside no wind	25
αi = wind factor inside	7,69
a = absortion factor sun radiation, approx	0,5

(a) Inside surface temperature formulas and input values.



(b) Inside surface temperature results versus the Rc-value.

Figure 5.40: Roof insulation calculation formulas, input values and results.

5.7.3. Conclusion

From the analytical calculations it can be concluded that roof insulation influences the inside temperature by an exponential decaying trend. The significant difference of 83% made is made for a Rc-value of 1 m^2K/W. Increasing the insulation value converges the inside surface temperature to the indoor temperatures.

5.8. Roof angle

To study the influence of changing the roof angle, first the validation results are analysed and discussed. It is followed by a further literature study to base the conclusion on. The following hypotheses is tested.

"Increasing the roof angle, decreases the yearly mean radiant temperature."

5.8.1. Results and discussion

The results and case description is depicted in the table of figure 5.41. As can be seen, the yearly mean radiant temperature of the living zone does not decrease when increasing the roof angle in respectively the single-zone and multi-zone cases. The yearly mean radiant temperature of the roof zone does decrease slightly. The hourly temperatures on the other hand are influenced considerably. They decrease with several degrees Celsius.

case	description
1	0 degrees
2	30 degrees
3	60 degrees
4	30 degrees multi-zone
5	60 degrees multi-zone

outdoor	
Date: 02-01	
Time	11AM
dbtemp [°C]	30,5
Windspeed [m/s]	3
wind direction	80
Cloud cover 0-10	5
Air wall air mixture	0,2

performance zone living	1	2	3	4	5
dbtemp zonal [°C]	43	42,7	42,5	41,7	41,4
radtemp zonal [°C]	43,5	43,4	42,9	41,5	41,1
operative temp [°C]	43,2	43,1	42,7	41,6	41,2
Yearly average mean radiant	30,6	30,6	30,6	30,4	30,4
performance Zone Roof					
dbtemp zonal [°C]				42,3	42
radtemp zonal [°C]				45,8	44,4
operative temp [°C]				44	43,2
Yearly average mean radiant				31,3	31,1

Figure 5.41: Results validation study on roof angle. On the left the case description and on the right the performance results.

The decrease of the zonal temperatures at 11AM is explained by literature [35]. Increasing the roof angle increases the area subject to solar radiation during peak hours. Since the increased area is subject to the same amount of solar radiation, the temperatures during midday decrease. However, in the mornings and afternoons, this effect is reversed because the more amount of solar radiation is captured. This effects explains the differences found in yearly mean radiant temperature to be insignificant.

In addition, the computational model does not transmit the radiant temperature between zones. As a results, the influence of heat radiated to the living zone by the roof panels is not taken into account. Since the means are lacking to further study roof angle on mean radiant temperature, literature is used for the conclusions.

5.8.2. Literature results and discussion

In section 4.2.6, the results are shortly presented and discussed. It is found that increasing the roof angle is beneficial for indoor temperatures by increasing the roof angle during peak hours [35]. During non-peak hours the temperatures increased [35]. However, the influence of solar radiation is less significant during these hours. In addition, increasing the angle also benefits the zone underneath by the incident angle of the radiated heat. Therefore, increasing the roof angle is deemed to decrease the radiant temperature overall, benefit the incident angle of radiant heat and thereby increase comfort.

Another consideration on roof angle is to be able to provide buoyancy driven ventilation. Increasing the height of the building increases this effect as explained in section 2.2. It must be noted that roof openings should be present to provide stack ventilation.

5.8.3. Conclusion

Since the means are lacking for an appropriate study, the conclusion is based on literature [35]. Increasing the roof angle decreases mean radiant temperature overall and benefits the incident angle of radiant heat. If roof openings are used, increasing the roof angle enhances stack ventilation which benefit heat dissipation.

5.9. Conclusion

In this chapter, the sub-question: *"How do these vernacular design strategies influence thermal comfort parameters?"* is answered. The findings are discussed per strategy.

Openings Openings influence air velocity by providing a flow through the building. This flow is directed by the opening configuration and location. When the flow is guided through the comfort zone, air velocity increases. If openings on the wind and leeward side are used, air velocity increases. Using additional openings on the other facades benefits air velocity. Alternating openings can also benefit air velocity when they direct the flow through the comfort zone. When inlet openings at middle height are used, adding a leeward roof opening increases the velocity and direct the flow upwards. If combined with other strategies, the location of the openings should be aligned to result in an unobstructed flow through the building to increase air velocity.

Stilts Increasing stilts influences air velocity but does not significantly influence the flow pattern in the building. Increasing stilts height increase air velocity in general with an exponential decaying trend. However, when inlet openings are used at middle height of the facade and stilts height below 0.5 m, a decrease in air velocity is obtained compared to stilts of 0 m. This is caused by the flow also going underneath the building.

Eaves Eave length and angle influence air velocity and radiant temperature. An increase in eave length or eave angle decreases the yearly mean radiant temperature with a slight exponential decay. Air velocity is influenced by the eave length and angle in combination with the opening variant. However, horizontal eaves and short eaves do not effect the velocity and flow significantly. Longer and inclined eaves change the initial direction of the flow before entering. As a result, the flow is directed upwards. For openings at middle facade height and small eave angles, this can benefit velocity by counteracting the downward flow pattern. For larger angles and larger lengths, velocity decreases since a major part of the flow is guided around the building and the remaining part is directed above the comfort zone.

Orientation Changing the orientation angle influences air velocity. The flow follows the initial direction wind direction through the opening before it is redirected to the other opening or obstruction. Therefore, varying the orientation angle to be in alignment with the inlet opening, comfort zone and outlet opening increases air velocity. Using openings on all sides, significantly increases indoor air velocity when the wind is not coming from the main directions. In combination with long inclined eaves and openings in the middle of the facade, a normal direction to the wind increases air velocity.

Roof insulation Roof insulation influences the inside temperature by an exponential decaying trend. The significant difference of 83% made is made for a Rc-value of 1 m^2K/W. Increasing the insulation value converges the inside surface temperature to the indoor temperatures.

Roof angle Since the means are lacking for appropriate study, the conclusion is based on literature [35]. Increasing the roof angle decreases mean radiant temperature overall and benefits the incident angle of radiant heat. If roof openings are used, increasing the roof angle enhances stack ventilation.

6

Influence study on comfort performance

In this chapter, the influence on comfort performance is studied. To obtain a representative comfort performance, using an actual design is necessary to take the influence of required rooms, usage characteristics and materials into account. This decreases the general applicability but allows the strategies to be assessed on their overall influence. The following question is thereby answered: *How do the design strategies influence thermal comfort performance?*. First, the method is discussed. Then, the computational model of the case study is validated. The results of the performance analyses of the case study are presented next, followed by the discussion of the influence study per strategy. The chapter is ended with a summary of the findings of this chapter.

6.1. Method

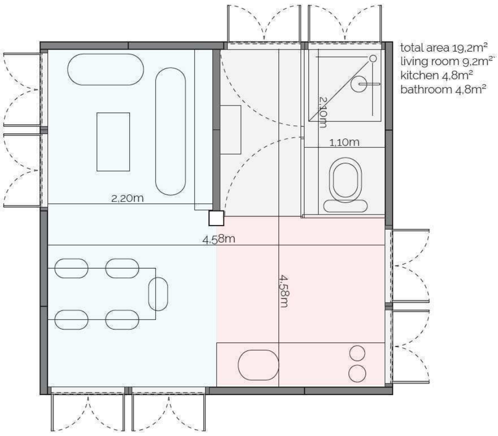
In this section, the method to answer the sub-question stated in the introduction of this chapter is discussed. The design of the case study is presented first. The steps to answer the question are defined next. It is followed by addressing the assessment criteria and hypotheses formulation. Then, the build-up of the computational simulation model is discussed before the paragraph is ended with a conclusion on the method.

6.1.1. Case study project

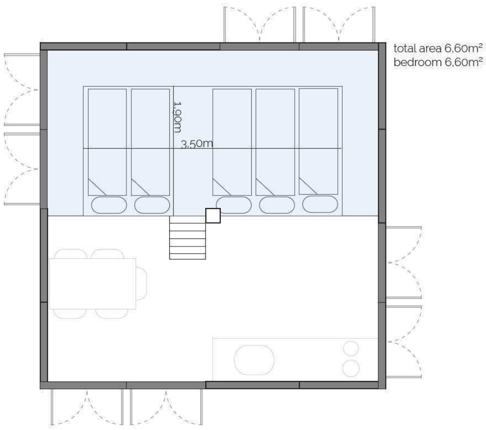
The case study project is the Finch Floating Homes project. It is located in the town of Macabebe, Pampanga, the Philippines which is situated just above Manila at the Manila bay. Figure 6.1 illustrates a render of its design [46]. For the purpose of this study, it is considered to be built on land. Figure 6.2 and 6.3a illustrate the floor plans and cross-sections with dimensions as used in this study. The used materials with corresponding properties and energy loads can be found in figure 6.3b. The height, width and roof angle are the same as used in chapter 5.

Figure 6.1: The Finch Floating Homes design [46]. For the purpose of this study it is considered to be built on land.

The design consists of multiple rooms. The living room and the bathroom are situated at the ground floor. The room on the first floor is open and covers half the ground floor area at the north side. The openings at every side span from ground floor to first floor. A roof insulation with a Rc-value of 0.5 m^2K/W and eaves of 1.3 m long at a 15 ° angle are used.



(a) Ground floor plan [46].

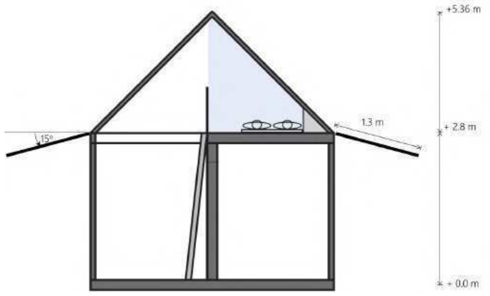


(b) First floor plan [46] with dimensions used.

Figure 6.2: The floor plans of the case study design as used in this research. The top side indicates the north direction. This is the 0° orientation angle.

6.1.2. Method in steps

The flow chart in figure 6.4 illustrates the three steps of this method. They are discussed per step below. The knowledge gained in chapter 5 is often applicable and therefore used to avoid unnecessary work.



(a) Cross section in north south direction [46]. For the purpose of this study, it is considered to not have roof openings.

Materials	Thickness [mm]	Rc-value [m^{2}K/W]	Solar abso coeff.	Thermal abso coeff.
Gypsum white façade panels	12,7	0,079	0,4	0,9
Floor Wood	25,4	0,17	0,5	0,9
GI metal roof panel	1,5	0,0017	0,5	0,9
Insulation material vary	x	0 to 3	x	0,9
Energy Loads	**Quantity**	**Unit**	**Description**	**Presence**
People	4		Persons	Scheduled
Lighting	3	W/m2	Few bulbs	Scheduled
Electric machines	3	W/m2	TV, 2 fans	Scheduled

(b) Case study materials, properties and energy loads definition.

Figure 6.3: Cross section of the case study and material properties as used in this research.

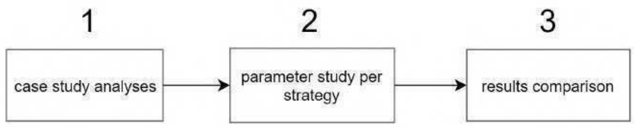


Figure 6.4: The three steps of the method taken in this chapter.

1. Case study analyses

It is expected that design features like the bathroom, the dimensions of the openings and the first floor have a significant influence on certain comfort parameters and thus comfort performance. Therefore, these influences are analysed first.

2. Parameter study per strategy

A similar parameter study to the one in chapter 5 is performed. Figure 5.4 illustrates the idea. Per strategy, the parameter is varied and assessed on comfort performance using the the case study design. No other combinations are used. This means the case study design is the only combination of other strategies studied. If the effect on the comfort parameter is significantly different than in chapter 5, the results are addressed. Several strategies require some alterations to this method. They are discussed below.

- **Openings** - The design features of the case study like the openings over the whole facade height are expected to influence the air velocity significantly. The opening variants studied are therefore determined after the case study is analysed.
- **Roof insulation** - When the roof insulation is varied to a Rc-value of 0 m^{2}K/W, the radiant heat emitted from the attic surfaces to the living room is expected to have a significant influence. However, the energy model does not transmit radiant heat through openings between zones. Therefore, a different calculation method is introduced at the corresponding section.
- **Roof angle** - The conclusions are based on a literature study as explained in chapter 5.

3. Results comparison of the strategies

In this step, the impact of the strategies on comfort are compared to each other. The knowledge gained can be used for designing the strategies and combinations.

6.1.3. Assessment method

The comfort performance is assessed by the adaptive thermal comfort model as explained in section 2.1. Two expressions are defined to indicate the performance regarding the adaptive thermal comfort model. The yearly average comfortable percentage and the accumulative difference comfort temperature. These are discussed after the air velocity assessment is adjusted to the case study.

Air velocity assessment method

Air velocity is assessed by the same method as explained in chapter 5. Since living during the day is done in the living area, this zone is used to define the comfort zone. Figure 6.5 illustrates the defined comfort zone in yellow and the test points in grey. The blue planes in figure 6.6 depict the locations where the air flow is considered in this chapter. The vertical plane is placed to the left instead of the middle to be able to capture the flow that enters the building. In appendix section C.0.1 it is checked how well the average velocity represents the air velocity experienced. It concludes to be representative.

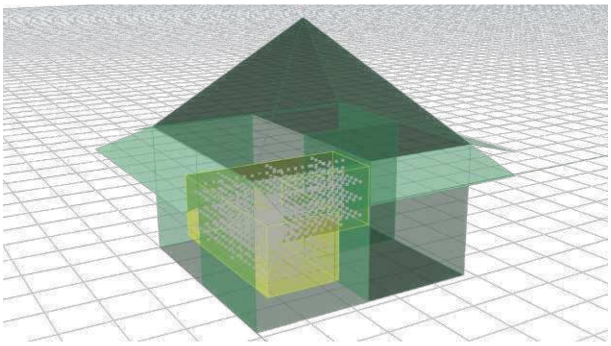


Figure 6.5: The case study with comfort zone and test points.

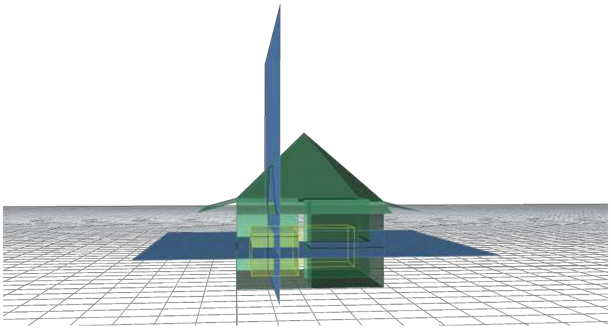


Figure 6.6: The case study with comfort zone and planes for vertical and horizontal air flow results.

Average exceeding temperature [K]
To indicate the absolute effect of the strategies on comfort, the average exceeding temperature (AET) in Kelvin is used. It indicates an average temperature in degrees kelvin which exceeds the upper comfortable limit. It expresses essentially the discomfort. A lower number thus means a better comfort performance.

It is calculated by first accumulating for every uncomfortable hour throughout the year the difference in Kelvin to the upper comfortable limit. This number is then divided by the hours that could be uncomfortable during the year. This number is based on a model that resulted in the most uncomfortable hours. These were obtained by modelling the case with no eaves, no ventilation, openings to let solar radiation in, no stilts and no roof insulation. This is benchmark number three in section 6.2. For 57.6% of the year it is uncomfortable. This translates to 3714 hours.

6.1.4. Hypotheses
Per step defined in sub-section 6.1.2 the hypotheses are discussed. The hypotheses are presented in their respective section to avoid repeating them.

1. Case study performance
The hypotheses for the case study are discussed per comfort parameter. Consequently, the comfort performance hypotheses can be evaluated.

Air velocity The openings over the vertical height of the facade allow the outdoor wind speed distribution to continue inside. The alignment of the openings of the living room direct the flow through the south opening and around the bathroom to the west opening. In the attic a recirculation of the flow is expected as found in chapter 5. In the bathroom the openings are parallel to the wind direction. Therefore, the living room is expected to have the highest air velocities and the other two rooms to have relatively low velocities.

Mean radiant temperature The inside surfaces in every zone are protected by roof insulation or eaves. Therefore, no significant differences in mean radiant temperature are expected.

Comfort performance The air velocities in the rooms are expected to be significantly different. The mean radiant temperature is expected to be the same. The differences in dry-bulb temperature are expected to be insignificant due to the air exchange between the rooms. Consequently, the difference in comfort performance is expected to correspond to air velocity.

2. Parameter study

Per strategy, the hypotheses are discussed.

- **Stilts** The openings over the vertical height are expected to result in the same indoor flow distribution as outside. Therefore, increasing stilts height increases air velocity by an exponential decay. It is expected that only the air velocity is affected by changing the height. Consequently, comfort performance has the same trend as air velocity.
- **Orientation** Changing the orientation angle influences the air velocity because the flow pattern follows the incident angle of the wind. Angles around 0°, 90°and 180° direct the flow through the comfort zone. As a result, higher air velocities are expected for these angles. Changing the orientation also influences radiant temperature. Since the bathroom can act as a buffer to protect the living room from low incoming solar radiation, the angle around 0 to 45 and 225 to 270 is expected to be beneficial for comfort. Since low incoming solar radiation is not that strong, air velocity is expected to be governing in the comfort trend.
- **Eaves** In chapter 5 it was found that increasing the eave length and angle, decreases air velocity but increases its protection versus solar radiation. Therefore, eaves that block solar radiation and do not significantly influence air velocity are expected to have the best comfort performance. Strongly inclined long eaves block the wind too much while short horizontal eaves protects the facades too little. Therefore, smaller angles with considerable lengths are expected to have the best comfort performance.
- **Roof insulation** Because roof insulation only influences the inside surface temperature directly, the same exponential decaying trend in comfort is expected.
- **Openings** Since the variants are defined in section 6.4, the corresponding hypotheses are also discussed in this section.

3. Results comparison

Openings provide air velocity and heat dissipation. Hence, they are expected to have the biggest impact on comfort. Eaves, orientation and stilts all considerably effect air flow or mean radiant temperature. Their influence on comfort is therefore expected to be of equal proportion. Roof insulation decreases the mean radiant temperature of the attic. Since the living room is covered by a first floor for half of the area, the influence of roof insulation is expected to be the smallest.

6.1.5. Computational simulation method

To be able to assess the computational model and its results, the built-up of the model is discussed. First, the combined model approach is addressed. Then, the built-up of the computational model is evaluated before it is concluded with the method of validation. Since the case study is an extension of the model used in chapter 5, the additions or changes to the model are validated accordingly. Unless specified otherwise, the same software and settings are used as specified in section 5.1.5.

Combined CFD and energy-model approach

In naturally ventilated building, the design is influenced significantly by natural ventilation and its corresponding properties like air inlet, inter-zonal exchange and flow pattern. However, the Energy model uses only basic estimations of these properties. Therefore, using CFD analyses to complement an energy calculation significantly improves the results. It is a known and advised method for naturally ventilated buildings [48]. The combined model uses the same geometry for the analyses. This means for example that a change in orientation angle occurs in the energy model and the CFD model. Consequently, the solar path and wind directions are adjusted appropriately.

Computational model built-up

Air velocity dependencies The CFD calculation is used to calculate the air velocity, the air inlet and an exchange rate for the inter-zonal exchange area between the attic and living room. They are defined to be linearly dependent to the outdoor wind speed in same direction. [4]. To improve the accuracy, the air inlet is adjusted to the wind direction throughout the year. As a consequence of not adjusting the air velocity and exchange rates, the comfort results are less precise for the parts of the year addressed in section 5.1.2. Figure 6.7 illustrates the calculation procedure. Since the bathroom and attic are not thoroughly studied on comfort, the inter-zonal exchange rate between the attic and living room suffices for an indication of the velocity in the bathroom and attic.

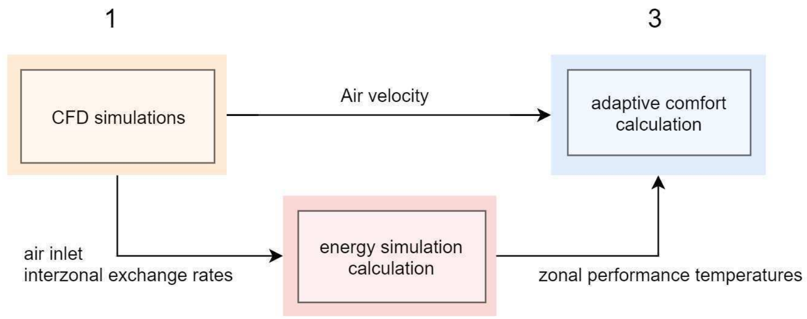


Figure 6.7: The calculation procedure of the combined model approach of CFD and Energy calculation.

Zonal definition Climatic zones are defined in the energy model to capture the effect of the separation between rooms. Consequently, the living room, attic and bathroom are defined as a zone. The opening betweens these zones exchange heat and air by definition of an air wall. Figure 6.8 illustrates the definition of the zones and air walls of the case study.

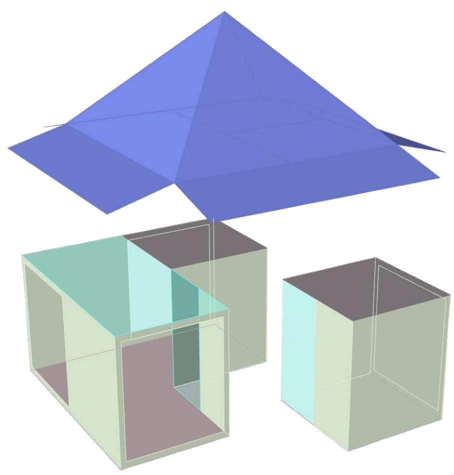


Figure 6.8: The energy model zones extruded with openings as transparent and "air walls" between zones in light blue.

Energy loads and usage characteristics The energy loads and usage characteristics are specified in the table of figure 6.3b. The "schedules" indicate the usage or presence of the energy load. The people schedules indicate two people at home from 8AM to 4PM. It also indicates that half the of the equipment and one-fifth of the lighting is used during these times.

6.1.6. Conclusion Method

To answer the sub-question, three steps are defined. First, the performance of the case study is analysed to study the influence of the design features. Second, a parameter study per strategy is performed on the case study to study the relation to comfort parameter and comfort performance. And third, results of the comfort performance are compared to each other to relate their significance in the design face. To indicate the effect of the strategies on comfort, the average exceedance temperature (AET) in Kelvin is used. The combination of the computational models for comfort assessment improves the accuracy significantly and gives a representative result for the significant part of the year.

6.2. Validation

The additional features of the case study and the additions to the computational model are validated in the same way as in section 5.2. The energy model and CFD model are validated respectively.

6.2.1. Energy model validation

Method

Like the validation in section 5.2, the energy model is validated by an empirical validation of the performance to a series of cases or benchmarks. The significant benchmarks are addressed on comfort.

Benchmark definition and hypotheses

The benchmarks and expected performance are shortly elaborated in this paragraph. They are listed in figure 6.9. The first benchmark is the case study modelled without openings and eaves. This is expected to result in a low comfort score since heat can't dissipate. Then, infiltration is added in benchmark two. Consequently, comfort increases slightly. Benchmark three includes openings to allow solar radiation to enter but no ventilation. As a result, the performance is decreased. Number four allows wind through the opening which increases comfort performance because heat can dissipate and air velocity is provided. Then, closing behaviour during the night is checked. This reduces the performance only slightly because discomfort occurs during the day. Benchmark six adds people and electrics in the form of energy loads. This decreasing performance slightly because heat is added. The last benchmark adds eaves and roof insulation. Hence, comfort increases.

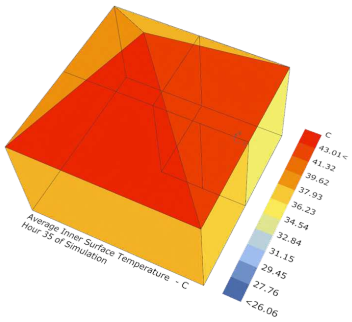
Benchmarks	Comf [%]	AET [K]
1. Closed	61,6%	5,91
2. Infiltration 0.022 [m3/s]	61,8%	5,78
3. Opening, no air inlet	57,6%	8,73
4. Adding air trough opening	74,2%	1,93
5. Closing openings at night	73,9%	1,97
6. Adding people and electrics	73,7%	1,98
7. Eaves and roof insulation	77,7%	1,27

Figure 6.9: Benchmark description and comfort results in average exceeding temperature and percentage of comfortable hours.

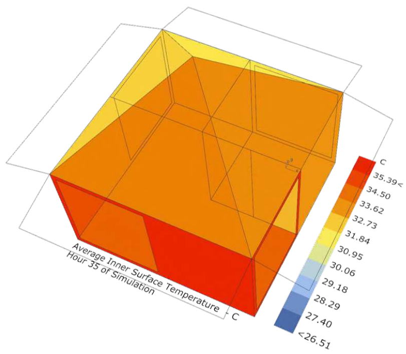
The comfort performance of the benchmarks are expected to follow the climate conditions. The outdoor solar radiation load, air velocity and dry-bulb-temperature are plotted for every hour of the year in appendix figure A.1. Based on the load of solar radiation and dry-bulb-temperature, the uncomfortable hours are concentrated during mid-day and diminish towards the evening and morning. The summer months April and May are expected to have the least comfort performance. Due to the low amount of solar radiation, dry-bulb temperature or a significant amount of wind, the best comfort performance is expected in September, October, November (except the beginning), December and between half July and half August.

Results and discussion

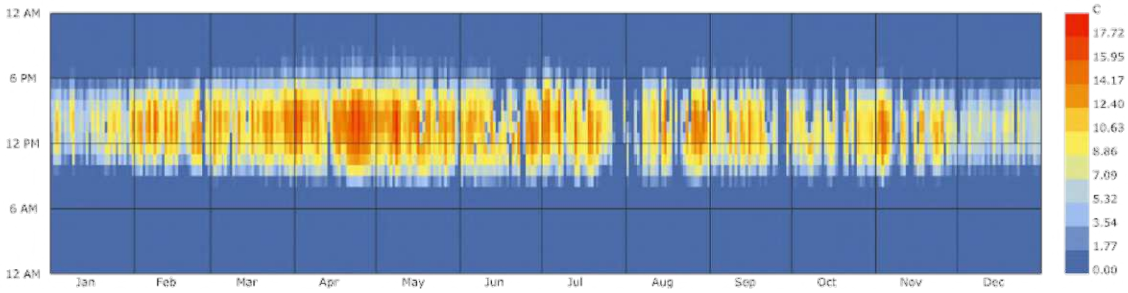
The results with corresponding benchmark description are shown in the table of figure 6.9. Figure 6.10 shows the inside surface temperature at hour thirty-five for benchmark two and seven and their two corresponding discomfort graphs. The colours indicate the difference for every hour to the upper comfortable limit when it is uncomfortable. It is observed that the comfort performance follows the radiant load and dry-bulb temperature for the discomfort results. This is lessened or diminished when high air velocities are present. The numeral results of the benchmarks and the hourly discomfort results show the trends defined by the hypotheses.



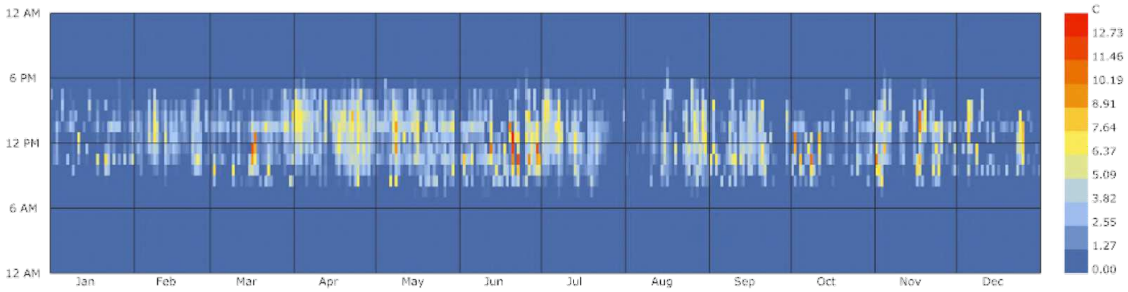
(a) Inside surface temperatures benchmark 2.



(b) Inside surface temperatures benchmark 7.



(c) Hourly discomfort results benchmark 2.



(d) Hourly discomfort results benchmark 7.

Figure 6.10: Inside surface temperature at hour 35 and hourly discomfort results for benchmark 2 and 7.

6.2.2. CFD Validation

Method and hypotheses

No specific wind tunnel tests are available of the additions to the design. Therefore, the same method will be used as in section5.2.2. The results are compared to the validated results to see if they make sense.

Results and discussion

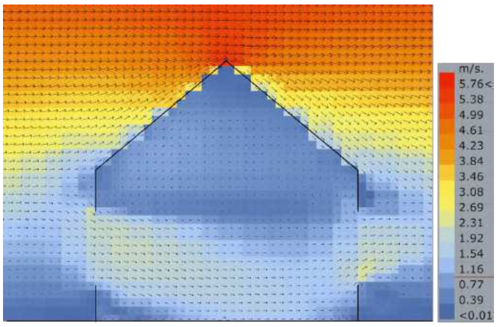
In fig 6.11 and 6.12a respectively, the vertical and horizontal results of the validated geometry of chapter 5 and the results of the case study CFD are shown. The openings over the whole facade height results in a continuous flow in the building, maintaining initial direction. Since the opening is not directly aligned the flow is redirected as can be seen in figure 6.12a.

6.2.3. Conclusion

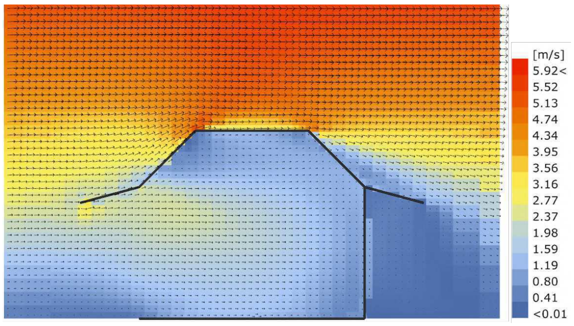
It can be concluded that the simulation model of the case study takes the added mechanisms and features into account as expected for the energy model, the CFD calculation and the comfort calculation. It also responds to the climate as expected.

6.3. Case study performance analyses

In this section, the performance of the case study is analysed. The results are discussed before the conclusions are drawn. The tested hypotheses are stated below.

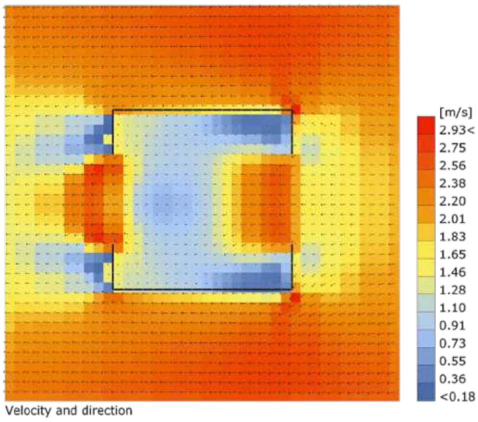


(a) Validated geometry result.

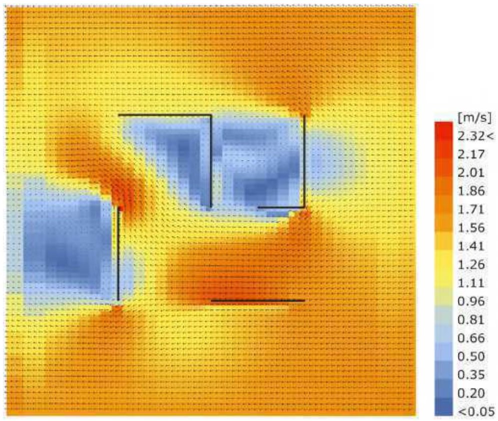


(b) Case study flow result at the plane as illustrated by figure 6.6.

Figure 6.11: Validation of the case study air flow results in vertical direction by comparison to geometry that is validated in section 5.2.2.



(a) Validated geometry result.



(b) Horizontal flow result.

Figure 6.12: Validation of the case study flow results in horizontal direction by comparison to geometry that is validated in section 5.2.2.

- *"The inside flow pattern has a similar speed distribution as the outdoor wind speed. In the attic a re-circulation is expected. The flow is directed from the east opening to the south opening and around the bathroom to the west opening. Low air velocities compared to the living room is expected in the bathroom."*
- *"The living room has a significantly better comfort performance than the attic and bathroom. The latter two have a similar comfort performance."*

6.3.1. Results

The results used for testing the hypotheses are presented here. The hourly exceeding temperature results and the energy balance per month are illustrated in appendix figure D.2 and D.1 respectively.

Results and discussion air velocity

In figure 6.11b the flow result in vertical plane is illustrated. As can be seen, a considerably even spread over the height is observed until two-third of the width of the section to the right. Then, the speed in parallel direction starts to diminish before it stops at the east wall at the right side. No circulation is observed in the attic.

The evenly distributed spread can be explained by the influence of the house and eaves. The eaves and building change the pressures a redirect the flow slightly upwards, causing a more evenly distributed spread. The first two parts of the first hypothesis are thereby tested as false.

In figure 6.12b the horizontal flow result is shown. As can be seen, the flow follows its initial direction with a slight redirection to the south facade after entering. It is then separated at the west wall and south opening. Most of it leaves the house at the west opening and the other part at the south opening. In the bathroom a small circulation is present with low velocity.

The second part of the first hypothesis is tested as true. The bathroom at the north side is observed to decrease air velocity since it blocks a part of the flow and redirects the flow slightly away from the comfort zone after entering.

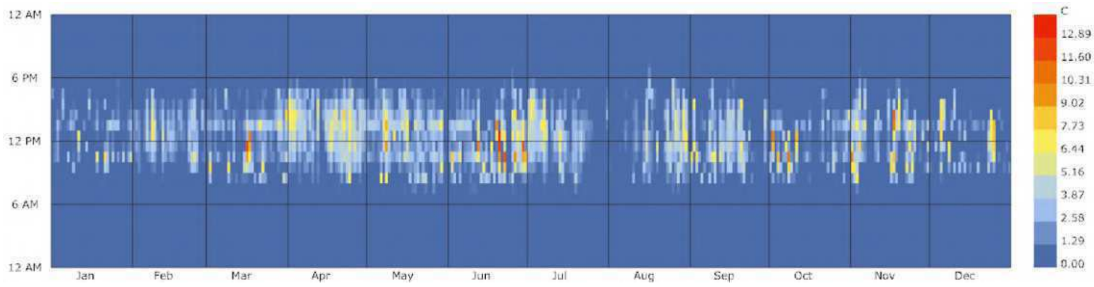
Results comfort performance

In figure 6.14 comfort performance criteria are illustrated per zone. As can be seen from the limited amount of warm colours in the figure, the living room performs the best. This performance is supported by the numeral results of figure 6.13. The attic and bathroom show similar comfort performance pattern but the bathroom is slightly more uncomfortable in the morning. In figure 6.10b the inside surface temperatures at midday are shown. As can be observed, the roof temperatures show lower inside surface temperature than the facade.

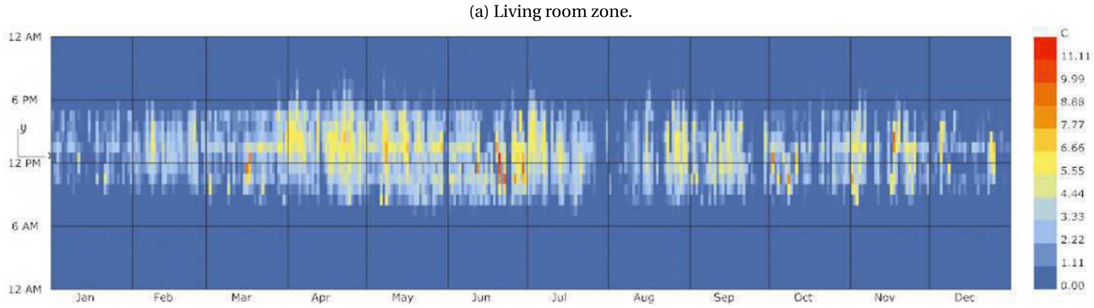
Performance	AET living [K]	AET bathroom [K]	AET attic [K]
Case study	1,26	2,04	1,88

Figure 6.13: Numerical results comfort performance.

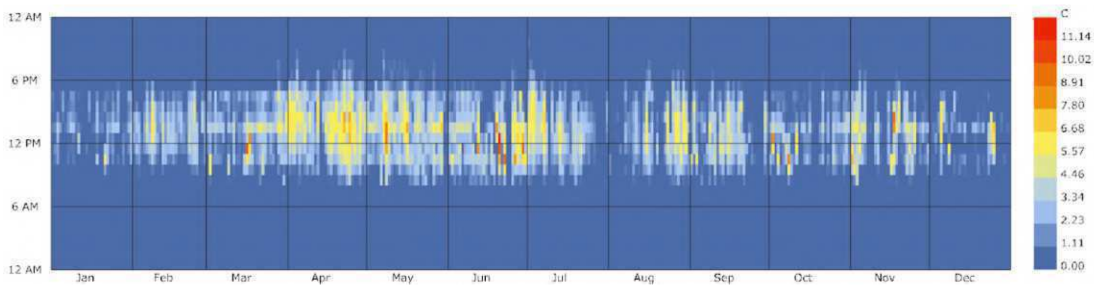
The second hypothesis is tested as true. The decrease in comfort of the bathroom in the morning is explained by its orientation to the north-east. As a result it suffers from direct solar radiation in the morning. The decrease in comfort is however small.



(a) Living room zone.



(b) Bathroom zone.



(c) Attic zone.

Figure 6.14: Hourly discomfort results per zone of the case study.

Conclusion

The openings over the vertical height cause the flow pattern to spread more evenly over the height of the building than compared to outside. As a result, the velocity close to the floor and in the attic increases. The configuration of the openings benefit air velocity by directing the flow through most of the comfort zone. Because the openings of the bathroom are parallel to the wind direction, it has a low air velocity and forms an obstruction for the flow in parallel direction. It thereby reduces air velocity in the living room.

Because the three zones are protected from most of the direct influence of solar radiation by the eaves or roof insulation, the comfort performance is strongly dependent on air velocity. Accordingly, the living room has a significantly better comfort performance. The north-east orientation of the bathroom results in direct solar radiation hitting the facade in the morning. As a result, the comfort performance of the bathroom is slightly reduced in the morning hours compared to the attic.

6.4. Openings

In this section, the results of the influence study of openings are discussed. The method is defined first. It is then followed by discussion of the results before the conclusions are drawn.

6.4.1. Method

Based on the knowledge gained in section 6.3, the hypotheses stated below are defined. Due to the limited time frame, several configurations are only studied on air velocity. To test the strategies, the opening variations illustrated in 6.15 are used. The roof openings have the same dimensions as used in 5 and are modelled as a roof panel since some kind of shading or shutters are assumed to be in place.

- *"Decreasing the height of the air inlet increases air velocity and comfort."*
- *"A roof opening on the leeward sides benefits air velocity and comfort."*
- *"Using a 90 degree orientation angle with all sides are open increases velocity."*
- *"Changing the first floor to the west side, decreases air velocity with and without leeward roof opening."*

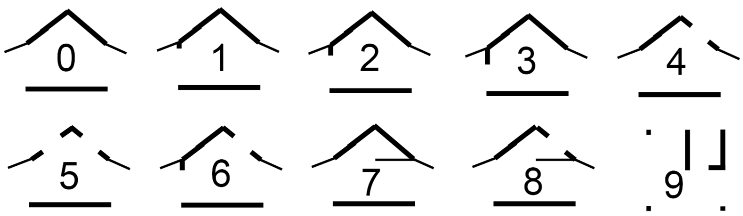


Figure 6.15: Opening variants tested. 0 to 8 are illustrated as vertical cross sections and 9 as floor plan.

6.4.2. Results and discussion

Figure 6.16a shows the numeral results on air velocity. Figure 6.17 and 6.18 show the velocity and direction results. The comfort performance results are illustrated in figure 6.16b. To keep it orderly, the results are discussed per hypotheses.

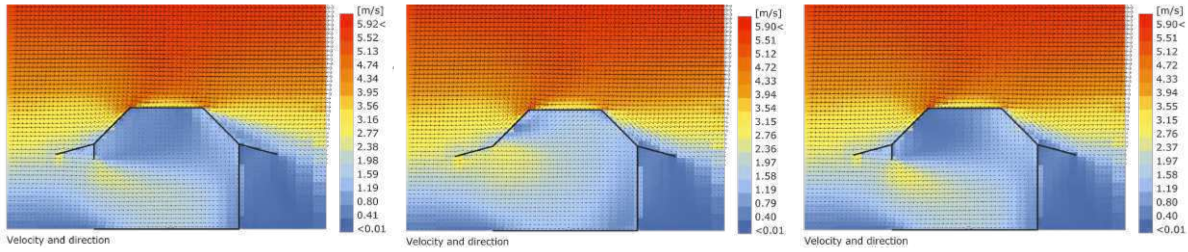
Opening configuration	Velocity [m/s]
0 - Case Study	1,26
1 - Height inlet - 0.3 [m]	1,36
2 - Height inlet - 0.5 [m]	1,41
3 - Height inlet - 0.7 [m]	1,41
4 -Leeward Roof Opening	1,21
5 - Lee and windward RO	1,16
6 - Hei Inlet - 0.5 [m] and leeward RO	1,41
7 - 1st floor to west side	1,19
8 - 1st floor west and leeward RO	1,16
9 - 90 [°] orien and facades all open	1,31

(a) Numeral air velocity results [m/s] per variant.

Opening configuration	AET [K]
0.0 Case study no openings	6,01
0 - Case Study	1,26
1 - Height inlet - 0.3 [m]	1,23
2 - Height inlet - 0.5 [m]	1,20
3 - Height inlet - 0.7 [m]	1,22
4 - Leeward Roof Opening	1,19
5 - Lee-and-windward RO	1,22
6 - HI - 0.5 [m] and leeward RO	1,07

(b) Comfort performance results per variant.

Figure 6.16: Air velocity and comfort performance results in AET of opening variants tested.



(a) Configuration 2. (b) Configuration 5. (c) Configuration 6.

Figure 6.17: Flow results for configuration 2, 5 and 6.

Height inlet The results show the velocity to increase when the height of the inlet is reduced. The flow results in figure 6.17a illustrate this by directing the flow more concentrated through the comfort zone. Decreasing the height from 0.5 and 0.7 meter does not result in a difference in velocity. However, it does decrease comfort by increasing the average exceeding temperature. When a leeward opening is added as in case 6, the velocity stays the same but comfort increases significantly compared to the other configurations.

The difference in comfort at the same air velocity are explained by the differences in air changes per hour. When the areas of the openings change, the air inlet and inter-zonal exchanges rates are influenced. As a result, the air exchange rates per hour increase or decrease. Consequently, comfort is influenced. When the inlet height is lowered, comfort increases. The hypotheses is thereby tested as true. However, the difference is small for only lowering the inlet height. But, when it is combined with a leeward roof opening, it increases significantly.

A rule of thumb for the opening height - If the building would be scaled, the same relation would be found of the reduced opening height to the facade height to improve air inlet and velocity. Reducing the height has shown to increase comfort significantly in the configuration with a leeward roof opening. This allows the formulation of a rule of thumb for the opening height if a leeward roof opening is present and for facade heights which is in reasonable range. Since the best performing opening height is 2.3 m on a facade height of 2.8 m. This would result in the rule of thumb stated below.

$$\frac{2.3}{2.8} \approx 0.85 \rightarrow O_h[m] = 0.85 \cdot F_h[m]$$

Where O_h in m is the height of the opening from ground floor and F_h in m is the facade height.

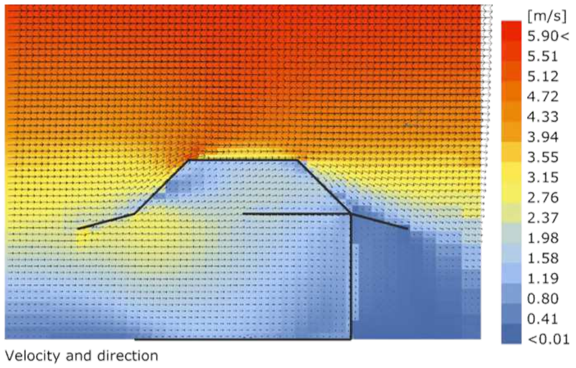
Leeward roof opening Adding a leeward roof opening is observed to decrease air velocity but increase comfort by decreasing the AET. The flow pattern in figure 6.17b illustrates this because the flow is directed upwards, away from the comfort zone. However, when the height of the inlet is decreased by 0.5 meter, adding a roof opening does increase the velocity and comfort.

The first part of the hypothesis does not hold while the second does hold. This can be explained by the provision of stack effect and heat mitigation. For inlet openings with decreased height of around 0.5 meter, the hypotheses is deemed as true.

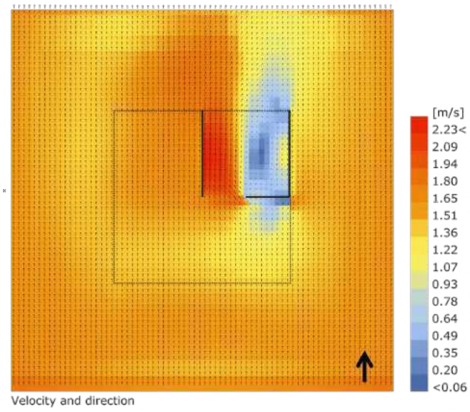
Changing first floor Changing the first floor to the west side is observed to decrease velocity both in configuration 7 and 8. The flow is illustrated in figure 6.18a and shows a direction upwards.

This can be explained by a recirculation of the wind upstairs before it leaves the building. It is not directed through the comfort zone. Since velocity decreases the comfort is expected to decrease.

All facades open and rotation of 90° If a 90° orientation angle with all facades open is used, it is observed that velocity increases. The flow pattern in figure 6.18b illustrates this by providing an almost continuous flow through the building and comfort zone. The hypothesis is thereby tested as true. However, the difference to the case study air velocity is relative small. This can be explained by the change of first floor to the leeward side. If the first floor is changed to align in the wind direction, the increase in air velocity is larger. Since the air exchange rates also increase considerably, comfort is expected to increase significantly.



(a) Configuration 8.



(b) Configuration 9.

Figure 6.18: Flow results for configuration 9 and 8.

6.4.3. Conclusion

Openings influence comfort by air velocity and air exchange rates per hour. Air velocity is found to be the governing factor. When velocity does not change significantly, air exchange rates determine the comfort performance.

Openings until ground floor with a reduced inlet height increase comfort and air velocity significantly if it is combined with a leeward roof opening. Based on the best performing configuration, the rule of thumb stated below is defined to relate the opening height (O_h [m]) to the facade height (F_h [m]). Only adding a leeward roof opening or decreasing the height, does not significantly influence comfort. Rotating the building with 90°, changing the first floor and having the facades in wind direction open increase air velocity and comfort significantly. Using openings yields a significant comfort increase of 4.94 AET Kelvin.

$$O_h[m] = 0.85 \cdot F_h[m]$$

6.5. Stilts

In this section, the influence of stilts height is addressed. The method as outlined in section 6.1.2 is used. The hypothesis stated below is thereby tested. The results are presented and discussed before the conclusions are drawn.

"Increasing stilts height increases air velocity and comfort performance with an exponential decaying trend."

6.5.1. Results and discussion

In figure 6.19 the air velocity is plotted over the stilts height. Figure 6.20 shows two corresponding flow results of 0.4 and 1.5 meter of stilt heights. The average exceeding temperature over the stilts height is plotted in figure 6.21. It is also plotted with a constant outdoor wind distribution over the height in figure 6.21b.

Air velocity

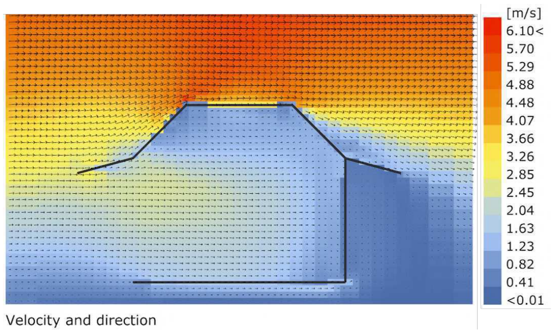
An exponential decaying trend is observed in air velocity over stilts height. For stilt heights below 5m the increase is relatively linear. As can be seen in figure 6.20, the flow pattern is the same and velocity increases when stilts height is raised. The general air velocity observed in the building is the same as the outdoor undisturbed wind speed at the middle of the facades height.

The hypothesis is tested as true. The difference in air velocity for smaller stilt heights is relatively large compared to the wind profile power law distribution depicted in figure 5.3a at roof height of 2.8m. This could be explained by the eaves which lower the reference speed as observed in figure 6.20.

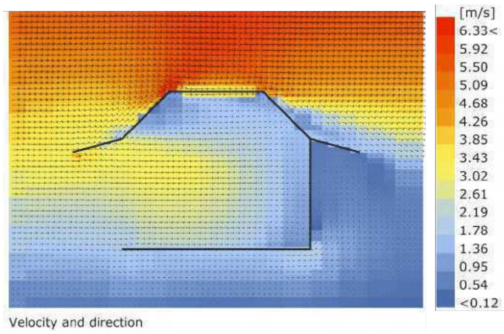
Comfort performance

A general exponential decaying trend with some fluctuations is observed in AET over stilts height for the common outdoor wind speed distribution. The hypotheses thereby holds. Using a stilts height of 5 meter reduces the AET with 0.55 Kelvin. For stilt heights between 5 to 10 meter it is almost constant. The constant part and fluctuations do not match the air velocity trend. However, these could be explained by the effect

Figure 6.19: Air velocity results of varying the stilts height.



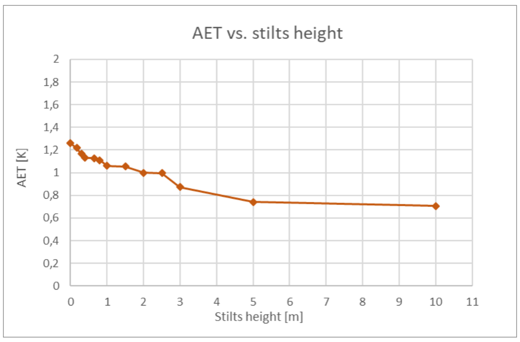
(a) Stilts height of 0.4 m



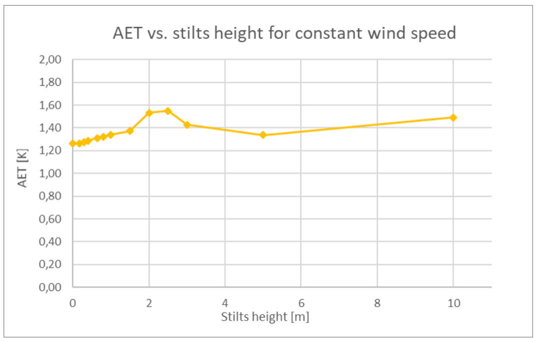
(b) Stilts height of 1.5 m

Figure 6.20: Flow results of stilts height 0.4 m and 1.5 m

of stilts height when the wind speed is kept constant. The general linear increase in AET for the constant outdoor wind speed counters the decrease in AET for common outdoor wind speed. Its deviations also explains the fluctuations between 1.5 and 3 meter. The influence when wind speed is kept constant is however unclear. It might be caused by radiation conditions dependent on height in the energy calculation method of EnergyPlus. Since the hypotheses holds, it is not further studied.



(a) The results with an outdoor wind profile power law distribution over the height.



(b) The results with a constant outdoor wind speed distribution over the height.

Figure 6.21: Results in AET of varying the stilts height with the standard outdoor wind speed profile power law distribution and with outdoor wind speed distribution which is constant over the height.

6.5.2. Conclusion

Increasing stilts height with openings over the facade height increases air velocity and comfort with an exponential decay. Using stilts with a height of 5 meter reduces the AET with about 0.55 Kelvin.

6.6. Orientation

In this section, the results of changing the orientation angle are shown and evaluated. The method as outlined in section 6.1.2 is used. The hypotheses stated below are thereby tested. A 0° angle considers the orientation of the building towards north as stated in figure6.2a with an upwards north direction. The rotation of the building is counter-clockwise. From the perspective of the wind direction, the rotation is clock-wise.

- *"Orientation angle around 0°, 90° and 180° benefit air velocity."*
- *"The comfort performance has the same trend as the air velocity with a better performance from 0° to 45° and 225° to 270°."*

6.6.1. Results

The air velocity results over the angle are plotted in figure 6.22. Several corresponding flow results are shown in figure 6.23 and the AET over the angle is plotted in figure 6.24.

Air velocity

A constant air velocity is observed from 0° to 30°. It drops to around 0.8 m/s from 60° to 120°before climbing to its second peak around 190°. Then it drops to 0.8 m/s from 255° to 285° before rising to 1.05 m/s for angles of 300° until 345°.

The flow pattern of 15°and 195 show how the air velocity benefits from the incident angle of the wind. It directs the flow through the major part of the comfort zone. Oppositely, the 105 degree angle, directs the flow through the bathroom and thereby avoids most of the comfort zone.

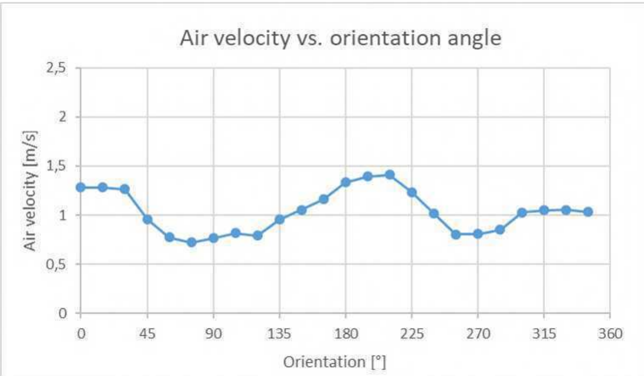


Figure 6.22: Air velocity results of varying the orientation angle.

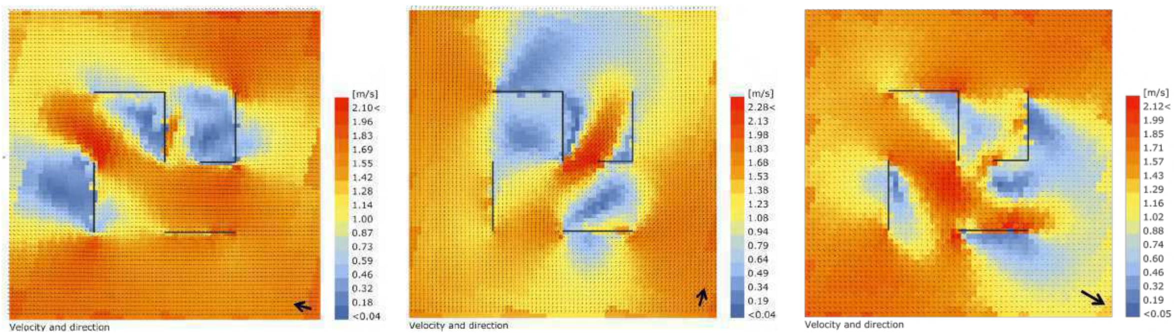


Figure 6.23: Flow results for several orientation angles.

(a) 15°. (b) 105°. (c) 210°.

Results comfort performance

The AET is in figure 6.24 show peaks at 0° and 195°, and troughs at 75° and 285°. The trend is disrupted slightly at 180°.

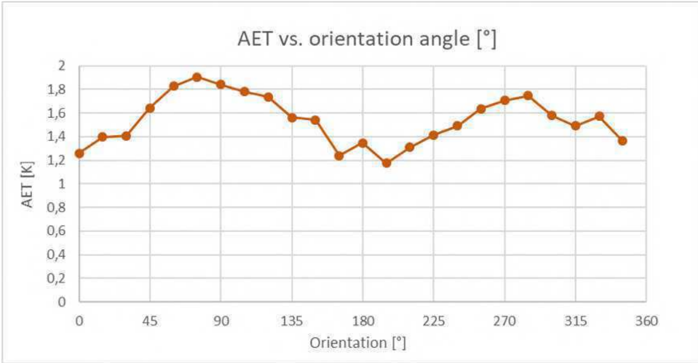


Figure 6.24: Results in AET of varying the orientation angle.

6.6.2. Discussion results

The incident angle of the wind is shown to have a significant impact in directing the flow through the comfort zone. The openings of the bathroom show to play an important role as well since it significantly decreases the flow through the comfort zone at a 105 degree angle. If the flow results of 15 and 30 degree are compared to the 0 degree flow, the change in direction of the flow benefits air velocity.

The air velocity and AET show a roughly similar inverse trend. The differences could be explained by factors like air inlet, inter-zonal exchange rates and solar radiation entering through the openings at certain hours. Since globally the same trend is observed, the first part of the second hypotheses holds.

The second part of the second hypothesis does not hold. This could be explained by the low intensity of the incoming solar radiation. Since the facade is protected by eaves, it is only exposed in the afternoon or early morning to a relatively weaker solar radiation load. As a result, it does not make a significant difference compared to the changes in air velocity.

6.6.3. Conclusion

The air velocity inside is positively influenced around 15° and 210° because the incident angle directs the flow through the comfort zone. It is negatively influenced between these angles.

It can be concluded that air velocity is the governing factor on comfort performance when changing the orientation angle. The angles around 180° or 0° show the best comfort performance while between those areas the performance is significantly less. The difference between the worst and best performing angle in the case study in AET is 0.73 Kelvin.

6.7. Eaves

In this section, the results of varying eave length and angle on air velocity and comfort performance are discussed. The method as outlined in section 6.1.2 is followed. The hypotheses stated below are thereby tested.

- *"Increasing eave length and angle decreases air velocity."*
- *"Eaves with small angles and considerable lengths result in the best comfort performance."*

6.7.1. Results

Figure 6.25 and 6.27 show the results of AET on respectively air velocity and comfort performance over the length for various angles. The flow for several eave lengths and angles is depicted in figure 6.26.

Results and discussion air velocity

It can be observed in figure 6.25 that for lengths greater than 0.8 meter and angles greater then 0°, increasing the length and angle reduces air velocity. Angles of 60° and 0° score the best for a length of 0.5 m. The eaves with a 0° angle have a constant air velocity over the length. An angle of 15° also is relatively constant between 0.5 and 1.6 m meter lengths. The flow pattern for a house with no eaves is depicted in figure 6.26a. It shows a slight downward pattern which spreads after entering with a small recirculation in the attic. The flow pattern corresponding to a horizontal eave of 1.3 meter length is observed to have a more even spread over the height, including the attic. A length of 1.5 meter with a 45° angle results in a significant part of the flow going around the building. The part that enters under the eave spreads diminishes over the height.

the two hypotheses given above do hold for most of the cases regarding the eaves length and angle with two exceptions. One, a 0° angle gives a constant air velocity. Secondly, a 60° eave angle with eave length of 0.5m however benefit the air velocity the most in comparison with angles lower than 60° for this eave length. The latter can be explained by the main flow being directed through the comfort zone.

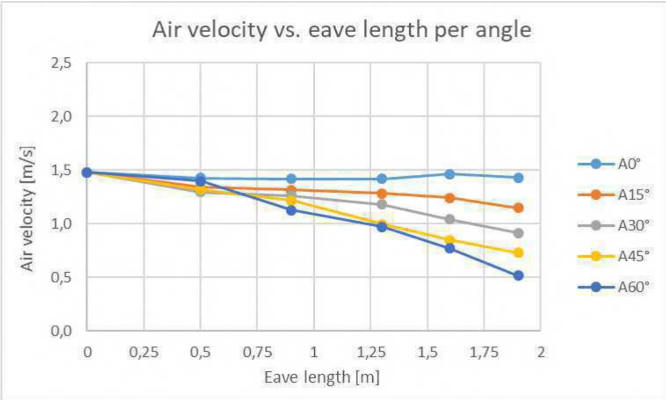
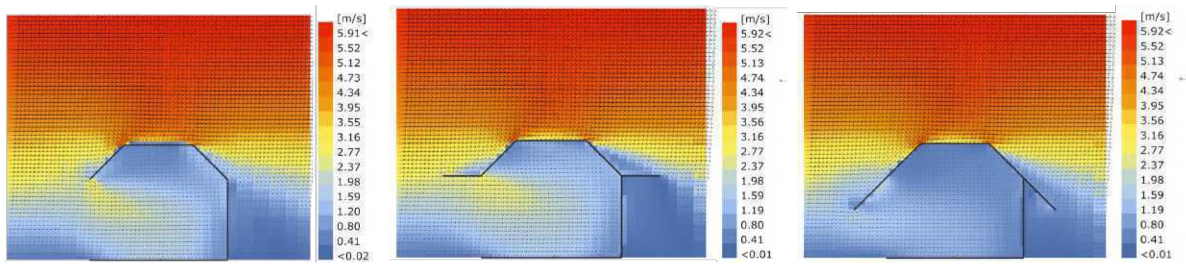


Figure 6.25: Air velocity results of varying the eave lengths and angles.



(a) No eaves. (b) Eaves of 1.3m and 0°. (c) Eaves of 1.6m and 45°.

Figure 6.26: Flow results for several eave lengths and angles.

Results and discussion comfort performance

The average exceeding temperature over the eave length in figure 6.27 show a general decreasing trend, with per angle, troughs at different lengths. The best performing eave lengths and angles are a 1.9 m length with a 0° degree angle and a length of 1.6 meter with a 15° angle. The difference found between the best performing eaves and no eaves in AET is 0.63 kelvin.

Thy hypotheses holds. Because the comfort criteria take the influence of solar radiation and air velocity into account, the length optimums are different per angle. Although a 0° eave angle does not have a significant impact on air velocity, it does block more solar radiation when increasing the eaves length. The observed exponential decaying trend for large eave lengths is thereby explained.

A rule of thumb for the eave length The effectiveness of eaves to block solar radiation is dependent on multiple aspects. These are the height of the facade, the eave length and the eave angle. If openings over the vertical height are used, eaves of 15° score the best or significantly close to the best for all relevant lengths. Therefore, if openings over the vertical height are used, eaves at an 15° angle are used to make a rule of thumb.

If the angle is known, the length of the eave can be related to the facade height. By dividing the length of the eave (1.6 m) by the facade height (1.8 m), a factor is found that can be multiplied by the facade height to obtain the desired eave length. This is illustrated in the equations below.

$$\frac{1.6}{2.8} = 0.57 \approx 0.6 \rightarrow E_{l,15^\circ} = 0.6 \cdot F_h$$

With $E_{l,15^\circ}$ in m is the eave length at 15° and F_h in m is the facade height.

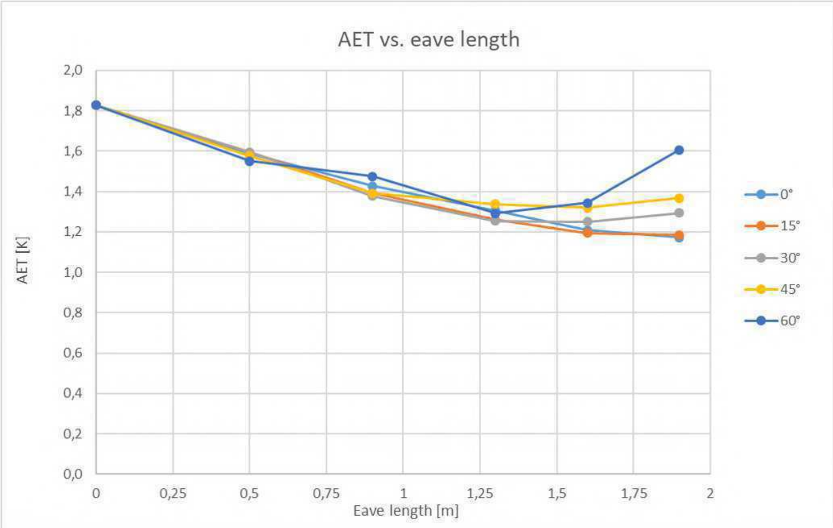


Figure 6.27: Results in AET of varying the eave lengths per angle.

6.7.2. Conclusion

In general, increasing the eave length and angle decreases indoor air velocity, although it is constant for a 0° angle. Eaves with small angles and considerable lengths result in the best comfort performance. For the case study, a 1.6 m eave length at a 15° angle results in the best performance and yields a decrease in AET of 0.63 Kelvin.

6.8. Roof insulation

In this section, the results of varying the roof insulation value on comfort are presented and discussed. First, the method is discussed. Then, the results of the parameter study are evaluated before the findings are concluded and the following hypothesis tested.

"Increasing roof insulation increases comfort performance with an exponential decaying trend."

6.8.1. Method

Method selection

To take the radiant heat into account that is emitted to the living room zone from the attic, two options are shortly discussed. The first method is to change the energy performance calculation. Changing the calculation requires thorough knowledge of the way its programmed in the links between Honeybee, OpenStudio and EnergyPlus. This would be time consuming and requires an additional validation study to examine the model and its performance. The second method is to use the results of the energy performance calculation and modify them before the comfort calculation is performed. By modifying the results, a clear dependency can be created to take the influence of the radiant heat into account. This is suitable for testing the hypothesis and would be less time consuming than the previous method. Therefore, the second method is applied.

Calculation method

The mean radiant temperature (MRT) of a zone is calculated as explained in section 5.1.2. It uses the weighted (on area) mean average of the inside surface temperatures times the thermal emittance coefficients of the surfaces enclosing the zone. To create the effect of the radiant heat emitted through the opening, the south roof surface temperature is used as the surface temperature of the opening. Subsequently, it is weighted with the remaining surface areas times the calculated MRT from the energy calculation. The relation is described in the formula below. The south roof panel is used because it is subjected to the significant part of the solar load during the day. It overestimates the influence during midday slightly and underestimates the effect in the morning and afternoon.

$$MRT_{new} = \frac{((SA_{zone} - SA_{airwall}) \cdot MRT + SA_{airwall} \cdot RT_{roof})}{SA_{zone}}$$

where:

$$SA = \text{Surface area } [\text{m}^2]$$
$$MRT = \text{Mean radiant temperature } [°\text{C}]$$
$$RT = \text{Radiant temperature } [°\text{C}] \text{ times emmitance factor } (0.9)$$

Using this method adds extra heat or energy to the building because the inside surface temperature is now taken into account twice. However, the overestimation of heat to the building is not deemed to have a significant influence on the effect studied because it is a constant overestimation of the effect.

6.8.2. Results and discussion

The results of roof insulation versus AET is plotted in the graph of figure 6.28. The influence on several surface temperatures are shown in the appendix in figure D.3. As can be be seen in the graph in figure 6.28, an exponential decaying trend is observed. The hypothesis is thereby tested as true. From Rc-value 0 m^2K/W to 1 m^2K/W the AET reduction is 0.10 Kelvin. The trend is the same as observed in section 5.7, and also shows about a 81% benefit made by an Rc-value of 1 m^2K/W.

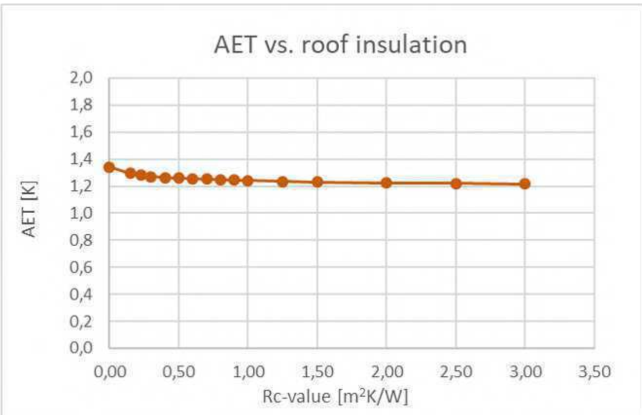


Figure 6.28: Results in AET of varying the Rc-value.

6.8.3. Conclusion

Increasing roof insulation increases comfort performance with an exponential decaying trend. The significant part (81%) is made from an Rc-value of 0 m^2K/W to 1.0 m^2K/W with a decrease in AET of 0.10 Kelvin.

6.9. Roof angle

As explained in section 5.8 results of literature are used for the conclusion on comfort. As stated; increasing the roof angle decreases mean radiant temperature overall and benefits the incident angle of radiant heat emitted to the living room. In addition, if roof openings are used, increasing the roof angle enhances stack ventilation and thus heat mitigation. During wind still times, this is expected to contribute significantly. It is therefore concluded that if roof openings are provided, comfort increases significantly with increasing roof angle.

6.10. Comparison strategy results

In this section, the results of this chapter are related to each other. First the method is introduced. The results are discussed next. It is followed by the discussion, and ended with the conclusion. The following hypothesis is thereby tested.

"Openings have the largest impact on comfort. It is followed by orientation, eaves and stilts with a similar proportion. The influence of roof insulation is the lowest."

6.10.1. Method

To relate the effect of the strategies, the criteria stated below are defined. Changing the roof angle is not taken into account since no data is available which can be compared.

- Total potential - It shows the potential of using the strategy as studied in this chapter. It is the difference between the zero or worst performing variant of the strategy to the best performing variant in AET Kelvin.
- Realised potential - This is the gain in comfort of the strategy as used in the design of the case study from the zero or worst performing variant in AET Kelvin.

The results should be considered as a rough indication for the following reasons. One, the effect of combinations of strategies is not taken into account. Two, the effect is now measured with the presence of the other strategies (except for stilts). And three, it is limited by the variants studied. For example, certain opening configurations are expected to increase comfort significantly but are not taken into account.

6.10.2. Results and discussion

The results are presented in figure 6.29. The left axis indicates the two criteria defined above. As can be seen, openings have the biggest total potential. Orientation, eaves and stilts give similar results, while roof insulation has a relatively small impact. All strategies excepts stilts have a considerable high realised potential in relation to their total potential. Stilts does not because it was not used yet.

The hypothesis is tested as true. The potential reached of all is considerably high in the case study except for stilts. However, significant benefit can still be gained by using combinations of strategies and openings variants which are not studied on comfort in this research or presented in this graph.

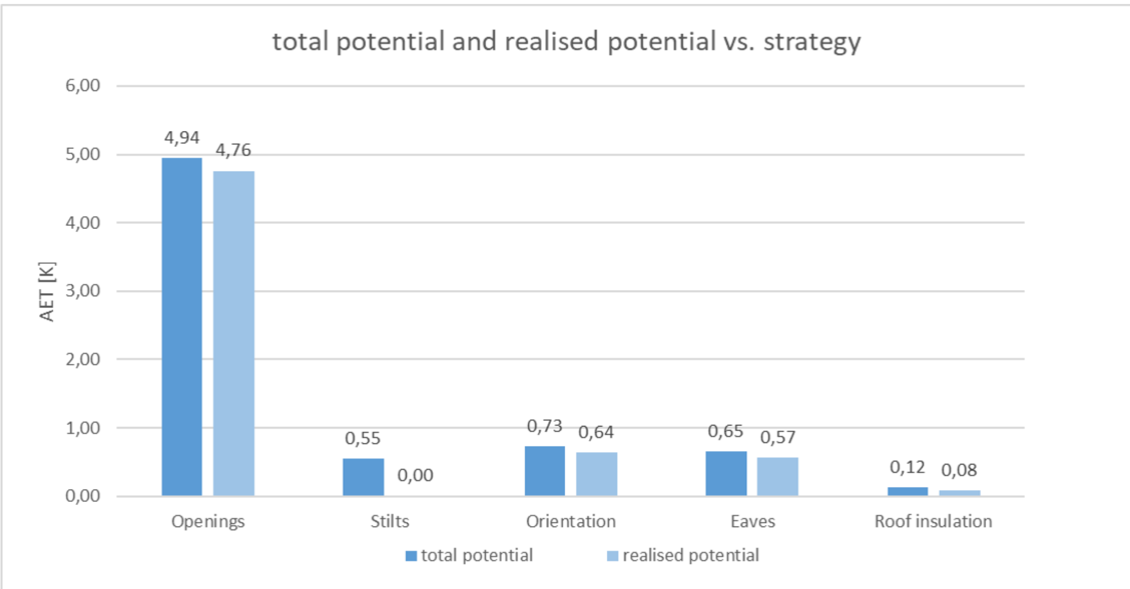


Figure 6.29: The total potential from zero to the best performing variant tested and the realised potential of the variants used in the case study design AET Kelvin. It must be noted that certain combinations of strategies and opening configurations are not taken into account which are expected to result in higher performances.

Relevance to general housing type

The intended housing type of this research consist of a of a single story building with a ground floor. The design of the case study added a partial first floor. The partial first floor influences radiant temperature and thereby roof insulation significantly.

Underestimation of roof insulation The partial first floor poses a barrier between the living room and the attic by reflecting radiant heat and obstructing air flow. Since a part of the radiant heat does not reach the living room, the influence of roof insulation is underestimated. Since a third of the living room is covered, removing this area would roughly add half of the influence to the effectiveness. As a result, the total potential effect of roof insulation would be a decrease of about 0.18 AET Kelvin instead of 0.12.

6.10.3. Conclusion

It can be concluded that openings have the most impact on comfort performance. It is a considerable amount of times higher than the others. Orientation, eaves and stilts respectively are next in the ranking and are close to each other in their impact. Roof insulation follows with an impact of about one-third of the impact of eaves. Their potential impact for the intended housing typology per strategy is about 5 degrees Kelvin for openings, 0.7 for orientation, 0.6 for eaves, 0.5 for stilts and 0.2 for roof insulation.

The potential reached of all is considerably high in the case study except stilts since they are not used yet. However, significant benefit can still be gained by using combinations of strategies which are not presented by these numbers.

6.11. Conclusion

In this chapter, the following sub-research question: *"How do the design strategies influence thermal comfort performance?"* is answered. Based on the results and discussion the following conclusions are drawn.

Openings Openings influence comfort mainly by air velocity. When velocity does not change significantly, air exchange rates determine the comfort performance. The opening configuration used in the case study perform relatively well in the main wind direction. Openings until ground floor with a reduced inlet height increase comfort and air velocity significantly if it is combined with a leeward roof opening. Based on the best performing configuration, the rule of thumb stated below is defined to relate the opening height (O_h [m]) to the facade height (F_h [m]). This rule is applicable if the height of the facade is within the usual range of single-story buildings. Only adding a leeward roof opening or decreasing the height, does not significantly influence comfort. Changing the first floor to the leeward side decreases velocity. The best comfort performance is obtained by rotating the building with 90°, changing the first floor to align in wind direction and having as much open area on the facade in wind direction as possible. Using openings yields a significant comfort increase of 4.94 Kelvin in AET.

$$O_h[m] = 0.85 \cdot F_h[m]$$

Stilts Increasing stilts height increases comfort and air velocity by an exponential decay. Using stilts with a height of three meter reduces the AET with 0.40 Kelvin in the case study.

Orientation It can be concluded that air velocity is the governing factor on comfort performance when changing the orientation angle. The angles around 180° or 0° show the best comfort performance while between those areas the performance is significantly less. The difference between the worst and best performing angle in the case study in AET is 0.73 Kelvin. In the case study, the air velocity is positively influenced around 15° and 210° and negatively between these angles.

Eaves Eaves influence comfort by air velocity and radiant temperature. Eaves with small angles and considerable lengths result in the best comfort performance. For the case study a 1.6m length at a 15 degree angle results in the best performance and yields a decrease in AET of 0.63 Kelvin. It is shown that eave angles of 15 degree perform the best or significantly close to the best for every eave length when openings over the vertical height are used. Therefore, the following rule of thumb can be defined to find the optimum eave length [m] based on the facade height [m].

$$E_{l,15^\circ}[m] = 0.6 \cdot F_h[m]$$

Roof insulation Increasing roof insulation increases comfort performance with an exponential decaying trend. The significant part of about 80% is made from an Rc-value of 0 m^2K/W to 1.0 m^2K/W with a decrease in AET of 0.10 Kelvin.

Roof angle Comfort is benefited by increasing the roof angle. In addition, adding roof openings allows heat to dissipate and provides air velocity. Comfort is thereby benefited significantly.

Comfort impact Per strategy, the potential impact for the intended housing typology is decrease of about 5 for openings, 0.7 for orientation, 0.6 for eaves, 0.5 for stilts and 0.2 for roof insulation. The potential reached per strategy is considerably high in the case study except stilts since they are not used yet. However, significant benefit can still be gained by using combinations of strategies which are not presented by these numbers.

In the chapters until now, the relation of the strategies to thermal comfort is obtained. In the following chapter, its implementation is studied so design guidelines to improve comfort can be provided.

7

Implementation of the strategies

In this chapter the sub-research question; *"How could the design strategies be implemented in this housing type to improve thermal comfort?"* is answered. Section one discusses the method of this chapter. Philippine disaster resilient design is reviewed in section two. Section three addresses the implementation considerations per strategy. The last section discusses the implementation of the strategies on the case study and concludes with the recommendations for the case study.

7.1. Method

In this section, the method is shortly discussed. The use of a case study implementation is briefly elaborated before the relevant considerations are addressed.

7.1.1. Case study implementation

An explorative case study design is used to discover the limitations in implementing the strategies. The Finch Floating Homes as addressed in section 6.1.1 is used for the design. Using a single design results in a thin basis for conclusions. However, certain limitations have to be dealt with in every design. Hence, implementing the strategies provides an insight in the relevant implementation considerations.

Implementation considerations Per strategy, the design considerations limiting the implementation are addressed. The considerations used are divided in the categories disaster resilient and practical. Disaster resilient design is approached by a literature study. The practical considerations are based on a design approach. Relevant aspects discussed are for example limitations in the use of the building and materialisation.

7.2. Disaster resilient design

Disaster resilient design in the Philippines is about typhoon and earthquake resiliency. They are addressed respectively. The general guidelines are presented afterwards.

7.2.1. Typhoon resilient design

Typhoon resilient behaviour contains multiple aspects like wind pressure development, impact behaviour, flooding resistance, replace-ability and post-impact behaviour. Pressure development and flood resistance are in line with the implementation level of this research and are therefore addressed. Figure A.2 illustrates the minimum typhoon wind speed per area in the Philippines where buildings have to deal with. Very high wind speeds of 310 km/h compared to the Eurocode have to be dealt with.

7.2.2. Earthquake resilient design

Most important in earthquake resilient design is to prevent the house from collapsing [7]. The intended housing typology is low-rise and light-weight. These are known to behave well in earthquakes when compared to multiple-story buildings.

7.2.3. Available guidelines

The building guidebooks on disaster resilient buildings focus on geometry, construction quality and connections [7] [11] [43]. They provide applicable knowledge on shape, materials, foundation systems and methods. An example of such recommendations are presented in figure 7.1. The relevant disaster resilient recommendations are presented in the section of the relevant strategy. The general recommendations are shortly presented below.

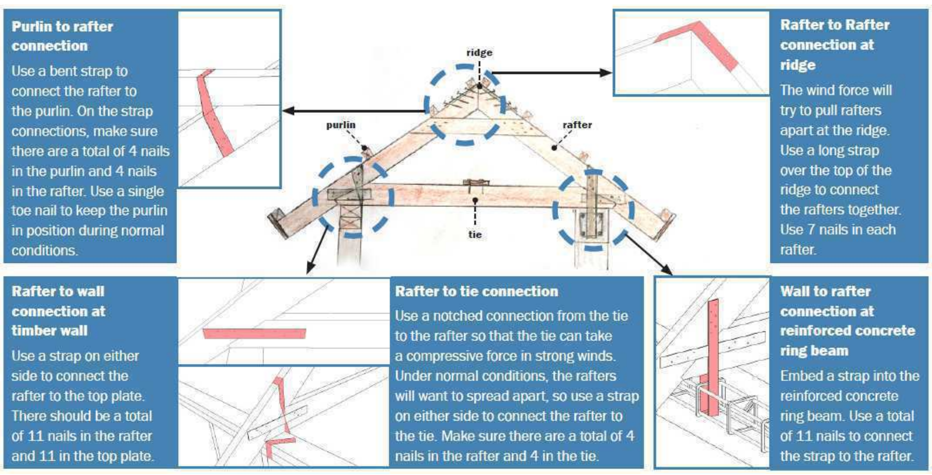


Figure 7.1: Disaster resilient structure advise of a rafter and tie system applicable for small and narrow floor spans. [7].

Disaster resilient deigns emphasizes the structural integrity [7] [11] of the building. Consequently, a lot of the recommendations are therefore on a structural level. It is recommended to use good materials, connections and structural design. For example, proper connections between the roof, walls and to the foundation should be used. Enough nails or steel straps to connect roof members strongly to one another should be used. An example of this is illustrated in figure 7.1. Wooden structures must be well connected to the foundation [11]. Also stated is that sufficient wind bracing is important and therefore the walls should not be to far apart. To decrease typhoon wind pressures, geometry should be made square or rectangular and symmetrical.

7.3. Implementation considerations

In this section, the implementation considerations are presented. Per strategy, the practical and disaster resilient design considerations are addressed. The relevant comfort considerations are found in the chapters of 5 and 6.

7.3.1. Openings

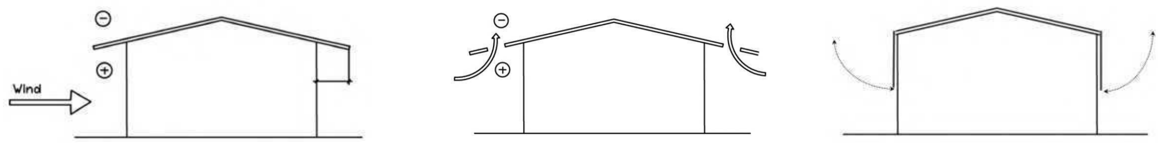
Practical considerations The indoor space should be inhabitable. Doors and openings should be at convenient locations. Furniture should be able to stand versus the wall. Also, view lines too outside and natural lighting are important. All the openings should be able to be closed. Some openings should have the possibility to be open during the night without allowing people to enter.

Disaster resilience For typhoon resilient design of openings it is generally advised to have a closed shell [7]. The openings should therefore be closable by strong shutters and a have strong connection to the structural frame [7]. Since enough wind bracing is important and openings decrease the structural integrity, opening locations are limited. Combining an opening with cross bracing could be an option. However, the crosses would then be visible through the opening. When using roof openings, extra attention should be paid to make the roof openings watertight considering the heavy rains in combination with high wind speeds. Columns are advised be be placed next to openings [7].

7.3.2. Eaves

Practical considerations Long eaves are not practical. They increase the size of the area of the house and cost a lot of material. Longer eaves should consider support from the foundation or ground. Shorter eaves on the other hand require less material and are more easily supported with diagonals from the house. If long strongly inclined eaves are used, doors or shutters are effected and can not open. Small inclinations angles are therefore advised.

Disaster resilience Eaves increase typhoon related pressures significantly [2] [42] [18] by changing the pressure development around the eave and house as illustrated in figure 7.2a. Several solutions are provided. They could be separated from the structural frame to avoid damage. However, they are still likely to be damaged or destroyed. They could be kept short although this is not advised for comfort. As depicted in figure 7.2c an opening close to the facade could be made in the eave. Although it is expected that still relative big pressures will develop. It would also be possible to use a lattice structure to let the wind through. However, this requires more material. Another option would be to make it hinged so they can be folded in during typhoons. It should be noted that a typhoon proof, continuous load path from the eave to the foundation should be provided. Also, the use of doors is affected when they are folded in.



(a) Normal eave design [43]. (b) Eave with an opening close to the facade [43]. (c) Hinged eaves.

Figure 7.2: Wind pressure development around different eave designs and a hinged eaves as solution.

A rule of thumb for northern eave length If the orientation of the building is aligned to the cardinal direction, the north eave length can be reduced significantly. The yearly solar load distribution in figure 5.2a shows the significant part of the solar load to reach 70° at its lowest. Consequently, the eave can be reduced to 0.7 meter and still protect the facade from the solar load. This is depicted in figure 7.3. Subsequently, a rule of thumb can be made for the north eave related to the facade height using the same method as in section 6.7. An angle of 15° is used because it is perpendicular to most of the low incoming solar load and does not influence air velocity significantly as found in section 6.7.

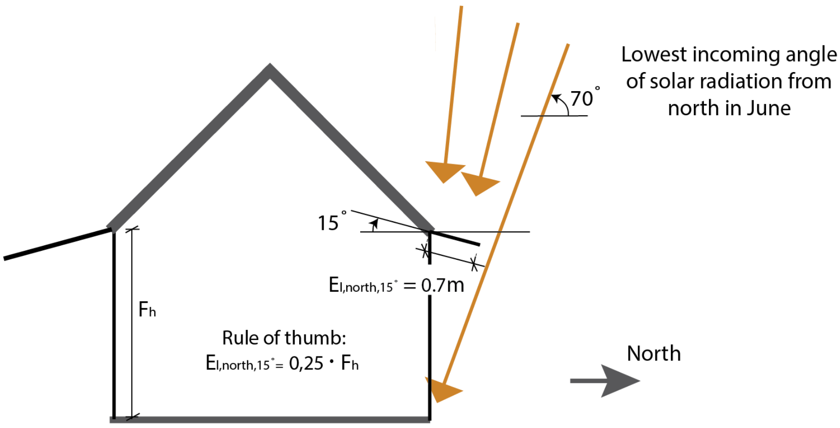


Figure 7.3: Reduction of north eave length based on the minimum angle of solar radiation from north direction. Consequently, material is saved and doors can be opened if the eaves are folded in.

7.3.3. Orientation

No relevant practical or disaster resilient considerations are found for orientation. Since typhoons have a rotational wind direction around its eye and show paths everywhere over the Philippines, no main wind direction is applicable for the high wind speeds.

7.3.4. Roof angle

Practical considerations Using a roof angle creates extra space and allows the use of roof openings. The current 45° angle, provides enough space for the sleeping purposes of this room [46]. The first floor also provides easy accessibility to close the openings.

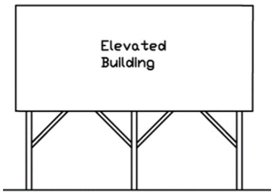
Disaster resilience The roof angle influences pressures during typhoon wind speeds. Based on analysing wind pressures [42] and failures after typhoons [23], it is concluded that hipped roofs perform better than gable roofs. An angle of 30° or close to 30° is found to have the best performance in pressures. A pitched roof also has the benefit of preventing leakages due to ponding of water. If metal sheets are used, thick metal sheets of at least 0.48 mm are advised. Enough fasteners should be used to be wind resistant [7].

7.3.5. Stilts

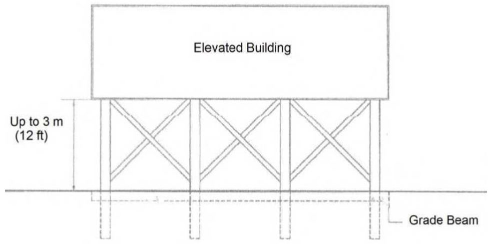
The case study is a floating structure. However, for the purpose of this implementation step it is considered to be on land.

Practical considerations Using stilts allows the use of the space underneath. The stilts height determines how much space can be used. However, long stilts heights and more expensive and less practical. For example, if eaves are used which are supported from the foundation, they require a very long support from. Foldable eaves from the house could be a solution. It should be considered how they can be operated at an elevated height. Stairs could be provided for example to fold the eaves and connect them to the facade.

Disaster resilience To reduce the risk of damage from floods and storm surges it is advised to elevate the structure [11] [43]. Proper bracing is necessary in order to reduce damage from wave action and wave-driven debris. Possible bracing as advised by Taher [43] are depicted in figure 7.4. Based on local flood levels the height should be adjusted to be above the flood levels to reduce damage if possible. Wooden stilts and structure are known to perform well in earthquake and are therefore advised. The influence on pressure development of stilt heights is not found.



(a) Knee bracing [43].



(b) Cross bracing [43]

Figure 7.4: Bracing types as advised [43].

7.3.6. Roof insulation

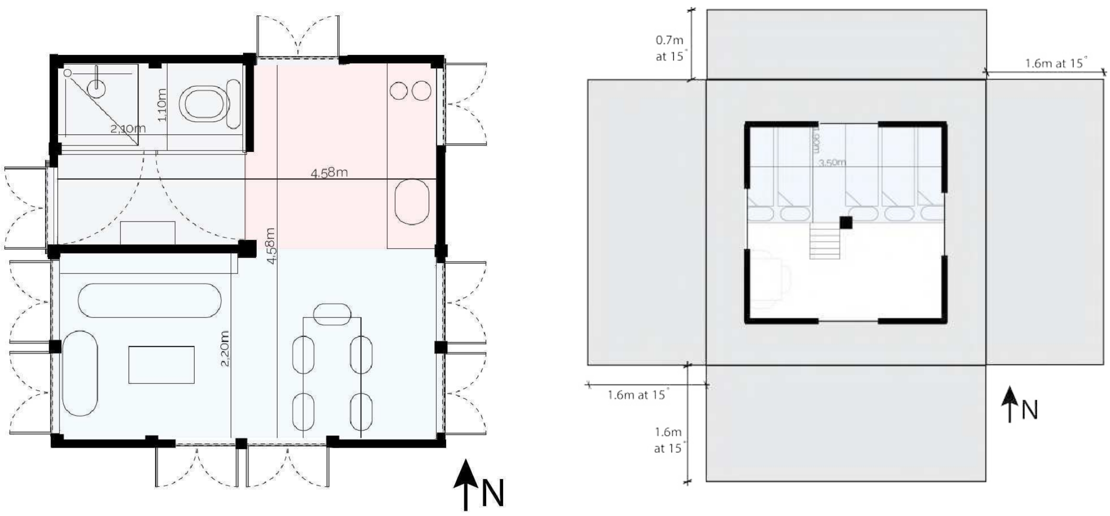
Practicality Since it is does not require big structural changes or influence typhoon resilient behaviour, implementing roof insulation is relatively easy. However, proper fastening should be used to increase its durability. If no proper insulation material is available, 6cm of straw or multiple bamboo reet mats can be used to make a significant difference.

7.4. Discussion and conclusion implementation steps

In this section, the implementation of the strategies are discussed and concluded per implementation step. The results are illustrated in the floor plans of figure 7.5.

- **Alignment of bathroom openings and first floor to main opposite sided wind direction** - To improve comfort, section 6.4 concluded that the openings, bathroom and first floor should be aligned in the opposite sided main wind direction. This would mean a 90° counter-clock wise rotation of the current design.
- **Roof angle of 45°** - This angle is advised to increase comfort, provide sufficient space underneath [46], allow roof openings to be placed and significantly reduce the pressures from typhoon wind speeds.
- **Openings from ground floor with a reduced height of 0.5 m and a leeward roof opening.** - This configuration concluded comfort to be improved by reducing the average exceeding temperature by about 5 K. This is 0.20 K if compared to the current opening lay out. It must be noted that it does not take the increased amount of openings and changed orientation into account. By providing these openings in every direction, comfort is significantly benefited since all the wind directions are enhanced.
- **As much open area on facades in main monsoon wind direction** - Figure 7.5a shows the openings at ground floor at the east and west side. Extra openings are added to increase wind speed and consequently comfort while sufficient room for wind bracing is provided. The opening at the north east corner benefits the spread of the flow from multiple directions. The main monsoon direction should be studied to effectively place the building.
- **Secondary openings in the middle of the width at the north and south facade** - Adding openings on the south and north facade are concluded to increase comfort significantly. In figure 5.26 variant 16C, it can be observed how openings in the corners benefit the flow at a 45° orientation. However, it can also be observed that only openings in the corners does not work if the wind is from a perpendicular direction. Since the main facades (facing west and east) already have openings on the corners, the performance from the inter cardinal directions (N-E, S-E, S.) is enhanced. Placing the openings in the middle on the south and north facade thereby increases the performance when the wind is coming in this direction. By only using the middle part of the facade for the openings, sufficient wind bracing possibilities remain on these facades.
- **Closing behaviour** - Dependent on the wind direction, only the roof openings on the leeward side need to be opened. If this is not done, an decrease of 0.07 K AET instead of 0.20 K is achieved. When the wind is coming from the west or east, the bathroom openings should stay open for optimal performance. During wind still times, they should all be opened to enhance stack ventilation.

- **Solid strong shutters** - Shutters are advised for practical considerations like privacy and to realise a closed shell during typhoons. The latter protects the inside and decreases the pressures during typhoons. To provide the desired strength, solid strong shutters are advised. These could be from wood for example. Attention should be paid to make sure the roof openings are water tight to be able to deal with the combinations of heavy rains and winds.
- **Hinged eaves of 1.6 m at a 15° angle** - Eaves of 1.6 m length at an 15° angle are advised to reduce the AET with 0.63 Kelvin. If compared to the original case study design of 1.3m length at an 15° angle, 0.07 Kelvin AET would be gained. The eaves are advised to be supported from the structure of the house to reduce the length of the supports. They are made hinged to so they can be folded in during typhoons and reduce the occurring pressures.
- **Reducing of north eave length** - If the monsoon directions follows the east and west direction, this allows the north eave angle to be reduced significantly. A length of 0.7 meter is advised to still cover the significant part of the solar radiation load. The shorter eave on the north allows the door to be fully operable when the eaves are folded in.
- **Wooden braced stilts** - Practical considerations play a significant role in stilts height. Important considerations are cost, local flood level and the use of the space underneath. Stilt heights of 1 meter are advised to gain about 0.17 K in AET. Stilts of 2 meter would gain 0.30 K in AET and 3 meter 0.40 K in AET. A braced wooden pile structure is advised to improve earthquake resilient behaviour, reduce damage due to floods and typhoon winds.
- **Rc-value of 1 m^2K/W** - An Rc-value of 1.0 m^2K/W is advised to reduce the AET with 0.10 Kelvin. It reduces the AET with 0.02 Kelvin when compared to the original design with an Rc-value of 0.5 m^2K/W. This decrease is relative small compared to the other strategies. However, on hot, wind-still days it is expected to still make a noteworthy difference.
- **Disaster resilient structural integrity** - The structure, foundation and connections should provide the desired strength and structural integrity to resist typhoon wind power, earthquakes and floods. In addition, the shutters, doors and eaves should be connected to transfer the load adequately.



(a) Floor plan with openings and 90° orientation change.

(b) First floor plan.

Figure 7.5: The floor plans of the new proposed case study design with implementation of the strategies.

8

Conclusions, recommendations and discussion

In this chapter, the main research questions is answered. *"How can Philippine vernacular climate responsive design strategies improve indoor thermal comfort for low-lying, sub-urban and rural, low-income housing in the Philippines?"* The conclusions are presented first. It is followed by the recommendations which illustrate the passive design guidelines. The chapter is concluded with discussion on the implication of this research is and definition of further research directions.

8.1. Conclusion

In this research, the following research question is answered: *"How can Philippine vernacular climate responsive design strategies improve indoor thermal comfort for low-lying, sub-urban and rural, low-income housing in the Philippines?"*. Based on thermal measurements, numerical predictions and conceptual implementation, it can be concluded that by using the provided passive design guidelines, thermal comfort increases significantly. If the guidelines presented below are followed, per strategy, the average exceeding temperature (AET) reduces by about 5 degrees Kelvin for openings, 0.7 Kelvin for orientation, 0.6 Kelvin for eaves, 0.3 Kelvin for stilts and 0.2 Kelvin for roof insulation. More impact is obtained if the strategies are implemented and combined as described by the passive design guidelines. Per strategy, the conclusions and corresponding guidelines are presented.

Openings Openings increase thermal comfort by enhancing the two natural ventilation modes. These are wind driven and buoyancy driven ventilation (stack effect). Wind driven flow is found to increase comfort significantly by increasing air velocity. Since openings direct the flow trough the house, they can increase air velocity by directing it through the living area. The opening configuration that results in the highest air velocity has leeward and windward facade openings until ground floor, a height of the opening (O_h [m]) based on the facade height (F_h [m]) by the formula depicted below, a roof opening on the leeward side and additional openings on the side facades. To improve comfort, provision of these configurations on every facade with as much open area is advised. However, sufficient area for typhoon resilient wind bracing should be provided. If wind is present, only the leeward roof opening should be opened. If there is no wind, all the roof openings should be opened to enhance buoyancy driven ventilation. Solid shutters should be provided to decrease typhoon related pressures and increase privacy. Attention should be paid to increase the watertightness of the roof openings considering the heavy rains in combination with high wind speeds.

$$O_h[m] = 0.85 \cdot F_h[m]$$

Orientation Changing the orientation influences comfort by effecting the flow of air through the building. Since the flow maintains its initial direction after entering, the alignment of openings, orientation and living area benefits air velocity and thus comfort. The main opposite sided monsoon wind direction should be used to align these to benefit comfort for the significant part of the year. To improve the performance if the wind is coming from the other directions, the openings should be placed in the middle of the width. Since the main monsoon direction varies slightly between north-east and south-west, or east and west, this direction should be checked at the location of the building.

Eaves Eaves influence comfort by air velocity and radiant temperature. Eaves with small angles and considerable lengths result in the best comfort performance since they block the solar radiation and do not significantly influence air velocity. In combination with the openings as advised and for considerable eave lengths, a 15° angle result in the best comfort performance. The first rule of thumb defined below calculates the optimum eave length in meter based on the facade height in meter. If the monsoon is in cardinal direction, the eave length at the north facade can be reduced as defined by the second formula depicted below. Hinged eaves are advised so they can be folded in to improve typhoon related pressures significantly.

$$E_{l,15^\circ}[m] = 0.6 \cdot F_h[m]$$

$$E_{nl,cardinal,15^\circ}[m] = 0.25 \cdot F_h[m]$$

Stilts Stilts height influences comfort by changing the air velocity while the indoor flow pattern stays the same. If the openings are used as advised, increasing stilts height increases comfort and air velocity by an exponential decay. If openings are used which are not until ground floor, small stilt heights (below 0.5 meter) are not advised because the flow is partly directed to pass below the building. Consequently, comfort reduces for these heights. Using 1 meter stilts reduces the AET with about 0.17 Kelvin, 2 meter would gain a reduction of 0.30 in AET or three meter 0.40 in AET. The following implementation considerations should be taken into account when the height of stilts is determined; cost, local flood level and the use of the space underneath. Braced, wooden stilts are advised to protect against the impact of floods and increase earthquake resilient behaviour.

Roof insulation Roof insulation increases comfort performance by an exponential decay by decreasing the mean radiant temperature. The significant part of about 80% is made at a Rc-value of 1 m^2K/W.

Roof angle Increasing the roof angle increases comfort during peak hours because it benefits the area subject to solar radiation and incident angle of radiant heat emitted [35]. Using a roof angle allows the use of roof openings, increases buoyancy driven ventilation and improves water drainage and damage due to ponding of water. An angle close to 30° is advised to decrease the pressures that develop during typhoon wind speed.

Disaster resilient implementation The structure, foundation and connections should provide the desired strength and structural integrity to resist typhoon wind power, earthquakes and floods. In addition, the shutters, doors and eaves should provide connections that can adequately transfer the load.

8.2. Recommendations

The recommendations to improve thermal comfort are illustrated in figure 8.1.

8.3. Discussion and further research

The aim of this research was to learn how Philippine vernacular design strategies can improve thermal comfort for low-lying, sub-urban and rural, low-income housing. Literature recognised that vernacular climate responsive design strategies increase thermal comfort significantly. However, the advice given is often on a qualitative level and thermal comfort analyses is lacking. This research took a step towards quantifying the influence of certain strategies and study how they could be implemented to obtain the best performance. It built upon the knowledge of certain strategies studied in literature by using their findings. It then took the next step and added results. For example, the influence on natural ventilation is further mapped by CFD analyses of openings, eaves, orientation and stilts or their combinations. Then, in addition with roof insulation, the effect of these strategies on comfort is considered. The results showed how these strategies could increase comfort significantly. Consequently, a sound scientific basis is provided for implementation of these strategies.

Although the results indicated how comfort is benefited, the contribution to comfort of the advised passive design guidelines is not exactly studied. It would increase the basis of the recommendations if these would be analysed. Furthermore, it would give insight how it could be improved further. The role of buoyancy driven ventilation is also not specifically studied. Since during 33% of the year no wind is present, its heat dissipation is expected to considerably improve thermal comfort. Therefore, in combination with roof angle and openings, further research could determine how these should be used.

To extend the list of passive design guidelines, more climate responsive strategies should be taken into account. In this research, the potential to increase comfort by using permeable walls, floors and using roof angle are recognised. However, these were not studied. Also, literature concluded that evaporative cooling, active stack effect and material properties like colour and reflectiveness benefit comfort significantly. Further study of these strategies would contribute to the objective and make satisfactory comfort performance by climate responsive strategies more realistic.

To assess the influence of the strategies on the relevant thermal comfort parameter, a general case with no specific design features is used. To asses comfort performance, a case study was used. This proved to be very time consuming and might not have been necessary for every strategy. For several strategies however, it extended the basis for conclusions. From hindsight, studying a general case on comfort would have gained more insight and allowed to study the strategies separately on their comfort parameter. For future studies, this would be advised.

As stated in the problem statement and found by measurements, the housing built in the Philippines is uncomfortable. It was also found that the applicable comfortable design guidelines were lacking or could be improved. Next to normal low-income housing built in the Philippines, shelter design is a relevant issue due the severe impact of disasters. The observed different shelter types were recognised to benefit significantly from passive design guidelines. By improving the comfort performance of these shelters, the durability of the buildings and the quality of living of the inhabitants would be increased. In other hot and humid climates, the

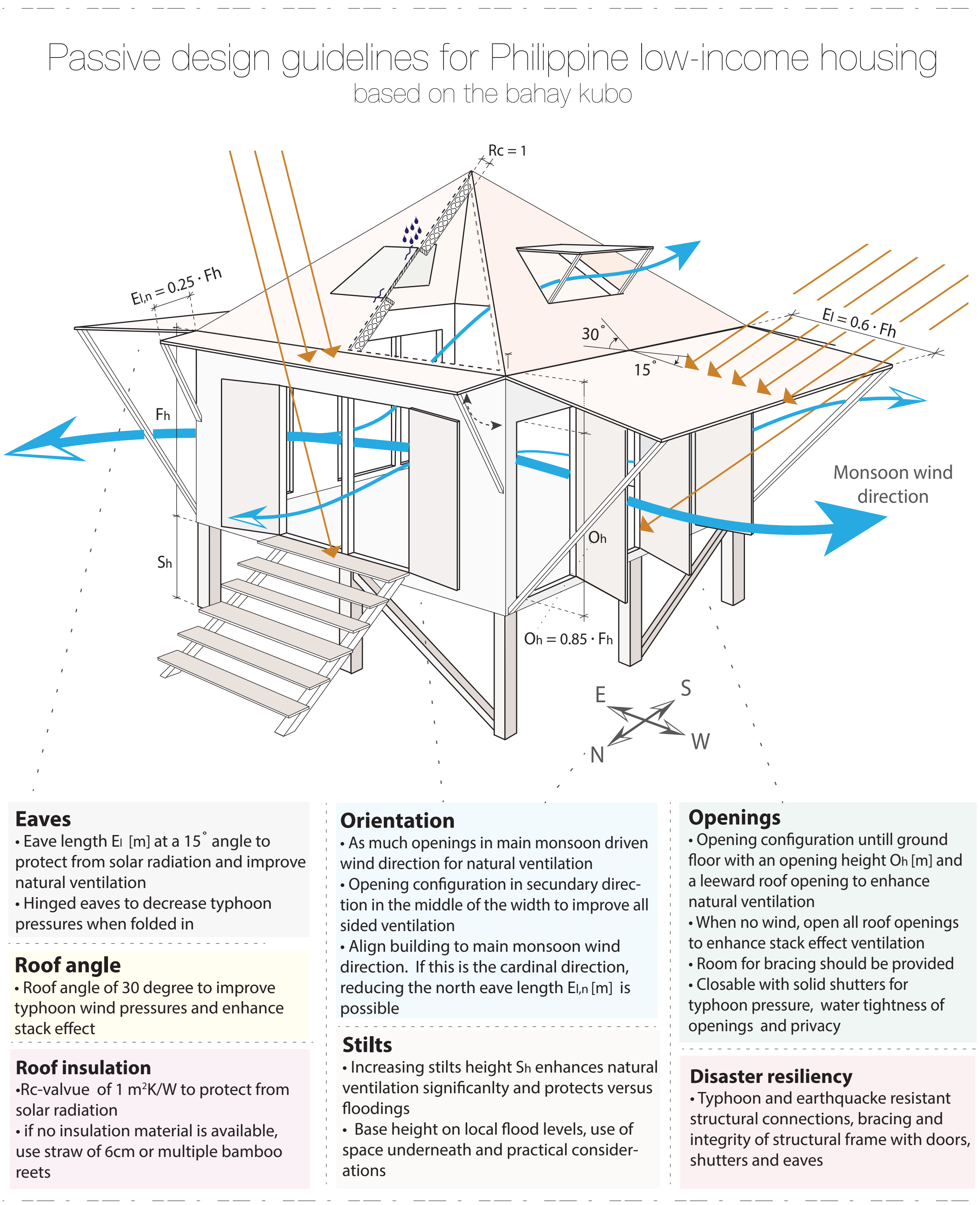


Figure 8.1: The recommendation of this research illustrated.

provided guidelines are also applicable. If natural disasters are irrelevant, the guidelines related to comfort can easily be filtered. An important aspect for implementation in these areas is knowledge of the local wind directions. These should be studied to use the provided design guidelines optimally.

The collaboration with OMRT helped to push the computational model to its limits. It showed the benefits of the parametric environment by doing a thorough extensive analyses in a limited time frame. The performed validation study showed the capabilities of the software and the model to obtain a high level of accuracy. It also showed the challenges involved with modelling naturally ventilated buildings accurately. Using CFD to improve the accuracy showed the accessibility of these analyses and the benefits it gains versus the time needed.

The Finch Floating Homes project is used as the case study for extensive analysis and implementation. It benefits of this research by an extensive knowledge of its performance and the influence of varying the strategies. It showed that the strategies as implemented in their design score considerably well. To increase this performance, the proposed design is advised to be implemented as fully as possible. It is thereby advised to study the proposed and future designs on comfort to see how much is gained and have a sound basis for the conclusions. Since a considerable amount of the year no wind is present and natural ventilation has proven to be a key element to improve comfort, working with stack effect is advised. It is advised that passive and active stack effects are considered, and should be studied how to be further used. In this research, the building was considered to have a stilts height of zero meter. However, the building is placed on a floating foundation. Its location and the floating foundations are expected to have several benefits. Raising it increases wind speed as found in this research. The location on water increases air velocity since less obstructions are present. Since the wind is blocked by the floating foundations to go underneath, air velocity is expected to increase. However, the precise effect could be further studied. Furthermore it is advised that the local (main) wind directions are studied to optimally benefit from this distribution.

Bibliography

[1] Ardalan Aflaki, Norhayati Mahyuddin, Zakaria Al-Cheikh Mahmoud, and Mohamad Rizal Baharum. A review on natural ventilation applications through building facade components and ventilation openings in tropical climates. *Energy and Buildings*, 101:153–162, 2015. ISSN 0378-7788. doi: https://doi.org/10.1016/j.enbuild.2015.04.033. URL http://www.sciencedirect.com/science/article/pii/S0378778815003321.

[2] Ankush Agarwal. Cyclone resistant building architecture, 2007.

[3] Francis Allard and Cristian Ghiaus. *Natural ventilation in the urban environment: assessment and design*. Routledge, 2012. ISBN 1136560637.

[4] R. M. Aynsley. Shape and flow: The essence of architectural aerodynamics. *Architectural Science Review*, 42(2):69–74, 1999. ISSN 0003-8628. doi: 10.1080/00038628.1999.9696854. URL https://doi.org/10.1080/00038628.1999.9696854.

[5] Callison. Climate analysis, manila philippines, 2008.

[6] S. Carlucci, L. Bai, R. de Dear, and L. Yang. Review of adaptive thermal comfort models in built environmental regulatory documents. *Building and Environment*, 137:73–89, 2018. ISSN 0360-1323. doi: https://doi.org/10.1016/j.buildenv.2018.03.053. URL http://www.sciencedirect.com/science/article/pii/S0360132318301884.

[7] Build Change. Residential design and construction guidelines, 2016.

[8] Angelos Chronis, Alexandre Dubor, Edouard Cabay, and Mostapha Sadeghipour Roudsari. *Integration of CFD in Computational Design - An evaluation of the current state of the art*. 2017.

[9] Diana Enescu. A review of thermal comfort models and indicators for indoor environments. *Renewable and Sustainable Energy Reviews*, 79:1353–1379, 2017. ISSN 1364-0321. doi: https://doi.org/10.1016/j.rser.2017.05.175. URL http://www.sciencedirect.com/science/article/pii/S1364032117308109.

[10] P. O. Fanger. *Thermal comfort: analysis and applications in environmental engineering*. McGraw-Hill, New York, 1972. ISBN 0070199159. URL //catalog.hathitrust.org/Record/001627231http://hdl.handle.net/2027/mdp.39015031202032. Summary in Danish. Originally presented as the author's thesis, Danmarks Tekniske HÃjskole, 1970 Bibliography: p. 225-240.

[11] FEMA. *Coastal construction manual : principles and practices of planning, siting, designing, constructing, and maintaining buildings in coastal areas*. Third edition. [Washington, D.C.] : U.S. Dept. of Homeland Security, FEMA, [2005], 2011. URL https://search.library.wisc.edu/catalog/9910091491402121.

[12] Rommel C. Gavieta. Mass housing based on traditional design and indigenous materials for passive cooling in the tropical urban climate of the philippines. *Energy and Buildings*, 16(3):925–932, 1991. ISSN 0378-7788. doi: https://doi.org/10.1016/0378-7788(91)90087-J. URL http://www.sciencedirect.com/science/article/pii/037877889190087J.

[13] Baruch Givoni. *Passive low energy cooling of buildings*. John Wiley Sons, 1994. ISBN 0471284734.

[14] Sebastian Valeriu Hudisteanu, Ca ta lin George Popovici, and Nelu-Cristian Chereches. *Wind tunnel study of natural ventilation of building integrated photovoltaics double skin facade*, volume 32. 2018. doi: 10.1051/e3sconf/20183201020.

[15] L. James Lo, David Banks, and Atila Novoselac. Combined wind tunnel and cfd analysis for indoor airflow prediction of wind-driven cross ventilation. *Building and Environment*, 60:12–23, 2013. ISSN 0360-1323. doi: https://doi.org/10.1016/j.buildenv.2012.10.022. URL `http://www.sciencedirect.com/science/article/pii/S0360132312002879`.

[16] Yi Jiang, Camille Allocca, and Qingyan Chen. Validation of cfd simulations for natural ventilation. *International Journal of Ventilation*, 2(4):359–369, 2004. ISSN 1473-3315. doi: 10.1080/14733315.2004.11683678. URL `https://doi.org/10.1080/14733315.2004.11683678`.

[17] editor John F. Wendt and J. D. Anderson with contributions by. *Computational fluid dynamics : an introduction*. Second edition. Berlin ; New York : Springer, [1996] Â©1996, 1996. URL `https://search.library.wisc.edu/catalog/999802997202121`. [and others] quot;A Von Karman Institute bookquot;–Cover.;Includes bibliographicasl references and index.

[18] Shreyas Keote, Dhanendra Kumar, and Rishabh Singh. *Construction of Low Rise Buildings in Cyclone Prone Areas and Modification of Cyclone*, volume 2. 2015.

[19] Tetsu Kubota and Doris Hooi Chyee Toe. Application of passive cooling techniques in vernacular houses to modern urban houses: A case study of malaysia. *Procedia - Social and Behavioral Sciences*, 179:29–39, 2015. ISSN 1877-0428. doi: https://doi.org/10.1016/j.sbspro.2015.02.408. URL `http://www.sciencedirect.com/science/article/pii/S1877042815017620`.

[20] Tetsu Kubota, Hom Rijal, and Hiroto Takaguchi. *Sustainable Houses and Living in the Hot-Humid Climates of Asia*. 2018. ISBN 978-981-10-8464-5. doi: 10.1007/978-981-10-8465-2.

[21] Gerard Lico. *Arkitekturang Filipino : a history of architecture and urbanism in the Philippines*. University of the Philippines Press, Diliman, Quezon City, 2008. ISBN 9789715425797 9715425798.

[22] Xiao-Yu Ma, Yue Peng, Fu-Yun Zhao, Cheng-Wei Liu, and Shuo-Jun Mei. Full numerical investigations on the wind driven natural ventilation: Cross ventilation and single-sided ventilation. *Procedia Engineering*, 205:3797–3803, 2017. ISSN 1877-7058. doi: https://doi.org/10.1016/j.proeng.2017.10.128. URL `http://www.sciencedirect.com/science/article/pii/S1877705817346842`.

[23] Joseph Minor and F. Asce. *Lessons Learned from Failures of the Building Envelope in Windstorms*, volume 11. 2005. doi: 10.1061/(ASCE)1076-0431(2005)11:1(10).

[24] Nur Farhana Mohamad Kasim, sheikh ahmad zaki shaikh salim, Mohamed Sukri Mat Ali, Ahmad Mohammad, and Azli Abd Razak. *A Verification and Validation Study of CFD Simulation of Wind-Induced Ventilation on Building with Single-Sided Opening*, volume 554. 2014. doi: 10.4028/www.scientific.net/AMM.554.696.

[25] A. Nguyen, Q. Tran, D. Tran, and S. Reiter. An investigation on climate responsive design strategies of vernacular housing in vietnam. *Building and Environment*, 46(10):2088–2106, 2011. ISSN 0360-1323. doi: https://doi.org/10.1016/j.buildenv.2011.04.019. URL `http://www.sciencedirect.com/science/article/pii/S0360132311001211`.

[26] Fergus Nicol. *Adaptive thermal comfort standards in the hotâhumid tropics*, volume 36. 2004. doi: 10.1016/j.enbuild.2004.01.016.

[27] J. F. Nicol and M. A. Humphreys. Adaptive thermal comfort and sustainable thermal standards for buildings. *Energy and Buildings*, 34(6):563–572, 2002. ISSN 0378-7788. doi: https://doi.org/10.1016/S0378-7788(02)00006-3. URL `http://www.sciencedirect.com/science/article/pii/S0378778802000063`.

[28] M. D. C. Noche. History of philippine architecture, 12-08-2018 2015.

[29] P. Ole Fanger and JÃ¸rn Toftum. Extension of the pmv model to non-air-conditioned buildings in warm climates. *Energy and Buildings*, 34(6):533–536, 2002. ISSN 0378-7788. doi: https://doi.org/10.1016/S0378-7788(02)00003-8. URL `http://www.sciencedirect.com/science/article/pii/S0378778802000038`.

[30] Sara Omrani, Veronica Garcia-Hansen, Robin Drogemuller, and Bianca Capra. Predicting environmental conditions at building site for natural ventilation design: Correlation of meteorological data to air speed at building openings. The Architectural Science Association and The University of Adelaide.

[31] Sara Omrani, Veronica Garcia-Hansen, Bianca R. Capra, and Robin Drogemuller. Effect of natural ventilation mode on thermal comfort and ventilation performance: Full-scale measurement. *Energy and Buildings*, 156:1–16, 2017. ISSN 0378-7788. doi: https://doi.org/10.1016/j.enbuild.2017.09.061. URL `http://www.sciencedirect.com/science/article/pii/S0378778817307636`.

[32] PAGASA. Climate of the philippines, 2018.

[33] Rodrigo D. Perez, Rosario S. Encarnacion, and Julian E. Dacanay. *Folk architecture*. GCF Books, Quezon City, Philippines, 1989.

[34] J. I. Perén, T. van Hooff, B. C. C. Leite, and B. Blocken. Cfd analysis of cross-ventilation of a generic isolated building with asymmetric opening positions: Impact of roof angle and opening location. *Building and Environment*, 85:263–276, 2015. ISSN 0360-1323. doi: https://doi.org/10.1016/j.buildenv.2014.12.007. URL `http://www.sciencedirect.com/science/article/pii/S0360132314004181`.

[35] A. B. Ramly and M. A. A. Hussain. The effect of roof angles on indoor air temperatures in terrace houses in malaysia. *Journal of Design and Built Environment; Vol 2 No 1 (2006)*, 2006. URL `https://ejournal.um.edu.my/index.php/jdbe/article/view/4948`.

[36] R. Ramponi and B. Blocken. Cfd simulation of cross-ventilation flow for different isolated building configurations: Validation with wind tunnel measurements and analysis of physical and numerical diffusion effects. *Journal of Wind Engineering and Industrial Aerodynamics*, 104-106:408–418, 2012. ISSN 0167-6105. doi: https://doi.org/10.1016/j.jweia.2012.02.005. URL `http://www.sciencedirect.com/science/article/pii/S0167610512000293`.

[37] Sigrid Reiter. *Validation Process for CFD Simulations of Wind Around Buildings*. 2019.

[38] Qairuniza Roslan, Siti Halipah Ibrahim, Rohaida Affandi, Mohd Nasrun Mohd Nawi, and Azhaili Baharun. A literature review on the improvement strategies of passive design for the roofing system of the modern house in a hot and humid climate region. *Frontiers of Architectural Research*, 5(1):126–133, 2016. ISSN 2095-2635. doi: https://doi.org/10.1016/j.foar.2015.10.002. URL `http://www.sciencedirect.com/science/article/pii/S2095263515000564`.

[39] Helenice Sacht and Marieli Azoia Lukiantchuki. Windows size and the performance of natural ventilation. *Procedia Engineering*, 196:972–979, 2017. ISSN 1877-7058. doi: https://doi.org/10.1016/j.proeng.2017.08.038. URL `http://www.sciencedirect.com/science/article/pii/S1877705817331600`.

[40] Ibrahim Siti Halipah, N. A. Azhari, Mohd Nasrun Mohd Nawi, A. Baharun, and Rohaida Affandi. *Study on the effect of the roof opening on the temperature underneath*, volume 9. 2014.

[41] J Straube. Bsd-014: Air flow control in buildings, 19/06/2019 2007. URL `https://www.buildingscience.com/documents/digests/bsd-014-air-flow-control-in-buildings`.

[42] Rima Taher. *Design of Low-Rise Buildings for Extreme Wind Events*, volume 13. 2007. doi: 10.1061/(ASCE)1076-0431(2007)13:1(54).

[43] Rima Taher. General recommendations for improved building practices in earthquake and hurricane prone areas, 2010.

[44] Doris Hooi Chyee Toe and Tetsu Kubota. Development of an adaptive thermal comfort equation for naturally ventilated buildings in hot and humid climates using ashrae rp-884 database. *Frontiers of Architectural Research*, 2(3):278–291, 2013. ISSN 2095-2635. doi: https://doi.org/10.1016/j.foar.2013.06.003. URL `http://www.sciencedirect.com/science/article/pii/S2095263513000320`.

[45] Eric van den Ham. Ventilatie lecture, bk2te3 klimaatontwerp, 23-03-2018 2018.

[46] J.W.J. Van Schaik. *Finch Philippines. An economical prefabricated residence for Hagonoy, a typhoon prone municipality in the Philippines: analysis, design and implementation*. Thesis, 2016.

[47] Marika Vellei, Manuel Herrera, Daniel Fosas, and Sukumar Natarajan. The influence of relative humidity on adaptive thermal comfort. *Building and Environment*, 124:171–185, 2017. ISSN 0360-1323. doi: https://doi.org/10.1016/j.buildenv.2017.08.005. URL http://www.sciencedirect.com/science/article/pii/S0360132317303505.

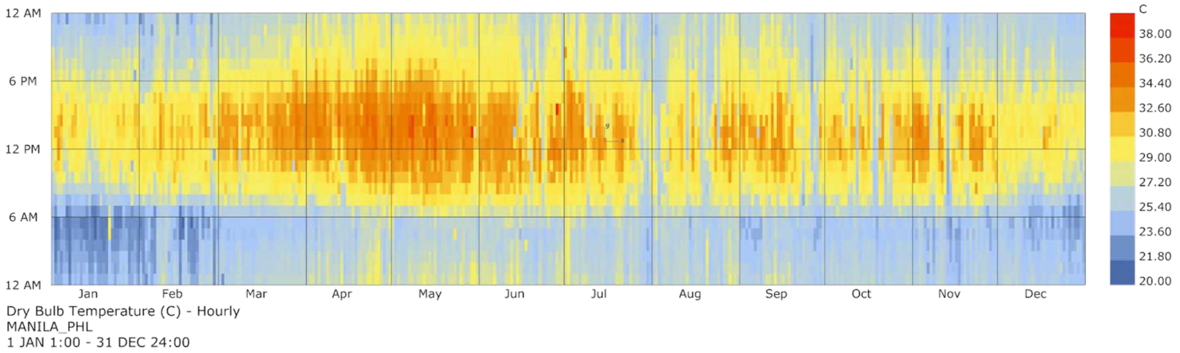
[48] Nari Yoon and Ali Malkawi. Predicting the effectiveness of wind-driven natural ventilation strategy for interactive building design, 2017.

[49] Fernando N. Zialcita and Martin I. Tinio. Philippine ancestral houses (1810-1930). 1980. URL http://books.google.com/books?id=A7AOAQAAMAAJ.

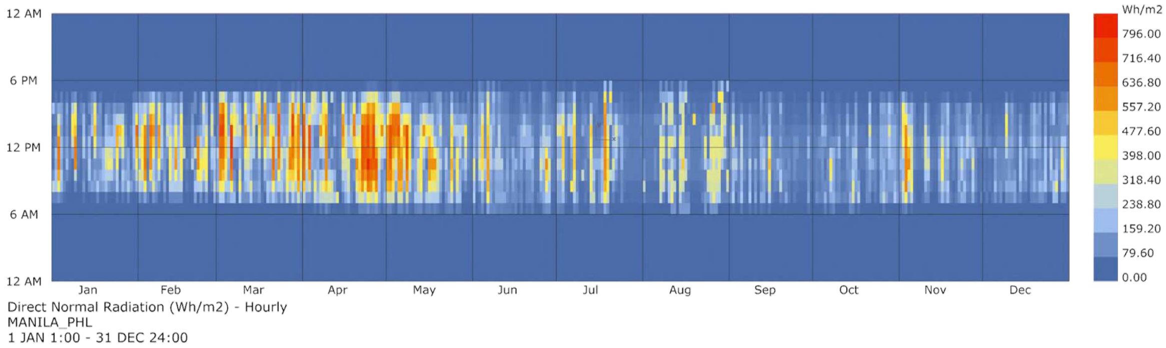
Appendices

A

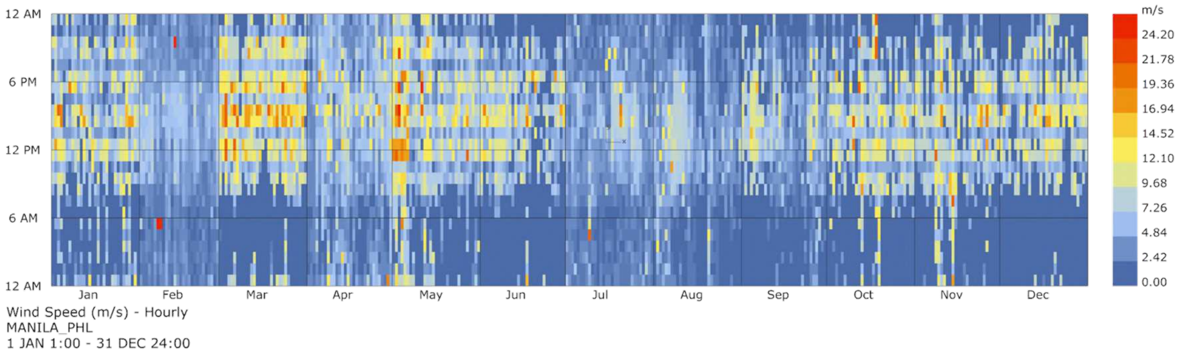
Philippine climate



(a) Dry-bulb temperature.



(b) Radiation load.



(c) Wind speed at 10 meters height.

Figure A.1: Climate data as used in the computational simulations per hour of the year in Manila.

Figure A.2: Building code (NBCP) minimum wind speed requirements per area in the Philippines.

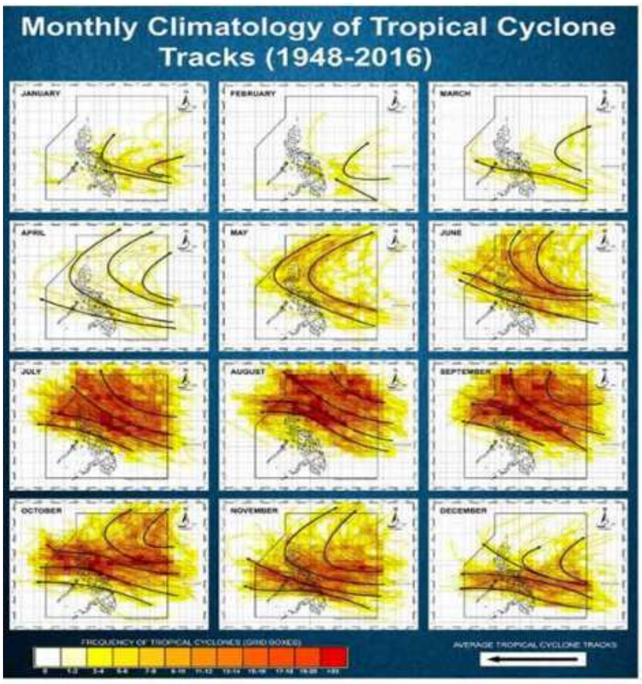


Figure A.3: Recorded typhoon paths 1948-2016 over the Philippines per month [32].

B

In situ measurements thermal performance

B.1. Background of measurement object of housing type

After super typhoon Yolanda hit the building in 2013, everything except the hollow core cement blocks was destroyed. It was rebuilt in the following way and reasons. The hollow core cement blocks and floor were used because they were already there. They were finished with a plastered layer to increase its durability. The roof was rebuilt using GI panels instead of Nipa leaves for durability and availability. The GI was donated to he inhabitants after the storm. They were happy with the choice of GI because Nipa leaves have to be replaced in a one to two year interval. The choice for sawali mats for the facade was due to its price. The inhabitants want to improve the house by repairing windows but did not do this yet because the landlord wants to sell the area. The joints were nailed. Stilts were not used because they would be too expensive. Typhoon resilient behaviour was increased by strengthening the connections with metal strips. The preparations for a typhoon included tying the roof down with cables and closing everything off. To increase the strength of the structure, wooden posts are embedded in cemented columns.

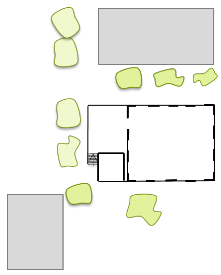
B.2. Bahay na bato measurement results

B.2.1. Results thermal measurements

The building, measurement plan and results are presented in figure B.1, B.2 and B.3 respectively. The following observations are done. The temperature is fairly constant. This is different from the bahay kubo where it would start to cool down before 5 pm. This slower responsive time can be explained by the protection of the higher thermal mass and the corridor. The indoor environment was experienced as comfortable due to the significant breeze and considerably lower temperatures then outside. Rooms on the sun-striken side heated up a bit more more then the others in late afternoon (Thobo1).

(a) west facade of the building.

(b) Nort west room picture.



(c) Surroundings plan. In grey, buildings with similar height. In green, trees of about building height.

Figure B.1: The bahay na bato backside, inside and surroundings.

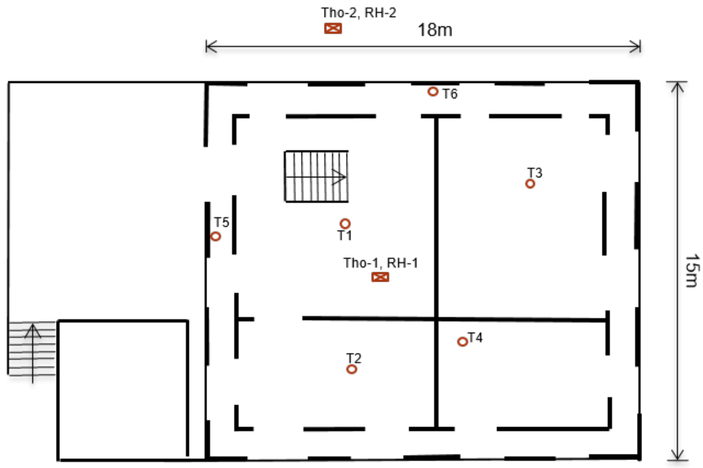


Figure B.2: Bahay na bato measurement plan.

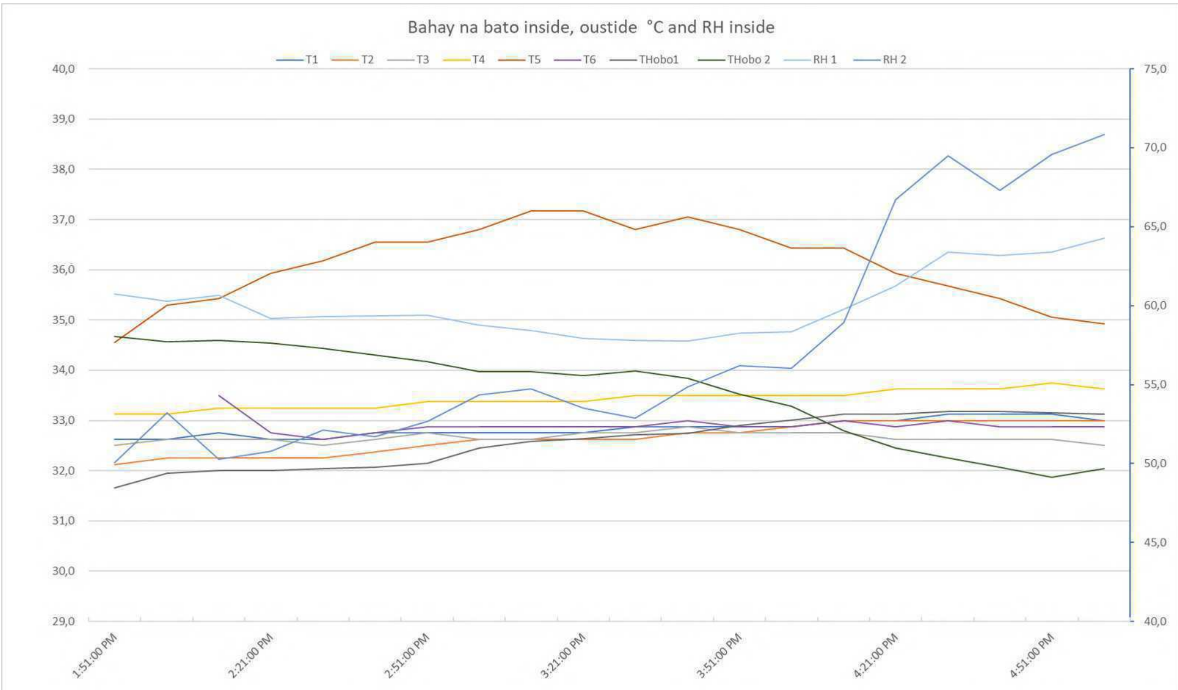


Figure B.3: Bahay na bato temperature and humidity results versus time. The scale in temperature is indicated in degrees Celsius on the left y-axis. The relative humidity is indicated on the right y-axis.

B.2.2. Results air velocity bahay na bato

The results are illustrated at their corresponding location [m/s]. The following observations are done. The wind speed measured at the openings are the highest. The openings close to the wind direction show the highest wind speed. The wind speed measured in the north-west room is significantly lower then at all the openings. The wind speed in the north west opening is several times lower then at the openings, even more than might be expected. This can be explained by the alignment of the openings. The openings do not provide a path for the flow in that direction. Therefore, the little flow in the room results in the low wind speed. At the east opening measurement location the highest velocity is observed (1.0 [m/s]). The speeds at the west side or south side are half that. This can be explained by how the air flows through the building. The north east room obstructs the flow and directs it along its sides, increasing air velocity there. After the opening the flow can spread to the openings on the west or south side. Thereby its wind speed decreases. The measurements therefore illustrate how the openings determine the flow and speed through the building and its dependency on openings.

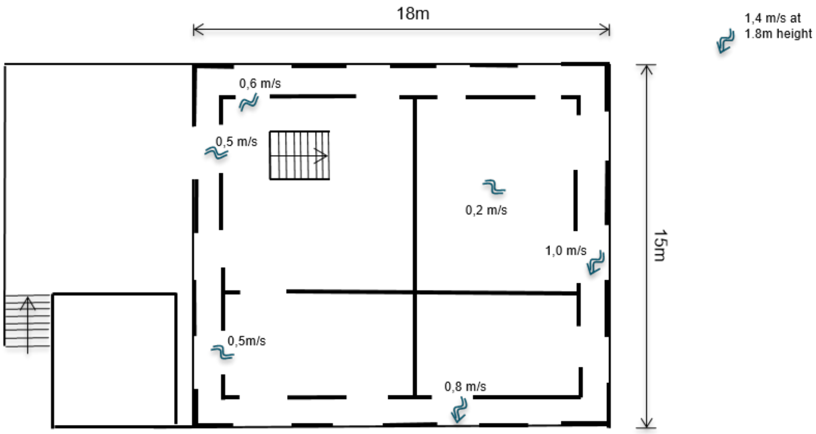


Figure B.4: Wind speed results at the first floor level.

B.3. Bamboo hut resort measurement results

The measurement plan and results are depicted in figure B.5 and B.6. As can be seen, the permeability of the facade is high, there are many huts close to each other and the building is covered by a tree.

The following observations are done on the results. During night, the indoor temperature is on average one degree higher then outside. All the inside temperatures are close to each other. The light blue arrow is the expected wind flow direction. In the floor plan, the measured wind speeds are highlighted. It didn't contribute noticeably to ventilation. On the porch air velocity was noticeable due to big openings in wind direction. It was noticed how the surrounding influences the wind direction by directing the wind between the corridor of buildings. In the morning the building has a fast response time. which can be explained by the low thermal mass and openings in facade. Stack effect is not observed in the temperature results or air velocity results.

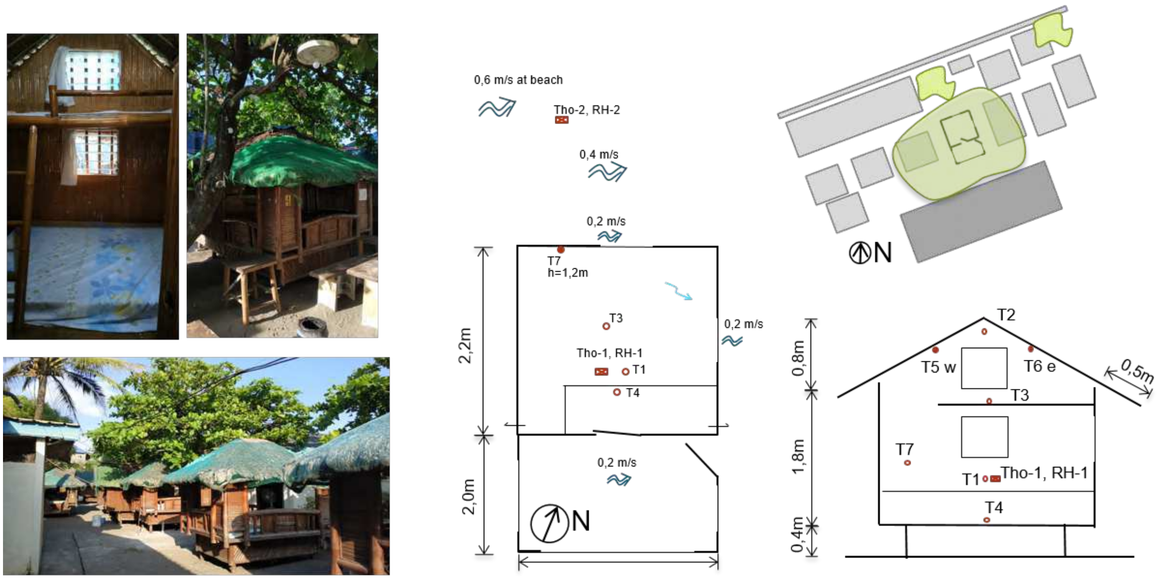


Figure B.5: Bamboo hut surroundings, the facades, measurement plan and air velocity results.

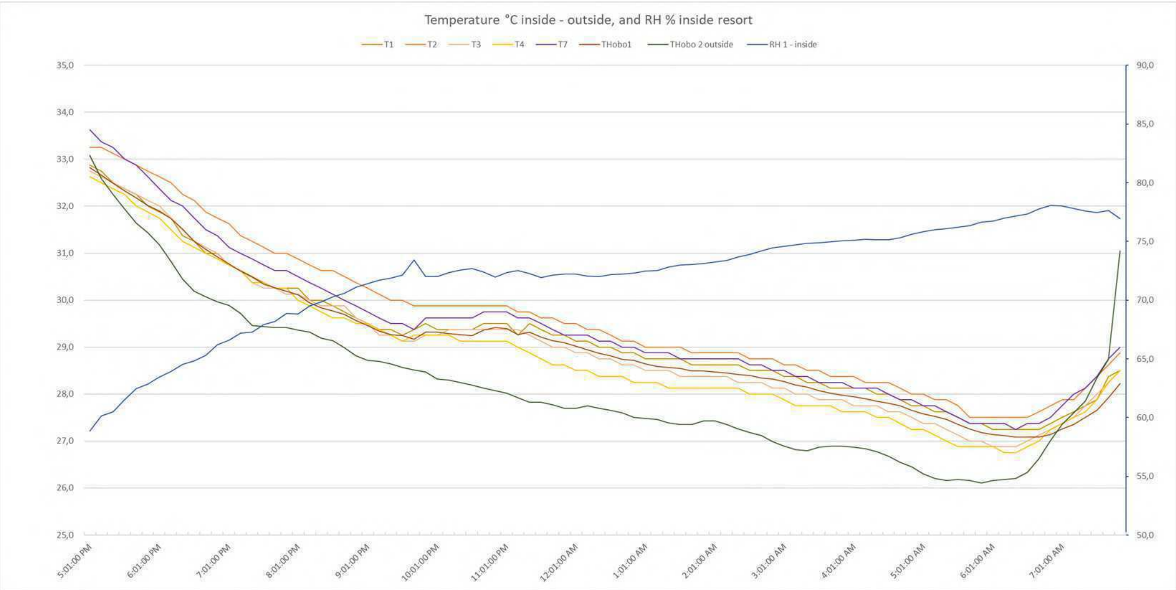


Figure B.6: Bamboo hut temperature and relative humidity results versus the time. The scale in temperature is indicated in degrees Celsius on the left y-axis. The relative humidity is indicated on the right y-axis.

C

Computational model validation

C.0.1. Comfort zone results evaluation

The design features and comfort zone are less homogenous then the general geometry and comfort zone in chapter 5. As a result, the differences in the results are expected to increase. Hence, the results of the case study is analysed. The results of the velocity per test point in the case study are illustrated in figure C.1. As can be seen, the majority of the points is close to the average of 1.31 [m/s]. Therefore, it can be concluded that the air velocity is representative for the comfort zone.

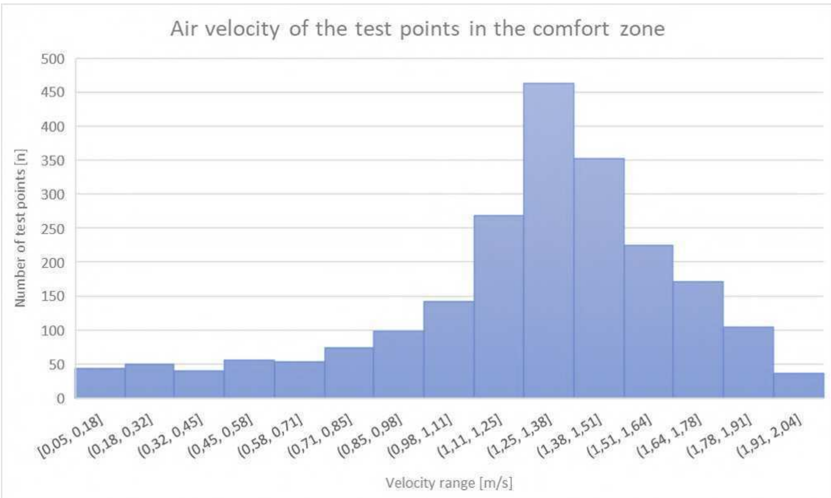


Figure C.1: Velocity per test point in the comfort zone for the case study geometry.

C.0.2. Computational model validation results

Analytical calculations The results of the analytical calculation are depicted in figure C.2. It can be concluded that the results of th model correspond with the analytical calculations.

	Validation G	Study G
$V_{i,calc}$ [m3/s]	18,55	5,70
$V_{i,CFD}$ [m3/s]	19,54	6,18

Figure C.2: Analytical validation calculation results. Validation G indicates the validation geometry, i.e., the exact copy of the wind tunnel. Study g indicates the geometry and dimensions used to test the strategies in chapter 5.

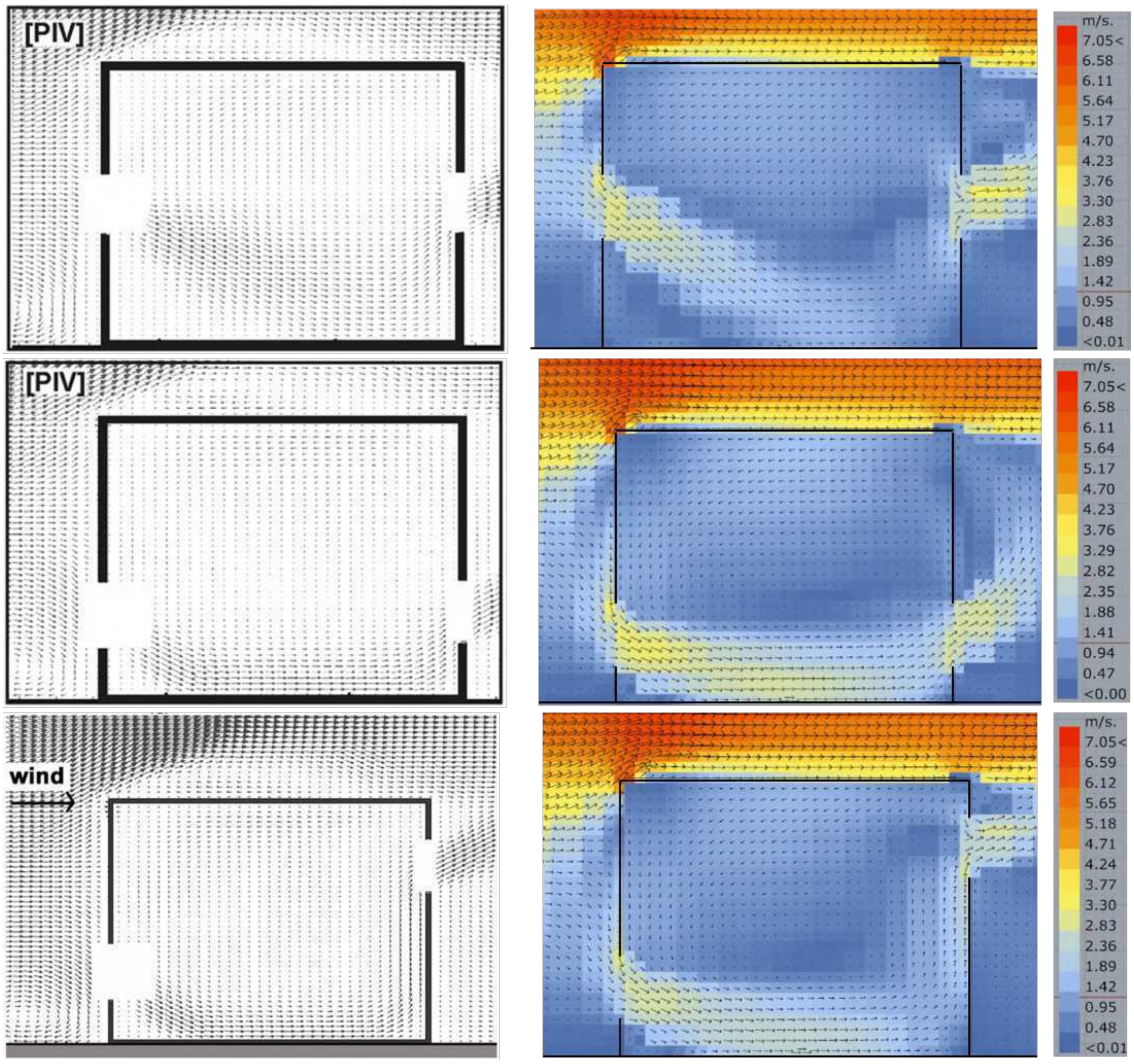


Figure C.3: Validation of computational model by rebuilding wind tunnel test. The depicted wind tunnel tests are taken from Ramponi [36].

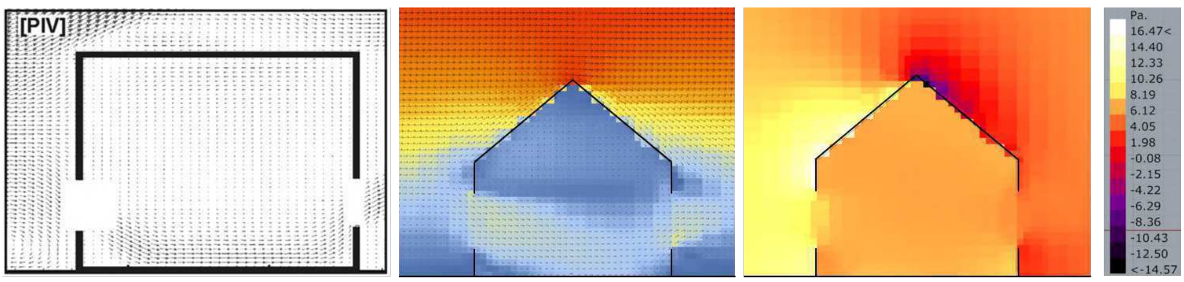


Figure C.4: Validation steps in vertical direction of strategy roof angle. The depicted wind tunnel test is taken from Ramponi [36]. On the right side the pressure distribution with corresponding scale is depicted.

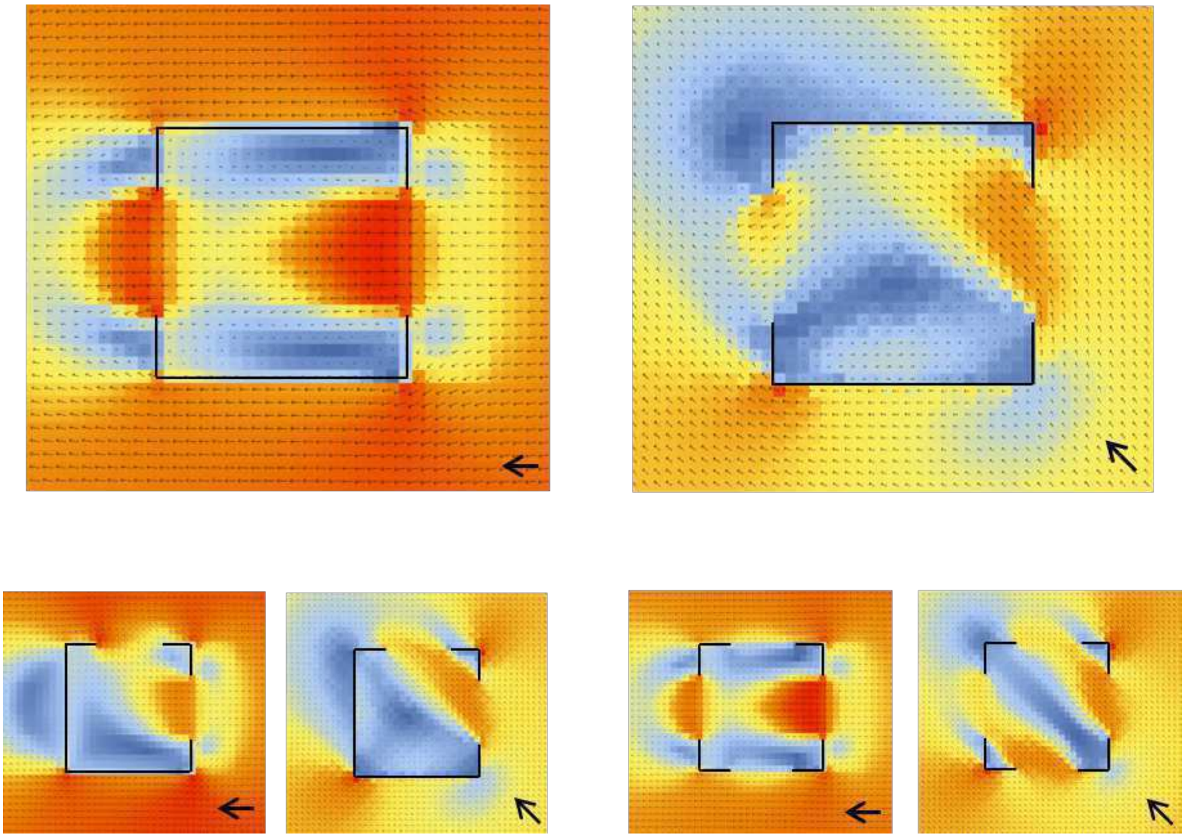


Figure C.5: Validation steps in horizontal direction of the strategy orientation. From left to right, a 0 degree followed by a 45 degrees orientation of the same geometry.

Air wall air mixture as parameter [m3/m2/s	0,045	0,0963	0,19	0,4
[m3/s]	1,40	2,2	4,4	9,2
performance Zone living				
dbtemp zonal [°C]	29,6	29,4	29,1	28,5
radtemp zonal [°C]	37,3	37,1	37	36,7
operative temp [°C]	33,5	33,3	33	32,6
surf-temp inside [°C]				
air flow (inlet) [m3/s]	3,4	3,4	3,4	3,4
air speed [m/s] horizontal	0,25	0,25	0,25	0,25
Yearly average mean radiant	29,5	29,5	29,5	29,5
performance Zone Roof				
dbtemp zonal [°C]	30,3	29,6	29,1	28,4
radtemp zonal [°C]	39,8	39,5	39,3	38,9
operative temp [°C]	35	34,6	34,2	33,6
surf-temp inside [°C]				
air flow (inlet) [m3/s]	0	0	0	0
air speed [m/s] vertical	0	0	0	0
Yearly average mean radiant	30	30	30	30

Figure C.6: Validation temperature results on the influence of air mixture rates.

D

Case study results

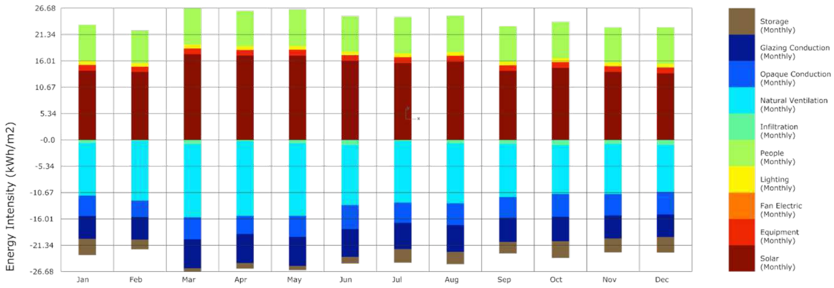


Figure D.1: Energy balance per month results of the case study.

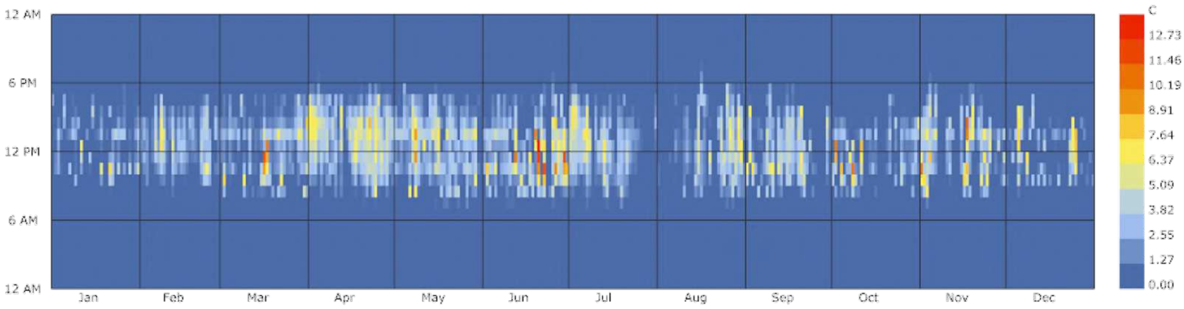
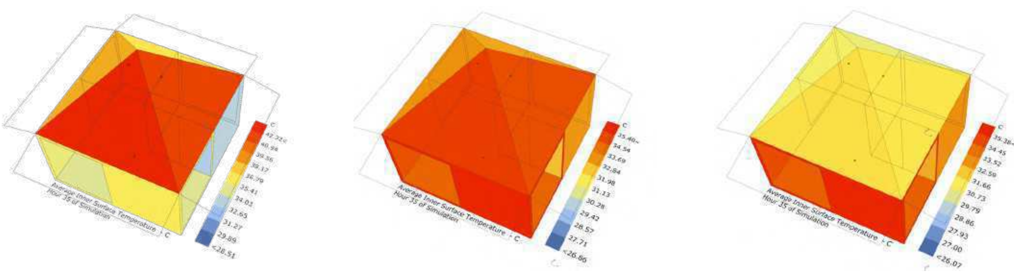


Figure D.2: Hourly exceeding temperature results of the case study.



(a) Rc-value of 0.

(b) Rc-value of 0.3.

(c) Rc-value of 0.9.

Figure D.3: Inside surface temperature results for several roof insulation values in m2K/W on the case study.