Multidisciplinary Project Philippines

Floating Homes Philippines

Multidisciplinary project

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Finch Floating Homes

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Multidisciplinary Project
Delft University of Technology
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Preface

As part of our master's degree, we decided to partake in a multidisciplinary project. As we came together, we decided we wanted to create something useful for those who really need it. Intrigued by the project of Finch Floating Homes in the Philippines, we felt that this was the project where we could share our knowledge and develop ourselves at the same time. And so, the multidisciplinary team *Floating Homes Philippines* was formed.

Our team consists of six students with various backgrounds. Despite all being master students at the Civil Engineering and Geoscience faculty of the Delft University of Technology, the team is undeniably multidisciplinary because of our different disciplines. After starting a collaboration with Finch Floating Homes and TU Delft PhD candidate P.H. Ham we created a plan to benefit the ongoing floating house project as well as the local people of a flood prone area in the Philippines. There was already a plan to build a pilot of the floating home in June of 2018 in Macabebe, Pampanga, the Philippines. But in order for this pilot to be successful and show the local people the possibilities of a safer and healthier future, more research was needed. We travelled to Macabebe, a beautiful town full of extraordinarily kind people, to experience the local conditions for ourselves and conduct the research to its full potential. We focussed on the development of the roof, mooring system and sanitary design and the construction process, where we take our experiences from our visit and conversations with the local people into account.

This project would not have gotten where it did, without the help of several people. We would like to thank Pieter Ham and Finch Floating Homes, for guiding us through the project, providing us with helpful information, data and contacts in the Philippines. Secondly, thank you to our supervisors, J.D. Brinker, G.A. van Nederveen and M.K. de Kreuk, for safeguarding the level of the research and helping us with their expertise in their fields. Third, we would like to thank Bembong Balgan, the municipal counsellor, and the other counsellors and employees of the municipality of Macabebe. We were given the warmest welcome by all of them and throughout our stay they have been very helpful with everything in order to make this project happen. Also, the mayors and counsellors of the neighbouring cities, especially Angel L. Cruz, who involved us in the Delta Program Alliance to show us the need of solutions against flooding. Lastly, a special thanks to Dam Beh, Gheng, Rhestie and Lianne, for providing a welcome and loving home.

Summary

In this report the following question will be answered using sub-questions: "*How can the design and development of the pilot project, as currently designed by Finch Floating Homes, be improved in order to perform an optimal test of the floating house in Macabebe, the Philippines?*"

The first thing that needed to be further enhanced was the roof structure of the floating house, leading to the following sub-question: "*How can the roof structure be redesigned to assure a buildable and affordable pilot project?*". Based on a revision of the roof shape, the hip roof turned out to be the best shape in a typhoon prone area. During the design, the geometry of the housing unit was slightly changed into a double symmetrical geometry. This change increases the constructability and simplicity of the floating house. After this, the design of the roof structure, consisting of four identical prefabricated frames, was made. For the structural analysis, wind loads on the structure were computed. The SLS turned out to be decisive for the element design, the unity check for ULS turned out to be very high. Further optimisation of the cross sections can only be achieved if the SLS requirements regarding maximum deflection are reconsidered. After prefabrication, the frames will be connected to the house and to each other on-site. At this point, the designed foldable balconies will be placed in the frames. The roof sheeting material used in the design is corrugated steel roof sheeting. However, bamboo roof sheeting should be used as soon as it is available. A first design of the connections of the roof structure has been made. The connection design was based only on detailing and no structural analysis of the connections has been performed.

The final roof shape will be used to calculate the rainwater collection, this information is needed to answer the second sub-question: "*How can a socially accepted, sustainable and durable sanitary facility be created?*". The floating house requires a self-sustaining system that fulfils the needs of both drinking water and wastewater treatment. To set the requirements for the system, a technical and a social analysis were conducted. This resulted in the choice for the human water system. This system consists of three separate systems: rainwater harvesting, storage of water and wastewater treatment. Although it is an integrated system, the three parts have their own constraints. Within these constrains, the possible solution for the three systems was designed. The rainwater harvesting system consists of a drainage system, first flush barrel system and a sand filter. It is capable of filtering the most common maximum rain shower in a year for regular usage inside the house. The storage system is capable of storing sufficient water for one-third of the total usage over 80% of the year. At last, the wastewater treatment system is based on natural treatment before discharge into the surface water. This natural treatment contains a septic tank and a wetland filter.

Among other things, the configuration of the water management system within the floating foundation and the wind load on the floating house influence the motions of the floating structure and the forces on the mooring system. Adding the external loads caused by waves and current during a typhoon, this results in the vertical motion and rotation of the floating structure. A short analysis of the various options for mooring systems leads to the decision of using mooring piles. After the configuration of the four mooring piles was chosen, it followed from the dynamic analysis that the total stiffness of the piles influences the horizontal motion and rotation of the platform. The vertical motion is a free behaviour; it is not influenced by the mooring piles. The dependency of the motions on the mooring piles is highly non-linear and also depending on the connection between the structure and the mooring piles. Therefore, it is needed to choose a specific combination of pile length and bending stiffness, after which the strength of the pile is checked. Thus, the third sub-question, "*How does the motion of the floating structure depend on the stiffness of the mooring system?*", was answered.

The overall design and resources are used to answer the final sub-question: "*What construction plan can ensure timely completion of the pilot project?*". The project construction plan focuses on the time, risk and change management of the pilot project. The resources and construction activities were identified and combined with its duration to develop the pilot project schedule. The schedule

is clarified with advice on the actions that should be taken and a control plan to execute. This control plan was made to ensure timely completion. When starting construction the first week of June 2018, the handover will take place in the last week of August 2018. The process is accompanied by several risks. Response strategies for these risks are proposed in order to setup a risk mitigation plan. Finally, advice is given on how to manage possible design changes regarding new research, the development of a more detailed design and the up-scaling changes after a successful pilot project.

With the help of the previously described research, the general question, "*How can the design and development of the pilot project, as currently designed by Finch Floating Homes, be improved in order to perform an optimal test of the floating house in Macabebe, the Philippines?",* can be answered. From this project it is clear that in order to perform an optimal test of the pilot project, some topics should be researched more into detail. The roof connections need to be checked on strength, social acceptance of the sanitary system should be checked, the mooring system should be revisited using software, and construction of the floating house requires more insight in construction management. When these topics are addressed before construction starts, the pilot project can be an optimal test of the floating house.

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List of Abbreviations

₱	Philippine peso
ABB-BP	Alyansa ng mag Baybaying Bayan ng Bulacan at Pampanga
AC	Activated Carbon
BOD	Biochemical Oxygen Demand
CC2	Consequence Class 2
CH_4	Methane
CME	Construction Management and Engineering
CO_2	Carbondioxide
COD	Chemical Oxygen Demand
CSRS	Corrugated Steel Roof Sheeting
GAC	Granular Activated Carbon
H_2S	Hydrogensulfide
HE	Hydraulic Engineering
HRT	Hydraulic Retention Time
HWS	Human Water System
IDM	Integral Design Management
kWh	Kilowatt hour
LPG	Liquefied Petroleum Gas
lpcd	Litre per capita a day
N	Nitrogen
N_2	Nitrogengas
NGO	Non-governmental organisation
NH_3	Ammonia
NH_4	Ammonium
NO_3	Nitrate
NWRB	National water resources board
P	Phosphorus
PESTLE	Political, Economic, Social, Technical, Legal and Environmental
PO_4	Phosphate
pH	Potential of Hydrogen
SE	Structural Engineering
SLS	Serviceability limit state
SS	Suspended Solids
SSHWS	Saffir-Simpson Hurrican Wind Scale
TKN	Total Kjeldhal Nitrogen
TSS	Total Suspended Solids
ULS	Ultimate limit state
UV	Ultraviolet
WM	Water Management

Nomenclature

Parameter	Description	Unit
A	Area	[m^2]
A_{WL}	Waterplane area	[m^2]
a	Added mass coefficient	[kg] or [kgm^2]
b	Width	[m]
b_s	Width of foundation	[m]
C	Run-off coefficient	[-]
C_{2D}	Chezy coefficient	[m$^{1/2}$/s]
C_{cap}	Capita	[-]
C_d	Wind drag coefficient	[-]
c	Hydrodynamic damping coefficient	[kg/s]
c_{dir}	Directional factor	[-]
c_e	Effluent concentration	[kg/m^3]
c_0	Start concentration	[kg/m^3]
c_{0r}	Orography factor	[-]
$c_{pe,1}$	Local pressure coefficient	[-]
$c_{pe,10}$	Global pressure coefficient	[-]
c_r	Roughness factor	[-]
c_sc_d	Structural factor	[-]
c_{season}	Seasonal factor	[-]
c_w	Dimensionless wind drag coefficient	[-]
D	Draft	[m]
d	Water depth	[m]
d_0	Pore space diameter	[mm]
d_{10}	Lowest ten percentile of sample's mass	[mm]
C_u	Uniformity coefficient	[-]
E	Young's modulus	[kN/m^2] or [N/mm^2]
F	Force	[kN]
F_a	Force amplitude	[kN]
F_F	Fetch	[m]
F_s	Support force	[kN]
f	Temperature ratio	[-]
f_y	Yield stress	[N/mm^2]
G_k	Characteristic permanent load	[kN/m^3] or [kN/m]
$\overline{GM}$	Metacentric height	[m]
g	Gravity constant	10 [m/s^2]
H	Wave height	[m]
H_0	Filter resistance	[m]
H_s	Significant wave height	[m]
h	height	[m]
I	Second moment of inertia	[m^4]

I_{yy}	Mass moment of inertia	[kgm^2]
I_v	Turbulence intensity	[-]
i	Water level gradient	[-]
k	Spring or restoring coefficient	Multiple
k_L	Turbulence factor	[-]
k_R	Terrain factor	[-]
k_w	Wave number	[1/m]
L	Wave length	[m]
l	Length	[m]
l_{mix}	Turbulent mixing length	[m]
M	Mass	[kg]
n	Desludging rate	[y]
P	Precipitation	[mm/y] or [mm/month]
p	Pressure	[kN/m^3]
p_0	Porosity	[-]
Q	Discharge	[m/s]
Q_k	Characteristic variable load	[kN/m]
q	Distributed load	[kN/m]
q_c	Flow of waste water	[lpcd]
q_d	Design variable load	[kN/m]
q_p	Peak velocity pressure	[kN/m^2]
q_w	Wind load	[kN/m^2]
R_d	Design resistance	[kN/m^2]
s	Sludge accumulation	[L]
T	Moment	[kNm]
T_p	Wave peak period	[s]
T_q	Filter run time	[s]
t	Time	[s]
u	Horizontal water velocity	[m/s]
$\bar{u}$	Depth average horizontal velocity	[m/s]
u'	Horizontal turbulent velocity	[m/s]
uv	Vertical water velocity	[m/s]
u_*	Shear velocity	[m/s]
V_{yearly}	Available quantity of water	[m^3/y]
v_b	Basic wind velocity	[m/s]
$v_{b,0}$	Fundamental value of the basic wind velocity	[m/s]
v_m	Mean wind velocity	[m/s]
W	Section modulus	[mm^3]
w	Deflection	[m]
x	Surge motion	[m]
x_a	Surge amplitude	[m]
y	Sway motion	[m]
z	Heave motion	[m]
z_a	Heave amplitude	[m]
z_e	Reference height for external wind action	[m]
z_0	Roughness length	[m]

z_{roof}	Height of roof structure	[m]
α	Filtration coefficient	[1/s]
β	Bottom height of fishpond	[m]
ε	Phase angle	[rad]
ζ	Water level/elevation	[m]
ζ_a	Wave amplitude	[m]
κ	Von Karman constant	0.41 [-]
λ_0	Filtration coefficient	[1/m]
ν_{kin}	Kinematic viscosity	[m^2/s]
ν_t	Turbulent viscosity	[m^2/s]
ρ_{air}	Air density	1.2 [kg/m^3]
ρ_d	Mass density of impurities	[kg/m3]
ρ_w	Water density	1,025 [kg/m^3]
σ	Stress	[N/mm^2]
τ	Shear stress	[N/mm^2]
Ψ_0	Incoming wave potential	[m]
$\Psi_{0,1}$	Combination factor	[-]
Ψ_p	Pitch motion	[rad]
$\Psi_{p,a}$	Pitch amplitude	[rad]
Ψ_r	Roll motion	[rad]
Ψ_y	Yaw motion	[rad]
ω	Frequency	[rad/s]
∇	Displaced water volume	[m^3]
$\varnothing$	Diameter	[mm]

1 Introduction

Natural disasters are a large threat to mankind all over the world. The Philippines is one of the most natural disaster prone countries in the world, being affected by volcanic eruptions, earthquakes, typhoons and floods. In combination with the population growth, unplanned urbanisation, environmental degradation and global warming this creates immense problems for the Philippine people, land and culture (World Bank, 2005). Measures are being taken to reduce the risk of natural disasters, but in the meantime the inhabitants of the Philippines have to cope with the consequences of the volcanic eruptions, earthquakes, typhoons and floods on a regular basis. Most common of these natural disasters are the floods, especially in delta regions like the provinces of Bulacan and Pampanga, north of the capital Manila. In these regions floods occur daily and some towns can be flooded during the entire rainy season, from June to October. The houses of the inhabitants get flooded regularly, decreasing the living quality and reducing the structural integrity. Presently, the knowledge and resources in the Philippines are not developed far enough to reduce the consequences of the floods for the people in these flood-prone regions.

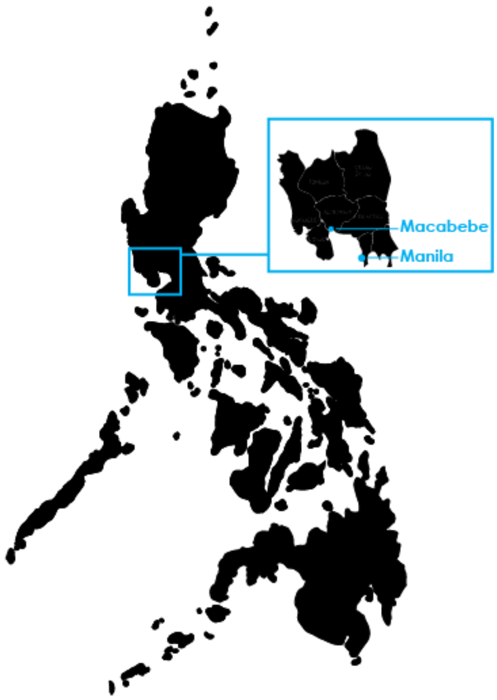

Figure 1.1 Map of the Philippines and project location (own illustration)

In the Netherlands multiple organizations and companies are working daily on finding solutions to these flood related problems. One of these organisations is Finch Floating Homes, who designs wooden, modular floating homes. In 2016, P.H. Ham and J.W.J. van Schaik graduated on research conducted on the implementation of amphibious, floating residences in foreign countries, more specifically in the province of Bulacan, the Philippines. The aim of Finch Floating Homes is to create affordable, sustainable and typhoon resilient homes for developing regions such as Bulacan and Pampanga in the Philippines. The design of the house made during the graduation theses is not ready for implementation yet, the design needs improvement before a pilot version of the floating house can be built. The goal of this report is to provide an improved redesign and implementation plan for the first pilot project.

The research for the redesign is conducted on location by the multidisciplinary team. The project location is Macabebe, a town situated in the Pampanga Delta adjacent to the Manila Bay. The area of Macabebe has to cope with daily flooding, caused by high water from both the rivers and the sea. Additionally, groundwater is pumped by local industries, causing land subsidence and worsening the flood problems. A long time ago, the land was used for rice cultivation, but when the relative water level rose the rice could not grow on these lands anymore. The rice fields were filled with brackish water and turned into fishponds, a different source of income. Unfortunately, the fish could escape the ponds during high water, lowering the harvest to an unprofitable amount. The waters are now plain ponds, without a purpose and could be a perfect location for floating residences. Besides the usual flooding during the rainy season, typhoons strike the region regularly, increasing the problem and severely damaging the existing houses. This results in a higher demand for affordable, sustainable and typhoon resilient homes. The Finch Floating Homes project provides a well-suited solution.

2 Project description

Due to the multidisciplinary character of the project this chapter is reserved to formulate the general project description. This includes a general problem statement, project goal and scope, personal and mutual research question, and adopted design principles.

2.1 Problem statement

In June 2018, Finch Floating Homes will start constructing the first pilot house based on the research of J.W.J. van Schaik and P.H. Ham. However, the design of the floating house is currently not ready to realistically start construction of the pilot project.

Assumptions were made regarding typhoon conditions at the project location and its influence on wind characteristics and water behaviour, like waves and currents. The behaviour of the floating foundation and the mooring system during a typhoon is uncertain. Only a brief investigation has been performed to get a first insight into the behaviour, this is what the current design is based on. The investigation is not thorough enough for the pilot project to be an effective and successful test of the floating house.

The design of the floating house is still a concept but, needs to be at least a detailed design before starting the pilot project. The house, and especially the roof due to its complexity, need further optimisation of its shape and structure. The connections have not been designed yet. Besides that, the wish is to integrate water management into the pilot project. A design of waste- and rainwater collection and treatment is currently not available. Water management can be integrated in the roof design.

Before starting the construction of the first pilot project, a comprehensive construction plan is needed. It is not fully clear yet what resources are needed for the construction. The aim is to use local resources, but the type and their origins are undefined. It is important to have an overview of the project time schedule and project risks prior to the start of construction to prevent unexpected events or delays.

2.2 Goal and scope

The goal of this multidisciplinary project is to improve the current design of the pilot model regarding the different problems as stated in section 2.1. Hereby it is important to ensure that the floating house is structurally safe, liveable, and constructible. Summarised, the research is performed on the following topics:

- Design of the roof structure
- Design of the human water system
- Design of the mooring system
- Project construction plan

The scope of the project is the pilot model design. This is currently the priority for Finch Floating Homes. All assumptions made regarding the design principles and dimensions are therefore based on the current pilot model design as specified in the master theses written by P.H. Ham (Ham, 2016) and J.W.J. van Schaik (Schaik, 2016).

2.3 Research question

In order to investigate the problems as stated in section 2.1, several research questions for this project are developed. The purpose of setting up these research questions is to guide the different disciplines within this multidisciplinary team towards answering the general research question. By doing this, freedom is given to the different team members to conduct research in their own field of expertise while working together on answering the general research question.

General research question:

How can the design and development of the pilot project, as currently designed by Finch Floating Homes, be improved in order to perform an optimal test of the floating house in Macabebe, the Philippines?

Sub-questions:

Design of the roof structure:

How can the roof structure be redesigned to assure a buildable and affordable pilot project?

Design of the human water system:

How can a socially accepted, sustainable and durable sanitary facility be created?

Design of the mooring system:

How does the motion of the floating structure depend on the stiffness of the mooring system?

Project construction plan:

What construction plan can ensure timely completion of the pilot project?

Multidisciplinary research:
To give a better overview of the different connections between the specialties in the multidisciplinary project team a visualization is given in Figure 2.1 and Figure 2.2. In the report the different sub-questions will be treated in successive chapters. This is explained in further detail in the reader's guide included in section 2.4.

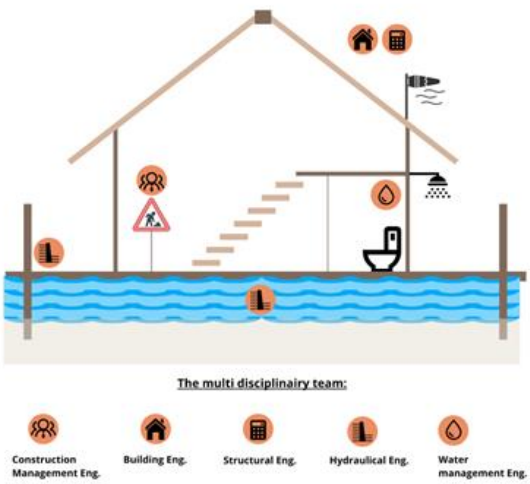

Figure 2.1 Different disciplines and topics in the multidisciplinary team

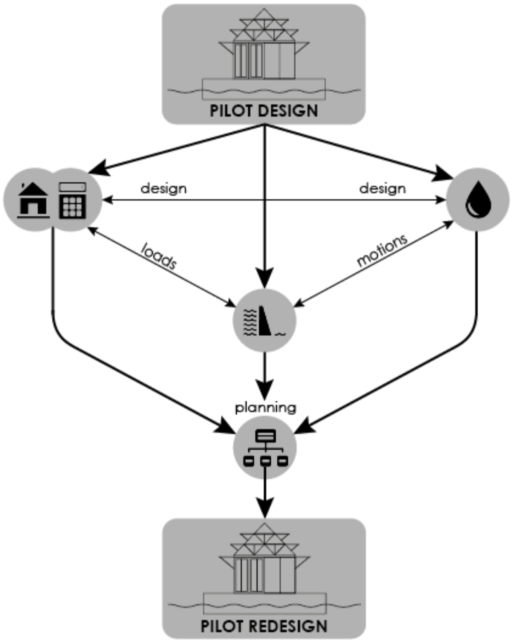

Figure 2.2 Links between the different disciplines

The topics addressed in this multidisciplinary project by the different teams are connected. The design of the roof has impact on the catchment and storage of rainwater, but also the wind loads on the mooring system. The design of drink- and rainwater storage impacts the motions of the floating house and thus the forces acting on the mooring system. This connectivity between the several disciplines are beneficial to an integrated design, but can also cause obstacles. When information is required from a different discipline and this information is not available (yet) research should continue regardless. The team should resort to assumptions, estimations, and the previous research.

2.4 Methodology

In this section the work method is clarified, and a reader's guide will be presented.

The research was carried out in several steps:

1. Elaboration on previous research
   The research starts with going through the research of P.H. Ham and J.W.J. van Schaik, to get full understanding of the current design. In this step, the boundary conditions that will be used for the redesign are argued and established.

2. Collecting information at the project location
   This phase will be used to fully comprehend the magnitude and effect of the problem on the local community. Doing this helps to find an applicable solution, optimised to the conditions of the pilot location. Local construction methods, available tools and materials, and habits will be investigated, showing the possibilities, challenges and impossibilities for the pilot project. This information is gathered through surveys, interviews and meetings with experts.

3. Working out the results into solutions and adaptations
   After collecting the required information from the previous research and the project location, the information is processed. Additional research will be carried out and processed, using different computer software like Python, Maple, MS Project, MS Excel, MS Visio, MatrixFrame, Delft3D and Rhino. The output from the research will lead to solutions and adaptations of the design of the floating houses.

4. Implementation into the design of Finch Floating Homes
   The solutions and adaptations need to be implemented into the present design. Visualisation of the results is also part of this. Implementation can be done in several ways. The addressed aspect of the pilot design could be (re)designed completely, adjusted accordingly or optimised to better suit the pilot project.

The previously mentioned steps were used to find the solutions for all sub-questions. The questions are divided over several chapters. The report will start with the investigation of the first sub-question, "*How can the roof structure be redesigned to assure a buildable and affordable pilot project?"*, in chapter 3. The final roof shape will be used to calculate the rainwater collection, this is the start of answering the second sub-question, "*How can a socially accepted, sustainable and durable sanitary facility be created?"*, in chapter 4. Chapter 5 focuses on the sub-question "*How does the motion of the floating structure depend on the stiffness of the mooring system?"*. The wind loads on the floating house, as was treated in chapter 3, and the mass of the water management system, as established in chapter 4, have a strong influence on the motions of the floating structure. In chapter 6, the overall design and project resources are used to answer the question "*What construction plan can ensure timely completion of the pilot project?"*. For each chapter conclusions and recommendations are provided. The conclusions and recommendations are summarised in chapters 7 and 8.

2.5 Design principles

During the (re)design of the project the design principles as used in the current design by Finch Floating Homes will function as guideline. In this paragraph the main design principles as of interest for this project are listed and explained in few sentences. All disciplines will use these principles as starting point for their design and will expand upon these principles where needed. This approach will strive towards an integrated design among the different disciplines, based on the same principles.

2.5.1 General design principles

Based on the current design as made by Finch Floating Homes certain boundary conditions with respect to dimensioning arise. Besides dimensions of the housing and foundation unit the conditions of the project location form important design principles to consider for all disciplines. In this section the general design principles of dimensions, typhoon resilience, and prefabrication are discussed.

Dimensions

The current dimensions on which the designs of the different disciplines will be based are depicted in Figure 2.3. For designs made in this project the size of a single one-story unit on a single floating foundation unit will be considered.

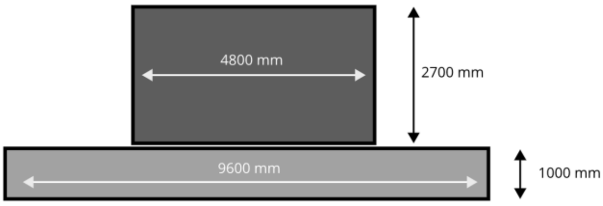

Figure 2.3 Dimensions housing unit on foundation

The foundation and housing unit are square, which means that the width dimension shown in Figure 2.1 is the same in both directions. The depicted dimensions are very general. If more specific dimensions from the current design are used in this project in the different disciplines, then these values will be listed in the respective design chapters.

Typhoons

The project location is in the province of Pampanga, which is a province labelled as high-risk area to typhoons. For this project that means that the designs of the mooring structure and the roof must be typhoon resilient. Please notice that the word "resilience" is used instead of typhoon proof.

In this design two main factors in the design of a typhoon resilient structure are considered.

Maintenance, repair, and replacement of damaged parts should be regarded in the design. This principle ensures that people living in the houses can continue to use their housing unit after typhoon damage.

Aerodynamics of the roof structure is of great influence on the design factors used in live load calculations on the roof structure. The more optimization of aerodynamics is considered in the roof design, the more wind force is naturally "neglected" by the building shape. To determine the calculation value of wind pressure on the building the wind speed is required. This calculation is performed in Appendix A.2.

Prefabrication

Lack of transportation possibilities to the project location and storage of material on site are the main reason for design for prefabrication in the design. Designing for prefabrication comes with two main design principles.

Simplicity for the structural members and especially their connections to ensure on site make-ability.

Transportation as limiting factor for the prefabricated parts.

2.5.2 Finch Floating Homes principles

Since this project is a research conducted primarily for Finch Floating Homes it is important to include their principles in the design. In this section the main principles as adopted by parent company Finch Buildings are discussed. Finch Floating Homes has adopted the principles sustainability, adaptability, and health to create a suitable design for the Philippines. Additionally, the principle "affordability" with respect to the income of the target group has been adapted to ensure that the houses are affordable for the local community.

Sustainability

Sustainability for the designs made for this project will include seven design principles. Originally the location formed the eighth sustainable design principles, but in this project the location is assumed a fixed design parameter. This leaves the following seven design principles for sustainable decision making.

Structural design efficiency is focused on the use of "simple connections", efficient force distribution, and total use of material.

Energy efficiency as sustainable principle includes the energy used to construct (embodied energy) the floating house as well as the energy used to operate it (energy usage). Here the type of energy used for construction and operation is preferred to be renewable where possible.

Water efficiency in this project will center around the collection of rainwater, reduction of water consumption, and reuse of wastewater. The problematic situation of land subsidence in Macabebe strives towards reducing the pumping of water from aquifers as main water source.

Material efficiency focusses on the use of sustainable material and optimization of the structural members. Optimization of structural members will result in a lower use of material and is therefore an important parameter for material efficiency.

Indoor environmental quality makes the house livable. In this project the indoor environmental quality is mainly considered in the roof design, where air circulation and light inlets form sub criteria for the design.

Maintenance is of great importance to assure a sustainable building. It is therefore the aim to keep it simple for all found design solutions to ensure maintenance by the local community is possible.

Waste reduction aims at reduction of waste in both the construction and use phase of the project. Prefabrication of the main structural members allows for optimization in the construction phase with respect to building materials. In the use phase this project will look at reuse of wastewater as tool to decrease water waste.

Adaptability

The designed buildings should be able to adapt to changes on several levels to be future resistant. For this project adaptability is considered on two different levels.

Environmental adaptability considers environmental change and its influence on external factors. This means that during the design the external factors such a wind force, water level, and rainfall as based on future trends rather than the current situation.

Social adaptability makes sure upscaling of the project is possible. While the project scope is the pilot project all designs made must also be applicable to a larger scale project where multiple housing and foundation units are coupled.

Health

The concept of health is focused on designing "passive" improvements in the living environment. This is done by including improvements regarding ventilation, indoor temperature, day light, and sanitary. Since the (re)design of the housing unit is not within the scope of this project the three building physics aspects (ventilation, temperature, day light) will only be taken into account in chapter 3.

Ventilation is an important design criterion for improving living conditions as it contributes to a healthy indoor air quality.

Indoor temperature can quickly rise in the warm climate of the Philippines. Indoor temperature is strongly related to ventilation as natural flow of air through the building can lower the indoor temperature significantly.

Day light improves overall liveability of the floating houses and determines the use ability of certain areas in the building. The roof is an important part for letting in natural day light.

Sanitary makes sure that people do not end up living in their own waste. Living on water brings along its own challenges regarding this subject. To ensure healthy conditions a well-designed and maintainable sanitary situation will be designed with equal or better standards than comparable housing units on land.

Affordability

Relating to the target group of Finch Floating Homes the cost must be kept as low as possible to ensure affordability for most people. The cost reduction is aimed for in three factors. An optimization of these three factors will result in the most affordable design

Material cost considers type of materials used, their local price, and the amount of material used.

Manufacturing cost is split in cost of prefabrication and cost of on-site assembly.

Transportation cost consists of transport of materials to the prefabrication site and transport of prefabricated parts to the project location

3 Design of the roof

3.1 Introduction to the roof design

Former U.S president John F. Kennedy once said:

"The time to repair the roof is when the sun is shining"

Designing a roof for a house in a typhoon prone area makes this quote very relatable for this project. Under normal conditions the roof must fulfil its regular task of providing shelter and creating a liveable environment in the house. But in times of typhoons the roof must survive, be typhoon resilient, and repairable once the sun is shining again.

In section 3.1.1 the design approach followed in this chapter is discussed. Further in this paragraph the boundary conditions and list of requirements will be discussed on which the roof design is based. The discussion of the physical boundary conditions is done in section 3.1.2. The list of requirements which form the design principles for the roof will be discussed in section 3.1.3.

3.1.1 Design approach

The design approach is set up to critically analyse the current roof design and improve it where needed. First a sketch design of different roof types and possible layouts will be made. From here three designs will be chosen to design in more detail. The goal of this exercise is to stay open about other possibilities and not get fixated on the current pyramid shaped roof design.

After this the current roof design will be critically analysed based on the requirements set up in section 3.1.3. Here it is important to highlight the positive and negative aspects of the current design and improve it where needed. This step concludes the shape and function analysis.

Based on the conclusion of the shape and function analysis the forces on the structure will be analysed. This will be done by first discussing the chosen materials. Then setting up the norms and design codes, followed by analysing the consequence class of the structure and the governing load combinations. Correctly assuming the wind load based on retrieved typhoon data will be a critical part of the force analysis. The calculations performed in the frame design chapter will be concluded with a choice of member cross sections that fulfils the requirements of local and global force analysis during a typhoon (ULS) and a tropical storm (SLS).

Once the cross sections for each member have been chosen the detailed design of roof and connections will follow. Here it is again important to choose suitable member sizes and connections based upon local availability of the different elements. To prove the buildability of the structural design a construction manual will be made. A visualization of the new roof construction during the different construction phases will support this manual.

3.1.2 Boundary conditions

The design of the roof structure will be based on the present design of the underlying house. This means that the dimensions of this house need to be used as a starting point for the dimensions of the roof structure.

The general dimensions as shown in section 2.5 do not give enough information for the design of the roof structure on a housing unit with set dimensions. Therefore, the structure underneath the roof must be examined in more detail. This has been done based on the current design as discussed in the master thesis document of Joran van Schaik (Schaik, 2016).

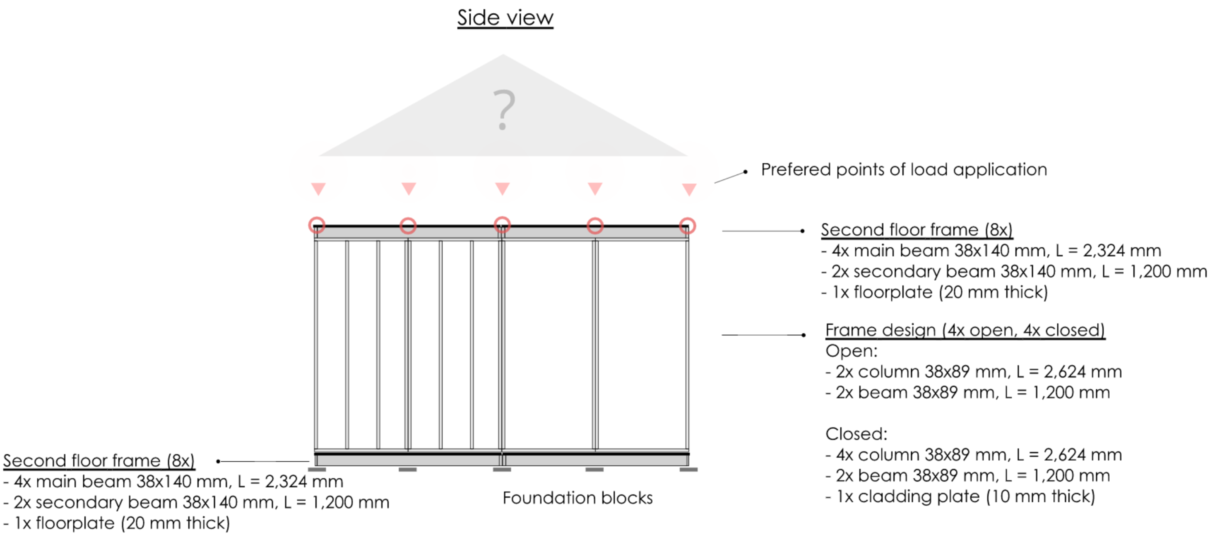

Figure 3.1 Structure as based on the current Finch Floating Homes design

Modularity of the housing unit is very well visible in the current design. As seen in Figure 3.1, one building module can be built using three different frames: open wall frames, closed wall frames, and the floor frames (same dimensions for ground floor and second floor). Despite the modularity of the total structural framework it was noticed that there is a slight irregularity in the positioning of the wall panels. This might not form a problem for the housing unit, but it might lead to unwanted complication in the roof design. Therefore, a small redesign to the wall frame layout is proposed as displayed in Figure 3.2.

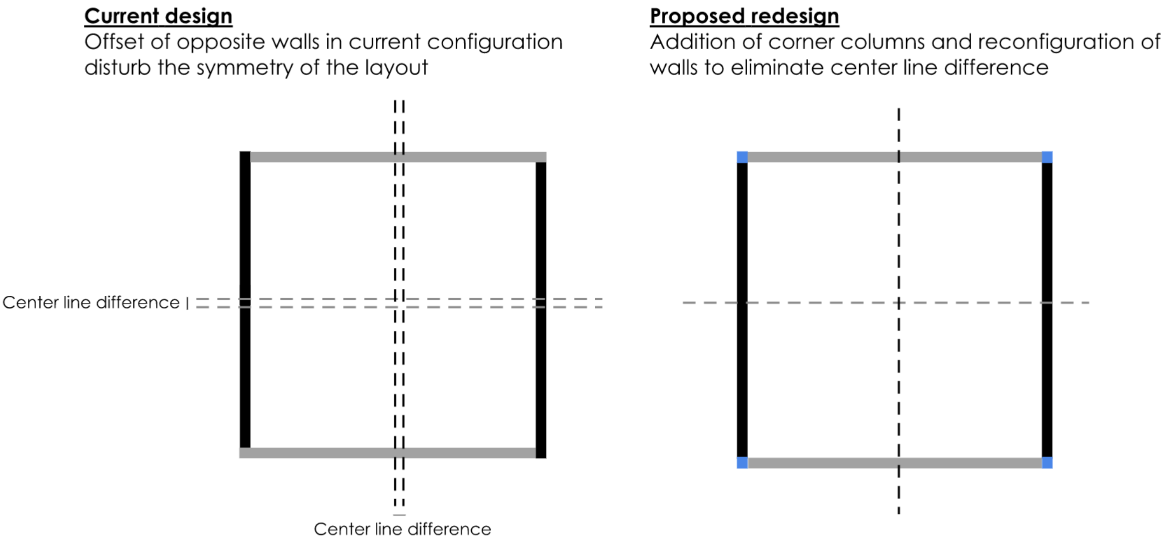

Figure 3.2 Proposed redesign of the wall layout

The proposed redesign adds a square column of 89 x 89 mm in each corner of the housing unit. This allows for a new wall panel layout based on optimal use of symmetry. For the roof this gives the possibility to design based on a two-axis symmetrical base. Besides this advantage there are the following benefits from adding the four structural corner columns:

- Allows for stronger connections in the corner between perpendicular wall panels.
- Enhances the overall stiffness and stability of the wall frames.
- Increased vertical load transfer possibilities compared to the current design.
- In case of hollow sections, allows for hidden cable and pipe transport.

It is beyond the scope of this section (see section 2.2) to redesign the housing unit based on the altered wall panel layout. It can be noted that the proposed redesign pushes the walls of the structure “outwards”, resulting in slightly larger width of the structure. The structural members of the floor frames and the connection detailing should be checked and altered accordingly to ensure that integrity of the housing unit remains. The resulting change in dimensions of the structural members are assumed to be small and therefore assumed to have little impact on the structural soundness of the housing unit. Justification of the proposed repositioning of the wall panels is based on these assumptions.

3.1.3 List of requirements

The floating houses are a project of Finch Floating Homes. Finch has its own principles that need to be met in the design: sustainability, adaptability, health, and affordability. Besides that, there are general requirements that apply to the project as a whole: typhoon resilient design and prefabrication. Further clarification of these principles and requirements can be found in section 2.5.

In this chapter, the additional requirements that apply specifically to the roof structure will be discussed.

Density is important as the idea is to eventually build a community with the floating houses. To achieve this, it is important that the single houses can be connected and can be placed close to each other. Irregular shapes and overhanging elements should be avoided for this purpose as they decrease the density of the grouped houses.

Aesthetics is very subjective, good or bad aesthetics depend on personal opinion. However, it is possible to measure the aesthetics looking at the culture, current roof structures and local acceptance. The appearance must meet what the local community thinks is good aesthetics.

Use of space is important since the total amount of space inside the house is limited. The space inside the roof structure will be used as the second floor of the house. The larger the area a person can functionally use on the second floor, the more efficient the design of the roof structure is.

Rainwater collection is an important aspect in this project, mainly the collection of rainwater and the reuse of this water. When designing the roof shape, the collection of rainwater should be considered. The rainwater must be transferred from the roof to the storage barrels.

Fire safety needs to be met according to the requirements as stated in the building codes. How safe a structure behaves regarding fire depends on the materials used, the spacing between separate buildings, the usage of the house and the measures that are taken in case fire breaks out.

Stability of the roof structure when undergoing horizontal loads needs to be evaluated. If necessary, stability elements need to be designed and calculated. These stability elements will lead to additional loads on the underlying structure.

3.2 Shape and function analysis

In this section, the current design for the roof structure will be checked. Many design variants for the roof shape were sketched as alternatives to the current design. Three of them were chosen as feasible variants. Using the list of requirements, the current design is tested and compared to the other variants. The best variant will be selected and further developed. The outcome of this chapter is a roof structure ready to go into the detailed design phase.

3.2.1 Design variants

The three chosen variants plus the current design will be discussed in this paragraph. The paragraph ends with the selection of the roof shape and an evaluation of positive and negative aspects of the design. The negative aspects will be used for further development of the roof structure.

Variant 1: Gable roof

The first variant is a traditional gable roof, this is a well-known roof type. The roof consists of three triangular frames, with a spacing of approximately 2.4 m.

The frames provide stability in one direction and are built up of three smaller triangular elements connected by the outer frame. These smaller elements further stiffen the structure.

The span between the frames will be made by beams. To guarantee stability in the other direction, bracings need to be placed between the frames and the beams. The beams will be covered with roofing material.

In total four different elements are needed for this roof: the triangle frame, two types of beams and the bracings.

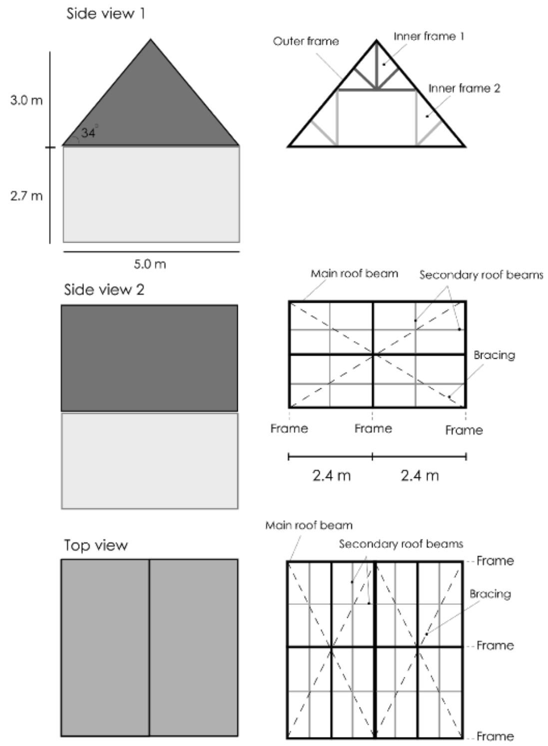

Figure 3.3 Variant 1: Gable roof

Variant 2: Crossed gable roof

An alternative to the traditional gable roof is the crossed gable roof. This roof is double symmetric, it is the same in all four main directions.

The roof structure consists of four head frames and four beams leaning on the head frames and the middle column. To close the roof, eight roof panel frames covered with roofing material will be added. In total, three different elements are needed to construct this roof: the head frames, roof beams, and roof panel frames.

What makes this roof an interesting variant, is the possibility to collect rainwater in the four corners of the building.

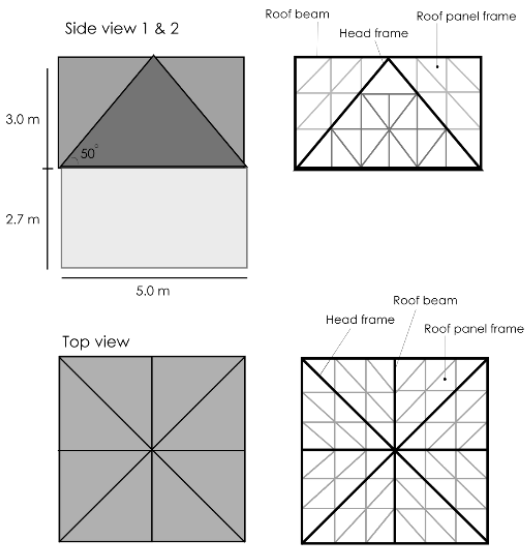

Figure 3.4 Variant 2: Crossed gable roof

Variant 3: Mono-pitched roof

The third variant is a mono-pitched roof. The roof structure consists of three frames, which consist of an outer frame and inner frame.

The span in between the roof frames of approximately 2.4 m is connected by roof beams covered with roofing material. The bracing in the vertical roof part provides the stability in one direction, the frames provide stability in the other direction.

In total, five different elements are needed to construct this roof: the triangle frames, rectangle frames, two types of roof beams, and the bracing.

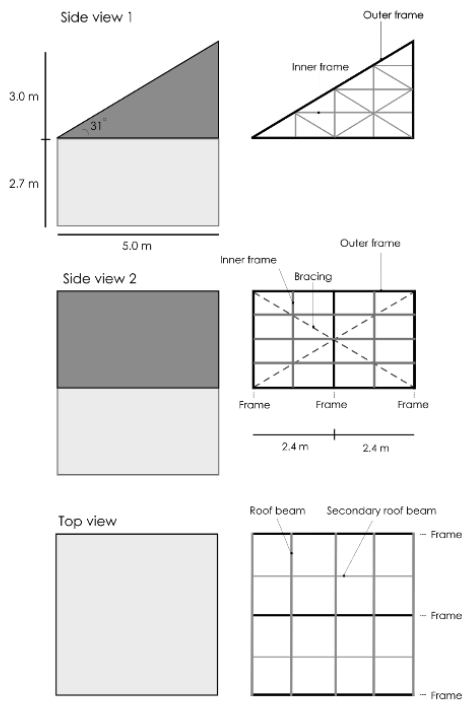

Figure 3.5 Variant 3: Mono-pitched roof

Variant 4: Current design, hip roof

This variant is the current roof design as designed by Finch Floating Homes. The design is worked out in far more detail than the other three variants, so for good comparison current design is displayed in a less detailed way.

The roof structure is a symmetrical hip roof. It consists of four main beams pitched at a 50° angle to form the hip roof shape. In between these beams a framework of vertical, horizontal, and diagonal beams is placed. This configuration provides stability in both directions.

To compare the current design at the same level of detail as the other three variants one could state the roof consist of two different elements: the roof beams and the inner frame.

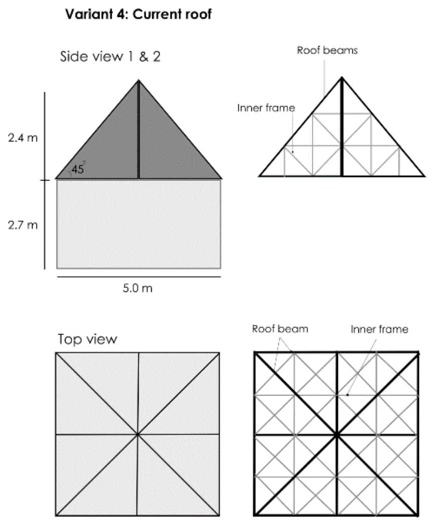

Figure 3.6 Variant 4: Current design, hip roof

Chosen variant

The chosen roof structure is the current design, the hip roof. This roof structure is by far the best looking at aerodynamics. Besides that, it is a simple, well-known shape. The hip frames straight forward design makes the hip roof score good on structural design efficiency. Structural design efficiency reduces the amount of needed material and is therefore linked to affordability. The framing can be designed in many ways. Therefore the current frame and material choice for the construction elements will be reanalysed in section 3.3 and 3.4, keeping in mind the buildability and feasibility of the pilot project as main design criteria.

3.3 Material choice

Staying close to design of the floating house as designed by Finch Floating Homes the aim is to incorporate wood in the roof design as much as possible. For the pilot model the following aspects are of most importance:

- **Availability** of the material at the time of construction.
- **Strength** of the material, as it is used for structural members.
- **Durability** of the material against the surrounding water and the weather conditions.

The roof elements will be summarized into three parts: the roof frame elements, roof sheeting, and connections. For each of these parts a suitable material will be chosen which complies to all the aspects as listed above. As setup for the calculations in paragraph 3.4 "Frame design" the most important structural properties of the chosen materials will be listed.

3.3.1 Roof frame elements

The original material choice for the roof frame elements was Eucalyptus Grandis, a strong yet workable wood species suitable for frame construction. Unfortunately, this wood species is no longer available in the Philippines. This makes the choice of Eucalyptus Grandis unsuitable for the construction of the pilot model.

Recent talks by Finch Floating Homes and local timber company Filtra have indicated Azobé as suitable replacement for the unavailable Eucalyptus Grandis. The main differences between the two timber species are listed in Table 3.1. The Azobé properties are based on the material database of (Matbase, n.d.).

Table 3.1 Comparison of timber properties.

Structural properties:	**Azobé**	**Eucalyptus Grandis**
Average dried weight (kg/m^3)	1040	640
Mean crushing strength (N/mm^2)	88	59
Mean bending strength (N/mm^2)	180	103
E-modulus (N/mm^2)	22000	15200
Strength class	-	D_{50}
Other properties:	**Azobé**	**Eucalyptus Grandis**
Workability	Low	Low
Common uses	Decking, boats, wood framing	Wood framing, flooring
Predrilling	Required	Required
Use in humid environment	Temporary and permanent	Only temporary
Natural durability	High	Low

When comparing the timber species, Azobé seems like a higher quality alternative to Eucalyptus Grandis. It has great natural durability and is very strong. Added to this is it has high natural fire resistance and low heat conductivity. On the negative side it is relatively heavy, difficult to impregnate and has low workability. This means it requires predrilling of the wood and the use of heavier saw equipment for cutting.

Overall Azobé is a great choice for the structural (roof) members of the building as it is available, very strong and naturally durable.

3.3.2 Roof sheeting

The roof sheeting material originally chosen is corrugated bamboo sheets. This material shows great promise due to its strength, resistance against humidity, thermal isolation, workability, and sustainability. Unfortunately, this product is still in the research and development phase, so availability forms a problem for using corrugated bamboo sheets as material in the pilot model. However, after for follow up projects of the pilot model this bamboo roof sheeting might be very interesting.

Table 3.2 Properties of CSRS

Thickness (mm)	Purlin spacing (m)	Deflection	Allowable load (kN/m^2)
0.4	0.7, 1.0, 1.2	L/350	1.92, 0.58, 0.38
	0.7, 1.0, 1.2	L/120	5.89, 1.55, 1.07
0.5	0.7, 1.0, 1.2	L/350	2.42, 0.65, 0.45
	0.7, 1.0, 1.2	L/120	7.43, 1.95, 1.37
0.6	0.7, 1.0, 1.2	L/350	2.84, 0.75, 0.53
	0.7, 1.0, 1.2	L/120	8.71, 2.29, 1.61


Figure 3.1 CSRS plate

A roof sheeting that is widely available in the Philippines is corrugated steel roof sheeting (CSRS) as shown in Figure 3.7.The load bearing properties of this roof sheeting material is summarized in Table 3.2. The use of steel compared to bamboo for the roof sheeting results in lower thermal isolation and needs a coating to obtain resistance against humidity. Water resistant paint will provide protection against humidity and rain and special heat reflective coatings can be applied to increase the thermal isolation. Since this will probably not be enough to create a pleasant indoor temperature, it is advised to apply an additional thermal insulator.

Insulation

Three alternatives for insulation will be discussed.

1. **Nipa leaves**
   An environmentally friendly and locally available roof material is the so-called nipa leaves as applied on the roof shown Figure 3.8. This is a natural material that was originally used in the Philippines for the roof sheeting of houses. Although it is locally available there is not much known on its actual insulation properties. It is also very labour intensive to correctly apply it on the roof and the durability of nipa leaves roof sheeting is only 2 to 3 years (Umar, 2017).


Figure 3.2 Nipa leaf roof

2. **Polyethylene foam insulation (aluminium coated)**
   This cellular foam is covered with a layer of aluminium to increase the reflective properties. These insulation sheets are easy to install and widely available in the Philippines, but it is not very environmentally friendly to produce. They come in a variety of thicknesses with up to 50 m length and 1 m width. The material is water resistant and has high insulation value. Although it is normally used in closed cavities, its workability and insulation value make it a promising insulation material.


Figure 3.3 Polyethylene foam insulation

3. **Fiberglass**
   Currently the most commonly used insulator in the world is fiberglass. It has proven to minimize heat transfer and it has good fire resistance. The problem with fiberglass is correctly handling it. Measures should be taken during installation to prevent touching and breathing in the particles coming from fiberglass. The material should also be covered up on the inside of the building, as allowing small particles to get into the house can lead to a dangerous living environment.


Figure 3.4 Fiberglass insulation

It is expected that the nipa leaves will not provide enough thermal insulation in combination with the CSRS. The fiberglass material would provide great insulation, but at the cost of bad workability. The best choice for the pilot model is installing the polyethylene foam insulation.

3.3.3 Connection types

Section 3.5.2 the connections for the different elements within the structure are shown. The sizing of the different types of fasteners are listed in Appendix B.4. For now, the most common connections used in timber construction are shortly described below.

Nail
Nails are commonly used in timber-to-timber connections. If it were to be used in the hard Azobé wood members a hole must be predrilled smaller than 80% of the nail diameter (Livingstone, n.d.). Lateral loaded nails perform well, but they are very weak when subjected to axial loads as their withdrawal capacity is low.

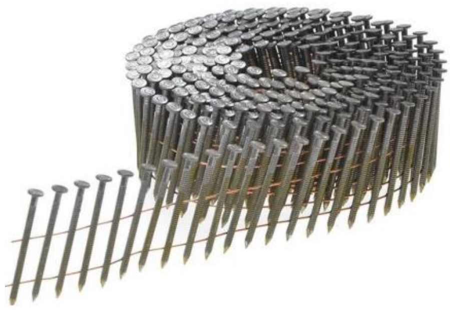

Figure 3.11 Structural nails (Livingstone, n.d.)

Screws
Screws are applicable in connecting steel-to-timber and timber-to-timber connections. They perform rather similar to nails in terms of lateral loading capacity, but they have a significantly higher withdrawal capacity. For connecting thicker timber elements, it is advised to predrill holes to avoid splitting of the wood during the screwing process.

Figure 3.12 Wood screws (Livingstone, n.d.)

Dowels
Dowels are large timber-to-timber connectors with a minimum diameter of 6 mm. They can be made of wood, steel, or carbon-reinforced plastics (Livingstone, n.d.). Two or more wooden pieces are lined up and connected by driving a dowel through a slightly undersized hole. This hole must be drilled with great precision. If preparation of drilling the holes is done correctly, the dowel type connection can be a cheap, easy to assemble, and strong connection.

Figure 3.13 Dowel connection (Livingstone, n.d.)

Bolts
Bolts are like dowels but are closed off at each end with a head and a nut. Unlike dowels, bolts require an oversized hole to be drilled at the connection. The main benefit of bolts is that they can be retightened after the wood has reached equilibrium moisture content. Bolts provide a tight connection, strong in lateral and axial direction.

Figure 3.14 Bolt connection

3.4 Frame design

As concluded from section 3.2, the chosen shape is that of a hip roof. Prefabrication is a very important design principle for Finch Floating Homes and therefore this should be considered in the frame design. This is done by designing the same frame for all four sides, which can be prefabricated and eventually assembled on site.

3.4.1 Frame elements

The frame consists of several elements which will be discussed briefly in this section. Figure 3.15 shows the dimensions and frame elements. The dimensions of the cross sections are calculated in section 3.4.4.

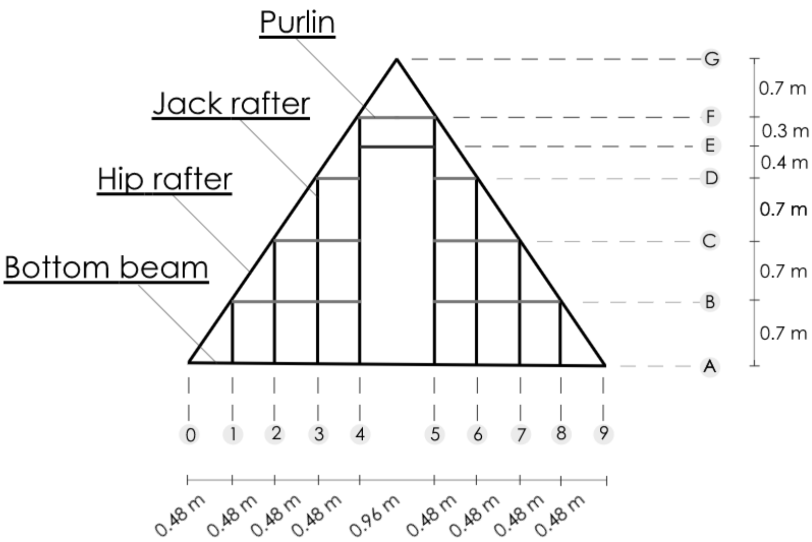

Figure 3.15 Roof frame layout

Purlin

The purlins in the frame have the sole purpose of connecting the roof sheeting to the frame. They are spaced at 0,7 m from each other, which follows from the maximum wind load working on the roof and the requirements as stated in Table 3.2.

Jack rafter

These elements from the vertical components of the frame. A total of 32 jack rafters are used in the roof (8 per frame). Their spacing follows from the purlin spacing requirements. The jack rafters numbered 4 & 5 are slightly different as they will be used to connect the openable element to the roof frame.

Hip rafter

The hip rafter is the corner member of the frame. A total of 8 hip rafters are used in the roof (2 per frame). The connection between two hip rafters of connected frames is very important since this connection will provide stability and it connects the separate frames into one roof. The connection at the top (section G) is a difficult connection as 8 different hip rafters come together here. The connections are discussed in more detail in section 3.5.

Bottom beam

Both the hip rafter and the jack rafter are connected to the bottom beam. Additionally, the bottom beam will be connected to the underlaying structure to attach the roof to the house.

Openings
Noticeable in Figure 3.15 is the space in between section 4 and 5. This section of the roof frame is reserved for the openings. Three different options for the openings are given.

1. **Horizontal shutters**
   This alternative allows for incoming daylight and natural ventilation when opened, but it protects against the environment when closed. Attention should be payed to additional protection during storms and typhoons.

Figure 3.5 Horizontal shutters

2. **Foldable balconies**
   Foldable balconies are a great way of extending the useable space underneath a sloped roof. Their real function shows when fully opening them, but they should also be partially openable by just opening the top part to allow for daylight and natural ventilation. During a storm or typhoon, the elements of the foldable balcony should match or exceed the calculated strength requirements to ensure the typhoon resilience of the roof. The glass in the example as shown in Figure 3.17 should be replaced by plating material.

Figure 3.6 Foldable balconies

3. **Awning plates**
   This option is currently considered by Finch Floating Homes. Vertically openable plates which cover the opening while closed and provide shading from the sun while still allowing daylight and natural ventilation when opened. While currently these awning plates are designed in a triangular shape, it is advised to make them rectangular if they were used in the roof layout as shown in Figure 3.15. To ensure typhoon resilience the glass shown in the example of Figure 3.18 must be replaced by plating material.

Figure 3.7 Awning windows

All three alternatives can fulfil the requirement of naturally ventilating the floating house. Providing several options for the roof openings enhances the concept of modularity and provides a tool for personalization of the floating house. From the three options the foldable balconies are found to be the most innovative alternative, they are described in more detail in section 3.5.1.

3.4.2 Norms and design codes

For the design of the roof structure the Eurocodes will be followed. The listed codes, including the Dutch National Annex (NB), are applicable to the roof structure.

- Eurocode 0 (EN 1990) Basis of structural design
- Eurocode 1 (EN 1991) Actions on structures
- Eurocode 3 (EN 1993) Steel
- Eurocode 5 (EN 1995) Design of timber structures

From these codes several requirements follow regarding the design of the structure.

Consequence class
According to Eurocode 0 the consequence class for a residential building is CC2. The design life is 50 years. The building category for the roof structure of the floating houses is Category H (roofs).

Deformation
The maximum vertical deformations in serviceability limit state (SLS) for the roof structure are given in Eurocode 0. For roofs the restriction is given in Eq. 3.1.

$$w_2 + w_3 \leq \frac{1}{250} l_{Rep} \tag{3.1}$$

Here w_2 is the long-term deformation caused by the permanent loads and w_3 is the extra deformation caused by the variable loads with short-term characteristics. The length of the span or twice the length of a cantilever is given by l_{rep}.

The SLS will not be calculated for the case of wind load during a typhoon. During a typhoon the roof structure should not fail, but large deformations are allowed. Therefore, the serviceability limit state will be calculated for a representative wind load during a tropical storm, not taking the typhoon wind load into consideration. All wind related analyses are included in Appendix A.

Fire safety
The floating houses are a structure with a residential function and with no residential floors above 7 m. According to the bouwbesluit 2012 (Rijksoverheid, 2012) the fire resistance should be at least 60 minutes.

3.4.3 Loads

The loads on the structure are distinguished as permanent and variable loads. The permanent loads consist of the own weight of the structural elements. The wind governs the variable loads.

Load combinations
For the ultimate limit state (ULS) and SLS, the load case combinations as shown in Table 3.3 need to be applied:

Table 3.3 Load combination in ULS and SLS

	Permanent loads		Variable loads	
ULS	Unfavourable	Favourable	Governing load	Other
CC2 6.10	1.2 G_k	0.9 G_k	1.5 Q_k	1.5 $\Psi_{0,1}$ Q_k
CC2 6.10	1.35 G_k	0.9 G_k		1.5 $\Psi_{0,1}$ Q_k
SLS	Unfavourable	Favourable	Governing load	Other
CC2	G_k	G_k	Q_k	$\Psi_{0,1}$ Q_k

According to Eurocode 0, for roof design all "Ψ" factors are equal to zero. Because this is the only variable load considered, this is the governing variable load.

Permanent loads
The permanent loads on the roof structure consist of the roofing material and the timber used for the roof frame.

Roof sheeting

Table 3.4 Roof sheeting own weight

Corrugated Steel Roof Sheeting (CSRS):	0.0005 m x 78 kN/m^2	0.039	kN/m^2
Polyethene foam insulation:		0.007	kN/m^2
Total load due to roof sheeting:		0.046	kN/m^2

Framing
For the roof frame Azobé timber will be used. The mean average dried weight of Azobé is 10.40 kN/m^2.

Variable loads
The designed roof slope angle is 45 degrees. According to Eurocode 1 this means that the variable loading during maintenance of the roof can be neglected. The large slope also prevents water accumulation on the roof. Therefore, additional water loads, and risk of ponding will not be considered as variable load case. Obviously snow load is not considered in the Philippines.

Wind load
Wind load is a very important aspect in the design of the roof structure. Two wind scenarios can be drawn as given in Appendix A.1.

- Typhoon category 2. Rarely reach Macabebe, the aim is that the roof structure stays intact, but large deformations are accepted. Only ULS is important. The wind velocity is 49 m/s.
- Tropical storm. Occurs relatively often, both ULS and SLS are important. Since ULS was already calculated for the more extreme situation of a typhoon, only the SLS needs to be calculated. The wind velocity is 32 m/s.

The occurrence of significant storm events and their related wind speeds is shown in Appendix A.1. The corresponding wind speeds are used to calculate the peak velocity pressure in Appendix A.2. This results in:

- Typhoon category 2: $q_{p,uls}(z_e)$ is 2.40 kN/m^2;
- Tropical storm: $q_{p,sls}(z_e)$ is 1.02 kN/m^2.

These peak velocities pressure are used as input to calculate the roof wind loading in Appendix A.3. The terrain category of the floating houses is category II: an area with low vegetation and freestanding obstacles with a distance of at least 20 obstacle heights. The building height is approximately 6.5 m.

The roof and building geometry are used in Appendix A.4 to calculate the net horizontal wind force. This information will be used as input to calculate the force on the mooring piles in chapter 5.

3.4.4 Force analysis
The force analysis is based on the frame design and the loads as discussed in the previous sections. The full calculation, governing load cases, and used equations can be found in Appendix B.1. In this section a summary of the force analysis will be given, concluded by a cross sectional dimension of

the frame elements. This dimension will be based on the governing limit state requirement and corresponding load cases.

Since the local properties of the elements are analysed, all calculations are projected on the local axis. Also, the wind force used is the local wind force. The distinction made between local and global wind force can be found in Appendix A.3.

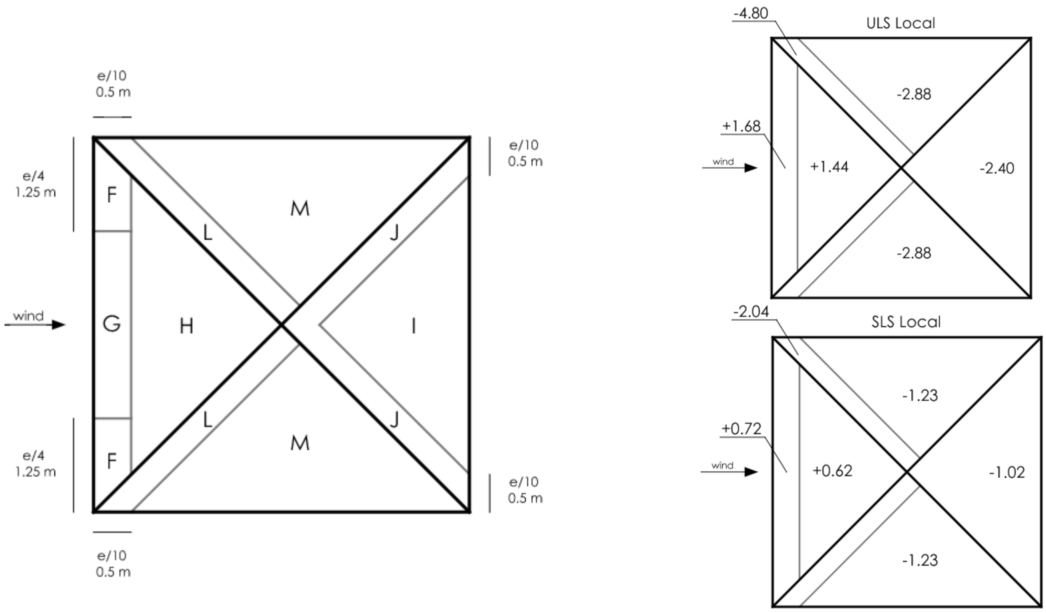

Figure 3.19 Wind load surface sections (left), corresponding local roof loading in ULS and SLS (right)

Roof sheeting
The maximum wind load that the roof sheeting has to withstand is (-) 4.8 kN/m^2 (). This is the wind load for local ULS conditions. For ULS there are no limitations to the deflection.

Using Puyat Steel Corporation's APO GALFAN CORSPAN corrugated steel roof sheeting (CSRS) the dimensions as listed below pass the unity check. The properties of this material is given in Table 3.2.

- thickness = 0.5 mm
- purlin spacing = 0.7 mm

Purlin
Only the governing purlin will be calculated. All other purlins will be designed using the same cross section. The governing purlin is the purlin shown on axis F in Figure 3.15. This purlin is simply supported on only two supports, is undergoing the governing high wind load for tension from area L and for compression area from area G (Figure 3.19) and has the largest length of 0.96 m. The purlins are spaced at 0.70 m.

From force analysis it follows that the SLS requirement of maximum deflection (L/250) is governing. This results in the following cross section:

- h = 38 mm (1.5 inch)
- b = 64 mm (2.5 inch)

A larger width rather than a larger height was chosen to fulfill the SLS requirement. This is done to make the connection of the purlin to the jack rafters, and the connection of the roofing material to the purlins easier.

Jack rafter
The governing jack rafters are the jack rafters on axis 4 and 5 (Figure 3.15). These rafters are the longest with their length of 2.8 m. They undergo load from the purlins and load from the roof openings. The wind load on the roof openings is lower than was used for the purlins, since it is not located in area L. Area M is governing for tension and area G is still governing for compression (Figure 3.19).

From this loading assumption the following cross section passes both the ULS and SLS requirements:

- h = 89 mm (3.5 inch)
- b = 64 mm (2.5 inch)

Hip rafter
The length of the hip rafters is 4.07 m. As load on the hip rafter, the support reaction of the largest jack rafter will be applied for all the jack rafters. This is conservative, but because the hip rafter will also have a global stability function extra capacity will be needed. The global stability will be determined section 3.4.5.

From this loading assumption the following cross section passes both the ULS and SLS requirements:

- h = 140 mm (5.5 inch)
- b = 140 mm (5.5 inch)

Bottom beam
The bottom beam is loaded by the hip rafters, the jack rafters and self-weight. The bottom beam is supported every 1.20 m by the wall panels. To provide sufficient area for the connection of the jack rafter to the bottom beam and the hip rafter to the bottom beam, the width of the beam is set to be 140 mm. The height is free to choose. The local coordinate system of the bottom beam is according to the global coordinate system. This time the load due to wind should be transformed to the global coordinate system. Only the load in the global z axis will be determined, this is governing.

When checking the ULS and SLS requirements for the bottom beam it turns out that they are not governing. It is the detailing of the bottom beam connections on which the following dimensions are based:

- h = 89 mm (3.5 inch)
- b = 140 mm (5.5 inch)

3.4.5 Global stability
Determining the global stability of the complete frame is quite complex as the different faces of the frame undergo both in plane and out of plane forces. The choice was made to use the structural analysis software Karamba to get an indication of the global frame behaviour. The loads applied are chosen based on the most extreme global load case for each of the four faces as described in Appendix A.3: Roof wind load calculation. Additional to the wind load the dead weight of the structural elements is added.

The model uses assumptions which may strongly affect the results. The member connections are modelled infinitely stiff, which is an overestimation of the connection strength. The connection of the frame to the underlaying structure is modelled as simple supported, which is an underestimation of the strength of this connection. Lastly, as mentioned earlier, the applied wind load is an overestimation of the actual wind load working on the structure.

Global deflection

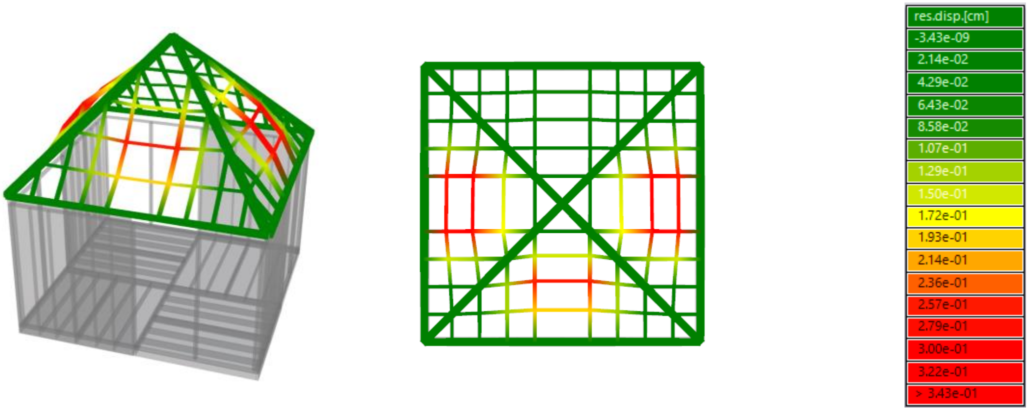

Figure 3.20 Global deformation during SLS loading (display scale: x75).

The loads applied are chosen based on the most extreme case for each load face as described in Appendix A.3. Additional to the wind load the dead weight of the structural elements is added. This load combination leads to the following maximum displacements:

- SLS maximum displacement = 4 mm

Due to the model assumptions as discussed, one could argue that the maximum displacements shown are not completely reliable. Comparing the global displacements to the local displacements as calculated in 0 shows that the order of magnitude (< 10 mm) obtained from the structural analysis model is correct.

Figure 3.20 shows the exaggerated situation of deformation during SLS wind load conditions (equivalent to a storm). The location with the highest deflections coincides with the locations of the openings. Therefore, it is important that the possibility to transfer force between the openable parts of the roof and the other roof members is guaranteed.

Utilization of the cross sections

Figure 3.21 global utilization analysis during ULS loading

In the structural model the utilization ratio is calculated as the ratio between axial stress in the beam and the yield stress of the material. For both compression and tension stresses the analysed utilization ratio is:

- ULS utilization ratio ≤ 15 %

Comparing this to the ULS results obtained from the calculations in Appendix B.1: Member calculation, the order of magnitude again shows to be correct. In terms of utilization of the cross sections, the structural members are over dimensioned by quite a bit. This is the result of SLS conditions of maximum allowed deflection being governing for the dimensioning of all members (see Appendix B.1).

Not indicated by the utilization ratio, but worth mentioning, is that the analysed results do not give any indication of failure due to shear or buckling. Since shear failure is the most common failure mode for Azobé wood members (Kuilen, 2004) further investigation in global shear stress distribution is advised.

3.5 Detailed design

For the detailed design the frame design as discussed in section 3.4 will be expended upon. Extra attention will be given to the openable roof sections, the important connections, and the make-ability of the frame.

3.5.1 Openings

As suggested in section 3.4.1 there are three possibilities for the openings in the roof frame. The second alternative, openable balconies, was found to be the most interesting to investigate in more detail.

Figure 3.22 Roof frame in closed position

Here the openable balcony system is shown in closed position. The steel rods connecting the jack rafters to the balcony system ensures the force transfer from the openings to the frame when closed. When removing the steel rods the balcony sections can be opened, with the rods then functioning as the supports shown in Figure 3.24.

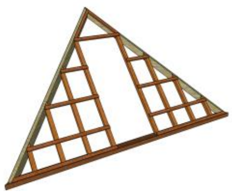

Figure 3.23 Roof frame without opening element

By leaving an opening in the middle of the frame the owner of the house can chose what kind of window system is preferred. This concept adds to the modularity and adaptability of the homes.

Figure 3.24 Roof frame in open position

The top part of the system can be opened separately from the bottom part. This allows for partial opening of the system when a full balcony is not required.

The full potential of the system however is when both the top and bottom part are opened. The effective floor space on the second floor is increased and a large area for natural ventilation is created.

A more detailed explanation on how the system works is included in Appendix B.2.

3.5.2 Assembly procedure

Make-ability is a key part of the roof frame and is found of two levels. First the make-ability of the prefabricated roof frames must be guaranteed. Since the single frames will be prefabricated in a controlled environment a higher level of construction difficulty is accepted. Secondly, the four frames must be combined into one roof frame. This is done on-site and therefore easy to perform assembling methods are aimed for.

When designing the frame, the make-ability was kept in mind to ensure that all elements would fit together. The following sequence shows the summary of steps that need to be taken to assemble a single frame, connect the four frames into one roof, and finally apply the roof finishing. A more detailed construction manual and the indicated details shown in Figure 3.26 - Figure 3.33 are worked out in in Appendix B.3.

1. **Preparing the bottom beam.**

The bottom beam connects to many different elements. Preparation of this beam includes:

- Sawing:
  - Correct length
  - Ends at 45 degrees
- Predrilling:
  - Fully: Bolted connections
  - Partially: Screwed connections

Good preparation of this beam will ensure that all roof members are placed correctly onto this beam.

Figure 3.25 Bottom beam element

2. **Connecting the hip rafters to the bottom beam.**

The hip rafters form the crucial corner sections of the hip roof. In section 3.4.4 the necessary cross section for these elements is determined to be 140 x 140 mm. Since one hip rafter is comprised of two frame sections coming together in the corner, the hip rafter element of one single frame has a cross section of 140 x 70 mm. Preparation of this element includes:

- Sawing:
  - Correct length
  - At angles of 56, 34, 45 degrees (see detail Appendix B.3)
- Predrilling:
  - Fully: Bolted connections
  - Partially: Screwed connections

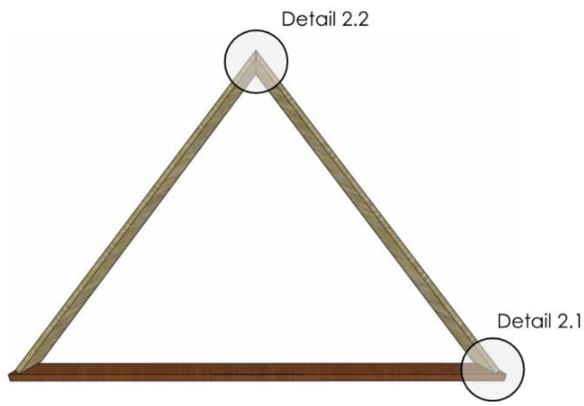

Figure 3.26 Hip rafter to bottom beam connection

3. Connecting the jack rafters to the bottom beam and hip rafter

The jack rafters are the connection points for the purlins. Their connection to the bottom beam and hip rafter is important for distribution of wind loads through the frame. Sawing the jack rafters correctly is very important to ensure a tight fit into the boundary frame. Preparation of this element includes:

- Sawing:
  - Correct length
  - At angles of 45 degrees (see detailing Appendix B.3)
- Predrilling:
  - Partially: Screwed connections

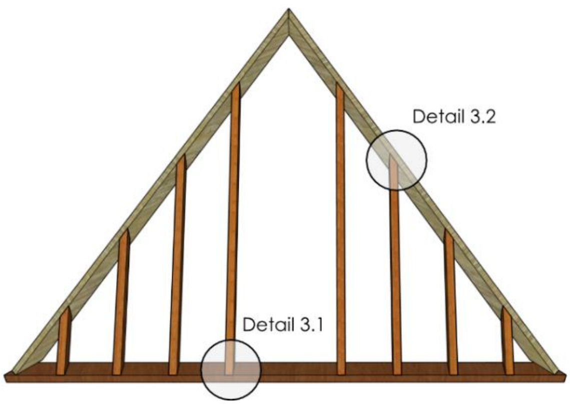

Figure 3.27 Jack rafter instalment

4. Installing purlin holders

The purlins will be installed onto the jack rafters. The three corner points in the frame provide no support for the purlins as there are no jack rafters located here. To overcome this problem a purlin holder will be installed in each corner. The purlin holders can be sawn from leftover purlin cuts.

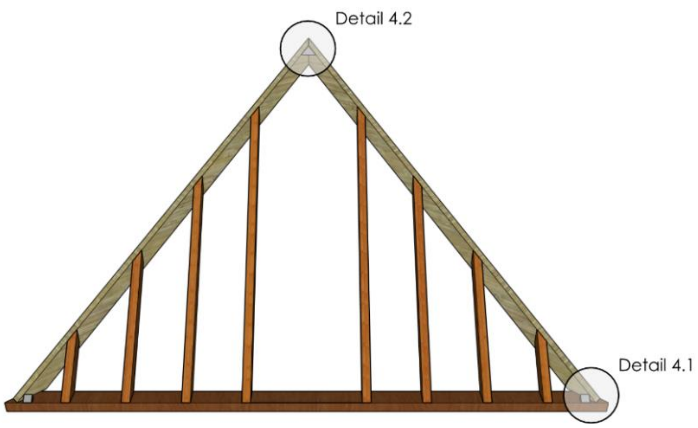

Figure 3.28 Purlin holder instalment

5. Installing opening elements

The opening elements as described in section 3.5.1 will be placed into the frame after instalment of the jack rafters. They can be separately prefabricated using the elements as illustrated in Appendix B.2.

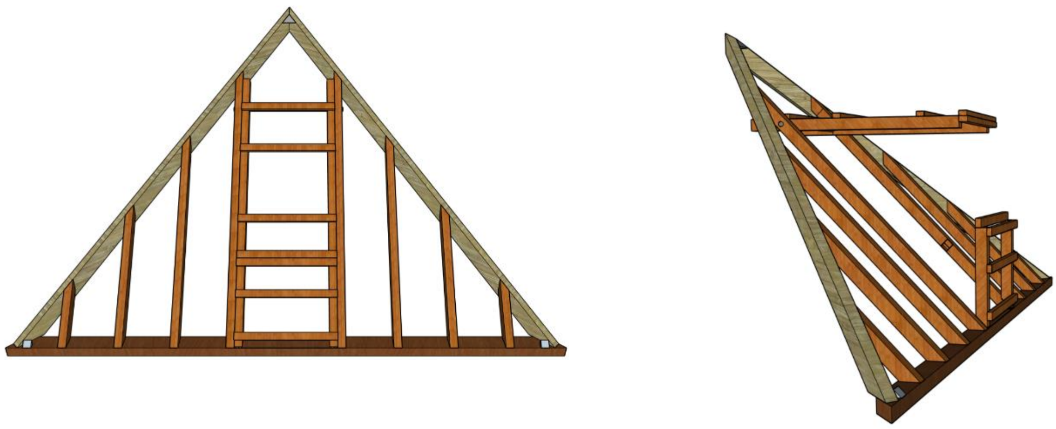

Figure 3.29 Opening element installation

6. Installing the purlins

The purlins are installed onto the jack rafters and serve as connection points for the insulation and roof cladding. Due to the low thickness of the purlins it is assumed that predrilling is not required. Preparation of this element includes:

- Sawing:
    - Correct length
    - Angle of 45 degrees at ends of top purlins

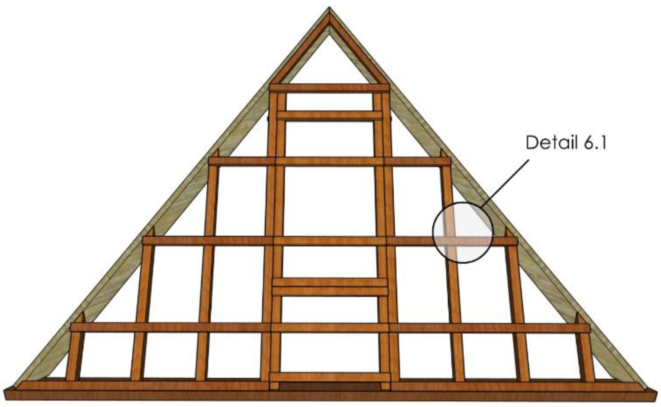

Figure 3.30 Purlin instalment

7. Assembling of the roof frames into one roof

After the purlins are installed the prefabrication phase of the roof frames is finished. The four prefabricated frames are transported to the construction site where they will be attached on top of the building and assembled into one roof frame.

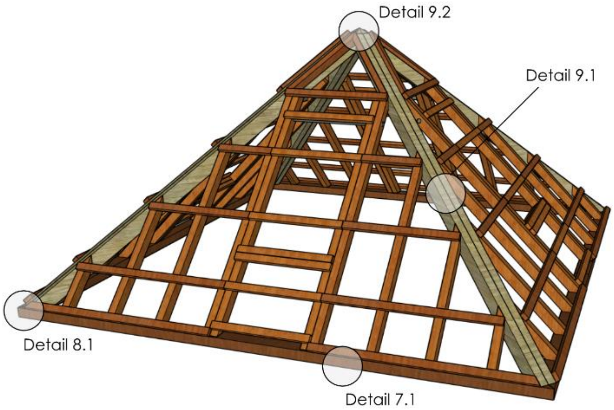

Figure 3.31 Assembling of the separate roof frames

8. Apply insulation and CSRS

A layer of insulation is first applied to the jack rafters. On top of the insulation layer the roof sheeting is applied. Since the roof sheeting will undergo suction force screws must be used to connect the CSRS to the purlins

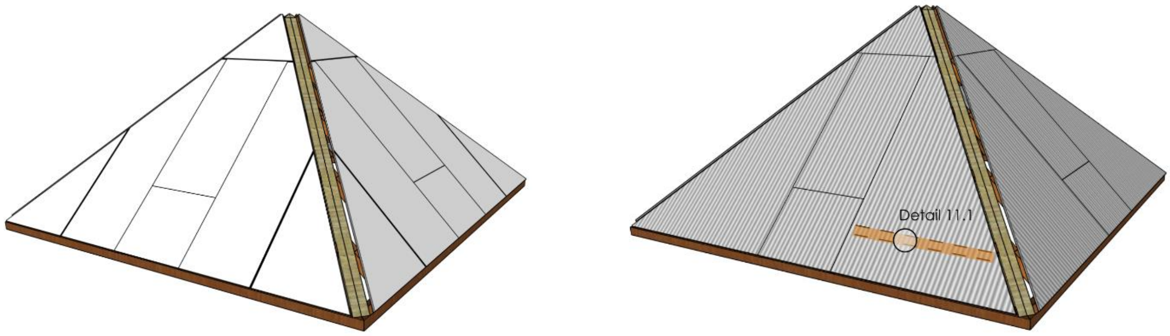

Figure 3.32 Insulation and CSRS instalment

9. Finishing

Finishing the roof consists of applying hip rafter covers, a crown cover, and rain gutter. The latter is an important attribute of the rainwater collection as discussed in chapter 4. The bamboo rain gutter is placed at every side of the roof to maximize the collection of rainwater falling on the roof. From here it is transported to the corners, where it is collected.

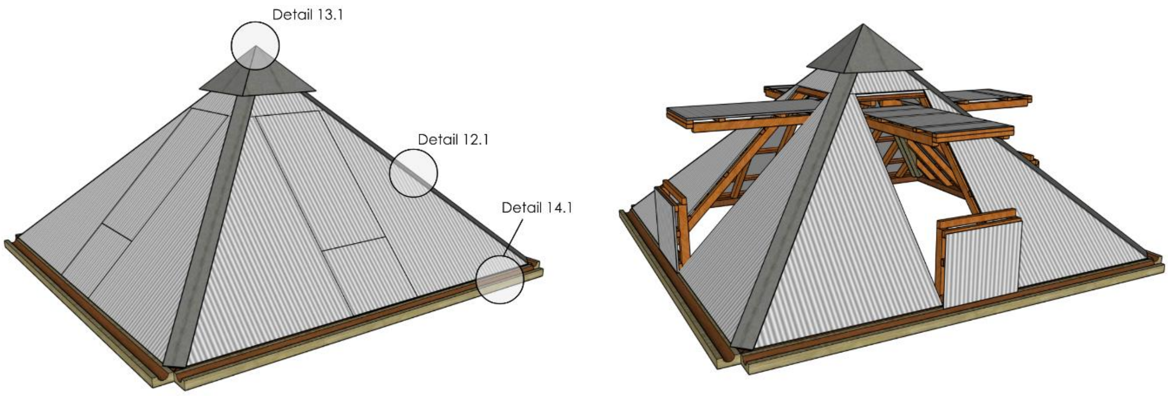

Figure 3.33 Finishing of the roof frame

3.6 Conclusion and recommendation

The conclusions and recommendations will cover the different sections discussed in this chapter.

Introduction to the roof design

- **Conclusion:**
  The geometry of the housing unit was found to be less symmetrical than is suggested in the available technical drawings. Due to the slight offset in center line axis of the opposite facing wall panels there is no symmetrical base for the roof to connect to. This complicates the design of the roof.

- **Recommendation:**
  Since prefabrication of the roof is a requirement, it is recommended to construct four equal roof frames, each connecting to one side of the building. To do this an alteration in the building geometry must be made to create truly symmetrical wall panels. The easiest way of doing this would be to place a corner column in each of the four corners of the building. Additional advantages that come along with installing four columns are stronger connections between perpendicular wall panels, an increase in overall stiffness and stability of the floating house, increased vertical load carrying capacity, and use of the interior of the columns in case of hollow sections.

Shape and function analysis

- **Conclusion:**
  The hip roof performs well in terms of aerodynamics. With the pilot model being built in a typhoon prone area it is therefore a good roof choice. Structural efficiency and simplicity are also positive factors of choosing a hip roof. The most important negative aspect of the hip roof has turned out to be its buildability.

- **Recommendation:**
  Creating a hip roof out of four prefabricated roof frames comes with a challenge. Especially the connection of two hip rafters in each corner and the connections of all hip rafters at the top. It is recommended to reconsider prefabrication of the roof frame and construct the hip rafters out of four solid beams. This reduces the problem of connecting the different hip rafters at the crown and makes the connection between hip rafters from the different prefabricated frames obsolete.

Material choice

- **Conclusion:**
  - <u>Roof frame material</u>: Azobé
  - <u>Roof sheeting material</u>: Corrugated steel roof sheeting (CSRS)
  - <u>Insulation material</u>: Polyethylene foam insulation

- **Recommendation:**
  Materials were chosen with availability in mind. This has led to the choice of CSRS, a widely available type of roof sheeting. There are negative aesthetical and environmental aspects to this material. It also performs far from ideal in the environment in which the pilot model is placed. It is prone to rust and has very low thermal insulation properties. It is therefore recommended to closely follow the progression of the bamboo alternative to CSRS; bamboo corrugated roof sheeting. This material shows to be very promising, but is still in the research and development phase, therefore it is currently expected that it will not yet be available for the pilot model.

Frame design

- **Conclusion:**
  There are many ways to design the hip roof layout. For any layout however, the frame will consist of primary elements:

  - bottom beam
  - hip rafter
  - jack rafter
  - purlins

  Dimensioning of these elements have shown to be governed by the SLS requirements with respect to maximum displacements under critical load combination. The unity checks for both local and global ULS analyses have shown to be very high, indicating an over dimensioning of the elements regarding their strength.

- **Recommendation:**
  With the high unity checks resulting from the ULS analysis it is advised to reconsider the allowed maximum deflection in the roof frame. Further optimization of the cross sections can only be achieved if the SLS requirements regarding maximum deflection are reconsidered. Currently the requirement for maximum deflection is set to be L/250. It is recommended to reconsider this requirement and optimize the cross sections allowing a maximum deflection of L/150 – L/200.

Detailed design

- **Conclusion:**
  The connecting members are currently designed based on research into standard connection sizing and application of different connection types. The resulting connections are focused on make ability, but lack structural analysis to guarantee the fulfillment of strength requirements.

- **Recommendation:**
  The overall recommendation for the detailed design is to continue based on the level of detailing provided in this report. This mainly involves three parts:

  - <u>Openings</u>: detailing of the suggested opening alternatives
  - <u>Connections</u>: performing strength analysis on the connections
  - <u>Assembly procedure</u>: Further develop the construction manual

  Additionally, it is recommended to either use the awning plates or horizontal shutters for the pilot model. These alternatives require less complicated detailing than the openable balconies. The openable balcony would be a great addition to the design once information is gathered from testing the pilot model.

4 Design of the human water system

A first draft of a possible rain and sewage water treatment is made in previous research by Ir. P.H. Ham. (Ham P. H., 2016) This is no more than a conceptual idea what needs to be worked out in detail. Therefore. the scope of the research is to create a social accepted, sustainable and durable solution for the local inhabitants of the Finch Floating Home.

Life itself and the floating house both show interference with water, these components are therefore relevant for this specific research. These components together are the human water system of the house. The components have social and technical interactions on the system, therefore social and technical research will be conducted. This chapter fill focus on answering the sub question regarding the human water system:

"How can a socially accepted, sustainable and durable sanitary facility be created?"

An overview of the methodology and further sub questions for this specific chapter can be found in Appendix C.1.

The research's focus will start with the analysis of the local situation and its influences. From these influences the requirements are set, which will be the constrains for the final design. Within these constrains the possible solutions have to fit which will form the human water system together. At last the possible designs will be tested according several calculations which will result in the final design. After which the conclusion and the recommendations regarding the human water system will be discussed.

Chapter 5 will look further into the influences of the human water system on the floating behaviour.

4.1 Analysis

To create a complete list of requirements for the human water system the current situation needs to be analysed. The analysis of the current situation will be regional and local, social, and the current design will be addressed as well, finally the important stakeholders analysed. The complete analysis will give new insights in present problems and current wishes that will function as requirements within the final design of the human water system.

4.1.1 Regional analysis

In the following paragraphs the regional sanitary situation will be discussed. This includes the influences on the system that have an interface with the house. Some of the influences come from other parts of the conducted research, if addressed there will be a reference to this specific part.

Regional influences mainly consist of the external influences on the system, such as weather and location of the area. Relevant weather influences are temperature, wind and precipitation, which are all dependent on the regional differences, especially interesting will be the monthly or seasonal variances on the system.

Temperature

Temperature is a necessary factor, influencing both the drinking water and waste water system. The drinking water system is influenced by temperature, a serious risk for development of Legionella, Salmonella and other waterborne diseases occurs above 25°C. (Feachem, Bradley, Garelick, & Mara, 1983)

Temperature is an influence on the behaviour of the bacteria, the converting potential of organic matter, during the treatment of waste water. The monthly variation in average temperature over the year can be seen in Figure 4.1, the average temperature from 1986 to 2005 fluctuates between 24.8 to 27.1 °C. (Data retrieved from (The World Bank Group, 2018) The yearly average will increase on average by 1.6°C per twenty years, so the system should either be resistant or adaptive to this increase. A table of the results can be found in Appendix C.2.

Precipitation

Precipitation forms an influence on the water bodies in the region, like recharging of groundwater and surface water. Precipitation could be a fresh source of water to use in daily life. The Philippines have a dry and wet season, June till November, over a year as can be seen in Figure 4.2 (Data retrieved from (The World Bank Group, 2018)). The yearly average increase will be by 114.7 mm or 5% with respect to historical data. The largest significant increases will be in the months March, April, September and October. A table of the results can be found in Appendix C.2.

The increase in precipitation is a motivation for floating structures, due an increase in run-off the chance for a flood increases as well. Though it might be an opportunity to give the rainwater another purpose within the area.

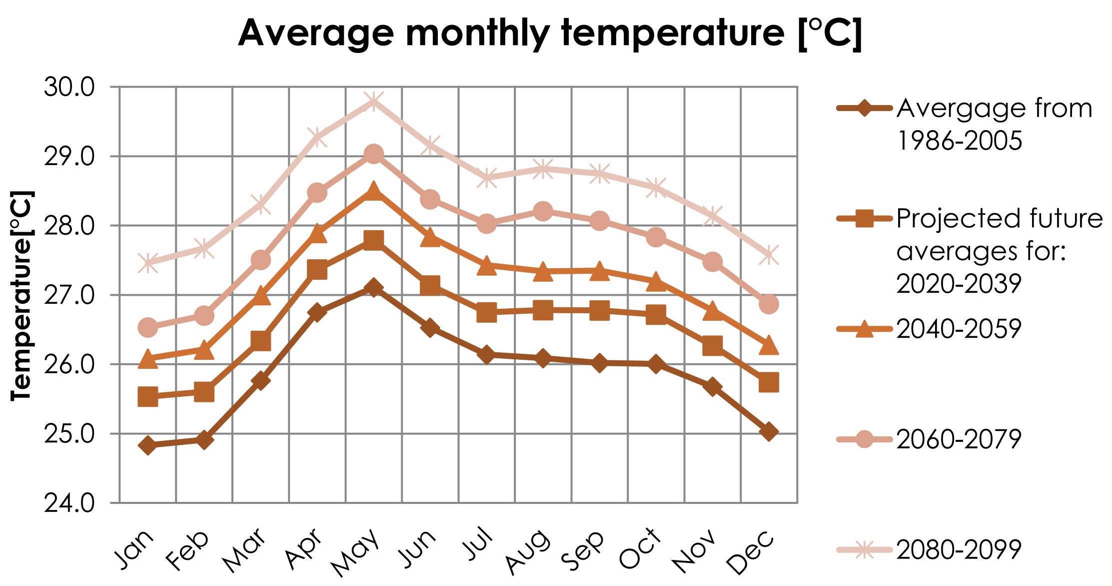

Figure 4.1 Average monthly temperature

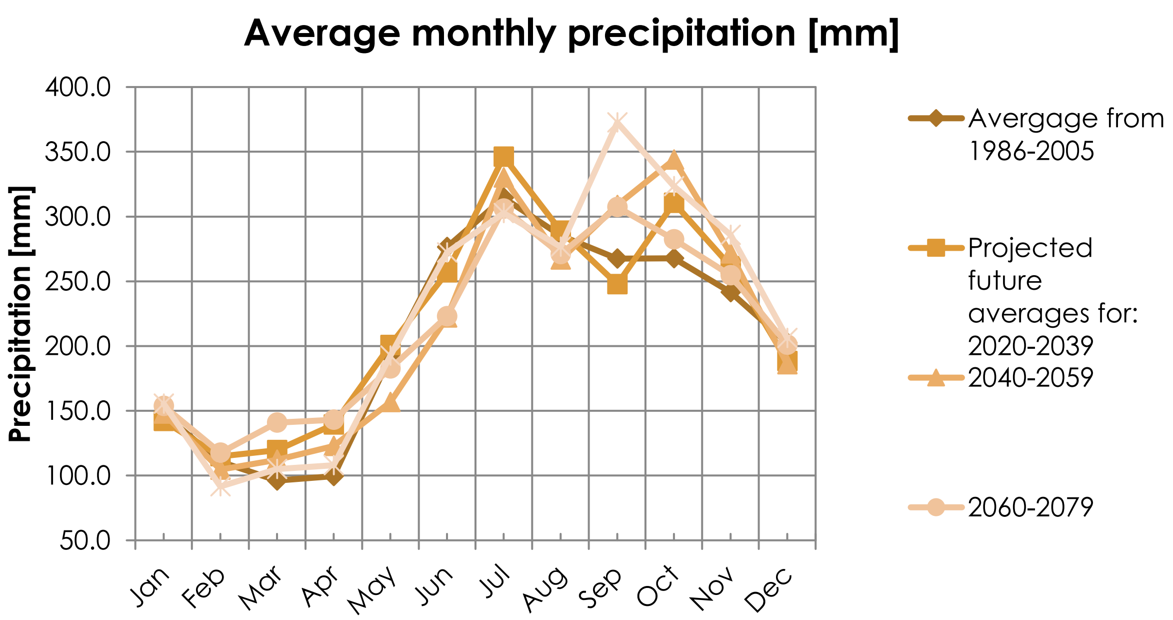

Figure 4.2 Average monthly precipitation

4.1.2 Local analysis

The local analysis aims for local standards which comes from available data of the government and other relevant sources. The focus will be on the population, domestic water usage and energy usage.

Population

The municipality of Macabebe is situated in the province of Pampanga and in 2015 the municipality had 78,850 inhabitants. Just like the pilots design to accommodate five people (Schaik J. , 2016), the average household size was 5.38 people in 2000. (Local Water Utilities Administration)

From 2000 to 2015 the municipality increased from 65,346 to 78,850 inhabitants. As can be seen in

Figure 4.3 with other previous data combined this will give an increase to 88,000 inhabitants in 2020 and 100,000 inhabitants in 2025. Not only will these people have a need for homes, but as well other necessities of life, like clean and safe sanitation. The house is aimed for low-income class, though the pilot is aimed for middle-income class (Schaik J. , 2016).

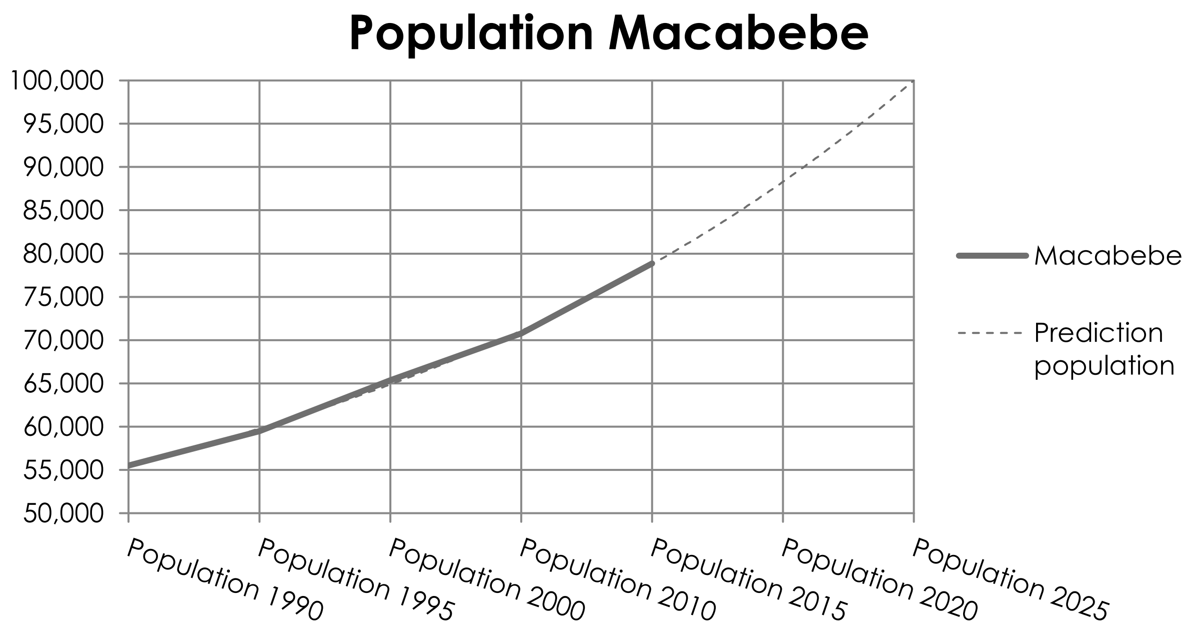

Figure 4.3 Population Macabebe

Water usage

According to Local Water Utilities Administration the municipality of Macabebe is an average sized Water District within Pampanga. The municipality has eight wells, which produce on average 200,396 m³/month. Of the total municipality of Macabebe there are 6,537 connections, last measured in 2016. The average consumption was 17.67 m³ per household, from which can be concluded that almost 120 lpcd of tap water is used, excluding drinking water (Local Water Utilities Administation). Though, the 120 lpcd includes usage at public buildings and offices, therefore the actual usage at homes could result in lower values. The basic requirements for water usage have been examined by P.H. Gleick, this resulted in a basic water requirement of 80 lpcd. (Gleick, 1996) This consist of water for consumption, sanitation and cooking.

The cost per 20 m³ of tap water is ₱403.50. The houses are not connected to a local sewerage, the effluent of the houses will flow into the nearby river (Schaik J. , 2016).

Tap water is not used as drinking water, because the standards are too low for consumption, therefore drinking water comes from bottled water. The potential water treatment should be able to treat both the tap water and bottled water consumption. Bottled water comes from local private companies which distribute the water by tricycles.

These private drinking water treatment plants treat the tap water till the quality of drinking water in the Phillippines. The purification process has a standardized design and looks mainly like the scheme in Figure 4.4 (Blue Gold Premium Drinking Water, 2018). Some stations have a less extended treatment, though most consist out of at least a softening device, several micro-filtrations and reverse osmosis.

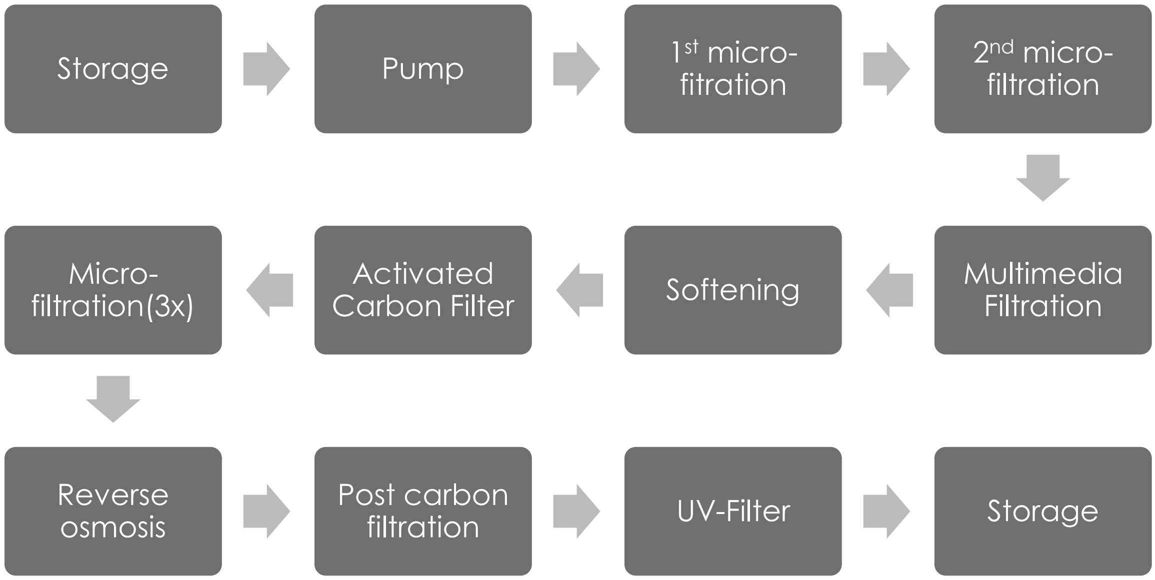

Figure 4.4 Treatment scheme DWTP

Energy usage

Macabebe is part of power plant PELCO 3 in Pampanga, situated in San Vicente, Apalit. The domestic price per kWh is ₱10.1 (Pampanga Electric Cooperative, 2013). According to the International Energy Agency the domestic energy consumption in the Philippines was 700 kWh per capita in 2014, in 2015 it rose to 740 kWh. (International Energy Agency, 2018)

4.1.3 Social analysis

The social analysis is based upon an interview aimed to map the current sanitary situation and cooking situation of a home, a total of four households were questioned near the site. The format and specific results can be found in Appendix C.3.

In general each home is constructed with an inside toilet, though every house lacks a physical shower, this is done by usage of a bucket with unheated tap water. Though every house has connection to tap water it is not connected to the sewerage. This is strengthened by previous research of J. van Schaik in the neighbouring region of Hagonoy, the interviewed houses where all not connected to the sewer and the river functioned as sewer (Schaik J. , 2016).

Bottled water is used for cooking and drinking and is distributed by local private parties. Cleaning is mainly done with tap water and a diluted powdered form of soap. Cooking is done on a stove with LPG gas distributed with gas tanks. Leftovers of food are mainly eaten later or distributed over family members or neighbours.

4.1.4 System breakdown

After addressing the regional, local and social aspects of the project location, the relation to the house and its components will be discussed. This will be done by dividing the project location and house in different relevant systems or segments with their aspects and relevant interfaces of the total system. Some segments are left aside because those do not fit within the scope of the project and the research, therefore there is no assignable requirement available. The breakdown of the system is based upon Wassons approach. (Wasson, 2005)

The system breakdown gives an indication of the complexity of the whole system and its environment. Through the realisation of the breakdown and the relevant objectives of the floating houses the system of interest is branched. The enabling systems are supporting the mission systems, for example are the three main enabling systems of the human water system separated into wastewater system, sanitation system and rainwater system. In

Figure 4.5 is an overview of the system breakdown visible, a more detailed version is presented in Appendix C.4

The systems requirements will be allocated to the system of interest or to one of its enabling systems. The set of requirements come from the analysis and previous research from Ham (Ham P.H., 2016) and Schaik (Schaik J., 2016).

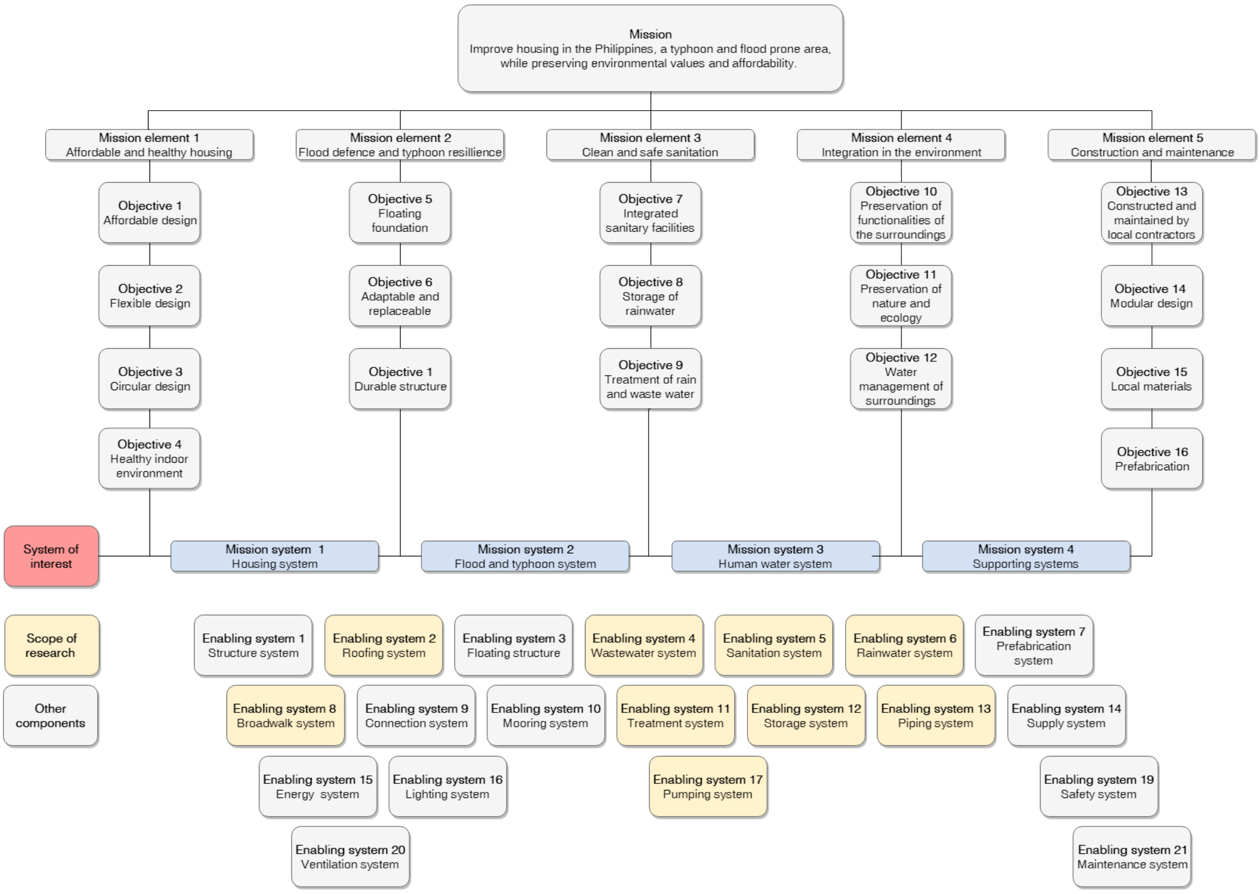

Figure 4.5 System breakdown

4.2 Stakeholder analysis

The following analysis maps the most important stakeholders which are relevant to the project. Their importance and influence on the project is given in a diagram to visualize the most important stakeholders for the research. If a stakeholder has its own requirements for the project, these will contribute to the list of requirements.

4.2.1 The alliance of eight coastal municipalities or ABB-BP

The alliance consists of the following municipalities: Macabebe and Masantol in Pampanga, Bulacan, Calumpit, Hagonoy, Malolos, Obando and Paombong in Bulacan. Each municipality will contribute to their vision to adapt to the challenges of environmental change. (Fostering Education & Environment for Development, 2017)

The alliance is embracing several solutions to prevent their five challenges that are being investigated by their technical working group. The chairman of this group, Angel L. Cruz, has business relationships in The Netherlands. Angel L. Cruz studied in The Netherlands and this created the possibility of the connection between the alliance and Finch Buildings (Schaik J. , 2016).

Eventually, the floating house will be part of their solution against tidal and fluvial flooding, therefore the alliance has a lot of interest in the design. Every municipality is supporting the efforts and due very alike environments and situations in each municipality the design could easily be adapted to each location.

4.2.2 Finch Buildings and Finch Floating Homes

Finch Floating Homes is the NGO of Finch Buildings, which is responsible for the design and construction of the floating houses. The initiative of the project started with Finch Buildings, which conducted preliminary research in Hagonoy, one of the alliance's municipalities. Their goal is to improve living conditions of inhabitants of flood prone areas by researching and implementing flood resilient housing.

The preliminary research resulted in a pilot design for a floating house and Finch is currently working on the development of the design.

4.2.3 Residents of Macabebe

The local population will be benefitting by the floating houses such that they are less harmed by the floods and typhoons. As future residents of the houses their input sets a norm or threshold, which should be translated into requirements. Their wishes should be taken into account when designing the various systems.

Many residents are affected by floods and typhoons and need a solution against these threads, a possible outcome could be the floating house. There will be a certain interest in the project, though factors depending on their wishes and demands should be balanced to their necessities and wishes. Any excessive demands could lead to unaffordable housing, which is not in line with the goals of Finch Buildings.

4.2.4 Local contractors

The goal of the design is that eventually local products and local contractors take care of the building process (Ham P. H., The design of a modular, amphibious structure for a flood and typhoon-prone municipality; Hagonoy, the Philippines, 2016). Contractors do not influence the physical view of the building, though the contractors should be able to construct and maintain the building, so planning, used materials and building techniques could be influenced.

4.2.5 Soliman E.C. Septic tank disposal

Soliman E.C. is a company that will supply septic tanks for Macabebe. The possible use of a septic tank might be an option for the wastewater collection and treatment. Their available products could decide what cost the system will have, though it is as well a market for the company (Soliman E.C., 2018). Their interest is low because they are not involved in the project and they will not influence the design of the system, because this is a possible market their interest could gain overtime.

4.2.6 National water resources board (NWRB)

This is a governmental institute and is responsible for policy making regarding all the water resources in the Philippines. All the water related activities that have an influence on the environment and economy of the Philippines (National Water Resources Board, 2018).

The interest of the NWRB for the project is low, just like their influence. The NWRB could not directly profit from the project, though it could contribute to their goals. Their influence on the project is mainly due policy making and possible guidelines for water management.

4.2.7 Local drinking water companies

As stated during the Water usage analysis, drinking water is distributed by barrels not by a network of pipes. The design should therefore be adaptable to the local network that is available. The local companies that distribute the water therefore have low interest on a single home, though on a bigger scale a company might be interested in treating and distributing water for the floating houses. Their influence is low because the design is not dependent, nor influenced by these companies.

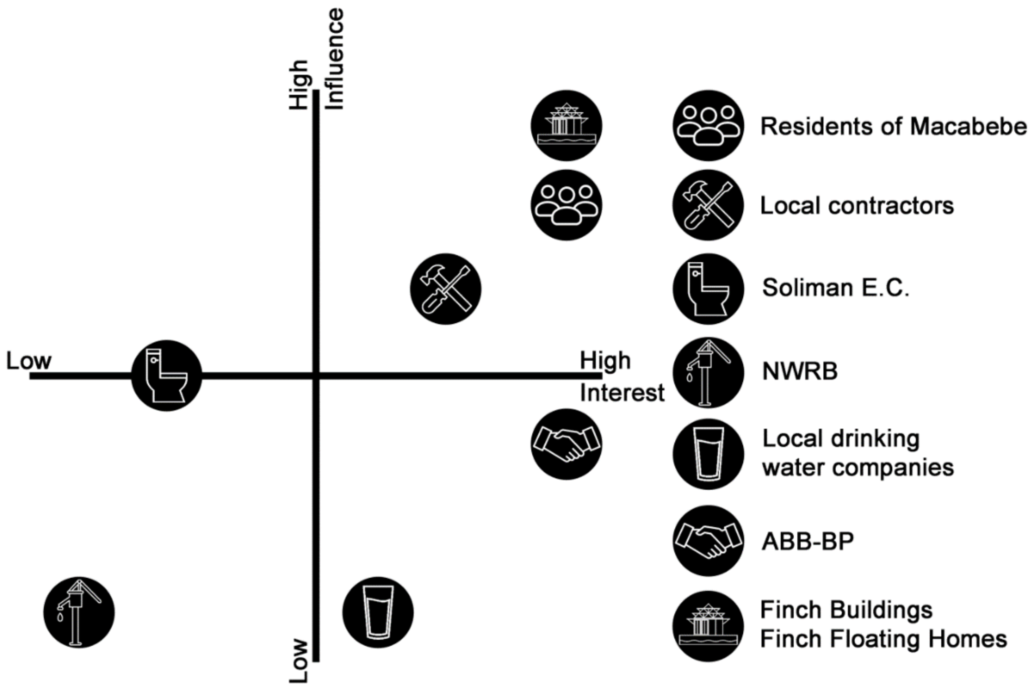

Figure 4.6 Power - interest diagram

4.3 List of requirements of the HWS

In the following paragraphs the total set of requirements, obtained from previous research and the analysis, will be listed in a table together with their allocation within the system. This has a high priority, the allocation will ensure that requirements do not influence the wrong (enabling) system. Within some phases of the design, construction or operational phases the requirements have to be validated, this is based upon Wassons approach of system engineering. (Wasson, 2005)

The list of requirements consists of two parts, based upon section 2.5, the general design principles translated to requirements, Table 4.1, and a list based upon the HWS, Table 4.2. Both lists consist of the parent requirements and the most important child requirements applicable for the system. During the design process the list of requirements will be extended, because the systems design has to fulfil the parent requirements set.

Table 4.1 General list of requirements

Parent requirement	Child requirement
Building concept requirements	
Innovative design	Sustainable design
	Implement new technologies
	Use new ways of thinking
Flexible design	Easily modified
	Future proof
Circular design	Technical circular
	Biological circular
Healthy design	Healthy indoor environment
Affordable design	Costs adapted to the target group
Floating behaviour requirements	
Floating design	Light-weighted structure
	Low centre of gravity
	Rigid connections
Location based requirements	
Resistant to weather influences	Wind resistant
	Heat resistant
	Cope with water influences
Adjustable to future social influences	Meet with energy demand
	Meet with water demand
	Meet with living demand

Table 4.2 Human water systems list of requirements

Parent requirement	Child requirement
Healthy sanitary situation	Availability of a toilet
	Availability of a bucket shower
	Availability of a sink
	Availability of a drain
	Presence of plumbing
Drinkwater demand	Availability of water tanks
	Availability of a water dispenser
	Availability of water for cooking
Rainwater harvesting	Water storage
	Rainwater collection
	Transport of rainwater
	Meet with effluent characteristics for reuse
Wastewater treatment	Collection of wastewater
	Treatment of wastewater
	Meet with effluent characteristics for reuse or discharge
Cope with precipitation influences	Drainage of precipitation from the roof
Cope with surface water influences	Cope with tidal influences
	Cope with wave influences

4.4 Possible solutions

The fulfilment the requirements could be achieved through different approaches. To design best and integrated human water system a set of choices has to be made, this will be done on several aspects that will be set during this chapter. Firstly, the rainwater harvesting with in the human water system will be addressed, secondly the wastewater system, including treatment and at last the integration within the house.

4.4.1 Rainwater harvesting

From the analysis can be concluded that there is a rainy season and a dry season, so the harvest system has to cope with these fluctuations. Firstly, the needed storage capacity will be calculated from here the potential treatment demand will be discussed and designed.

Collection of rainwater

Collected rainwater could replace water used for aspects, for example flushing toilets, showering or even as drinking water, though some might have a need for a more extensive or different treatment, see section “Treatment of Rainwater” (Thomas & Martinson, 2007).

According to Thomas & Martinson there are five possibilities for the use of domestic rainwater harvesting. These are all based upon storage size, demand volume and type, duration of the wet season, and amount of precipitation. Combining these parameters results in Table 4.3, which gives an overview of the adaptable parameters.

The fixed parameters are the duration of the wet season, June till November, so six months. The average future rainfall over the wet season is approximately 1,735 mm, with a total of approximately 2,615 mm per year. The storage size is adaptable, though only by multiplications of 400 L, the barrels have a value of 200 L and for floating behavioural of the structure it is favourable to balance the system. The favourable amount of storage is depending on the demand volume and type, though there is a maximum value limiting the buoyancy of the structure. The maximum value will be assumed through the maximum draft of 800 mm, corresponding with 128 barrels or 25,600 L.

Table 4.3 Design parameters rainwater harvesting

Parameters					
Storage size	400 L	800 L	…	25,200 L	25,600 L
Demand type	Sole source	70% annual water use	Wet season use	Portable source	Emergency
Demand volume	Adaptive	120 lpcd	80 lpcd	50 lpcd	

Drinking water can be relatively easily delivered, as described during the section Precipitation, to the home like the population is used to. Therefore, is usage of rainwater as a sole or potable source an inadequate solution for the floating house. The house will be occupied all year so other unattractive applications are the emergency and wet season use. Most suitable therefore is usage of rainwater by means of 70% of the annual water usage in the home, though can the system fulfil this demand and for what demand volume.

This satisfaction is dependent on the available yearly quantity of water, which is given by equation 4.1,

$$V_{yearly} = C \cdot P \cdot A \tag{4.1}$$

The run-off coefficient is depending on evaporation, type of roofing and, losses in the storage tank and pipes. For humid tropics and wooden roofing, a good assumption is between 0.8-0.85 depending on the age of the wood roofing (Thomas & Martinson, 2007). This results in an flow of 50.8 m³/y or 140 L/d.

For a household size of five and their daily need of 80 lpcd, the harvested rainwater is equal to 35% of their daily usage. Though, this is only applicable when all the water will be stored during the whole year and no overflow of the system occurs. A calculation based upon the inflow and outflow will result in the ideal size of tank for usage of 140 L, though what if 160 L is used or less than the average amount of rainfall.

To gain more insight in this process a monthly volume – discharge balance of the system is set up according the basic principle of formula 4.2, where the inflow is based upon the monthly rainfall and outflow on the daily usage of water.

$$\frac{dQ}{dt} = Q_{inflow} - Q_{outflow} \tag{4.2}$$

This gives insight in the needed capacity and harvested precipitation for usage and percentage of total water demand, see Table 4.4 for an overview. From this table can be concluded that if the system is overused the storage capacity will be reduced and the water stress during the dry season will increase. If assumed the delivery of 70% annual usage by rainwater the usage, there is still a water shortage of 65-82 days when assumed the minimum amount of water of 50 lpcd. Therefore, should be looked into other processes to reuse water within the system, for example wastewater reuse or a connection to tap water, which both come with their own challenges. Though the ideal storage amount would be in the range of 4,400 to 6,400 L, possibly with a flexible usage over the year. The actual storage is higher than the maximum storage needed, this is due the balance of the structure. The balance of the system is done by equal distribution of barrels over the modules, therefore two barrels with a volume of 200L per side should be added.

Table 4.4 Rainwater harvesting, for the calculation see Appendix C.2

Usage as $Q_{outflow}$ [L/d]	Maximum storage as dQ/dt [L]	Barrels for long storage	Actual storage [L]	Waterstress [months][1]	Shortage [days][2]
120	Infinite	None	Only temporarily	None	0
140	7,969	40	8,000	1	2
150	6,169	32	6,400	3	26
160	4,369	22	4,400	4	47
170	2,856	16	3,200	6	65
180	1,656	10	2,000	6	82

Treatment of rainwater

Since the harvested rainwater will not be used as drinking water the treatment of it does not have to be extended, though there is still a necessity of treatment for reuse.

As can be seen in Table 4.5 rainwater is high in alkalinity concentration with respect to other water sources, besides there is a presence of nitrate and ammonium. Another threat are protozoa and, biological matter and metals from the drains or roof. The so called first flush of the rainwater is highly diluted with these compounds. To cope with this water it can be treated, though it is more efficient for the system to discharge the first flush in an efficient way, if the potential loss of water

[1] Water stress is defined here as an empty tank at the end of the month.
[2] Shortage is defined here as the average days where the daily demand is not met.

is allowed. The acidity, measured in pH, of rainwater is mostly around 5, but it can be as low as 3 for acid precipitation (Fondriest Environmental Inc., 2016).

Table 4.5 Water bound contaminants proportion with respect to source

	Rainwater	**Oxic groundwater**	**Anoxic groundwater**	**Oxic surface water**	**Sewage water**
O_2	++	+	0	+	0
NO_3	+	0 -- ++	0 -- +	0 -- ++	0 -- +
CO_2	-	++	+++	+	++
CH_4	-	0	0 -- ++	0	+
NH_4	+	-	+	-	++
PO_4	0	-	+	-	++
Fe, Mn	-	-	++	-	-
COD	0	-	+	-	++
Pathogens	0	0 -- +	-	0 -- ++	++
Turbidity	0	-	-	0 -- ++	+
OMPs	0	0 -- +	-	0 -- ++	+

The first flush can be handled in several manners in several locations, though for all types the same parent requirements should be applicable. Filters placed within the system should comply with:

- The system should be easy to clean or largely self-cleaning;
- The system should not block often and blockages should be easy to identify;
- Blockages should be easily be maintained;
- Filters should not provide an entrance for additional contamination, even if the filter is left uncleaned (Thomas & Martinson, 2007).

The solution to handle the first flush will either be discharging and filtering with a coarse and/or fine filter or a combination of the given possibilities. The optimal system has to be designed especially to provide a healthy water quality for reuse for a specific average discharge.

A standalone coarse filter will not be satisfactory, because it will not threat the dissolved and small particles, though a coarse filter will enable to make use of a non-self-cleaning fine conventional filter, for example a sand or activated carbon (AC) filter.

A self-cleaning cloth filter will be able to filter even small particles, though there will be a loss of water due to run-off from the cloth. (Thomas & Martinson, 2007) A disadvantage for this application is that the filter must be available locally when replacement is needed.

The last option to be discussed is the first flush system, this could be a pipe that will be able to filter the first flush by filling a secondary pipe before the main drain. In this side pipe the first flush can be stored temporarily and removed by a removable cap at the end. Another possibility is to design an overflow barrel system in which the solids will settle, and the rainwater can be drained to either the next filter or storage unit (Thomas & Martinson, 2007).

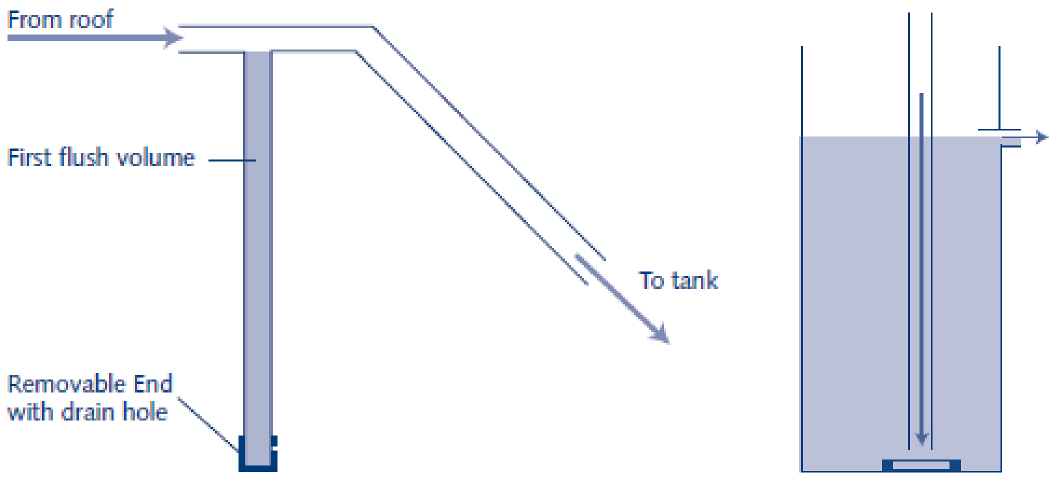

Figure 4.7 First flush systems, left: pipe system; right: barrel system

All the options together form the table below with their applicability and integration within the system, maintenance sensitivity and projected effluent quality. Based upon these characteristics a concrete solution for rainwater harvesting will be conducted. The final configuration of the system will be discussed in section Configuration rainwater harvesting.

Table 4.6 Treatment possibilities rainwater

Medium	Applicable for	Integration	Maintenance	Disadvantage	Effluent
Coarse filter	Large solids, i.e. leaves and sticks	Top or bottom of the drain	Check regularly	Only pre-treatment	Diluted, not ready for use
Cloth filter	Till small particles, sand and leaves	Bottom of the drain	Self-cleaning	Must be locally available, loss of water	Ready for use, though maybe some health risks after storage
Conventional filter	Small particles, nitrification, bacteria and, odour and colour(when AC is used)	Bottom of drain or in foundation	Clogging, replacing media or backwashing	Relatively expensive and need of pre-treatment	Relatively high quality, no or little health risk when properly maintained
First flush pipe system	Small solids and bacteria	Top of drain	Empty after rain shower	Loss of water, potential shortening of solids	Usable when properly designed and maintained
First flush barrel system	Solids	Bottom of drain	Check regularly	Could clog after some time, development of pathogens	Diluted, not ready for use

4.4.2 Wastewater collection and treatment

The water usage within the house results in a flow of waste water within the home. The sources of the flow originate from sanitary use and cooking. The standards for the sanitary system were set during the social analysis. As stated in the section Water usage the water usage is estimated on 80 lpcd. Wastewater consists of specific combination of contaminants, these contaminants could result in an environmental or health risk for society, therefore the water should be treated before discharged in the surface water.

For surface water the amount of phosphorous and nitrogen could be harmful, these compounds could lead to algae blooms and depletion of oxygen and mortality of fish in the surface water. These effects have to be minimized while social life could benefit from the treatment.

The wastewater has to be treated to meet with local characteristics, therefore is a need for characterization of the influent. The municipal waste water influent could either consist of dissolved or suspended matter, in Table 4.7 is a list of most important chemical characteristics of wastewater. The fourth and fifth columns presents the effluent requirements of respectively The Netherlands (Lozingenbesluit WVO stedelijk afvalwater, 2009) and the Philippines (WEPA, 1990). There are no significant differences between both effluent requirements, therefore the Philippines' standard will be the design standard.

Table 4.7 Characteristics influent and effluent wastewater

Parameter	Unit	Influent	Effluent requirement (NL)	Effluent requirement(Ph)
BOD_5^{20}	mg/l	174	20	30
COD	mg/l	471	125	60
TSS	mg/l	223	30	85
P-total	mg/l	6.7	1-2	1
P-PO_4	mg/l	4.4	-	-
N-Kj	mg/l	-	20	-
N-total	mg/l	44	10-15	-
N-NH_4	mg/l	~30	-	-
N-NO_3	mg/l	-	-	14
N-NH_3	mg/l	-	-	0.5
Alkalinity	mg/l	430	-	-
pH	-	-	-	6.0-9.0

To discharge the water the effluent has a need for treatment of the waste water. Main contaminants that should be treated resulting Table 4.7 are suspended solids, the BOD and COD, and nitrogen and phosphorous concentrations in the effluent. To treat these contaminants till required standards several treatment steps have been considered to fulfil the demand of treatment. In Table 4.8 is an total overview of these treatment possibilities, which are compared regarding their abilities and disabilities of treatment.

The several treatments can be either combined or singular, this depends on the extensiveness needed to fulfil the effluent demand and potential reuse of the water. This depends on the efficiency of the treatment system and social interaction with the system. An option is to short circuit the urine, and to treat the faeces separately, though this could lead to clogging in the pipes when not properly maintained. Poor maintenance is a risk to reduce to a minimum, therefore separate treatment is not taken into account in this research.

Table 4.8 Possibilities regarding waste water treatment [1] (Eawag & Stauffer, Free-Water Surface Constructed Wetland, 2018; Masi & Bresciani, Horizontal flow constructed wetlands, 2018; Masi & Bresciani, Vertical flow constructed wetland, 2018)

Treatment kind	Removal of	Maintenance	Advantage(s)	Disadvantage(s)
Septic tank (Eawag & Spuhler, Septic tank, 2018)	SS, turbidity, COD/BOD, CH_4	Little maintenance, except when biogas is retained	CH_4 conversion Simple and robust, low cost, implemented in foundation, no energy usage	Desludging, risk of leaks, low reduction of solids, pathogens and organics, effluent must be treated to ensure appropriate discharge
Filter treatment (Stauffer & Spuhler, 2018)	SS, turbidity, N, pathogens	Regular checking of filter and backwashing or replacement of media	No energy usage, effective and cheap solution	Heavy construction, high on maintenance, less suitable for waste water treatment (more suitable for greywater treatment)
Wetland or helophyte filter[1]	BOD, pathogens N+P removal, suspended solids	Regular checking for clogging and short circuiting, long term maintenance, control vegetation regularly	No energy usage, low operating costs, extended treatment, generating food or income	Risk of clogging, heavy construction
Aquaculture, floating plant pond (Eawag, Sacher, Gensch, & Spuhler, 2018)	SS and BOD, low reduction of pathogens	Requires constant monitoring of the plants	Rapid conversion, can be designed with local materials	Right species of plant is needed otherwise it will be invasive, low reduction of pathogens
Aquaculture, fish pond (Eawag, Gensch, Sacher, & Patil, 2018)	SS and BOD, sludge treatment	Requires constant monitoring of the fish	Biomass conversion, generates income or food, can be designed with local materials	Possible social disapproval, chance of health risks when improperly prepared

There are still questions regarding the sludge, biogas and the effluent of the system. Sludge consists of valuable resources which can be used by the society or industries. A possible solution would be as a fertilizer or fish food. As a fertilizer the sludge needs an area where the sludge can be died till it can be used. Though usage could lead to hazardous situations and health risks when improperly cooked. Another solution could be drying the sludge and use it as a source of energy.

Energy conversion and energy usage within the house could be a valuable point to take into account. Since extended treatment might would need energy as well, the energy could become self-sufficient when properly used. Other sustainable resources of energy available are wind and solar energy, though both will need batteries for storage, where biogas itself could be used for cooking or converted into electrical energy by a generator.

Effluent is a valuable source of water and consists of potential nutrition for agriculture. The final usage of the effluent depends on the extensiveness of the system. The different components should be designed to work together to clean the characteristic influent till it meets the wanted effluent. Therefore, certain specific systems only work when they are placed in a certain sequence, important is to start with sludge and fluid separation before the fluids are filtered. This transition prevents that any filter will decline, and risks of clogging will be increased.

In the following paragraphs potential configurations of the human water system will be addressed.

4.4.3 Configurations

During the following paragraphs the total human water system will be described according their potential treatment schemes for rainwater harvesting, and sewage collection and treatment.

Configuration rainwater harvesting

Some configurations are not possible because these will not satisfy to the given parameters, therefore the following combinations will be addressed, every pipe has a coarse filter to prevent clogs in drainage pipes or filters:

- Standalone conventional filter (with or without GAC); The conventional filter removes suspended solids, protozoa and denitrifies the water. The potential GAC layer of the filter removes any colour and odour of the water.
- First flush barrel and conventional filter (with or without GAC); The first flush barrel removes settable solids that potentially clogs the conventional filter, the conventional filter removes residual solids, protozoa and denitrifies the water.
- First flush pipe system and cloth filter; Primarily, the pipe system removes small particles and the hazardous first flush, secondary filters the cloth resulting manner from the pipes.
- Cloth filter and conventional filter (without GAC); These steps ensure filtration of solids, protozoa and denitrification of the water.

In theory all four configurations are able to meet with the effluent characteristics. The first flush pipe system is less desirable due the availability of barrels for the system. The cloth filter can be applied, though availability and maintainability are not assured, therefore these are less applicable for the current system. Therefore, the system will either consist of a conventional filter with or without GAC filter and with or without first flush barrel.

The most basic system would be a conventional filter with sand, this filter would be able to filter the pollutants necessary for reuse. The system can be adapted, expanded or replaced if this would be necessary. Adaption or expansion of the system could be due various reasons, in case of a standalone sand filter this would probably be due clogging of the filter bed. The conventional filter is sensitive to clogging so if the system would require an upgrade the first upgrade could be a first flush barrel system. Both systems could easily be integrated within the barrels.

The ideal situation for the first floating home might be to integrate both designs to monitor what design is more favourable by the inhabitants or is the most efficient system.

Rainwater harvesting - Filter design

If rainwater runoff is treated through sand and other media filters, primarily constituents are removed through a physical process of filtering particles from the water. The filter type used and its characteristics, as grainsize, determine the removal efficiency. Coarser sands have larger pore spaces that result in high flow rates but pass larger suspended particles. A very fine sand, or other fine media filter like anthracite, has smaller pore spaces with slow flow rates and filters out smaller total suspended solids. Some soil types, such as peat-sand mix, may provide adhesion or exchange of ions for some dissolved constituents, which further enhances effluent quality. (Urbonas, 1999)

The filter that will be designed is constrained by factors of pressure height, filter area and height, and discharge capacity. From previous research conducted the maximum rainfall intensity in the Pampanga basin is 111 mm/d, this intensity has a return period of one year (de Vos, Hamer, Diederen, & Zorić, 2014). Together with formula 4.3 this results in a maximum flow of 1.09 m^3/d per filter. Maximum filter height and area both are depending on the barrel size and type, the height and diameter of the barrel are respectively 930 mm and 530mm.

From the section Temperature can be concluded that the average temperature fluctuates between 25.0 °C and 27 °C, which will both increase one to two degrees over the upcoming decades. The temperature will influence the kinematic viscosity; therefore it will vary from $0.80*10^{-6}$ m²/s and $0.90*10^{-6}$ m²/s over the upcoming decades.

From the formula 4.3 of head-length ratio of a filter can be used to check whether there is enough height difference or not. The porosity is assumed to vary between 0.4 and 0.5, and the particle size, d_0, varies from 0.5mm to 1mm. These values imply the respectable head loss over the filter, which could be up to approximately 930 mm, if the barrel would be used till full capacity.

$$\frac{H_0}{l} = 180 \cdot \frac{\nu_{kin}}{g} \cdot \frac{(1-p_0)^2}{p_0^3} \cdot \frac{u}{d_0^2} \tag{4.3}$$

These calculations for values of the kinematic viscosity give very low values for the head loss relation, representation for both summer and winter can be seen in Figure 4.8. The parameters of the filter media compared to regular filter beds are not special or different. The slow supernatant velocity in the filter gives a realistic value of 0.05 mm/s for slow sand filtration, where values of 0.028 mm/s to 0.11 mm/s are normal for slow sand filtration (Huisman & Wood, 1974).

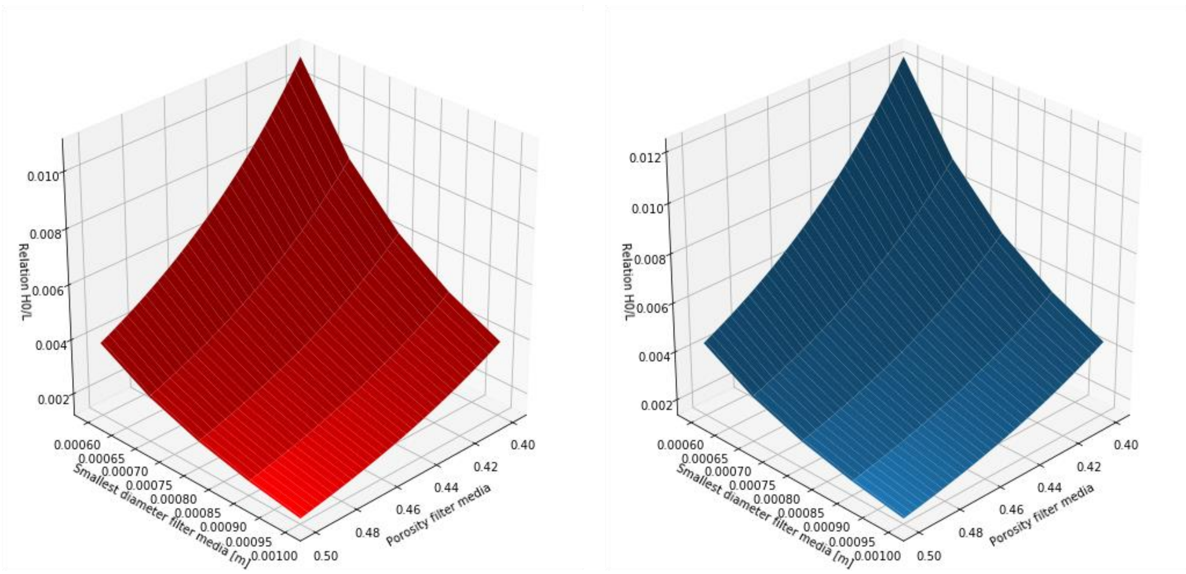

Figure 4.8 Relation H_0 and L for filter media (summer left, winter right)

This calculation result in the highest value for 0.6 mm with a density of 0.4 results in a relation of H_0/L between 0.011 and 0.012 for respectively summer and winter. Knowing the parameters for the sand filter the assumed runtime of the filter can be calculated. Assuming the top and bottom 20 mm will be lost due placement of pipes and distribution systems, the filter length will be 890 mm, with d_0 equal to 0.6 mm with a porosity between 0.4 and 0.45 for the filter bed. Following Lerk's theory for removal of solids, the efficiency of the filter can be calculated, assuming a maximum inflow of TSS of 15 g/m³.

$$c_e = c_0 \cdot \frac{e^{a*T_q}}{e^{\lambda_0 * l} + e^{a*T_q} - 1} \tag{4.4}$$

$$with\ T_q: Filter\ run\ time\ in\ seconds$$

$$\lambda_0 = \frac{9 \cdot 10^{-18}}{\nu_{kin} \cdot u \cdot d_0^3}$$

$$a = \frac{(9 * 10^{-18} * c_0)}{\rho_d \cdot p_0 \cdot \nu_{kin} * d_0^3}$$

Together with formula 4.4 the clog time of the filter can be calculated, this gives insight in the maintenance rate of the filter. An approximation of the filter time is calculated for both porosities, though for the average velocity that is applicable, an overview can be seen in Figure 4.9. These calculations give an impression of the capabilities of the runtime of the filter during summer and winter for different porosities. There is no significant difference between summer and winter.

The filters will clog completely around 127 and 142 days of constant treatment of the water, this would mean a quantity between 28,000 mm and 31,600 mm of precipitation on the roof surface. The filter will be dry several periods during which biological processes could occur that potentially increase the clog rate. The actual inflow of solids could be higher or the total amount of rainfall lower, both parameters influence the filter process directly. Therefore, a maintenance rate of once a year should be efficient enough, instead of the full potential flow. To provide a safe quality of water regularly testing of the quality is advised. According to the Philippine standards for drinking water effluent the maximum amount of dissolved solids is 0.5 g/L and the pH should range from 6.5 to 8.5 (Republic of the Philippines; Department of Health, 2007). As described should the filter require a certain type of filter, though what should the characteristics of the filter media be. Discussed are the porosity, smallest pore space diameter and possible types of media.

Though to have an effective filter another aspect is very important, the uniformity of the media type. The uniformity is described by Cu=d60/d10, which is described by sand sieve test. The uniformity coefficient should be lower than 5 and ideally lower than 3 (Logsdon, Kohne, Abel, & LaBonde, 2002).

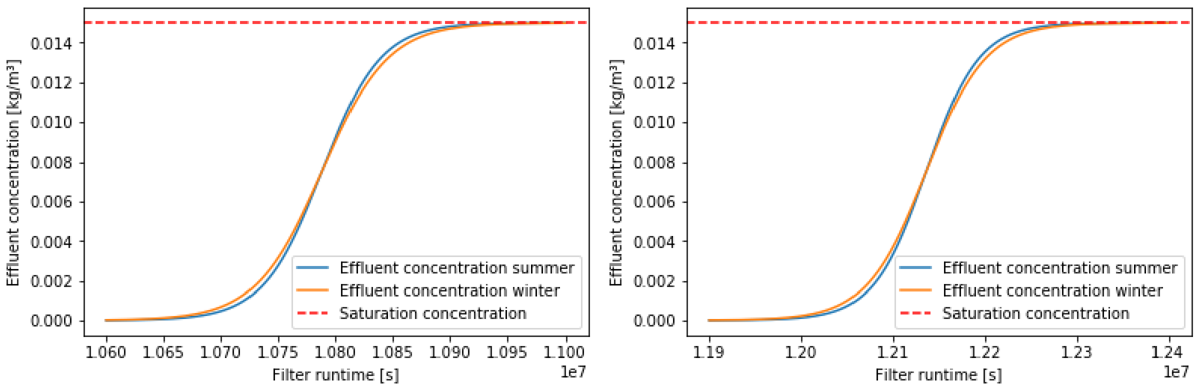

Figure 4.9 Filter run time for summer, respectively a porosity of 0.4 (left) and 0.45 (right)

Configuration storage

The water has to be stored in a closed environment in such a manner that chance on leakage of the tanks is reduced till a minimum. Wave motion has an important influence on the storage of water, it is influencing the hydraulics and could induce backflow within the pipes. Therefore, the barrels for storage have to be connected to ensure a certain distribution within the system and to prevent backflow into the wrong direction.

The storage system has two main purposes, storage of water and providing pressure to pump the water to a certain level. This can be translated to the barrel that has continuously the most water stored will be addressed as pumping barrel. Since the water has to flow from barrel to barrel without backflow in the system from the main barrel to another each barrel has to be connected to another, while not every barrel fills up at the same time. This could lead to losses and a long retention time within the system.

Each barrel is therefore connected to another barrel by two pipes such that the water can freely flow when the maximum capacity is reached, the top pipe is open, so when the maximum water level is reached the next barrel will be filled, a visual representation can be seen in Figure 4.10. The bottom pipe has a one way valve in the pipe such that backflow in the system is not possible, there will only be a flow from one to another barrel when the water level in or closest to the pumping barrel is lower than in the given barrel. In Figure 4.10 is a representation of the steps in the system to ensure a volume in the pumping barrel. Another option is to replace the amount of barrels to a single or multiple large barrels, though this might be a less responsible choice since the availability of barrels.

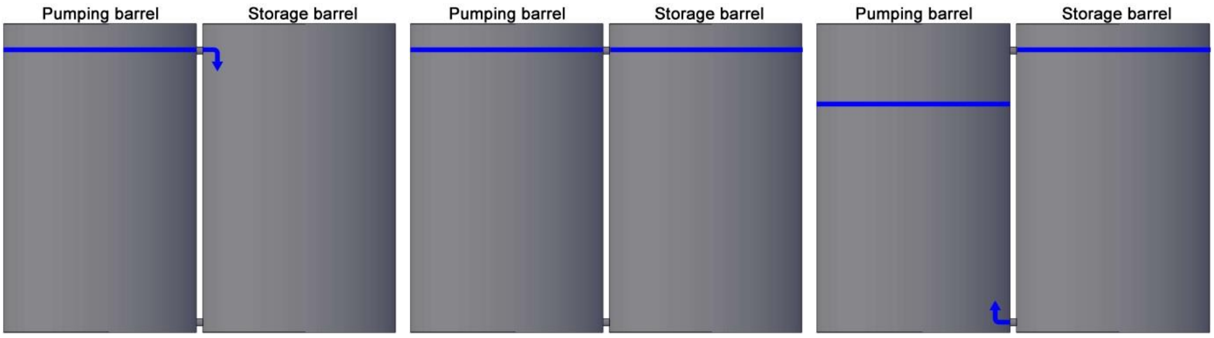

Figure 4.10 Barrel system

4.4.4 Configuration wastewater treatment

After usage of water the water it has to be treated, according to Table 4.8 there are several treatment steps possible that could meet with the required effluent for the system. Due these requirements, aquaculture, both plant and fish, will not meet with the requirements because this would include discharging directly to the surface water. On the other side fish aquaculture could be a beneficial solution for sludge treatment.

To treat the influent the system has to cope with BOD, COD, TSS, nitrogen and phosphorus removal. An efficient treatment can be established through removal of TSS and conversion of BOD and COD followed by an more extensive treatment, like filtration or wetland treatment.

The optimal solution therefore consist out of one of the following possibilities:

- Septic tank treatment;
- Septic tank and filter treatment;
- Septic tank and wetland treatment;
- Septic tank, filter and wetland treatment.

The septic tank is a common solution for all four options, therefore the septic tank design is the most important aspect of the treatment scheme. For the design of the septic tank some aspects influence the efficiency of the whole system and are therefore important to the whole waste water system. These characteristics are:

- Tank size;
- Tank configuration;
- Inflow distribution;
- Sludge retention and sludge digest rate.

The tank size is the most important factor because this influences the complete configuration of the tank. The tank is designed to separate suspended solids, digest sludge and scum till biogases, stabilization of organic material by anaerobic bacteria and growth of micro-organisms (Rajput, 1982). According to Rajput the size of a septic tank can be described by formula 4.4, which can be derived into two parts, hydraulic retention and solids retention and digestion. This formula takes into account the number of capita served as C_{cap}, the desludging rate for a given temperature is given as n, the temperature ratio as f, furthermore s is the sludge accumulation rate per year per capita and q is the daily flow of waste water per capita.

$$V = C_{cap} \cdot n \cdot f \cdot s + C_{cap} \cdot q \tag{4.4}$$

This results in a capacity for complete tank of 562.5 L, based upon 80 lpcd and a desludging rate of once a year. If an average HRT of 24 hours is assumed for the tank this results in a size of 400 L, or two barrels of the system. So therefore, the first chamber exists out of two separate chambers from which both are connected to a third barrel to reach the 562.5 L for an efficient retention. In case of an expansion of the household, the system can easily be increased by placing one or multiple additional tanks and addition of the pipes.

If the sludge accumulation rate is estimated to be 0.254 L/ca/day, if we convert this to a yearly amount for five inhabitants this would be 464 L on a yearly basis (Gray, 2010). Therefore, the maintenance rate of desludging would be once a year.

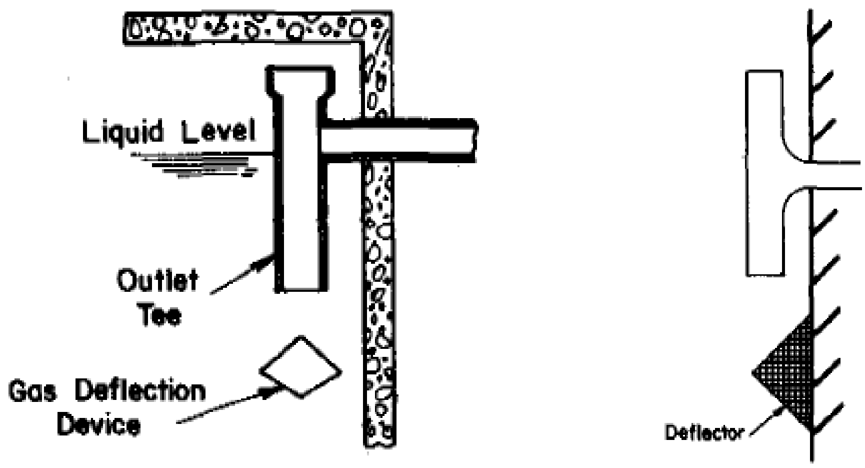

Figure 4.11 Configuration T-pipe and possibility deflection device (Rajput, 1982)

Important within the tank is to prevent short circuiting of solids and to provide efficient gas discharge out of the tank. The solution for short circuiting in normal situations can be done by placing screens inside tanks, though this is not necessary because this tank exists out of multiple barrels. Another solution to prevent floating matter, like fats and oils, to short circuit is to adapt the inlet and outlet pipes for each barrel. This can be done by placing T-pipes as inlet of the barrel, there are other possibilities as described by Rajput, though these are not applicable for barrel systems.

Gas fumes have to be collected or discharged and deflected from the inlet and outlet pipes. Deflection is possible by creating a levee inside the tank that redirects the fumes away from the T-pipe. This levee can be rectangular bar or a triangular baffle, this can be seen in Figure 4.11 together with an example for the T-pipe.

Gas diffusion within the tank occurs after digestion of biological matter to H_2S, CO_2, CH_4 and N_2. These will accumulate on top of the liquid level, to avoid dangerous health situations these gasses have to be either discharged or collected separately. Collection of these gasses could potentially generate energy after conversion, though this is a costly process and requires intensive maintenance. Therefore, for the first draft of the system it is more applicable to discharge the gasses by a vent in combination with a pipe.

The expected effluent of a septic tank according to Rajput based upon several researches is given in Table 4.9, from this table can be assumed that further treatment of the water is essential. Since a sand filter does not have the capabilities to treat phosphorus wetland is more suitable. A wetland has the abilities to convert P and N while filtering out TSS, coliforms and potential pathogens.

Table 4.9 Effluent characteristics and standards.

Parameter	Estimated effluent concentration [mg/L]	Effluent standards discharge [mg/L]
BOD_5^{20}	90-130	30
COD	323	60
TSS	40-74	50
P-total	18	1
P-PO_4	20	-
N-Kj	5.4-10	20
N-total	32	10-15
N-NO_3	0.11-0.15	14
N-NH_3	14-25	0.5
Sulphates	50	
Alkalinity	300-400	
Coliforms total	10^5/100 ml	
Faecal coliforms	10^5/100 ml	10^2/100ml
pH	7-8	6.0-9.0

The wetland's capacity to treat TSS can be derived from the same theory used to calculate the sand filter, though due roots and imperfections the porosity will be larger. Sand is less suitable for root growth, therefore a clayey sand or peaty sand is more suitable. Instead of designing the filter knowing the velocity and length of the filter to decide the clog time, an ideal velocity for an ideal length will function as input of the model. Since a barrel is at least 580 mm wide the filter length will be designed in steps of 580 mm.

Since there is a daily flow of 400 L the filter should be able to cope with this flow, while having a sufficient retention time and a long filter run. The time of the filter run depends what the surface and length of the filter should be. To make a good estimate of maintenance the cases considered are, every six months, every three months, once a month and twice a month.

Table 4.10 Maintenance rate- volume relation wetland.

Maintenance rate	In seconds	Storage volume [L]
Every six months	$15.8*10^6$	Infinite
Every three months	$7.9*10^6$	Infinite
Once a month	$2.6*10^6$	54
Twice a month	$1.3*10^6$	27

As can be seen in Table 4.10 the necessary storage volume would increase in an unstable manner till infinity for long maintenance rates. Though, for possibly larger filter media the filter is more effective. Since respectively 54 L and 27 L are rather low values for storage and a minimum retention time of 24 hours is recommended the size will be 400 L (Davis, 1995). The assumed maintenance rate will be once a month, since this is assumed to be the maximum allowed

The recommended root depths for several species is in between 3 and 12 inch or 7.5 and 30.5 cm, to cope with all sorts of species an recommended depth of 30 cm should be sufficient (Davis, 1995). Therefore, a surface area of 1 m² would be sufficient to treat the water. From these calculations can be concluded that four barrels with 40 cm of filter media would be sufficient to treat the water.

4.5 Final design

After all the design steps taken a complete human water system is put together to create a healthy solution regarding waste water treatment and collection, rainwater harvesting and overall storage. An overview with impressions of the solutions can be found in this paragraph.

For rainwater harvesting are two designs possible which both have the same result regarding collection and filtration of rainwater, which can be seen in Figure 4.12 and Figure 4.13.

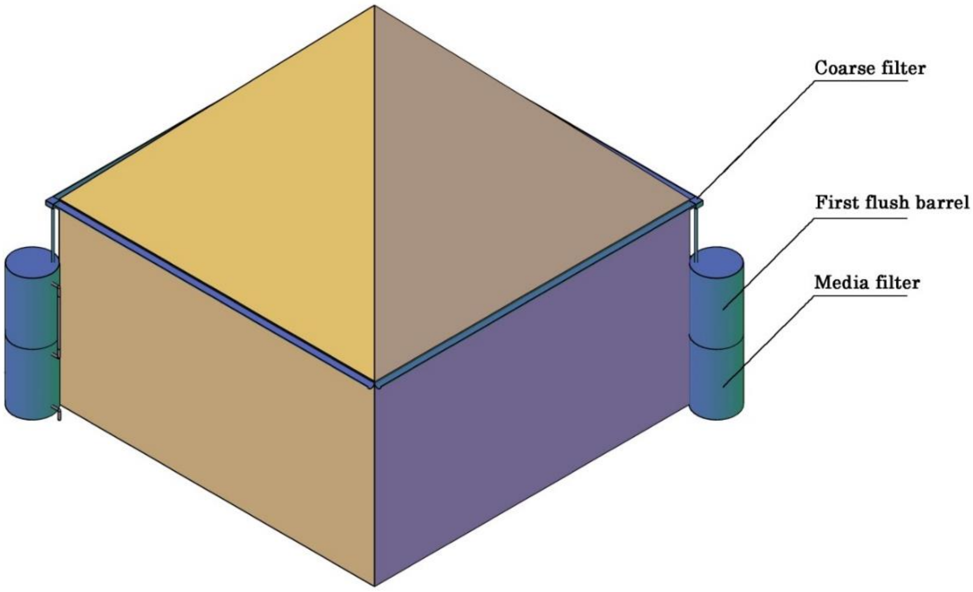

Figure 4.12 Rainwater harvesting, configuration one

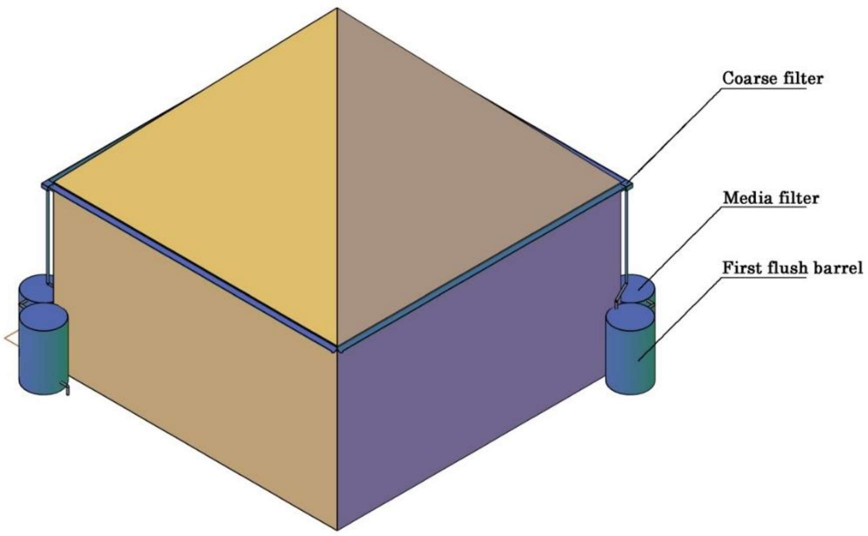

Figure 4.13 Rainwater harvesting, configuration two

This water will be stored in the foundation and later be used before treated as waste water. The following pictures give an overview of the septic tank and helophyte filters designed. These can be implemented within the foundation of the structure.

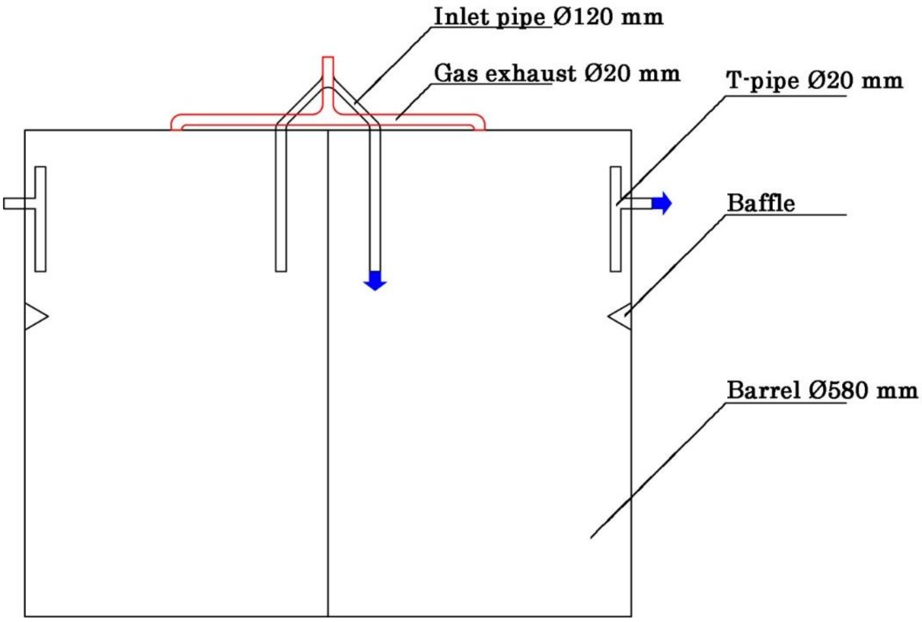

Figure 4.14 Septic tank design

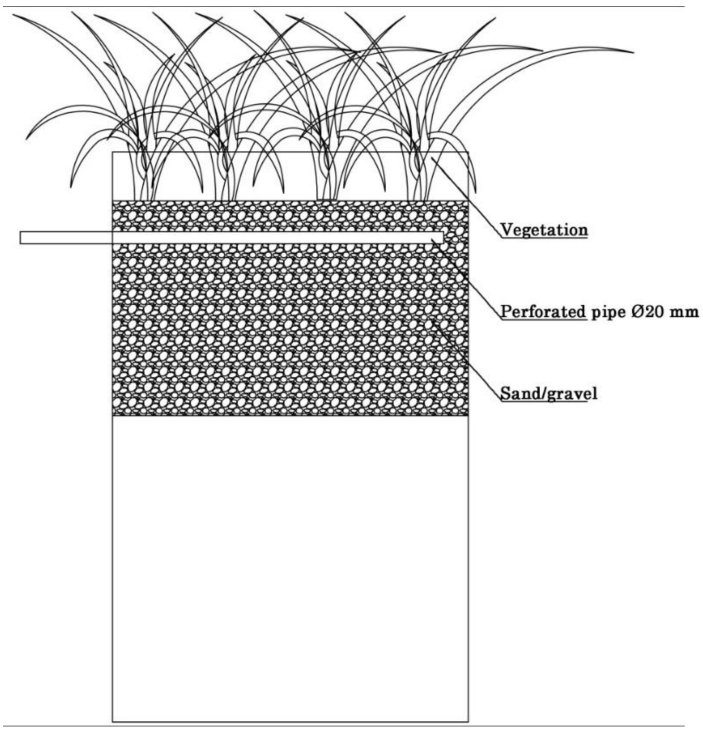

Figure 4.15 Helophyte filter

The last aspect of the process was to design sufficient water storage for rainwater harvesting. From the design steps can be concluded that 6,400 L storage is sufficient for a usage of 140 L/d. According to chapter 5 research the least influenceable position of the storage barrel is cantered as much as possible. A possible design of the barrel storage system can be seen in Figure 4.16.

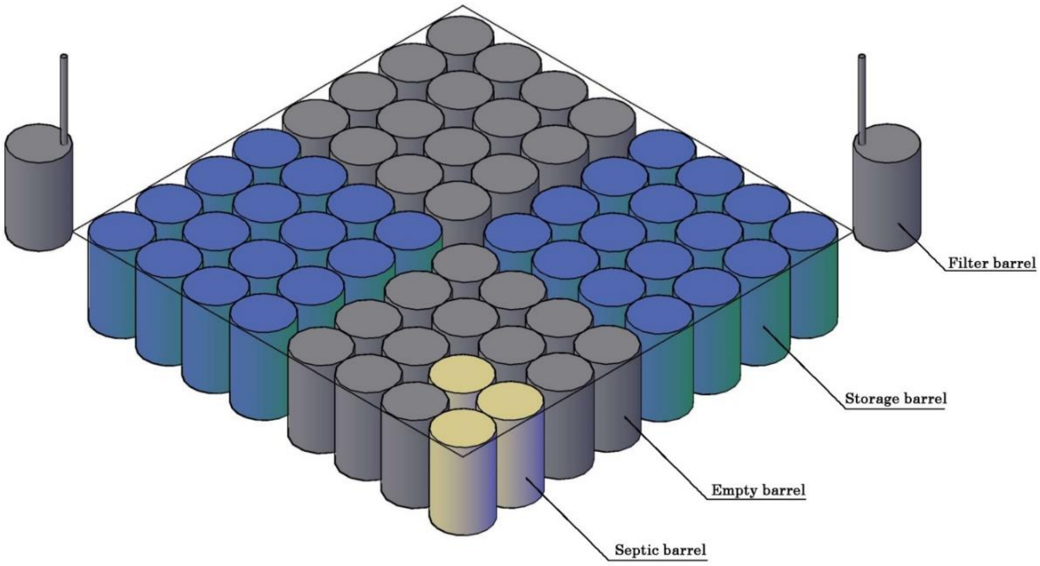

Figure 4.16 Storage configuration

The aspects of the design come together within the home as can be seen in Figure 4.17, when whished upon the system is fairly easy to expand and adapt. If the effluent from rainwater harvesting does not meet with the requirements a layer of GAC can be implemented or an extra media filter placed. If after a certain time the retention of waste water is not high enough the septic tank can be extended with extra or two extra tanks. The helophyte filter is the only maintenance rich aspect of the design, though it is still adaptable and extendable if the household requirement would rise.

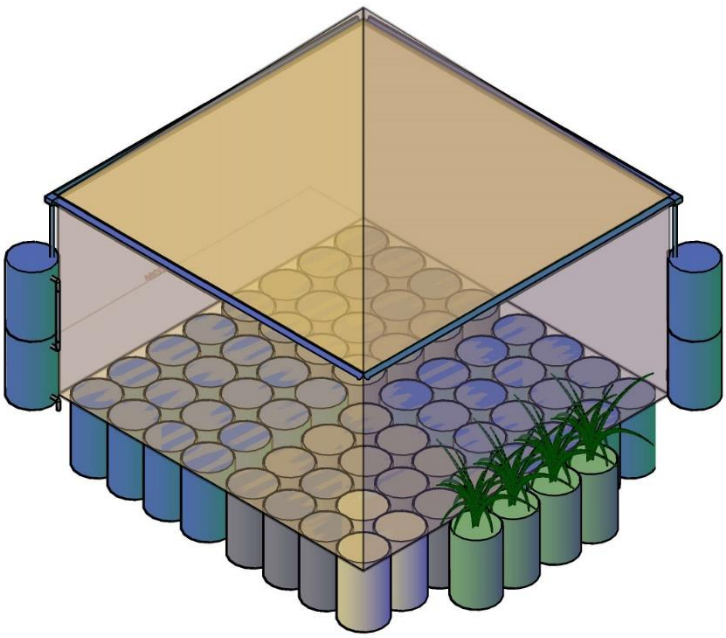

Figure 4.17 Integrated design

4.6 Conclusion human water system

The human water system is designed to be a social accepted solution for the local population of Macabebe inside a floating house. The solution had to require a solution to supply of drinking and tap water, and waste water collection and treatment.

The water usage of the inhabitants could partially be fulfilled by rainwater harvesting, 140 L to 160 L of the 400L requested. The rainwater harvest system is designed to catch, treat and store the water for usage as tap water. Since the rainwater harvest system does not meet with the required water demand the shortage has to be fulfilled from other sources.

Before this water is suitable for usage it has to be treated, main contaminants turned out to be concentrated in the first flush of the system. These contaminants mainly consisted out of large and solids in addition with some pathogens. The system copes with these by a coarse filter, first flush barrel system and a sand filter. The coarse filter is responsible for large organic matter, for example leaves, the first flush system for settable solids, like sand, and the sand filter is responsible for filtration of smaller particles and pathogens. Potentially the filter rinses the water by biological processes, though this is purely hypothetical.

According Phillippine law waste water may not discharged directly on surface water, therefore wastewater should be treated. According the design requirements there is a demand for a low or no enrgy usage for the water treatment. Main contaminants to be treated were suspended solids, BOD/COD, pathogens, nitrogen and phosphates. To cope with these contaminants a treatment consisting of a septic tank and a wetland filter is constructed. The septic tank reduces BOD and solids, while the wetland filters out more solids and treats pathogens, nitrogen and phosphates in the water. Usage in the home of heavy chemicals and drugs should be limited to a minimum.

The last part of the solution is the storage facility of the home, which should be capable of storage of 4,400 L to 6,400 L. There should be an efficient storage for this volume, without the possibility of backflow between tanks. Therefore, a special piping system is designed such that unfavoured backflow of water is not possible.

Other aspects discussed are integration, maintenance and adaptation of the human water system. All the components of the human water system are integrated in within the existing design of the structure and modules. Important are the connections from the roof till modules because these will influence the complete system. Since the separate systems are integrated within the systems original sizes and measurements the human water system can be expended and adapted to its needs. Though, expansion of the system requires a higher water need within the household. Since there is already waterstress within the house, there should be looked into a solution for these problems. Most promising solutions could be a tap connection to the local water distribution system or waste water reuse, which would need an extensive treatment and energy input.

Maintenance of the system is very important, influencing both human and environmental factors. The design is made to have a low maintenance rate, though the systems wetland filter has a higher maintenance rate. Furthermore, the coarse filter has to be checked after large rainshower, the first flush barrel and sand filter on a yearly basis, as well the septic tank. The wetland requires monthly maintenance since the vegetation needs to be checked and the filter needs to be restructured.

The human water system is an integrated sustainable and durable solution with a low maintenance rate. Though, water demand is not meet, so there are some questions regarding distribution of additional sources.

The social acceptance of the system is not completely assured. The human water system requires some maintenance and is different than current systems. Nonetheless, the need for treatment of both rainwater and waste water is critical for a healthy (living) environment.

5 Design of the mooring system

A floating structure is surrounded and partially supported by water. Unlike structures on soil, horizontal stability cannot be achieved by water because only buoyancy forces are acting on the structure. Friction forces at surface interfaces are negligible. A mooring system is needed to guarantee the horizontal stability. However, mooring systems influence the behaviour of the floating object under load. During the design of a mooring system this should be kept in mind, otherwise the motions or forces are computed incorrectly. This can cause forces larger than realistically occur.

In this chapter the mooring system is (re)designed. The main goal of the mooring system is keeping the floating house on the predetermined location. Even when a typhoon hits the area, the floating house should remain at that location. The conditions during typhoons are severe, though the mooring system has to withstand these extreme conditions. The mooring system has failed when the structure is detached from the mooring piles and drifts away from its location. Failure is unacceptable as the structure can be heavily damaged when detached from the mooring system (impact forces). When failure occurs the costs and time required to repair the system is deemed too high and not typhoon resilient and therefore unacceptable.

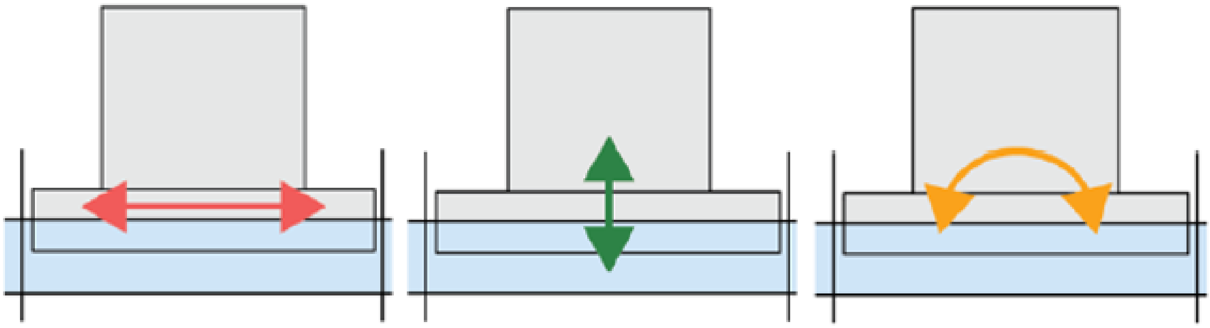

Figure 5.1 Motions of floating house that generate forces on the mooring system (Ham P. , 2016)

Before the mooring system is designed, the forces on the mooring system have to be determined. Three main phenomena that cause loads are distinguished: wind, waves and current. These loads sets the floating house into motion, see Figure 5.1. Wind loads on the house are already determined in chapter 3. However, the total wind force is needed for the design of the mooring system. The earlier used definitions of SLS and ULS are adopted in this chapter. Using the wind velocities, from these conditions the wave statistics, wind set-up and current are determined, each causing a load on the structure. These loads are translated into forces from which the dynamic motions can be determined. The motions generate loads on the mooring system while the mooring system limits motions causing a coupled system. This coupled system is solved for a fixed and free connection. A semi-free connection where the free motion is partially limited creates a non-linear problem that is not within the scope of this project. Besides wind, waves and current loads another aspect should be taken into account. For sanitary and drinking water purposes the structure is able to use barrels from the foundation as storage units, chapter 4. The volume and distribution of the water storage is extra mass and can cause eccentric loads. The effect of the water storage is determined.

Analysing the behaviour of the structure independently of the mooring system is not always possible. For horizontal motions the free motion is unbounded without a mooring system. This behaviour is analysed and is not solvable without the mooring system. A coupling system is required to design the mooring system. This coupling is extensively studied in section 5.5.

5.1 Hydrodynamic conditions

The first step to determine the loads on the structure is to determine the hydrodynamic conditions. In still water the weight of the structure is balanced with the buoyancy force. When the water is disturbed due to external forces it influences the structure These external forces, as wind, wave and currents are determining the hydrodynamic conditions, which will be discussed in this chapter. The wave conditions are statistically determined. Wind set-up, the water level gradient that occurs in a (semi) closed basin due to wind, and current are computed using software package Delft3D. An analytical solution for the wind set-up and current is derived and compared with Delft3D output. These computations are done for both SLS and ULS conditions, predetermined in chapter 3.

5.1.1 Wave statistics

In this section the significant wave height, peak period and corresponding wave length are computed for a range of wind velocities and water depths. Wind induced waves (wind waves for short) are waves caused by friction at the air-water boundary. As air moves over a water body, friction and pressures at the boundary destabilise the water surface, known as Kelvin-Helmoltz instabilities. These small disturbances (capillary waves) can grow when the change in friction and pressure resonate with the rising and falling of the water surface. This theory is shown in Figure 5.2. A lot of research on the growth of these waves in deep and shallow water is already done. As the water depth of the project location is maximum 2.5 m it is assumed that the waves are generated in shallow water with a flat bottom. Young & Verhagen (Young & Verhagen, 1995) developed a formula where the limited water depth is taken into account in the growth of waves. These formulas are presented as Eq. 5.2 and Eq. 5.3. The formulas use fetch, wind velocity and water depth as input, see Eq. 5.1. It is a modified version of the Sverdrup-Munk-Bretschneider formula used for deep water. From these formulas the significant wave height H_s and peak period T_p, the most common wave period, are computed. Using Eq. 5.4, the dispersion relation, the wave length is found iteratively.

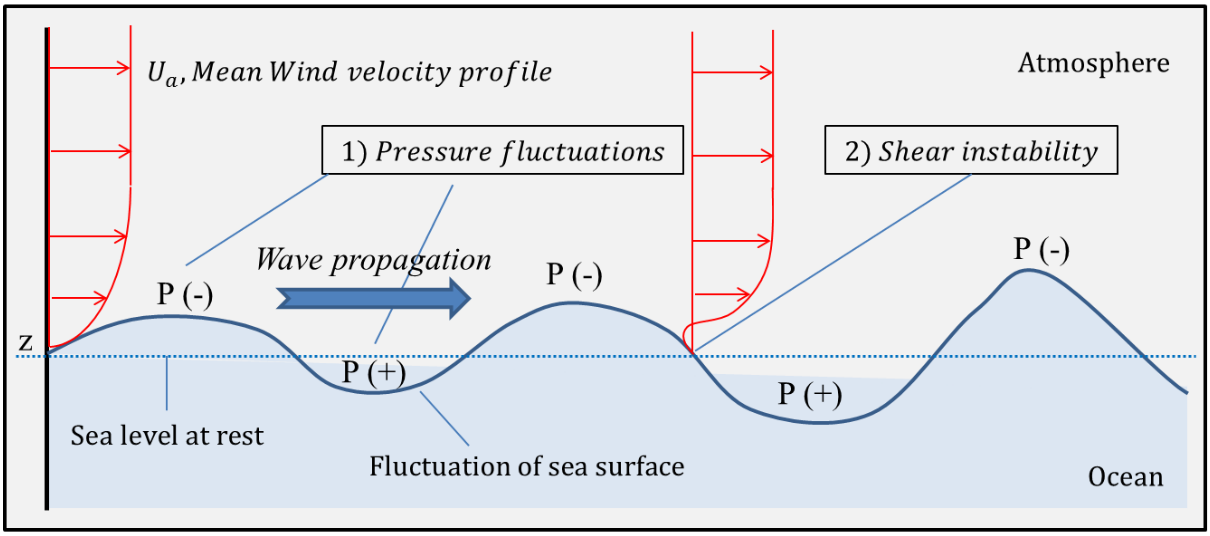

Figure 5.2 Growth of wind induced waves (Yang)

$$\tilde{d} = \frac{gd}{v_{b,0}^2} \qquad \widetilde{F_F} = \frac{gF_F}{v_{b,0}^2} \tag{5.1}$$

$$\frac{gH_s}{v_{b,0}^2} = 0.24\left(\tanh\left(0.343\tilde{d}^{1.14}\right) \cdot \tanh\left(\frac{4.14 \cdot 10 \cdot \widetilde{F_F}^{0.79}}{\tanh\left(0.343\tilde{d}^{1.14}\right)}\right)\right)^{0.572} \tag{5.2}$$

$$\frac{gT_p}{v_{b,0}} = 7.69\left(\tanh\left(0.100\tilde{d}^{2.01}\right) \cdot \tanh\left(\frac{2.77 \cdot 10 \cdot \widetilde{F_F}^{1.45}}{\tanh\left(0.100\tilde{d}^{2.01}\right)}\right)\right)^{0.187} \tag{5.3}$$

$$L = \frac{gT_p^2}{2\pi} \cdot \tanh\left(\frac{2\pi d}{L}\right) \tag{5.4}$$

As mentioned in chapter 3, the SLS condition is a tropical storm with wind velocities up to 32 m/s. The ULS condition is a typhoon with wind velocities up to 49 m/s. A range of wind velocities is used to assess the growth of the waves with increasing velocities. The fetch of the wind is set at 500 m. This is estimated to be the effective fetch of the wind at the pilot location. The depth of the lake is approximately 2.5 m everywhere. Smaller depths are possible, but input is limited to 1.5 m. Depths lower than 1.5 m are not within the scope of this project. Interactions between the bottom of the lake and the structure change the dynamic behaviour outside of the computation possibilities for this project. The parameters for both conditions are given in Table 5.1 as well as the computational input.

Table 5.1 Input parameters for calculation of wave conditions

	SLS	**ULS**	**Input**
Fetch	500 m	500 m	500 m
Wind velocity	32 m/s	49 m/s	1 – 59 m/s
Water depth	2.5 m	2.5 m	{1.5, 1.75, 2.0, 2.25, 2.5}

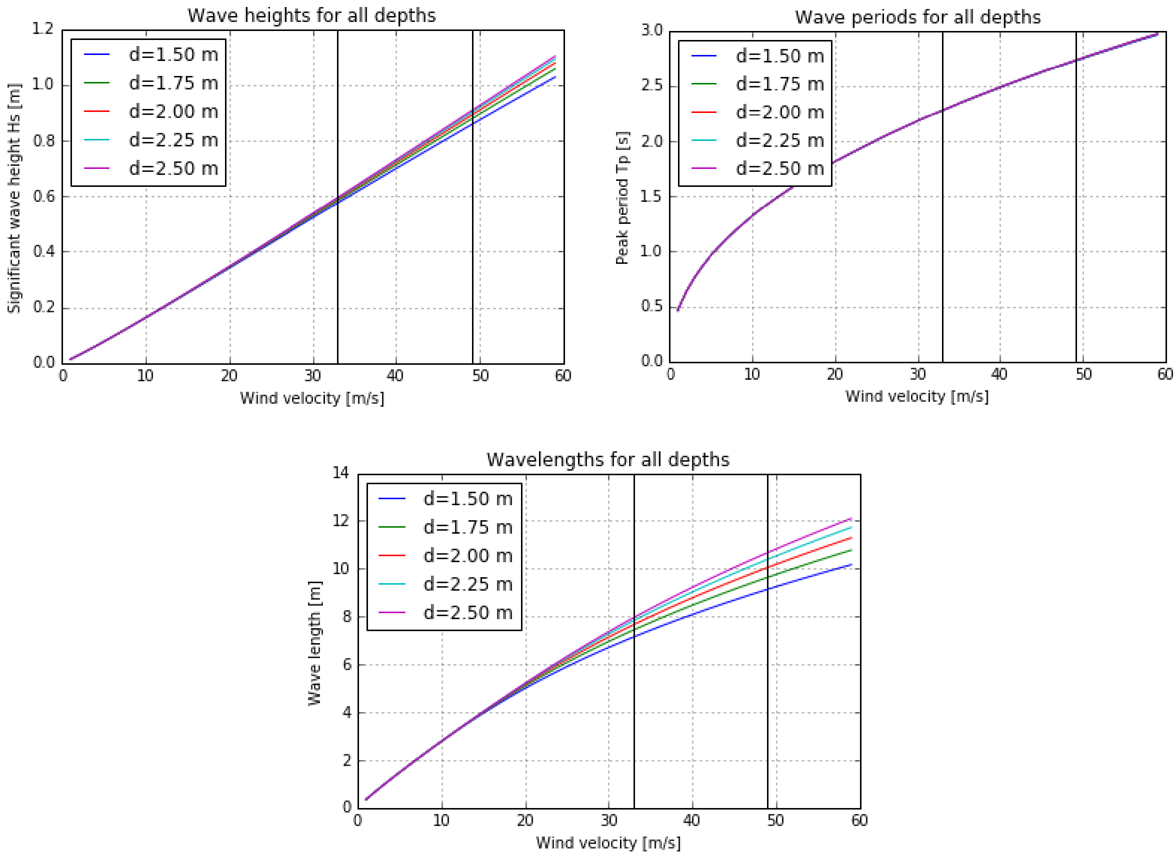

Figure 5.3 Resulting wave heights, wave periods and wave lengths

The results are plotted in Figure 5.3 for several water depths as a function of the wind speed. Wave heights diverge around 15 m/s, indicating the influence of the water depth on the growth of the waves. However, the wave periods are similar for all water depths indicating that the depth has no influence on the peak period of the waves. Computing the wavelengths for these wave periods shows the relation with the water depth. Waves in smaller depths have similar periods but shorter wavelengths. For waves of similar height this means that in smaller depths the waves are steeper representing a more mature wave state (in deeper water waves are able to achieve larger wave heights as the influence of bottom friction is less). The two black vertical bars indicate the SLS and ULS conditions. In Table 5.2 the results for SLS and ULS in 2.5 m water depth are given. Waves in 2.5 m water depth are larger in height which leads to higher loads on the structure. For all results see Appendix D. The water depth over wave length ratio is an indication of the water depth condition. Waves in water with ratios smaller than 0.05 are considered to propagate in shallow water, values larger than 0.5 in deep water. In between the condition is intermediate, which is the case for this project. For further research the waves are considered to propagate in deep water. A Rayleigh distribution is related to waves in deep water. Assuming this distribution an overestimation of the wave height is done, estimated to be small enough for the assumption to hold

Table 5.2 Wave conditions for SLS and ULS

Water depth = 2.5 m	SLS ($v_{b,0}$=32 m/s)	ULS ($v_{b,0}$=49 m/s)
H_s	0.575 m	0.906 m
T_p	2.246 s	2.730 s
L	7.757 m	10.671 m
d/L	0.322 -	0.234 -

5.1.2 Wind set-up and current

The shear stress from wind blowing over a water surface generates a current in the direction of the wind. This current causes the water level to rise at the far end of the fetch and lower at the opposite end. The water level gradient, known as wind set-up, generates a return flow near the bottom. This interaction is known as vertical circulation. Assuming that the wind shear stress is constant in space and time this process continues until the depth averaged current equals zero (stationary situation). The water level gradient is maximum and the velocity profile is in equilibrium.

Delft3D is used to numerically determine the wind set-up and the velocity profile. The domain of the numerical computations is a rectangular basin of 200 x 500 m (2 x 50 cells) of 2.5 m (50 layers each 0.05 m) depth. Wind from the east is generated from zero to storm or typhoon velocity linearly in six hours and remains this value for another six hours. This to ensure that the equilibrium situation is achieved in the computation. For all Delft3D input parameters, see Appendix E.1.

The velocity profile and water level gradient can be analytically approximated with the following equations (Zitman, 2017):

$$u(z) = v_{b,0}^2 \frac{d^2}{\nu_{t,vag}} \left(\frac{0.0505^2 \rho_{air}}{\rho_w} \ln\left(\frac{z-\beta}{z_0} \cdot \frac{\zeta - (z_0+\beta)}{\zeta - z} \right) - c_W \ln\left(\frac{z-\beta}{z_0} \right) \right) \tag{5.5}$$

$$d(x) = \sqrt{2 c_W \frac{v_{b,0}^2}{g} (x - x_0) + d_0^2} \tag{5.6}$$

The accuracy of the solutions compared to Delft3D is very dependent on the parameter input, which are difficult to determine. For derivation and explanation, see Appendix E.2. The largest influence of the analytical solution is the use of $\nu_{t,avg}$ and c_w which are theoretically undefined. The wind set-up and currents from the Delft3D computations are plotted in Figure 5.4.

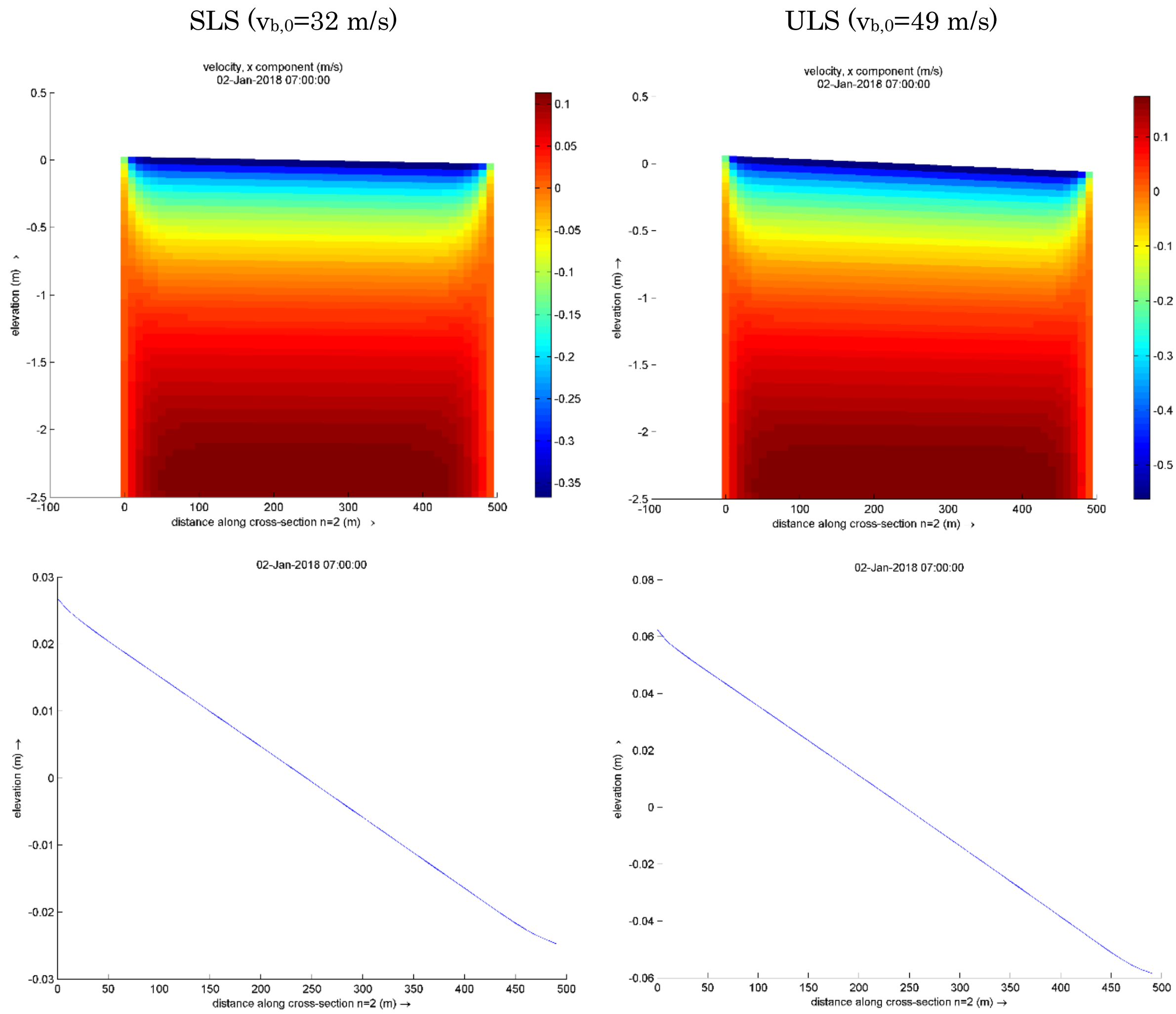

Figure 5.4 Wind set-up and currents from Delft3D (left tropical storm, right typhoon conditions)

From the top figures of Figure 5.4 the maximum surface and bottom current can be determined for both conditions. The bottom figures show the water level difference with the still water level. Notice that the depth at which the current equals zero is the same for both conditions but the maximum currents are larger during a typhoon, as expected. Also, for a wind velocity that is 1.5 times larger than during a storm, a typhoon wind generates a more than twice as large water level difference. The results are summarised in Table 5.3.

Table 5.3 Wind set-up and current results

	Storm	**Typhoon**
Maximum surface velocity	$0.37\ m/s$	$0.56\ m/s$
Water level gradient	$1.03 \cdot 10^{-4}$	$2.42 \cdot 10^{-4}$

5.2 External forces

The known hydrodynamic conditions are translated into external forces. When waves propagate the changing pressures generate forces on a floating structure. This happens in the vertical direction as a result from the wave height, and it happens as a turning moment as a result from the wave shape (harmonic). The turning moment is also dependent on the wave period (and thus wave length). Besides this, the water level gradient generates a hydrostatic pressure difference over the structure length and the current converts the momentum of water into a force. Together these forces (wave, wind set-up and current) are the external forces acting on the structure.

5.2.1 Hydrodynamic forces

The hydrodynamic forces can be calculated from the wave conditions determined in the previous section. The wave conditions are simplified by assuming that all waves propagate in the same direction. Moreover, act perpendicular to one of the platform edges. The force of undisturbed waves is called the Froude-Krilov force. This force does not take into account the presence of the floating structure. An incoming wave is mathematically described by Eq. 5.7 if it propagates in x-direction.

$$\zeta = \zeta_a \cdot \cos(\omega t - k_w x) \tag{5.7}$$

The formula states that the wave amplitude is dependent on space and time. The pressure in the wave has the same harmonic function. Integrating the wave pressure along the submersed area of the platform results in a force. It turns out that a horizontal force, a vertical force and a turning moment are present during a passing wave. The turning moment is calculated with respect to the coordinate system indicated in Figure 5.5.

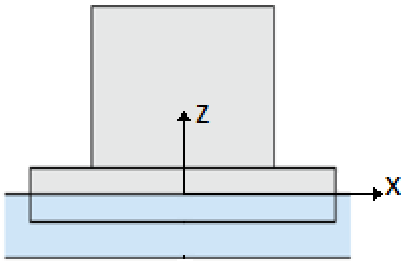

Figure 5.5 Location of the origin of the axes (Ham, 2016)

The forces and turning moment are only a harmonic function in time, like Eq. 5.8. It can have a small phase angle with the wave, but for the required computations this is negligible.

$$F = F_a \cdot \cos(\omega t + \varepsilon) \tag{5.8}$$

The amplitude of the force is a function of the wave amplitude, wave length, wave frequency and water depth. The forces are used to calculate the motions of the structure. As mentioned in section 5.1.1 the depth is taken equal to 2.5 m. The determination of the wave amplitude is more difficult, because wave frequency and wave amplitude are not linked. The only known parameters from Young & Verhagen are H_s and T_p. It is not per definition true that only waves with this height and period are formed. A wave with a particular wave height can have all possible wave periods as long as the wave is not affected by capillary forces (water surface tension) or breaks (steepness). To draw the so-called wave spectrum, which indicates the energy of the waves at every frequency, measurements of the project site are needed. In this report the most likely wave period and wave height are coupled. The most frequent wave period is T_p, the most frequent wave height is H_{mode}. The most frequent wave height can be calculated from the significant wave height by assuming a Rayleigh distribution of the wave heights (for deep water conditions, explained in section 5.1.1. The Rayleigh distribution and the two particular wave heights are shown in Figure 5.6 (left). With the probability density function of the Rayleigh distribution formula of the distribution Figure 5.6 (right) is constructed. The wave heights in this plot is used to calculate the wave forces.

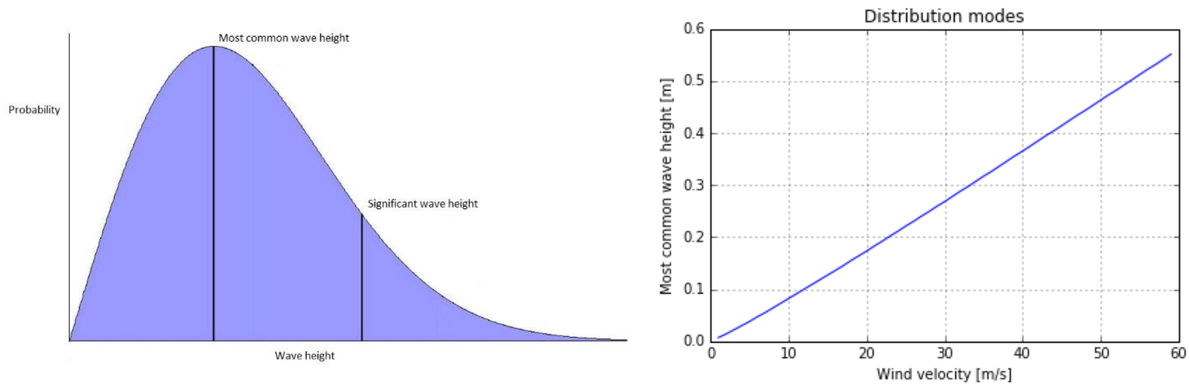

Figure 5.6 (Left) Rayleigh distribution (Berg & Rhome, 2005) (Right) Distribution modes

The exact calculation procedure of the wave forces can be found in Appendix F.1. Figure 5.7 shows the dynamic wave force amplitude as function of only the wave frequency. The shape of the curves will be discussed when the motions of the structure are analysed.

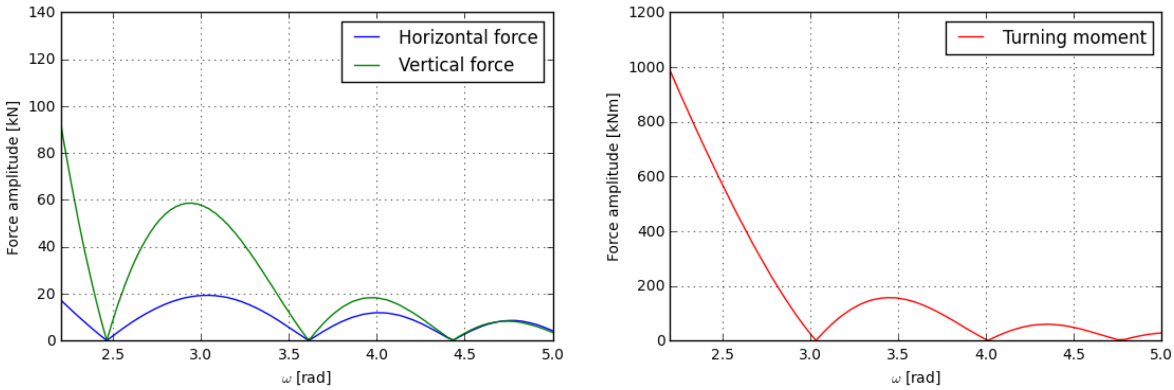

Figure 5.7 (Left) Dynamic horizontal and vertical force due to waves (Right) Turning moment due to waves

The water level gradient and currents are constant in space and time. The current pushes the structure in the direction of the flow (momentum), while the water level gradient pushes the structure in opposite direction (hydrostatic). This is drawn in Figure 5.8. Due to the water level gradient the structure tilts. For (very) small gradients the current still acts on the full draft. So also, the current results in horizontal forces and turning moments.

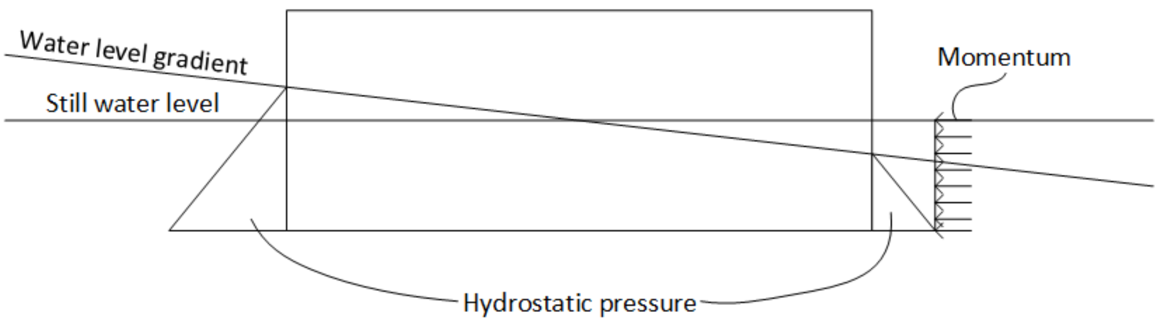

Figure 5.1 Resulting external forces due to wind set-up and current

The water level gradient is easily found by dividing the water level difference between both ends of the basin by the basin length.

$$i = \frac{d_{x=0} - d_{x=L}}{L} \tag{5.9}$$

The current velocity over the draft changes quickly. After 0.325 m, which is approximately the draft of the floating house, the velocity is already 40% of the average velocity in the top layer (first 5 cm). Therefore, the depth-average velocity over the draft is used for the momentum. The forces due to a hydrostatic difference and current per meter width are given in Eq. 5.10 and 5.11 respectively.

$$F_h = \frac{1}{2}\rho_w g (i l_s)^2 \tag{5.10}$$

Where l_s is the structure length.

$$F_c = \frac{1}{2}\rho_w D u_{draft}^2 \tag{5.11}$$

The total force on the structure (F_t) is determined by multiplying the forces by the structure width (b_s).

$$F_t = F_h b_s - F_c b_s \tag{5.12}$$

The results are given in Table 5.4.

Table 5.4 Resulting horizontal forces due to wind set-up and current

	Storm	Typhoon
i	$1.033 \cdot 10^{-4}$	$2.423 \cdot 10^{-4}$
u_{draft}	$0.21\ m/s$	$0.39\ m/s$
F_h	$4.84 \cdot 10^{-2}\ N$	$2.66 \cdot 10^{-1}\ N$
F_c	$68.13\ N$	$234.98\ N$
F_t	$-68.09\ N$	$-234.71\ N$

A quick comparison with Figure 5.7 shows that the horizontal forces due to the currents are very small. The same is true for the turning moment. Concluding, the forces due to wind set-up and current can be neglected.

5.2.2 Wind forces

Another resulting force is caused by the wind. Just like the forces due to wind set-up and current the wind forces are constant in space and time. The wind forces are earlier addressed in the Appendix A.4. In this appendix a horizontal force of 74.31 kN is given. Because the wind mainly acts on the house of the floating structure a turning moment is created. The calculated turning moment is equal to 152.45 kNm. The resulting moment is calculated with respect to the same point as for the turning moment due to the waves.

5.3 Dynamic behaviour

The external forces set the structure into motion. The wave, wind and current forces act on the structure simultaneously. The wind set-up and current forces are very small compared to the wave and wind forces and thus neglected in the calculations. The motions are determined using a general equation of motion where six degrees of freedom need to be solved. This coupled system can be simplified because the structure is 3D symmetric and such three motions remain: heave, surge, and pitch. These motions in turn generate the forces acting on the mooring system.

5.3.1 General equation of motion

Initially, the presence of the mooring system is neglected, because the outline of the mooring system is not known yet. Consequently, the floating structure will move freely in six degrees. The six degrees and the definitions of the motions are displayed in Figure 5.9 (Journée & Massie, 2008) and Table 5.5.

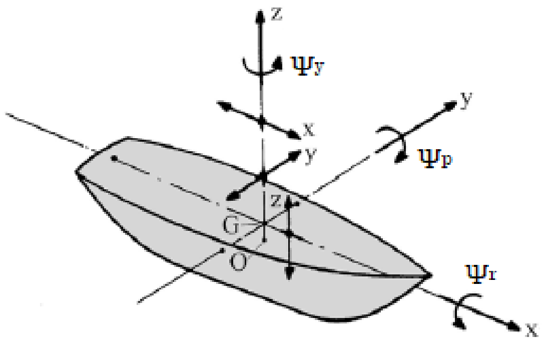

Figure 5.9 Symbols of six degrees of freedom (Journée & Massie, 2008)

Table 5.5 Definitions of six degrees of motion

Motion	Direction
1. Surge	Translation in x-direction
2. Sway	Translation in y-direction
3. Heave	Translation in z-direction
4. Roll	Rotation around x-direction
5. Pitch	Rotation around y-direction
6. Yaw	Rotation around z-direction

These six motions are the result of the forces and turning moments. The number of the degree of freedom is often used in the equations (e.g. k_1 is correlated with surge motion). The motions of the structure in each direction of freedom can be calculated by use of Newton's second law.

$$F = Ma \quad (5.13)$$

From now on the sway acceleration is denoted as $\ddot{x}$, which means the second derivative in time of the displacement. The mass and dimensions of the structure are obtained from (Ham, 2016). The house is supported using a floating platform of 9.6 x 9.6 m. The foundation consists of 32 modules of 1.2 x 2.4 m. Each module contains eight barrels with a mean area 0.2256 m^2. The self-weight and acting live loads result in a draft 0.314 m. Since the mass of the structure is equal to the mass of the displaced water volume:

$$M = \rho \text{AD} \cdot \#\text{barrels} = 1{,}025 \cdot 0.2256 \cdot 0.314 \cdot 8 \cdot 32 = 18{,}588 \; kg \quad (5.14)$$

The mass calculated in Eq. 5.14 does not include the water storage calculated in chapter 4. A sensitivity analysis of the mass due to water storage is added to the section 5.5.3. The floating house will be analysed in three situations. Firstly, without waves and motions, secondly without waves and with motions and thirdly with waves and without motions. All forces and motions are linearized which means that the total can be obtained by superposition. This procedure is performed in Appendix F.2. Eq. 5.15 is the resulting formula. There is extra inertia/mass added, damping and a restoring force is introduced. The excitation force only consists of the Froude-Krilov force. The horizontal force causes sway motion, the vertical force heave and the turning moment pitch.

$$(M + a)\ddot{x} + c\dot{x} + kx = F_{FK} \tag{5.15}$$

Eq. 5.15 is the equation of motion for surge. A similar equation can be formulated for the other five degrees of freedom. The Froude-Krilov force in direction 2, 4 and 6 is zero. Beware that for direction 5 the force is expressed in kNm and that instead of the mass, the moment of inertia has to be used. This is caused by the fact that this degree of freedom is a form of rotation, while surge and heave are translations.

5.3.2 Determination of factors in eq. of motion

The added mass, added damping and restoring coefficient in Eq. 5.15 are still unknown. The hydrodynamic forces are generally calculated with the help of other wave potentials than used in the Froude-Krilov force. In total six extra wave potentials have to be found which fulfil the six boundary conditions. Software is usually used for solving the potentials. One reason for using software is the coupling of the equations of motions. This coupling means that a motion in one direction results in forces in the other direction. For clarification Figure 5.10 is added.

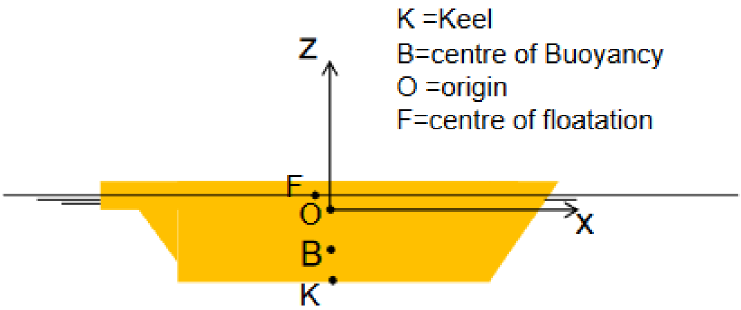

Figure 5.10 Coupling of equations of motion (Schreier & Naaijen, 2017)

In this example the effect of heave motion on pitch is examined. In Figure 5.10 the origin of the axis is not the same as the centre of floatation. When the ship moves downward, extra upward pressure is created at the total water plane area. The water plane area left and right of the centre of floatation is the same, which means that the water plane area left of the origin is larger than at the right. A turning moment is created which is equal to an exciting force in the equation of motion of the pitch motion. When the heave motion is more severe, at the left side of the ship the water plane area suddenly decreases. This will result in an exciting force in the equation of motion of pitch too.

Because of the coupling between the six degrees of freedom one ends up with 36 factors for the added mass as well as the added damping and the restoring coefficient. The added mass matrix with all its entries is shown below.

$$a = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & a_{26} \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} & a_{36} \\ a_{41} & a_{42} & a_{43} & a_{44} & a_{45} & a_{46} \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} & a_{56} \\ a_{61} & a_{62} & a_{63} & a_{64} & a_{65} & a_{66} \end{bmatrix} \tag{5.16}$$

By locating the origin at the centre of floatation, like in Figure 5.5 and the 3D-symmetry of the foundation of the floating structure, all coupled terms are zero. The only non-zero factors in the matrices are the diagonal terms (Brennen, 2006). The equations that are left are the uncoupled six equations of motions. Therefore, it is possible to make an analytical approximation of the motions of the floating structure.

However, the added mass and damping coefficient are dependent on the wave frequency. A lot of wave frequencies are possible as mentioned earlier and therefore each equation of motion needs to be solved for a range of wave frequencies. The added mass and damping is obtained from graphs. These graphs may only be used under certain conditions. The graphs can be used for the floating house, see Appendix G. The graphs show the added mass and damping per meter length of the structure as a function of the wave frequency. In the case of the floating house the value from the graph has to be multiplied with the width of 9.6 m. The used graphs have some limitations:

- The added mass and damping are also dependent on the width and draft of the structure and the ratio between them. It can be imagined that a connected foundation module has more added mass than one foundation module. The graphs only show the added mass and damping coefficients for ratios of two, four and eight, while this ratio is 30 for the floating house.
- At last, there is a dependency related to the water depth. Smaller water depths introduce interactions between the vibrating structure and the bottom, increasing the added mass. However, the ratio of draft over water depth in ULS is equal to 2.5 m / 0.314 m ≈ 8. The effects of shallow water can be neglected for every degree of freedom for ratios larger than 4, so this does not influence the rest of the calculation. (Xiong, Lu, Yang, & Zhao, 2015)

The final determination of the added mass and damping coefficients is done for each individual motion. First, the restoring coefficient k is addressed. The restoring coefficient due to the water is much easier obtained than the added mass and damping. From static analysis the restoring coefficients can be calculated. This has already been computed by (Ham, 2016). These results are copied and are presented below.

Table 5.6 Restoring coefficients

Degree of freedom	Restoring coefficient k
1	0
2	0
3	$k_{33} = \frac{\rho g \nabla}{D} = \frac{1025 \cdot 10 \cdot 0.2925 \cdot 8 \cdot 32 \cdot 0.314}{0.314} = 767.5\ kN/m$ (5.17)
4	$k_{44} = \rho g \nabla \overline{GM} = 1025 \cdot 10 \cdot 0.2925 \cdot 8 \cdot 32 \cdot 0.314 \cdot 22 = 5302\ kNm/rad$ (5.18)
5	$k_{55} = \rho g \nabla \overline{GM} = 5302\ kNm/rad$ (5.19)
6	0

Notice that water does not generate a restoring force in direction 1,2 and 6. This is logical, because a horizontal movement of the structure does not result in a change of the pressure around the structure. The restoring force in these directions has to be developed by the mooring system.

In the next sections the motions in the directions 3, 4 and 5 (all other directions are zero) will be analysed starting with direction 3 (heave) because the mooring system will not influence the vertical motion. Every motion will be analysed in the same way. The equation of motion given, the added mass and damping coefficients are determined using the graphs, the force amplitude is plotted, and the motion amplitude is calculated with Eq. 5.20.

$$x = \frac{F_a}{\sqrt{(k - (M + a)\omega^2)^2 + (c\omega)^2}} \tag{5.20}$$

5.3.3 Heave motion

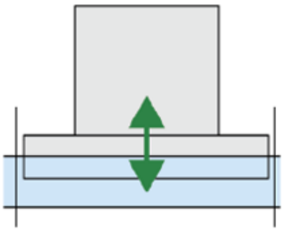

Figure 5.2 Visualisation heave motion

As the structure should be able to move up and down with the varying water levels in the fishpond, the mooring system does not play a role in the vertical motion of the floating structure. The resulting equation of motion is shown in Eq. 5.21.

The restoring coefficient and the excitation force are already known. The added mass and damping per meter width result from the following graphs in Figure 5.12. Note the modified wave frequency on the horizontal axis.

$$(M + a_{33})\ddot{z} + c_{33}\dot{z} + k_{33}z = F_3 \tag{5.21}$$

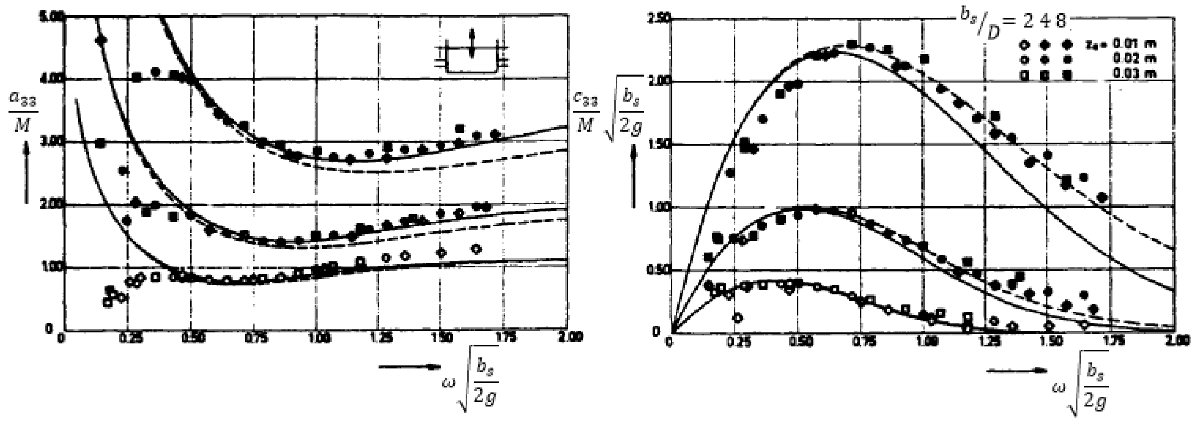

Figure 5.12 Added mass (left) and damping (right) graphs for heave motion (Lewis, 1989)

From wave analysis the peak wave period equals 2.73 s. The frequency of this wave is 2.30 rad/s. This means that only the right part of the graph will be used (from 1.59 to 2.00). Analysing this part of the graph of the added mass it looks like the curves behave asymptotically for very high frequencies. Evidence for this is found in the paper of (Koo & Kim, 2015). The added damping goes to zero for very high values of the frequency. It is imaginable that in the case of short motions of the floating structure smaller waves deviate from these motions. The energy of waves is proportional with the wave height squared, so consequentially less damping, loss of energy, is introduced in the system. The curves only show the exact values for a width over draft ratio of two, four and eight. For the design of the floating house this ratio is 30, so the added mass and damping has to be guesstimated. This has to be done with great care to remain conservative.

The amplitude of the motion is a function of the incoming wave. The force amplitude of the wave is plotted in Figure 5.13 with the same modified wave frequency as in Figure 5.12 on the horizontal axis, which makes comparison easier.

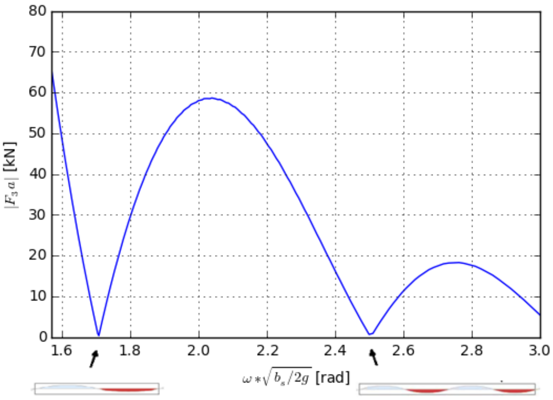

Figure 5.13 Force amplitude for heave motion (Ham, 2016)

The form of the graph can easily be explained with the help of (Ham, 2016). Figures from (Ham, 2016) indicate the situations of zero excitation force. A modified wave frequency of 1.7 rad/s^2 leads to a wave length of 9.6 m, exactly the same as the length of the foundation. The upward pressure caused by the wave crest is in equilibrium with the deficit of pressure at the wave trough. At a modified wave frequency of 2.5 rad/s^2 the wave length is equal to half the foundation length leading to the same effect.

The influence of the added mass and damping graphs can be seen by determining the amplitude of the resulting heave motion. The determination of the added mass and damping factors is extensively explained in Appendix H.1. In short, the added mass coefficients that result in resonance are computed for a range of frequencies. It is considered that this added mass coefficient is realistic with a guesstimate from Figure 5.12. Moreover, the uncertainty is addressed by a sensitivity analysis.

From Appendix H.1 it is clear that resonance can only occur at frequencies of approximately 2.30-2.50 rad/s. At higher frequencies the added mass is too large to create resonance. In the right graph of Figure 5.12 the damping is also large for these frequencies. It turns out that this damping is enough to limit the motion amplitude to 0.83 m. Bare your mind that this should be interpreted with care, because this is the most unfavourable situation when the added mass causes resonance. By guesstimating it is not possible to verify if this added mass coefficient will be induced in reality. Another fact which should not be forgotten is the distinction between SLS and ULS. The peak frequency of waves in SLS is 2.8 rad/s. Thus resonance is unlikely to occur. In ULS where resonance is more likely to occur inhabitants are evacuated so no human lives are in danger.

Not only the resonance frequencies are important to look into. The force amplitude can be a significant factor as it is large at frequencies around 3.00 rad/s. It is therefore important to analyse these frequencies too. Motion amplitudes of 0.40 m occur at these frequencies, while the wave amplitude is less than half of that. Because all factors are taken conservative, it is quite sure that the motions are not larger than this, but it cannot be said that the motions are definitely smaller. From the sensitivity analysis it can be concluded that the calculated numbers are only obtained by some specific combinations of added mass and damping coefficients. A slightly different combination leads to a 50% reduction of the motion amplitude. On the other hand, these values are calculated with the most frequent values of the Rayleigh-distribution, which means that there are much larger waves possible increasing the motion amplitude. A more precise analysis can be done with software.

5.3.4 Surge motion

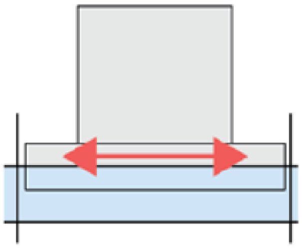

Figure 5.3 Visualisation surge motion

The motions that are calculated in this section are valid for surge when waves propagate in x-direction. When the waves propagate in y-direction the resulting sway motion is the same due to symmetry. Waves approaching the structure with an angle not perpendicular to the platform create a combination of surge and sway, but the motion of both is always smaller than what is calculated next. The equation of motion for surge is presented in Eq. 5.22.

The largest difference with the heave motion is the restoring coefficient. For this horizontal motion the water does not provide a restoring force. This restoring force has to be provided by the mooring system, but is still unknown.

The largest difference with the heave motion is the restoring coefficient. For this horizontal motion the water does not provide a restoring force. This restoring force has to be provided by the mooring system, but is still unknown.

$$(M + a_{11})\ddot{x} + c_{11}\dot{x} + k_{11}x = F_1 \tag{5.22}$$

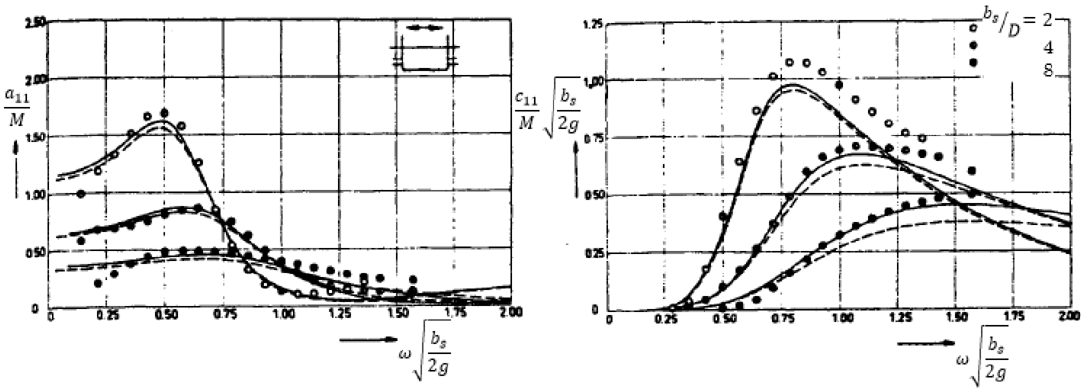

Figure 5.15 Added mass (left) and damping (right) graphs for surge motion (Lewis, 1989)

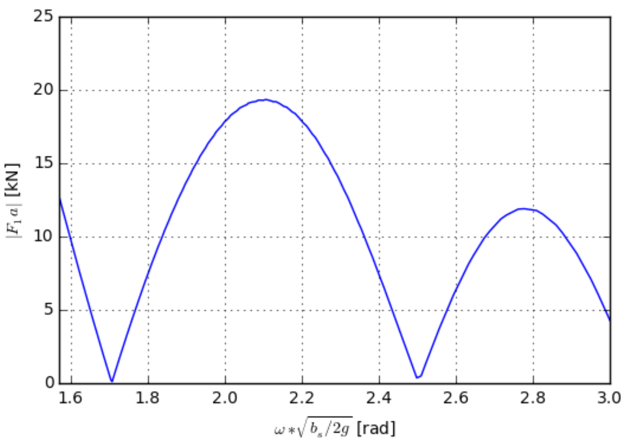

Figure 5.16 Force amplitude for surge motion

In Figure 5.15 and Figure 5.16 the added mass and damping curves and the force amplitude as function of the modified frequency are shown respectively. Especially the graph of the force amplitude looks the same as in the case of heave motion. The amplitude goes to zero at exactly the same frequencies. But note that the maximum force amplitude is a lot smaller than in the case of heave motion. The added mass coefficient is very small for the frequency range of the exciting waves and the added damping coefficient is a little bit smaller than the added damping coefficient for heave motion.

Again, a conservative approach is used. The damping coefficient for the higher frequencies is taken equal to 0.25. In Appendix H.2 the restoring coefficients causing resonance at the exciting frequencies are calculated. It turns out that the resonance will possibly occur for restoring coefficient larger than 98.3 kN/m. In Appendix H.2 the resulting motion amplitudes are calculated in the case of a restoring coefficient of 90.0 kN/m. It turns out that the horizontal amplitudes become 1.19 m in ULS and maximum 0.53 m in SLS.

5.3.5 Pitch motion

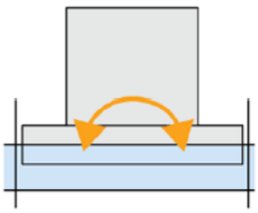

Figure 5.4 Visualisation pitch motion

The equation of motion for pitch is shown in Eq. 5.23. This equation is different from Eq. 5.21 and Eq. 5.22, because now the motion is a rotation instead of a translation. The mass of the structure is replaced by its moment of inertia. The motion itself, Ψ_p is expressed in radians instead of meters. The force F_5 is actually a turning moment. The moment of inertia of 141,470 kgm^2 is calculated from structure dimensions determined by (Ham, 2016) and (Schaik, 2016). The added mass and damping curves can be seen in Figure 5.18. Figure 5.19 shows the amplitude of the excitation force, which should be interpreted as a moment.

$$(I_{yy} + a_{55})\ddot{\Psi}_p + c_{55}\dot{\Psi}_p + k_{55}\Psi_p = F_5 \tag{5.23}$$

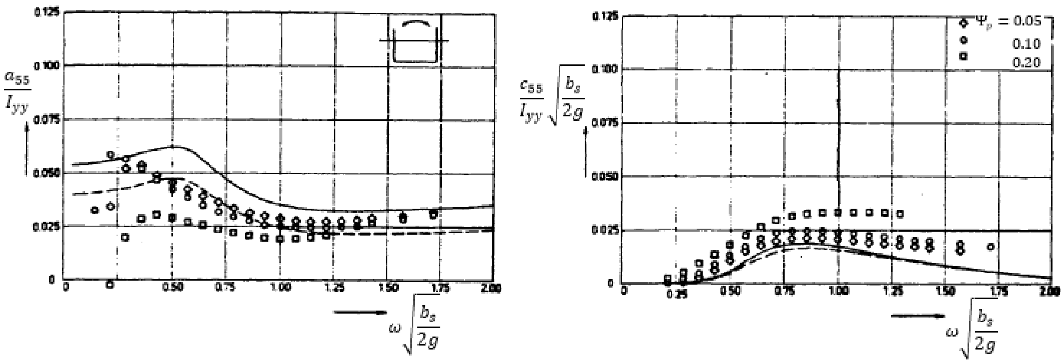

Figure 5.18 Added mass (left) and damping (right) graphs for pitch motion (Lewis, 1989)

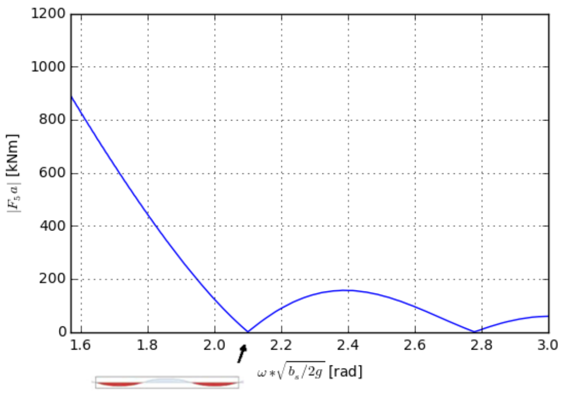

Figure 5.19 Force amplitude for pitch motion (Ham, 2016)

The graphs are slightly different from the graphs used in the analysis of the heave and pitch motion. The parameters on the vertical axis in Figure 5.18 changed due to the change of the equation of motion. The added mass and damping no longer depend on the width over draft ratio. The values for the added mass and damping are small compared to heave and surge.

The amplitude of the force shows the same damped behaviour. However, the damping is much stronger, so consequentially the force at high frequencies is much smaller. The frequencies at which the force is zero are different, too. In accordance with the results of (Ham, 2016) the force is zero when the foundation length is one and a half times the wave length. As can be seen in Figure 5.19 the wave troughs are situated at the sides in this situation with the wave crest in the middle. This results in equilibrium and thus no external moment. Linking this knowledge to the other two degrees of freedom results in the notion that when the heave and surge force have a local maximum, the pitch force is zero. When the pitch force is large, the heave and surge force are close to a minimum.

Just like the heave motion, the restoring coefficient of the pitch motion is known from Table 5.6. However, the mooring system adds resistance to rotations of the structure. This is neglected for now. With this information the added mass and damping coefficients that cause resonance can be calculated. This is elaborated in Appendix H.3. From this appendix resonance only occurs at very high frequencies (ca. 6.5 rad/s). The most frequent wave heights and thus the Froude-Krilov force are very small at these frequencies leading to the conclusion that resonance is no threat. However, during a typhoon the resulting excitation force is very large with pitch angles of 0.186 rad. The edges of the platform will have a vertical motion amplitude of 0.89 m.

5.4 Type of mooring systems

There are a lot of different mooring systems. Most research of mooring systems is done in the field of maritime technology. Vessels at the quay are mostly moored with boulders and mooring ropes. The boulders are placed at the top of the quay, which transfer the load to the fixed earth. The vessels are connected to the boulders with hawsers. To reduce the forces during berthing a fender is constructed in front of the quay. This fender works as an extra spring, which absorbs the kinetic energy of the vessel. Changes in water level require the mooring ropes to be tightened or eased off. For the floating house this is not a practical solution.

In a marina the sailing yachts are not moored at boulders on top of the quay. For better accessibility the yachts are moored to a jetty. More precisely, the yachts are moored to piles that have been drilled into the ground. Rings around the piles allow vertical motions like heave and limit horizontal motions and rotations. The extent of limitation is determined by the stiffness of the system. If the yachts are moored with loose mooring ropes, the horizontal motion and rotations is not much influenced by the mooring system.

The mooring systems above are used in harbours and ports. The vessel is connected with the anchor on the seabed with a steel chain or rope. The stiffness of the system is dependent on the chain or rope. The steel chain is heavier than water and has the tendency to sink. In un-stretched state the chain will sag down. When the vessel displaces, the distance between the anchor and the vessel increases and the steel chain is pulled tight. Strain in the steel chain is correlated with its stiffness. For this type of mooring system a long steel chain is needed to ensure that there is enough length to create a sagged cable line. A variant of this is the use of synthetic ropes, which creates the restoring force by the elastic stretch of the rope itself.

For the floating house most concepts above are not a practical application. A quay should be built for several tens of meters into the fishpond to reach the place of the floating house. Moreover, decrease of the water level could be problem. With very low water levels the mooring rope is too short and the weight of the floating house generates very large pulling forces. Mooring ropes are not strong enough to sustain these large forces. The result is a broken mooring system. Lastly, a quay wall of approximately of 2.5 m will stand next to the floating house, when the fishpond is empty. Aesthetically this situation is undesired. The offshore mooring systems are viable options to limit the horizontal motions of offshore vessels. However, pitch, roll and yaw are not resisted.

The maximum pitch angle of 0.186 rad of the floating house is too large to be unrestricted. Thus only anchoring at the bottom is not applicable.

The criteria the mooring system needs to satisfy is unrestricted heave motion, restricted surge motion and limited pitch motion. This can be achieved using mooring piles. Heave motion is unrestricted if the connection can move freely along the piles. Surge motion is restricted by the stiffness of the piles. Pitch motion can be split into three options: free, limited and restricted. Free pitch motion is only possible if the pitch motion due to the presence of the mooring system is within safe limits. Restricted pitch motion is possible only if piles are able to withstand the forces generated by the restricted motion. Limited pitch motion is the intermediate option. The floating house is able to pitch freely to a certain limit. When this limit is exceeded the mooring piles start to restrict further pitching. This last option creates a non-linear problem and is not within the scope of this project. Further research is limited to free or restricted pitch motion.

The mooring system with piles is designed in more detail. The following parameters are considered:

- Number of piles
- Pile configuration
- Length
- Stiffness

A minimum number of piles and the configuration is mostly determined by the degrees of freedom. One pile is insufficient for surge motion (no torsion in the pile). Two is sufficient (2b) if the piles are not on opposite edges (2a), however pitch motion is only active on one pile. Also, aesthetically this configuration (2b) is not appealing. Three piles create asymmetry and has no added effect on pitch on both directions. Four piles (4a and 4b) satisfy all conditions. Surge and pitch are limited in both directions and 3D-symmetry from the floating house is retained. All six options are visualised in Figure 5.20.

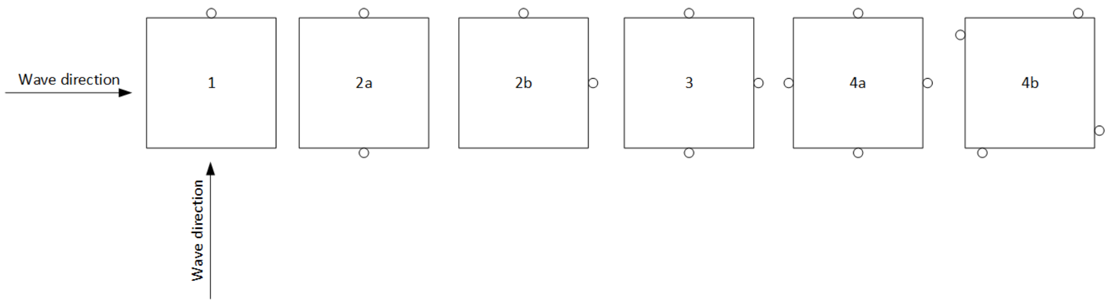

Figure 5.20 Pile configuration options

Yaw is not considered in the previous degrees of freedom because the incoming waves are perpendicular. In this case option 4a would suffice. In reality yaw can occur. When the floating house is yawing, the rotation exerts a horizontal force on the mooring piles. This horizontal force acts as a turning moment around the centre of gravity of the floating house. A longer lever arm for the turning moment reduces the horizontal force on the mooring pile. The recommended option thus is thus 4b.

The length and stiffness of the mooring piles is a coupled system. Besides the stiffness of the pile, the soil also acts as stiffness. Therefore, a longer pile with similar stiffness has a different combined stiffness due to the presence of the soil. This is researched in more detail in section 5.5.2

5.5 Influence of the mooring system

The mooring system works as a horizontal spring. If the mooring system is displaced horizontally it wants to rebound. Vertical displacements are not present. The pile-platform connection allows for free vertical motions. Waves generate horizontal and vertical forces as they propagate and pass the floating structure. Wind generates a horizontal force and turning moment on the floating structure. The horizontal forces and turning moment cause the mooring pile to displace horizontally and rotate. The stiffness of the mooring system is the force it can generate when displaced and rotated. In the previous section the influence of the mooring system is not entirely neglected. The surge motion requires a restoring coefficient. This coefficient is non-zero only when a mooring system is included. Without it the equation cannot be solved. Moreover, for pitch the restoring coefficient is partially determined by the mooring system. Only the heave motion is independent of the mooring system as this motion is free. In this section previous equations of motion are revisited to also include the effect of the mooring system on the motions.

5.5.1 General equation of motion including mooring system

As often mentioned before, the stiffness of the mooring system determines the restoring coefficient in the equation of motion. On the other hand, the stiffness influences the force in the mooring piles. Stiffer piles have to be stronger, because they attract more load. The equation of motion for surge and pitch motion is repeated below:

$$(M + a_{11})\ddot{x} + c_{11}\dot{x} + k_{11}x = F_1 \tag{5.24}$$

$$(I_{yy} + a_{55})\ddot{\Psi}_\text{p} + c_{55}\dot{\Psi}_\text{p} + k_{55}\Psi_\text{p} = F_5 \tag{5.25}$$

Filling in the forces and moments and specifying the restoring coefficients leads to:

$$(M + a_{11})\ddot{x} + c_{11}\dot{x} + k_{mooring}x = F_{1a} \cdot \sin(\omega t) + F_{wind} \tag{5.26}$$

$$\left(I_{yy} + a_{55}\right)\ddot{\Psi}_\text{p} + c_{55}\dot{\Psi}_\text{p} + (k_{55} + k_{mooring})\Psi_\text{p} = F_{5a} \cdot \sin(\omega t) + T_{wind} \tag{5.27}$$

These two equations have to be solved for all frequencies that can occur. This is required as some frequencies can cause resonance with the mooring system. The added mass and damping coefficients are quite constant according to Appendix H.2 and Appendix H.3. The stiffness of the mooring system is different for horizontal forces and turning moments. In order to compute the displacement and rotation of the pile a boundary condition is necessary. For now, the pile is clamped meaning displacement and rotation at the clamped end of the pile should be zero. Figure 5.21 shows the relation between the force (F) and turning moment (T), and the pile properties (EI, l). Insight of the stiffness of the mooring piles is obtained by looking at the standard displacement and turning moment formulas. If every pile is clamped in the soil, the following standard formulas can be used.

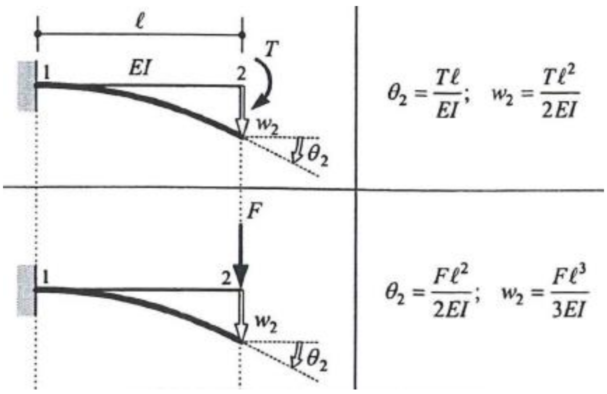

Figure 5.21 Rotation and deflection of a cantilever

From section 5.4 two scenarios are examined, free and fixed rotation of the floating structure. For free rotation only horizontal forces can act on the mooring piles. In this scenario the mooring system has a stiffness for displacement only. With fixed rotation two more stiffness parameter are necessary to also include the turning moment of the floating structure. Besides displacement a rotation of the platform leads to a turning moment on the mooring pile, also resulting in a deflection and rotation of the pile. Imagine that a turning moment acts on the pile. To get the same rotation as the platform the pile rotates as well, but this rotation is associated with an added displacement. The equations of motion for fixed rotation can be rewritten in a matrix:

$$\begin{bmatrix} (M + a_{11})\frac{\partial^2}{\partial t^2} + c_{11}\frac{\partial}{\partial t} + k_{trans} & k_{coupled} \\ k_{coupled} & (I_{yy} + a_{55})\frac{\partial^2}{\partial t^2} + c_{55}\frac{\partial}{\partial t} + k_{55} + k_{rot} \end{bmatrix} \cdot \begin{bmatrix} x \\ \Psi_p \end{bmatrix} = \begin{bmatrix} F_{wind} + F_{1a}\sin(\omega t) \\ T_{wind} + F_{5a}\sin(\omega t) \end{bmatrix} \quad (5.28)$$

Where k_{trans}, k_{rot} and $k_{coupled}$ are the mooring system stiffness parameters for pure deflection, pure rotation and coupled stiffness. In order to solve the equations a test equation for the solution is inserted, see Eq. 5.29.

$$\begin{gathered} x = C_1\sin(\omega t) + C_2\cos(\omega t) + C_3 \\ \Psi_p = D_1\sin(\omega t) + D_2\cos(\omega t) + D_3 \end{gathered} \quad (5.29)$$

Combining this matrix and test equation, six equations with six unknowns are obtained. These are solved for free and fixed rotation. In this section the solution to this matrix equation is discussed. In Appendix I a step by step analysis is presented. For free rotation the equations for surge and pitch are uncoupled and can be solved independently. The stiffness coefficients k_{rot} and $k_{coupled}$ are zero, leaving only k_{trans} and k_{55}. The six resulting equations are solved for the six unknowns. For fixed rotation k_{rot} and $k_{coupled}$ are non-zero creating a coupled system between the displacement and the rotation.

5.5.2 Mooring pile stiffness

Using the known forces and Table 5.6 the only unknowns left are the mooring system stiffness parameters. This is not only determined by the mooring pile properties. The soil also acts as a horizontal spring. The mooring piles are driven an undefined depth into the ground. The formulas from Figure 5.21 no longer hold because the representation of a cantilever is not similar to the mooring piles. The soil will take the external load over the entire embedded length. Over this length the soil is schematized as a spring. Larger displacements lead to larger forces in the soil resulting in smaller displacement than without the influence of the soil. The stiffness of the several soil layers is obtained from (Ham, 2016). The stiffness depends on the horizontal modulus of subgrade reaction, showed in Appendix J. The horizontal modulus of subgrade reaction is expressed in kN/m^3. The stiffness of a layer is obtained by multiplying with the embedded length of the layer and the width of the mooring pile.

A parametric analytical solution, including the influence of the soil stiffness, results in very large equations. An attempt was done to solve these equations using software (Maple 2017). A number of springs were used to model the soil stiffness. Unfortunately, a maximum of nine springs could be modelled for the embedded length. Further computation showed that this was insufficient to accurately compute displacements and rotations. Displacement increased as the embedded length increased, while the opposite is true. The method was abandoned and a more brute option was chosen. Using Matrixframe 5 the mooring pile is modelled with varying length, stiffness and diameter. The soil stiffness is dependent on the pile diameter. The mooring pile is not clamped but fully supported by the soil. Two load scenarios are used, a force and a turning moment. From the displacement and rotation by force and rotation by turning moment k_{trans}, k_{rot} and $k_{coupled}$ are determined respectively, see Eq. 5.30.

$$\frac{F}{u_F} = k_{trans} \quad \frac{F}{\theta_F} = k_{coupled} \quad \frac{T}{\theta_T} = k_{rot} \quad (5.30)$$

The parameter combinations are given in Table 5.7. Combined, 168 combinations can be examined. Very stiff long piles are practically not applicable as they are expensive. These combinations are not examined, leaving 146 combinations.

Table 5.7 Parameter combinations used in MatrixFrame 5

Embedded length [m]	{3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5}
Pile bending stiffness EI [kNm^2]	{400; 1,400; 2,400; 3,400; 4,400; 5,400; 6,400; 7,400; 8,400; 9,400; 10,400; 15,400; 20,400; 25,400; 30,400; 35,400; 40,400; 45,400; 50,400; 55,400; 60,400}

The results for a circular piles with a diameter of 325 mm are plotted in Figure 5.22. From these plots a six degree polynomial trend line is constructed for each stiffness parameter and embedded length. Note that using a polynomial trend line only allows for interpolation. Extrapolation of a polynomial can lead to very unrealistic values. To assess the influence of the pile diameter a short sensitivity analysis is done, see Appendix K.1. It shows that the pile diameter has a very large influence on the mooring system stiffness, and thus the displacements and rotations. Changing the pile diameter in the design should thus be done with a lot of care and if done so the following graphs should be reconstructed.

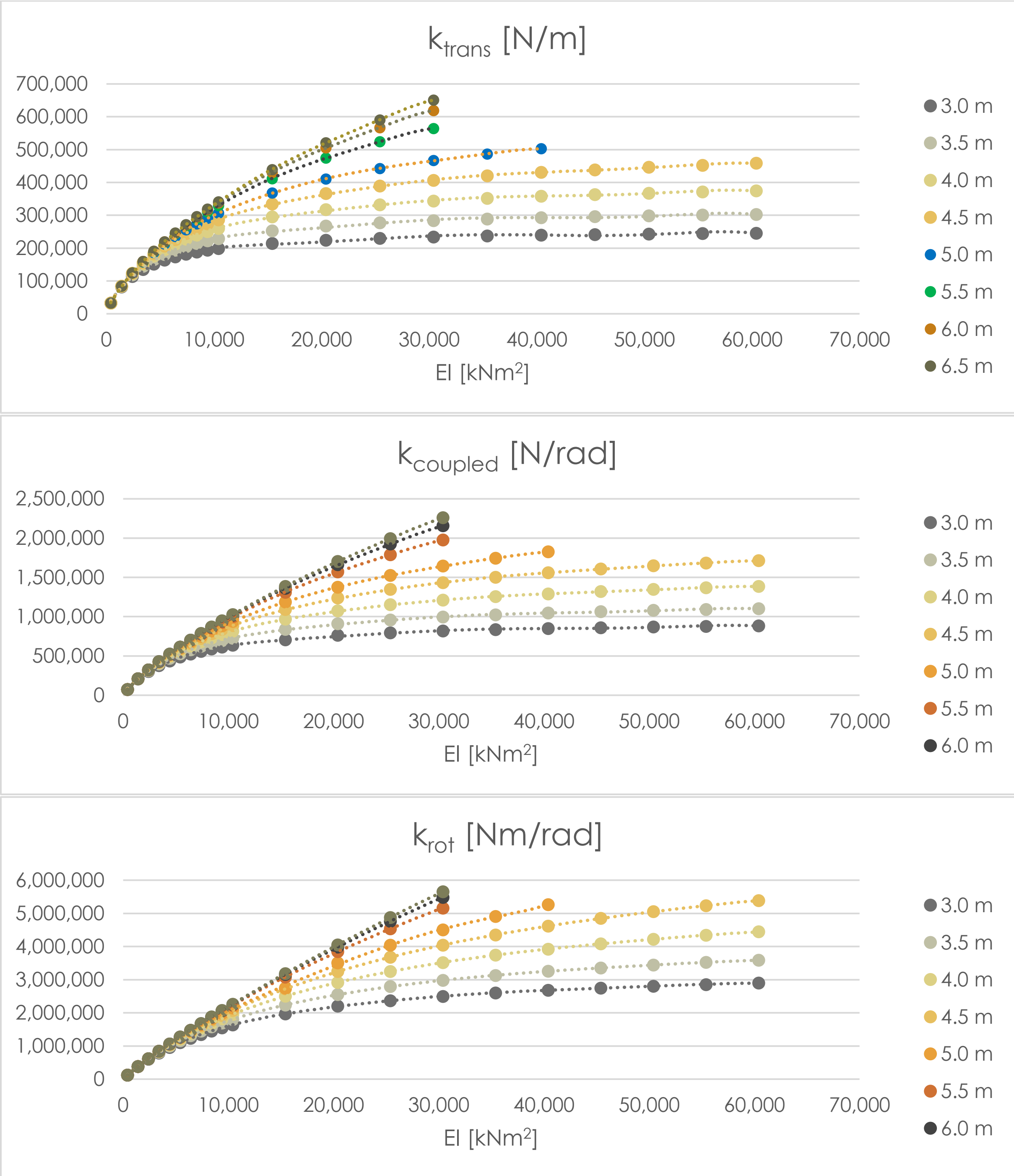

Figure 5.22 Matrixframe results and trendline for stiffness parameters

5.5.3 Solutions

The equations from the trend line are used in the previously solved equations, Eq. 5.30. All parameters are known and the total displacement and rotation can be computed for all frequencies. For four mooring piles the results from these computations are shown in Figure 5.23. The vertical axis represents the maximum displacement for all wave frequencies corresponding to the stiffness.

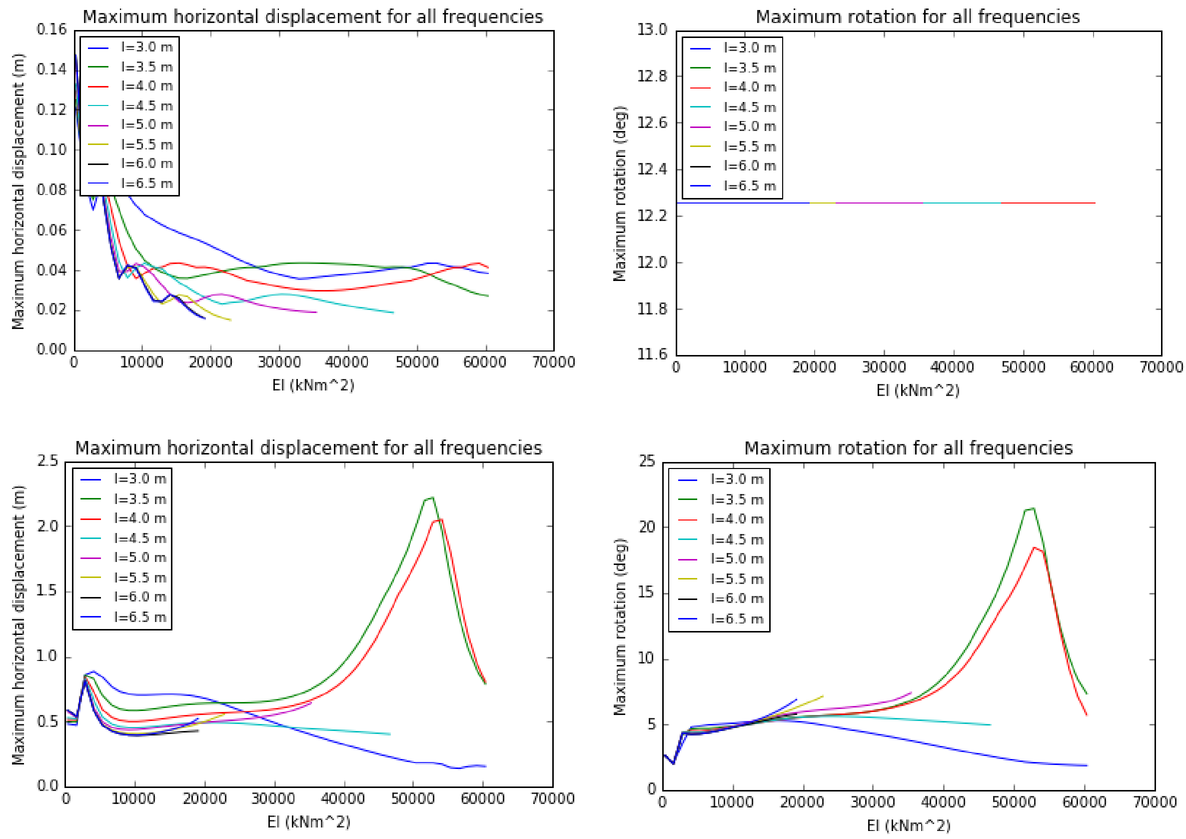

Figure 5.23 Maximum motion amplitude for each bending stiffness and pile length. Top graphs for free motion, bottom graphs for fixed motion.

From Figure 5.23 some features can be identified. For free motion, the horizontal displacement and rotation are fully uncoupled. The pile does not restrict the rotation, so it is the same for all pile lengths and bending stiffness. As mentioned before, the rotation in free motion is quite large with 12.25 degrees. The pile length and bending stiffness do have effect on the horizontal motions. Short piles show the most displacements. For very long piles the maximum displacement does not show much difference with a slightly stiffer or slacker pile. The fact that the curves cross each other and show multiple peaks can be explained by resonance. A specific combination of EI and l results in a k_{trans} causing resonance. For a length of four meters this peak is located at a bending stiffness of 60,000 kN/m^2. Increasing the length means that a smaller EI is needed to end up with the same k_{trans}. Therefore, the peak for a length of 4.5 m is located at 30,000 kN/m^2 and for a length of five meters at 22,000 kN/m^2.

For the fixed motion the coupling between the horizontal motion and rotation can easily be noticed. The two bottom graphs show the same pattern. Obviously, the short, stiff piles show resonance. For a smaller bending stiffness, the horizontal displacement generally decreases with increasing pile length. The rotation however is not different at a small bending stiffness for a short and a long pile. More detailed results for a pile with four meters embedded length can be found in Appendix L.

The water storage for rainwater storage and water treatment introduces changes in mass and inertia. A sensitivity analysis is done in Appendix K.2. It is advised to store the water in the middle of the platform. This has the least negative effect on the motions of the platform.

5.6 Remarks and further research

Throughout the project the computations to achieve a closed solution became more complex and less linear. Moreover, a lot of assumptions have been done in order to determine analytical solutions. This was already visible while determining the wave statistics. Besides the generation of waves in intermediate water, determining the significant wave introduced inaccuracy. To determine the significant wave more knowledge about the statistics is required than computed in this project. For this project the largest uncertainty in wave statistics is the wave period as this has no predetermined distribution and is usually obtained through measurements. A temporary solution has been used for this project by coupling the peak period with the most frequent wave height. The probability that this combination occurs is maximum. Also, for the water level gradient and surface current the analytical solution was too inaccurate to apply practically for this project. A solution was found but has not been verified with other scenarios.

The equations used to determine the external forces on the floating structure are dependent on the wave frequency. The formula for the wave pressure was applied for regular waves, while in reality the waves are irregular. By using regular waves, a specific condition was created in which one predetermined wave generates a force. The equations of motion for regular waves are sensitive to the wave frequency due to resonance. For irregular waves the probability that resonance occurs is less as more wave frequencies are present at one time interval. The added mass and added damping coefficients are dependent on the choice of the wave frequency. Analysing just one frequency results in a wrong impression of the motions of the floating structure. This is again due to irregular waves. In this project a range of wave frequencies is examined to semi-simulate irregular waves (assess motion for different frequencies separately). An option that has not been researched in this project is the use of Delft3D WAVE. When this is coupled with FLOW, wave-current interactions are also taken into account in the computations for the current and water level gradient. Generation of wind waves in Delft3D is possible but with limitations. Exact limitations are not examined in this project.

Determining the motions of the floating structure was first done without the influence of the mooring system. However, the surge equation is only solvable with the influence of the mooring system as water has no restoring coefficient for surge motions. The equations also require added mass and added damping coefficient. These were determined using graphs, but the ratios used as 'input' for the graphs are not within the domain. A guesstimate was done in order to determine the coefficients. This method introduces large uncertainties in the true added mass and added damping coefficient. More research to obtain more accurate values for these coefficients is recommended.

The equations of motion could only be solved for free and fixed rotation of the floating structure. Limited rotation results in non-linear behaviour. With free rotation only horizontal displacements occur. With fixed rotation a coupling system is created. The influence of the mooring system could not be analysed parametrically. The length of the resulting equations are far beyond computational capacities of Maple and hardware (RAM). The solution was found in MatrixFrame where 146 combinations of mooring pile length and stiffness are modelled to determine the mooring system stiffness parameters. A six-degree polynomial is fitted. Polynomials are very flexible functions to fit but cannot be used for extrapolation and thus the different combinations limit the possible solutions. Also, when the soil stiffness or pile diameter changes all 146 combinations need to be repeated. This process is very time consuming and reduces workability.

After all computations a graph of displacements and rotations is obtained for different pile lengths, stiffness and wave frequencies. From these graphs the optimum mooring pile properties cannot be extracted directly. The first step is to choose an EI and determine the corresponding displacement and rotation (free or fixed). From the displacement and rotation, the forces can be calculated. As the pile diameter is integrated in the chosen EI the moment of inertia is fixed and only the elasticity modulus can be changed. Choosing a pile material and profile the E is linked to I, creating EI again. This new EI corresponds with a new displacement and rotation. This iterative process is completed when the required EI for transferring the forces is smaller than the chosen EI. Due to time limitation this process is not examined.

5.7 Recommendation

From section 5.6 it is clear that the analytical method of calculation implies lots of assumptions. These assumptions provide simplifications, which makes the analytical calculation possible. However, these simplifications are always approximations of the total process. Because of all assumptions it is not possible to address the probability of waves and motions.

The equations and matrices for free and fixed motions can be used in the future. To improve the solution, the input in the equations has to be improved. It is recommended to get more insight in the wave statistics. This can be used to analyse irregular waves and to set up a wave spectrum. As a first istep a JONSWAP spectrum can be used. Software like NEMOH needs this spectrum to calculate the added mass and damping coefficients more accurate by solving the wave potentials. The geometry of the floating house can be imported from Salome into NEMOH. The effect of other pile diameters or soil stiffness should still be calculated with the help of MatrixFrame.

Every recommendation itself above will lead to a more plausible solution. If the situation of limited pitch wants to be investigated, a whole set of new equations have to be set up.

6 Project construction plan

This chapter contains information about the project time, risk and change management. The focus is on the time scheduling of the pilot project, with resources, duration, risk mitigation and possible changes incorporated in the plan. The final goal of the construction management discipline is to provide the local contractor and Finch Floating Homes with a plan which can be used during the construction phase of the pilot project in the Philippines. To achieve this, the following sub question which will be answered at the end of this chapter.

"*What construction plan can ensure timely completion of the pilot project?*"

In this chapter, the type of resources required for the construction phase and their origins are presented. The resources are a challenge of the project. Due to the many floods and typhoon risk, the materials, labour, and equipment have to be carefully allocated and managed in order to prevent delays and waste of the resources. The resource information is used in the next part of the report, where the construction activities are defined and a schedule for the construction phase is developed. During the construction phase many risks are present and if they occur, they can have great impact on the entire Floating Home project. The risks of the project are identified, and mitigation measures are presented. With this information, a construction plan for the pilot project is created. The combination of the time schedule and risk mitigation measures can be used by the local contractors and Finch Floating Homes to manage the construction phase and control any delays. One of the Finch Floating Homes principles is *adaptability*, see section 2.5. Since the design of the house is subject to change and the project is designed to be expanded in the future, the construction plan will have to be adapted to apply for the construction of multiple houses and eventually a floating community. In the end of this chapter, a short advice on how to manage those changes is given.

The input for the products in this chapter are a small survey and conversations with experts. The survey was conducted on resources, labour and transportation in the Philippines and has been answered by two contractors, two architects and the municipal engineer. The survey questions can e found in Appendix M.1. Several conversations, formal and informal, were held with local experts who have worked in construction, architecture, or municipal engineering for over 15 years. The design that has been used as input is the concept design of the 2016 Master thesis of J.W.J. van Schaik, see Figure 6.1 for a general depiction and Appendix M.2 for the complete sequence of erection of the pilot house.

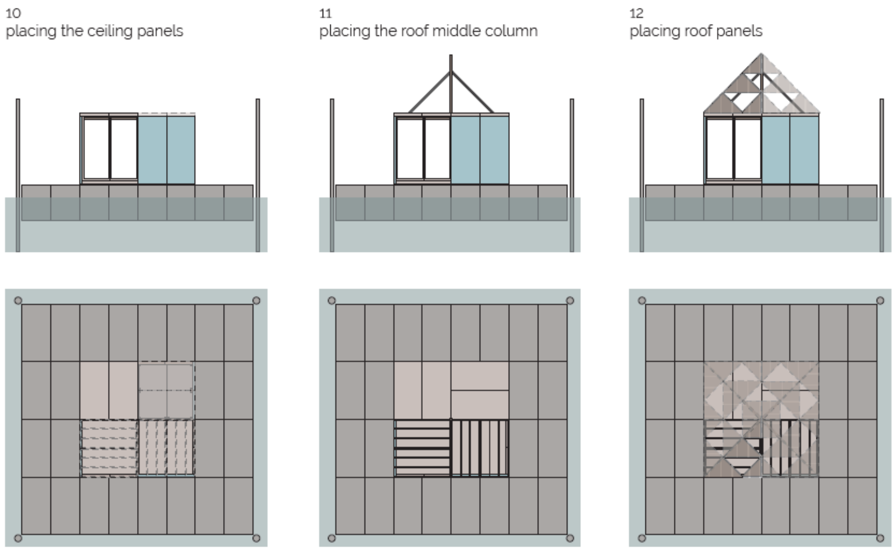

Figure 6.1 Part of the sequence of erection (Schaik, 2016)

6.1 Resources

The Philippine architecture has a rich history, with many different types of houses and materials. The architecture has been vastly influenced by the natural hazards and colonisations of the Philippines. In this section the history of architecture and the resources in the Philippine are discussed.

6.1.1 History of construction

Traditional architecture

The indigenous Philippine tribes used to build lean-to shelters from wood and leaves. It was made to be easily constructed and deconstructed to suit their travelling lift style. Later, the shelter evolved through ethnic tradition and protective needs into different types of huts, with the Bahay Kubo as the most famous type. The Bahay Kubo was made from wood, bamboo and nipa palm, often raised off the ground using piles. The concept of the hut was simple, constructed from local material, available in abundance, and using widely known methods of weaving, fitting and tying. The wood was never fully sealed, allowing for natural ventilation through floor splits, windows and crevices in the roof and walls. By being raised on piles but not being fixed in the ground, the houses were protected from earthquakes and floods. In Figure 6.2 the Ifugao house is shown, a predecessor of the Bahay Kubo, which can be seen in Figure 6.3 (Lumbera, 1991).

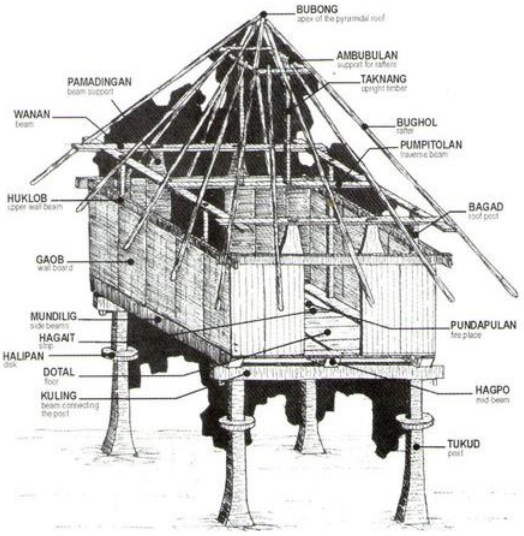

Figure 6.2 Ifugao House (historyofarchitecture.weebly.com)

Figure 6.3 Bahay Kubo (maison-monde.com)

The Spanish colonization

Wood, bamboo and leaves were nearly the only materials used until the 16th century, when the Spanish colonisers first settled in the south of the Philippines. In the beginning, the Spanish settlers also used wood and bamboo for construction, but soon found out it was not an effective material, since houses and churces were destroyed in fires. The Spanish discovered volcanic tuff quarries just outside of Manila, their capital, and harvested the volcanic tuff stone called Adobe. Since then, stone was used as a construction material by the colonials and local workmen were trained to build with stone under the supervision of the Spaniards. European models were used to build houses and churches of various types of stone, like adobe stone, coral stone or brick, glued together with a mortar made of natural products. Later, additions were made to the construction to strengthen the buildings for protection against earthquakes and other natural hazards. From these changes, the Bahay na Bato developed, still with the wooden house on stilts in the design, but the ground floor was walled in by brick, instead of open. The construction of the wooden, second floor was separated from the stone, ground floor wall for improved protection against earthquakes.

This type of house can be found all throughout Manila and the rest of the Philippines (Cultural Center of the Philippines, 1994).

The American colonization

With the arrival of the American colonials, development of cities as a whole was introduced together with new styles of architecture. Streets were improved, parks and waterfronts were developed and public facilities such as hospitals and schools were build. The new architectural style was rational and functional, close to the American neoclassic style, but altered to suit the tropical Philippine climate. The *Tsalet*, a wooden, suburban type of house characterised by its porch, was developed. Starting in the 19th century, steel was introduced, and construction technology kept developing for more daring and earthquake proof structural designs during the American colonisation.

The Philippines suffered great damage from World War II, especially Manila. Many buildings were ruined and hastily reconstructed. The new buildings relinquished from indigenous traditions and continued in the Spanish and American styles. However, later in the 20th century, nostalgia or nationalism resulted in houses featuring traditional designs, but with a structure composed of the newer materials like stone, steel and concrete (Cultural Center of the Philippines, 1994).

Figure 6.4 Bahay na Bato (historyofarchitecture.weebly.com)

Figure 6.5 American Tsalet (esquiremag.ph)

The present day

Nowadays, the influences of the Spanish and American colonisation are still visible in the streets of many towns and cities in the Philippines, with added modern influences from first world countries, like the high-rise buildings in Manila. However, there is a strong division between the poor and rich people. The rich people have a well-structured and designed house, which offers more protection against the natural hazards. The poor people cannot afford these houses, once the house they live in is damaged by floods, earthquakes or typhoons, they rebuild the house using scrap materials they can find or very cheap materials they can afford. This results in bad living conditions and even worse protection against the natural hazards.

6.1.2 Resource types

In order to construct the construction planning, it is necessary to have an accurate overview of the resources that are needed to execute the construction of the pilot project. The resources include the materials needed for the pilot house, the labour needed to construct the house and the equipment needed to realise this. As mentioned in chapter 1, the floating house is designed by Finch Floating Homes, established in the Netherlands. The researchers and designers are Dutch educated people, who put their knowledge to use in this Philippine context. The pilot project will be constructed in collaboration with local contractors, local suppliers, local construction workers and the municipality. The contractor and suppliers will be chosen by Finch Floating Homes in a later stage of the project.

Material

A challenge of this project is the choice of material. Due to the ban on timber harvesting and logging in the Philippines, it is impossible to use local wood for the pilot house (Cabico, 2018). Logging happens illegally or requires expensive permits, making the project unsustainable and unaffordable. Finch Floating Homes aims to use timber as the material for the floating house, because of the renewable nature of the resource and beneficial effects on the health of the environment (Schaik J. , 2016). The manufacturing process of timber uses a lower amount of fossil fuels than for example concrete or steel (Global Timber Forum, 2015) and timber provides a pleasant interior environment due to its insulation properties (English Heritage, 2010). In the original design, Eucalyptus Grandis was chosen as the structural material, but due to unavailability in the Philippines because of the logging bans in South East Asia (Waggener, 2001), it is not possible to acquire that material for the pilot project in a sustainable manner.

Azobé wood has been chosen by Finch Floating Homes as the structural wood. Azobé wood is a hardwood, with an advantageous strength to weight ratio, and is often used for marine purposes due to its resistance to wear, natural acid and water (Kaiser, 2011). A disadvantage of the wood is that it needs to be imported from Africa. Some suppliers have the material available, on the condition that the order is placed in time, since the delivery time is longer than usual. Other materials chosen for the house are stainless steel, plastic barrel, bamboo, jarrah, wood fibre cement board, oriented strand board, plywood, corrugated steel sheets and polyethylene foam insulation, as specified in the master theses of P.H. Ham and J.W.J. van Schaik and in the previous chapters. According to the local contractors and architects, these materials are all readily available in the area of the project location.

The Azobé timber is most the most important material to be ordered in time, since it has to be imported from Africa and is used for the construction of the first activity, the foundation module. The other materials, needed throughout the construction phase, can be ordered during the building preparations and delivered to a secure building site, so they are readily available when needed for construction. The amount of materials can be calculated when a detailed design is developed. An accurate calculation will benefit the construction process, since transportation and storage will be easier if there is no extreme excess of materials and the construction can be executed without delay if there is no shortage of materials during the construction phase.

From the survey it became apparent that wood is an unfavourable material for construction in the area of the project location. This is due to the fact that it is not affordable for the locals, harvesting timber in the Philippines is expensive due to permits and wood costs and importing timber is expensive due to the transportation costs. This increases the risk of the materials being stolen. Proper supervision and security is highly advised to prevent materials from getting stolen. This risk, among others, is specified in section 6.2.3.

Labour

The construction workers needed for the pilot project come from the area of the project location. According to the local contractors and architects, labour is widely available in the province. The construction workers will have to be hired on project basis, which means that that they are ₱ 50 more expensive on the daily basis. There are three types of construction workers, see Table 6.1, which can be hired for construction. The costs specified in the table below are based on the expert judgement of local contractors, architects and municipal engineers and include the ₱ 50 costs for project base work.

Table 6.1 Type of construction workers

Type	Definition	Costs
Skilled worker	A trained expert in a specific area of construction.	₱ 650 per day
Semi-skilled worker	A newly trained worker with educated knowledge of a certain construction area.	₱ 450 per day
Unskilled worker	The helper of the (semi-)skilled construction worker.	₱ 400 per day

During the construction, it is assumed that eight construction workers will work on the project simultaneously. The construction workers work in teams on the same or on different elements, in either the building location or the pilot location. To speed up the duration of construction, several smaller teams or one larger team will work on the elements, the number of workers required for the construction of each element are specified in section 6.2.1. The teams consist of a combination of skilled and unskilled construction workers and the tasks are divided based on the expertise of the worker and difficulty of the task. The skilled worker will connect the separate elements using specific construction techniques, whereas the helper saws and carries the materials to the needs of the skilled worker. The amount of skilled or unskilled workers in the team are dependent on the difficulty of the task and amount of work. This can be specified when the technical drawings are complete and the construction methods are determined. It should be taken into account that the construction methods in the Philippines might differ from the construction methods in the Netherlands, which the researchers and designers are educated in. Furthermore, given the innovative nature of the project, more skilled or semi-skilled workers might be needed compared to a standard project in the Philippines.

Equipment

Prefabrication of frames takes places in a secure building site and will be transported to the pilot location for assembly. This is due to the fact that floods can damage or wash away the materials and equipment and the risk of resources getting stolen from an unsecured pilot location, see section 6.2.3 for the construction risks.

The equipment needed for construction, such as heavy / light machinery, generators and pumps, scaffolding, safety and support equipment and hand tools are owned by the contractors or can be rented from businesses in the project location or nearby towns. There is no shortage of construction equipment in the area, the needed equipment can be ordered timely to be delivered on site on the days they are needed. The materials and other equipment will be stored at a secure building site, where prefabrication can take place. From this building location, the constructed elements will be transported to the pilot location, which is a section of a former fish pond close to downtown Macabebe, Pampanga in the Philippines (Figure 6.6). The equipment needed for prefabrication should be delivered and stored at the secure building site, the equipment needed for assembly of the house and placing the elements into the water should be delivered and stored at the project location. It might be required to double the order of some elements to ensure both locations have the equipment available at any time and to prevent delays by unavailability and transportation of the equipment.

6.2 Planning

The planning for the pilot project can be divided into three main areas; project time management construction cost, and risk management. The project time management consists of the definition and sequencing of activities, duration estimation and schedule development. These elements should be well understood by the project owner, who is responsible for the execution of the construction of the pilot project. If understood, the construction phase can be well prepared and monitored, to ensure timely completion of the pilot project in Macabebe, June 2018.

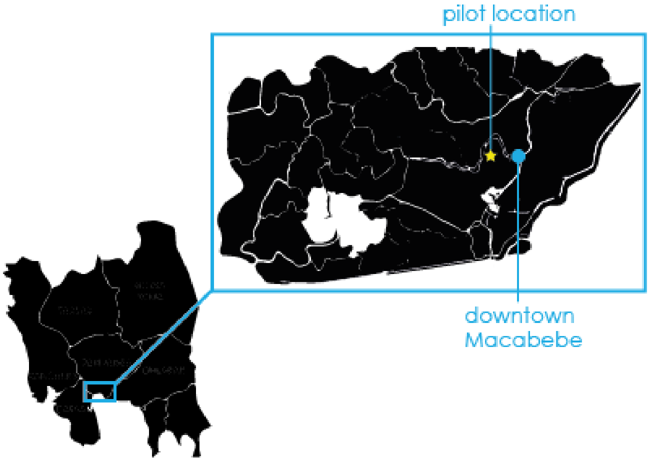

Figure 6.1 The pilot location (own illustration)

The design and construction process of the pilot have to comply with the Finch Principles specified in section 2.5. These principles, sustainability, adaptability, health and affordability are the drivers of the project and are of great importance in the decision-making process throughout the project. This report includes the planning solely for the pilot project. Once the pilot is completed, several volunteers will live in the house for a specific amount of time to test the house and the fulfilment of its goals. After success of the pilot, more pilots can be built, and the project can be upscaled over time.

6.2.1 Construction time management

The construction process of the floating home will differ from standard construction processes in the Netherlands, where Finch Floating Homes is based. This is due to the difference in resources, construction technique, customs and standards. To manage the construction process, knowledge of the local practices is required. This knowledge can be used to develop a time management plan, which the project owner can use to control the construction phase of the project. This is required to ensure completion of the project without delay and cost overruns. The time management plan consists of a list of activities, including their sequencing, estimated duration and schedule development (Project Management Institute, 2004). Since the pilot project is a small project, the time planning does not consist of these precisely defined products, but they are developed and used concurrently in one process, to provide a well interlinked advice on how the time can best be managed for the construction phase of the pilot project.

Assumptions

For the planning, several assumptions have been made regarding the construction process.

- Construction:
    - The house is constructed from bottom to top; first the base, then floor, structural frame, roof and lastly the interior and exterior.
    - The mooring system is according to the design of P.H. Ham, April 2016; four piles made of bundled bamboo stems.
    - Duration of structural elements include prefabrication of the element, transportation to the pilot location and assembly into the whole.

- **Labour:**
  - A workweek for the construction workers is Monday to Friday, 8AM to 5PM with 1 hour lunch break.
  - A maximum of 8 construction workers will work simultaneously on the project.
  - The construction workers work in teams combined of skilled, semi-skilled and unskilled workers.
- **Material:**
  - All materials are readily available.
  - All materials are raw materials and have to be sawn on site into the right dimensions.
  - The doors are bought as a whole and delivered to the pilot location, the estimated duration is the placement time of the doors into the frames.
  - Wall / floor panel prefabrication consists of the frame plus part of the cladding, the remaining cladding is installed after assembly into the whole.
  - Prefabrication of the foundation modules includes the connecting elements and transportation to the pilot location.

Activity definition

First, the activities have been defined, based on the previous research, the elements of the pilot of the floating house and information retrieved from the municipality. A work breakdown structure (WBS) has been created for an overview of the organised project components and project scope. An overview of the WBS can be seen in Figure 6.7. From the diagram of the work breakdown structure, several activities have been decomposed into more manageable components for better control and estimation. A full explanation of the different components in the WBS can be found in Appendix M.3.

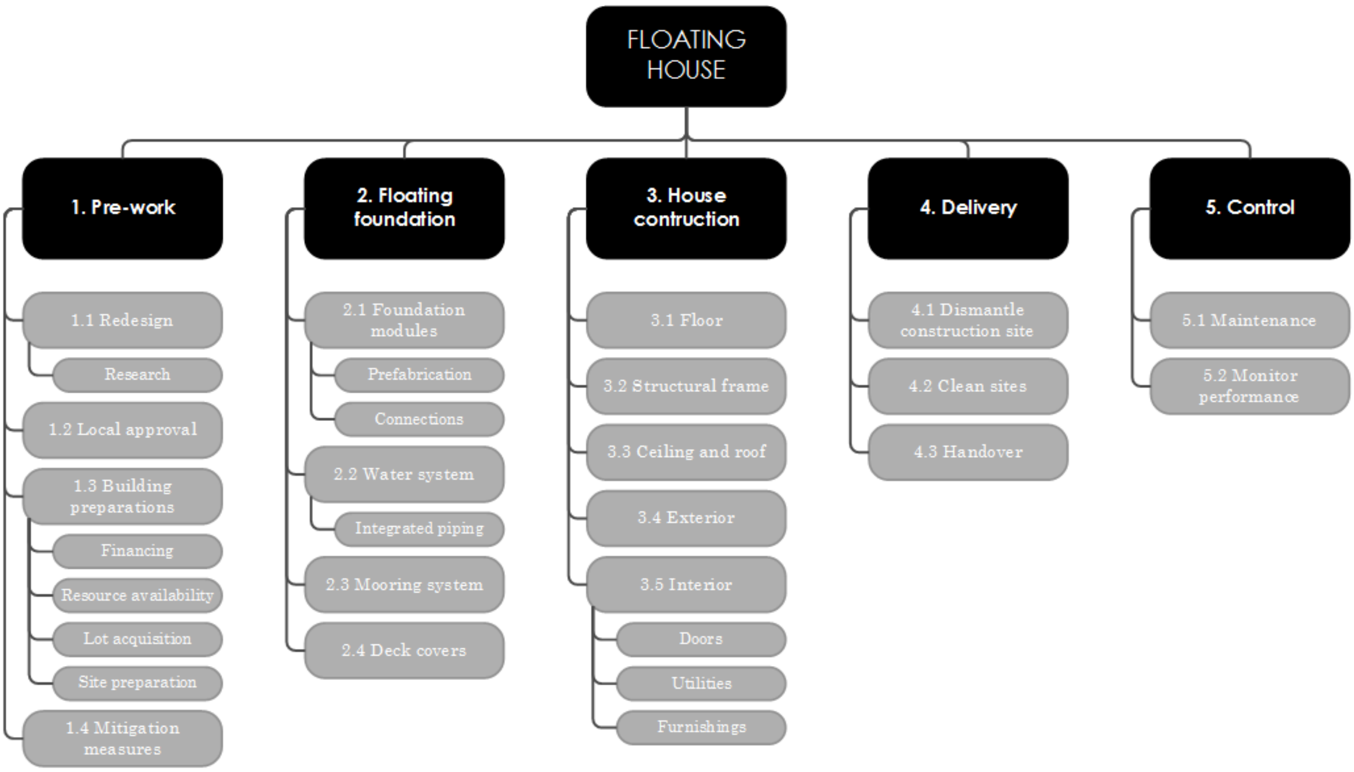

Figure 6.2 Work Breakdown Structure diagram

Activity sequencing

In order to translate the activities listed in Figure 6.7 into an achievable schedule, they must be sequenced and their relations must be known. Some of the activities are dependent upon preceding activities, as a result these activities cannot start before its preceding activity is finished. Because the pilot project includes solely the construction of one pilot house on top of one floating foundation, many of the activities must be constructed successively instead of concurrently. An overview of the sequencing should be made before developing the schedule (Project Management Institute, 2004).

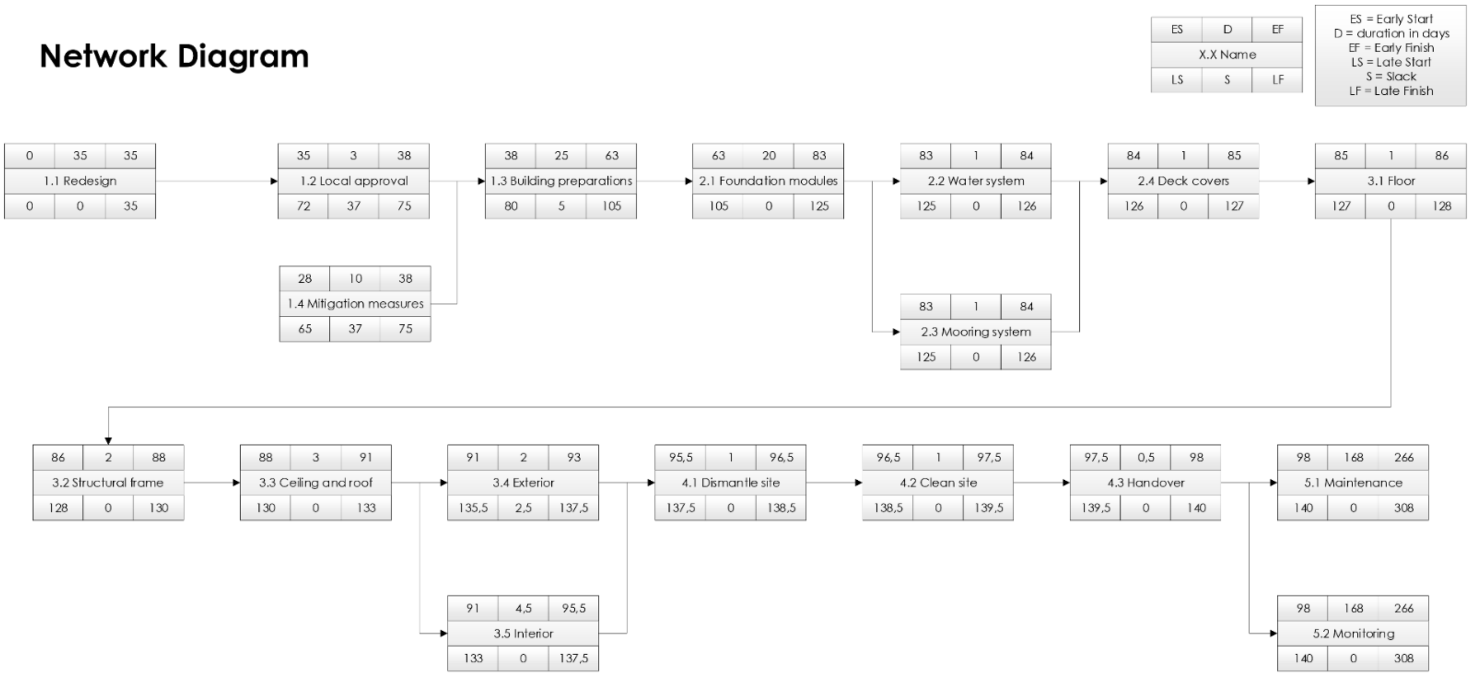

Figure 6.3 Activity-On-Note diagram of the floating house

Most activities in the project are succeeding, with the exception of activities 2.2 and 2.2, and 3.4 and 3.5, which are constructed concurrently. The activities are succeeding because the floating house is constructed from bottom to top; first the floating base, then the floor, structural frame and lastly the roof. Most relations are start-to-finish, which means the next activity can start as soon as the previous one ended.

The redesign is followed by a 37 day break due to absence of the project owner. As soon as the project owner is at the project location, the building preparations can start under his supervision.

Before the start of the building preparations, there is an extra 5 days slack to allow for a longer processing time for the permits. The mitigation measures should also be completed before the start of the building preparations, which means there is a finish-to-finish relation between activity 1.2 and 1.4. The mitigation measures can be executed at any desirable moment, but should not finish any later than when activity 1.2 is completed.

Activities 2.2 and 2.3 as well as activities 3.4 and 3.5 can be constructed concurrently, since the work takes place on different parts of the structure and not all workers are needed. For activity 3.4 there is a 2.5 day slack, as it takes shorter to construct than activity 3.5. Construction should start at the same time as activity 3.5 to prevent delay of the entire project in the case that only activity 3.4 is delayed. Activity 3.5 defines the critical path of the construction process.

The Activity-On-Node network diagram (Figure 6.8) has been constructed to identify the dependencies among the project activities. This network diagram has been used for the activity duration estimation and project schedule. The duration of each activity has then been added to the network diagram to create an overview of the duration of the entire project and its components. The estimation of the duration and activity sequencing is an iterative process. An explanation of the network diagram including narrative with activity connections can be found in Appendix M.4.

Project schedule

The duration of the activities is dependent on several elements, such as the amount of workers assigned to the activity and the capabilities of the construction workers. As specified above, there will be eight construction workers working on the project each day. These will work in groups where unskilled and skilled workers are combined. Given the limited amount of available data and expert, the estimates are uncertain and thus risky. The estimated duration of each activity including reasoning as well as the full project schedule can be found in Appendix M.5.

With the use of activity sequencing, duration, assumptions, constraints and Philippine calendar, a preliminary schedule has been developed. The preliminary schedule can be used in combination with confirmed resource allocation to develop the final project schedule. The entire project from redesign to handover, including the 37 day break and time allowance for permit processing, takes 140 working days. If the construction phase would start immediately after the redesign and it is presumed that no time allowance is needed for the permit processing, the entire project will take 98 working days from redesign to handover. The redesign started on February 12, 2018 and ended March 30, 2018. The construction phase commences in June 2018, when the project owner is on location for supervision. During the construction phase, three public holidays take place, on these days no work will be done. Taking all the non-working days into account, the handover will take place on August 29, 2018. The project schedule allows for an earlier handover if construction starts earlier, but due to the date constraint of the presence of the project owner, construction phase will take place later.

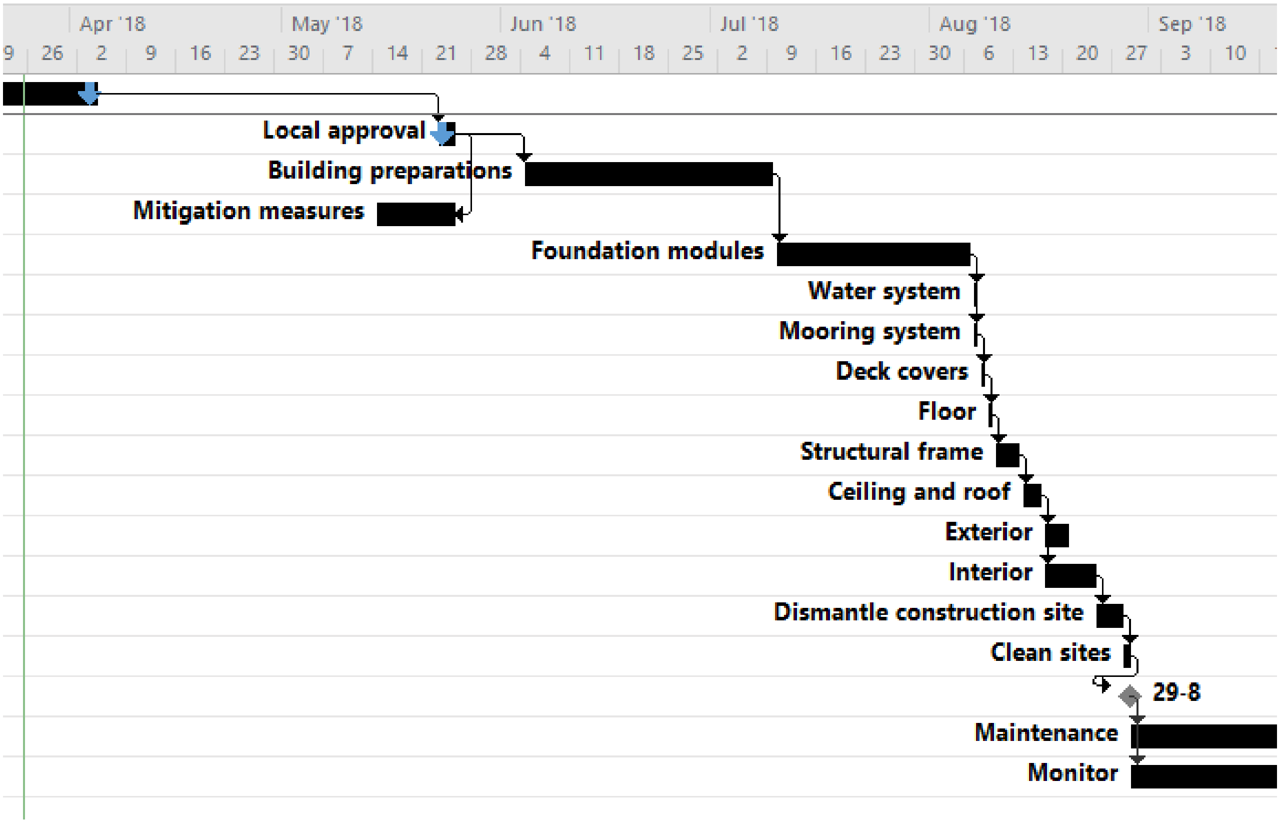

Figure 6.4 Section of the project schedule

In Figure 6.9, it can be seen that there are 2 important deadlines in the beginning of the project, namely the deadline for the research of the redesign and the deadline for completion of the construction documents. The latter deadline is very important, since the applying for the permits requires the finished construction documents and the contractor will need the drawings for calculations and preparations. According to this schedule, the mitigation measures are executed in May, just before the preparations start. As stated earlier, this is the latest moment that this should be executed, it is advised to do this earlier and elongate the risk monitoring process. The risks are identified in section 6.2.3.

The schedule can be controlled by keeping an eye on changes. The factors that cause schedule change can be influenced, if a change does occur it should be agreed upon and managed (Project Management Institute, 2004). This can be done using change management, elaborated on in section 6.3. Activities can be revised, the project owner can decide on a longer or shorter duration, a modified activity sequence or even an alternative schedule. From this revision and documentation, the schedules will be constantly updated and corrective action can be taken in time. If the schedule is updated at a regular basis, problems further along in the schedule will become apparent and a corrective action can be planned. The corrective action for time management often required a root-cause analysis to determine the cause of the change. Since many of the activities succeed each other in the schedule, a delay in the beginning of the construction phase might be cause by something that can also cause a delay in a later phase of the construction. If the cause is identified at an early stage, corrective actions can be taken to prevent that type of delay from occurring again. Types of corrective actions in this project may include adding resources, changing the activity sequencing from succeeding to concurrently, adapting the construction technique or eliminating the prefabrication and thus extra transportation.

6.2.2 Construction cost

In this phase of the project it is not possible to construct a well substantiated cost estimation. The design of the complete floating house is not well defined yet to measure the required amount of materials. Besides that, the materials have not yet been determined for all elements. A preliminary cost estimation would have been possible from the concept design, however, practices and prices in the Philippines differ from common practices and prices in the Netherlands. Not enough information is available to make a substantiated cost estimation. It is advised to define all materials in the design and develop more detailed concept design on which prices can be based. The prices for these materials can be inquired at local contractors. At the moment of research there is not enough data available for a cost estimation.

6.2.3 Construction risks

Due to the innovative nature of the project in the Philippines, many risks have to be taken into account. Risk management consists of risk identification, analysis, response planning and finally, monitoring and control (Project Management Institute, 2004). For the risk management of this project, the risks have been identified, analysed using qualitative analysis and response plans have been developed. The full explanation of these three steps and the full risk register is included in Appendix N. The risk owner can use the response plans to develop and execute procedures to mitigate the probability and/or impact of the risks.

Risk monitoring and control is not included in this report, as it falls outside the project scope. Ensuring the execution of the response procedure, evaluating their effectiveness and identification of new risks is the responsibility of the project manager, in this case the project owner. This should happen after the completion of the redesign and before the start of the building preparations, in accordance with the proposed construction process in section 6.2.1.

Identification

To identify the risks, the cause of the risk should be identified first. The risk cause is an uncertain factor that can impact the outcome of the project (Nicholas & Steyn, 2012). Once the cause is known, the risk event and the consequence can be identified to describe the full risk

Analysis

There are several aspects of importance prior to the start of the analysis. These aspects, such as project status, project type, data precision, scales and assumptions, are the input for the qualitative risk analysis and will influence the analysis (Project Management Institute, 2004).

- The **project status** determines the likeliness of whether the risks can be identified. In early phases of the project there are more undefined certain aspects are, resulting in more risks and higher uncertainties.
- Adding to the uncertainty of the risks is the **project type.** The floating house project is an innovative project. Being first of its kind, using foreign knowledge, the probability and occurrence of the risks are harder to predict.
- Little data about the project is available, the sources and data that were found, cannot be blindly relied upon. This uncertainty contributes in the ***data precision***.
- Different **scales** of probability and impact as the qualitative rating scale in Table 6.2.

Table 6.2 Scales of probability and impact

Probability	**very low**	**low**	**medium**	**high**	**very high**
Impact	very low	low	medium	high	very high

- The **assumptions** as listed at the start of section 6.2.1 contribute to the risks as they add extra initial uncertainty.

Response

For the response planning, the risk register is supplemented with the risk owner, response action including implementation advice, and a post-response assessment. In this case, the responsibility of many risks lie with one person, since the organisation behind the project is small. The different roles of project manager, PR-manager, marketing, designing and more, belong to only a few people. The project owner carries the most responsibility, this person makes the most decisions and fully dedicates his time to the project. Others involved are the organisation Finch Floating Homes, local contractors and suppliers, the local municipalities and people with interest in the project. Apart from being responsible for risks, these actors have some other responsibilities, see Table 6.3.

Table 6.3 Project team and their responsibilities

Project team member	**Responsibility**
Project owner	• project management • design • analyses • technical expertise • asset management • contract management
Finch Floating Homes	• business plan • design • social network • marketing • financial management
Local contractors and suppliers	• building the pilot • providing materials and equipment • hiring construction workers

Local municipalities	• providing data and information • providing the pilot location
People with interest	• financing (crowdfund)

The risk response can be done with different strategies, depending on whether it is a risk or an opportunity. Table 6.4 shows the different risk response strategies.

Table 6.4 Risk response strategies

Threats		**Opportunities**	
Avoid	Avoid the risk by changing the project plan, the cause will be eliminated or the project will be protected from the impact.	Exploit	Exploit the opportunity by eliminating uncertainties. The probability increases and realisation of the opportunity can be ensured.
Transfer	Transfer the risk by shifting responsibility and consequence of the risk to a third party. The risk will still exist, but the ownership lies with another party.	Share	Share the opportunity by shifting responsibility to a third party which is able to increase the probability and maximise the benefits of impact. Benefits are shared between the parties.
Reduce	Reduce the probability and / or impact of the risk by taking action in an early stage of the project. It is more effective than repairing the damage after impact. Costs of mitigating the risk versus the likely probability and impact should be taken into account	Enhance	Enhance the probability and / or impact of the opportunity by in an early stage of the project. With a higher probability and higher impact, the benefits will be greater. This is similar to the exploit strategy if the probability can be increased to 100 percent.
Accept	Accept the risk by not changing the project plan or dealing with the risk in advance. Accepting can be active or passive. Active acceptance includes the development of a contingency plan for if the risk occurs. Passive acceptance means doing nothing and only dealing with the consequences after the risk has occurred.	Accept	Accept the opportunity by not changing the project plan or dealing with the benefits in advance. The probability and / or impact of the upside risk are not increased, but the benefits are taken as is, if the upside risk occurs.

Most important risks

The most important risks for the floating home pilot project, for which responding and monitoring is highly advised, are listed below.

1. **The local people do not trust the materials and might not have faith in the project.** If the locals do not have faith in the floating house, they will not want to volunteer to live in the pilot and not want to buy and build the house themselves after the pilot project. Which means that the project will not have a future. In order for the people to believe that the house will stay floating and will be resilient in the case of a typhoon, the pilot house has to prove what it promises. The project owner can reduce this risk by ensuring good quality of materials for the given situation, so the project does not collapse during the floods and typhoons in the rainy season. Once the correct materials have been chosen, a marketing strategy can be created to inform the people about the capacities of the materials and how it will the house them from floods and typhoons, so they gain more faith in the project.
2. **Proper maintenance is not a common practice in the Philippines,** the materials or components of the house might deteriorate faster than expected and the pilot house might not be able to withstand the floods and typhoons as calculated. The project owner can reduce

the probability and impact of this risk by constructing a meeting with the volunteers and briefing them about the responsibilities of living in the pilot house. The people can be taught how they should maintain the house while none of the team members are around, in order for the house to maintain its designed quality for the desired period of time. The maintenance should be monitored extensively to protect the house from any damage. The probability of this risk is reduced, since the volunteers will be educated about what they will need to do to maintain the house. The impact is reduced, due to the fact that the maintenance that the volunteers will carry out, is of better quality than before the meeting. A secondary risk arises from this strategy, which is that the locals might not want to volunteer if they think that it is too much work or costs too much money to live in the pilot house. This can also be discussed during the meeting, to prevent the volunteers from getting the wrong idea.

3. **Typhoons occur during the rainy season from June to October**, **which is when the construction takes place**. The risk of a typhoon occurring during the construction period is low, because typhoons usually occur in the months of September and October (Philippine Atmospheric, Geophysical and Astronomical Services Administration, 2018). However, if a typhoon occurs the impact will be very high, as the project will be destroyed. This will cost a lot of money, due to the delay and the destructed materials, equipment and land. Since the probability is low, the project owner can choose to actively accept the risk. According to the locals, the project area is less prone to devastating typhoons, especially during June and July. The chances of a strong typhoon occurring during the construction period are low enough to accept. A contingency plan can be made on what to do with the materials in the case of a typhoon. A quick evacuation plan can prevent loss and damage of materials.

4. **Floods occur during the rainy season**, one might occur on the construction site during the construction period and can destroy and sweep away the project, materials and equipment. The probability and impact of this risk are both very high. According to the locals, many floods occur during the rainy season, varying in height and duration. Some floods can last for months and can be over one meter in height. The impact is high, because the work that has been done prior to the flood and the stored materials and equipment will be lost and / or damaged. This will cause a lot of delay and extra costs for the pilot project. It is advised that the project owner implements the avoid strategy. During the dry season, little to no floods occur, which makes it a safe and suitable time for constructing the pilot house. If the project owner chooses the avoid the risk, the probability is reduced to very low.

5. **Floods occur during the rainy season,** one might occur during or shortly prior to the construction period, making transportation of materials to the building site impossible. If the materials cannot be delivered, the project will be delayed to a later time, when the flood has subsided. The probability is, similar to the previous risk, very high. However, the impact is medium, since materials will not be lost or damaged, but the project will solely be delayed. The project owner can avoid this risk by shifting the construction period to the dry season, when little to no floods occur. The probability will be reduced to very low.

6. **A Black Swan risk is the occurrence of an earthquake in the project location.** If an earthquake occurs, the project location and surrounding municipalities might be destroyed severely. The project will be cancelled, since the municipalities in the project area support the project fully and have available locations for the pilot. If the area is destroyed, rebuilding of the current towns will get priority over the construction of the floating house. The probability is very low, since the project location does not sit on a fault line and has not experienced many earthquakes in the past (USGS National Earthquake Information Center, 2018). But the impact is very high, seeing it will cancel the project. In this case, the project owner can choose to passively accept the risk. Due to its very low probability, it is not profitable to take actions against this risk.

7. An issue present in the project is the involvement of Finch Building and the Finch Principles. **The design of the floating home has to comply with the Finch Building Principles.** This means that not the most optimal solution regarding the local situation is chosen for the resign of the house. There is no probability assessment, given the fact that it is an issue. The impact is medium, as the design can still be completed and the house may fulfil all requirements, however, it could have been more optimal in its environment and for the end user if different materials or principles had been chosen in the design. In this case, Finch Floating Homes can reduce the impact of this issue by analysing different alternatives to find the most optimal design which complies with the Finch Principles as well as offers the best solution given the local circumstances.

8. One of the opportunities of this project is the support of the local authorities in the area of the project location. Because of the interest, **other municipalities might want the next pilots to be built in their town**, as a consequence that multiple succeeding houses can be built in several of the surrounding municipalities. This opportunity can be exploited by Finch Floating Homes. Agreements can be made with the surrounding municipalities about locations for succeeding pilot houses. When several houses are built in several municipalities, more locals can see the success of the project and the demand for the floating house will increase, growing the project on the long term.

Other risks regarding the materials, labour and construction technique are also present in the project. These risks can be reduced by designing the pilot project in more detail and managing the project schedule in combination with managing the risks. The complete list of risks is stated in Appendix N.

6.3 Change management

As mentioned in section 6.2.1, the project schedule can change over time. Between completion of the project schedule, Appendix M.5, and start of construction is a period in which new research and decisions can change the design. Furthermore, the design will be made more detailed and technical drawings will be produced, which can lead to new insights and design changes. Besides design changes prior to construction of the pilot project, design changes will also occur after completion and monitoring of the pilot project. The project owner and volunteers living in the pilot house will collect data and monitor the performance, these results will be used for further research and development of the entire project. Another type of change will occur in the upscaling phase of the project. The aim of Finch Floating Homes is to create several floating communities on multiple locations over the world. The upscaling of the project requires changes to the construction plan, since short-term and long-term planning might be different in the Philippines. All these changes need to be managed to ensure timely completion of these parts of the project as well.

6.3.1 Design changes

A method to track the design information an changes is configuration management. Procedures and policies can be developed to document all the drawings, planning, specifications and more. By properly documenting these documents, it can be ensured that all project team members have the most current project information. Given that the project team is not extensive and the project is relatively small, it is important that the procedures for documenting are simple to implement, to prevent waste of time by having to adapt to a new system. It is advised to start with a the procedures and policies early in the project, so that the desired level of control can be achieved and it will cost less time to adopt the new procedures than when the procedures are implemented at a later stage. In order to implement the configuration control, configuration items need to be identified. These items are the design alternatives, risks, construction process and schedule, research documents, design drawings, list of materials and core activities as described in the work breakdown structure (Appendix M.3). The configuration documents regarding these items should be kept in a single, accessible location. It is recommended to store the documents in an online platform which every team member can easily access at all times. The contractor should have access to this platform too, since the materials which are ultimately used will need to be recorded and documented. Any changes and modifications regarding the design and research should be recorded in this platform and processed through all the relevant documents, so that the entire set of documents reflects the 'as-built' status of the project. These 'as-built' documents can later be used for maintenance and can be altered if the design needs to be improved after the data of monitoring the pilot project is collected.

The procedure for implementing a change is as follows:

1. Research, design detailing, performance requirements or similar demand for a design change.
2. The motivation for the change and the change itself should be documented in a standard change proposal document.
3. The impact of the change should be evaluated, the change should be the best alternative regarding performance, requirements, compliance with design principles, project schedule and risks.
4. The feasibility of the change should be evaluated, the resources and project schedule should be assessed.
5. The project owner approves or rejects the proposed change. It is advised to do this in concertation with the designer, municipality and Finch Floating Home team.
6. The work regarding the change should be planned, anything affected by the change should be identified and processed.
7. A verification of the change is needed to ensure compliance with the change proposal.

By properly documenting the configuration items and the changes, the project will take more time in early phases, but changes can quickly be assessed and implemented in later stages of the project. For now, the project is of small scale and changes are more easily manageable. However, when the project progresses the it becomes more difficult to maintain an overview of the proposed, rejected or implemented changes when not properly documented.

6.3.2 Upscaling changes

The aim of Finch Floating Homes is to eventually provide floating communities, constructed of several platforms with multiple homes, in locations all over the world. Floods and typhoons are still big issues for many people around the world in the present day. The Floating Home project will not only provide the solution for the municipality of Macabebe, Pampanga, but the floating house or floating community can be a solution to many flood prone areas in the world. This means that the design of the floating house will need to be upscaled and changed to accommodate for the performance requirements of multiple houses on the floating platform. These changes will be similarly documented, assessed, and implemented as stated in 6.3.1. There will be a difference in the project team and involved parties. Since the project will be of significant scale, the project team will have to grow to cope with the work and other parties like governments, investors and multiple contractors might get involved. This makes the change management and control more difficult, because more configuration items will have to be documented and accessed by a larger group of parties. In this case, it is essential that documentation happens thoroughly and the (online) platform which is used for documentation complies with the desired requirements. The procedure for implementing change should be used for the design changes, when the project scope concerns solely the construction of one pilot project. The procedure will be refined through use and the project team members will get familiar with it. Once the team grows, the procedure should not develop any further, to achieve one coherent environment of documentation and implementation procedures.

6.4 Conclusion

With the time, risk and change management advice given in the previous sections, the research question "What construction plan can ensure timely completion of the pilot project?" can be answered.

Time management

The project itself takes 98 workdays to complete. The building preparations do not immediately follow the redesign, because the project owner needs to be on site to supervise the construction phase. This results in a total duration of 140 workdays, excluding maintenance and monitoring. If the building preparations start in the first week of June 2018, the handover of the pilot will take place on August 29, 2018. Each activity has a certain duration with its specific resources and is preceded or succeeded by another activity. The scheduled activities should be monitored, managed and adapted where needed, to ensure that it stays up to date and the construction is executed accordingly.

Risk management

The construction of the pilot project will be accompanied by several risks. The most important risks have to do with social and environmental aspects, these will need to be mitigated prior to the start of the construction phase. Other risks regarding materials, labour and construction methods are more manageable, they can be reduced by developing a detailed design and controlling the project schedule closely. The mitigation plans can be created from the proposed risk response strategies and should be executed before June 2018, when the building preparations start.

Change management

The pilot project has to cope with two types of changes; design changes and upscaling changes. The design changes take place before the construction phase of the pilot project, the upscaling changes take place after completion of the pilot project. It is advised to set up a platform to share project documents with all project team members. The changes can be implemented by following a procedure, set up in early stages of the project. Thoroughly documenting the changes and deciding according to a standard procedure will stimulate the rejection or implementation of proposed changes. For the upscaling changes, the project team will grow and the platform will have to extend to cope with the project amplification. However, the documentation and implementation procedures must not change in order to keep a coherent method of managing changes.

Extensively managing the project schedule, risks and change will ensure that the project can be built according to the project plan and unforeseen events are minimised. If successful, the pilot project will be ready to accommodate its first residents. From this point the house will be maintained and monitored for half a year to collect data, this will be used for further research and project development.

Recommendations

The input for the research was collected through a survey and conversations with several locals. Only five experts responded to the survey and many conversations were held about different subjects. The experts have different opinions and practices, so the input is not as elaborate as desired. For the construction phase a more detailed planning will be needed, this can be done by inquiring information from several local contractors and suppliers. A greater amount of detailed information can be used to develop a final project schedule which can be relied upon for construction. The risks and changes will get more specified as the project progresses, these documents should be revised and monitored throughout the project development.

7 Conclusion

The aim of this project is to improve the current pilot project design to ensure that building and testing of the floating house would be successful. Several aspects of the design are addressed by the project group, each for their own discipline. From the conclusions in chapters 3 to 6, the sub-questions stated in chapter 2 can be answered. The sub-questions are copied here and answered for each discipline.

Design of the roof:

How can the roof structure be redesigned to assure a buildable and affordable pilot project?

The initial hip roof shape, designed by J.W.J van Schaik, turned out to fit the purpose of the floating house well. However, the housing unit was redesigned to be symmetrical and the roof frames needed extra attention. The frames needed to be easier to construct and worked out more in detail. Also, the building materials were assessed. Availability and effectiveness of the chosen material are taken into account, as well as the possibility to implement new techniques in the future.

The new design of the roof is increasing the buildability and affordability by lowering the complexity of the design. Some optimisations can still be done regarding the dimensions and connections. Especially the connections are still a topic of interest.

Water management:

How can a socially accepted, sustainable and durable sanitary facility be created?

In the pilot design only a conceptual design was made. As the floating house has no direct water supply a sanitary system is designed. A lot of focus is put on the complexity and maintenance of the system. A complex system is difficult to construct and repair if broken, and maintenance should be easy to avoid loss of functionality through its lifetime. Filters are made of durable materials to lower maintenance costs. The capacity of the designed system is insufficient to meet the water demand. It is recommended to search for more sources in order to meet the demand. Water storage is done using the barrels from the foundation.

The designed sanitary facility is a sustainable and durable system. Social acceptance of the system is a topic of further research. Maintenance is the main aspect that should be socially accepted, else the system will fail and water is contaminated. This can result in sickness and other hazardous situations.

Design of the mooring system:

How does the motion of the floating structure depend on the stiffness of the mooring system?

The mooring system is a complex process, due to many influences from motions. The motions of the floating house are dependent on the hydrodynamic conditions as well as the mooring system stiffness, which is undefined. A final design of the mooring system could not be made due the complexity of the system. Instead a graphical representation of the bending stiffness compared to the motions of the floating structure for different embedded lengths is created. The graphs display the motions of the floating house for different scenarios. By an iterative process and the graphs' parameters optimisation of the stiffness could be found, which is used for designing the mooring system.

The graphs are dependent on certain input parameters like hydrodynamic conditions and restoring coefficients. Determination of these parameters with more accuracy than is done in this project should be done using specialised software. The graphs are also limited to free and fixed rotation of the floating house. Graphs for limited rotation could not be obtained. More research on limited rotation is recommended.

Construction management:

What construction plan can ensure timely completion of the pilot project?

Construction planning can be split into three management tasks: time, risk and change. Time management concerns the time schedule of the construction. Taking into account delays and inspection, while monitoring the construction lead to a minimum and expected construction schedule. Management of time and resources during this phase should be done effectively. This can be done using risk management. Careful planning and detailed designing greatly reduce risks. Change management is more globally applied. Before construction starts changes to design can still be made. Effectively managing these changes increase efficiency during the construction phase. When the pilot project is successful the next step is evaluation and upscaling. Both are bound to come with design changes and optimisation. In order to ensure that the pilot project is built within the scheduled period these three management tasks should constantly be active and reviewed.

General research question:

How can the design and development of the pilot project, as currently designed by Finch Floating Homes, be improved in order to perform an optimal test of the floating house in Macabebe, the Philippines?

Several improvements are made to the pilot design by Finch Floating Homes. Topics of interest are revisited or newly researched. From the conclusions of all sub questions the general research question is answered. From this project it is clear that in order to perform an optimal test of the pilot project some topics should be researched in more detail. The roof connections need to be designed in more detail; social acceptance of the sanitary system should be checked; the mooring system should be revisited using software and construction of the floating house requires more insight in construction management. When these topics are addressed before the construction starts, the pilot project can be an optimal test of the floating house.

8 Recommendation

Generally, all the research and redesigning conducted in this report has to be followed up by a more detailed design of all the addressed topics. A more detailed design enables an optimal test of the floating house, minimizing the start-up problems and reducing the risk of failure. It is essential for the future of the Floating Homes project that the first pilot is successful. When successful, the local stakeholders will be convinced of its performance and will support any further development of the project. To achieve this the following recommendations are made, based on this report:

- To assure that the design of the roof structure leads to a buildable pilot, there are two recommendations. Firstly, it is advised to further look into the connection design of the roof structure. The current design of the connections is based on detailing. However, a strength analysis still has to be performed on the connections to make sure that it is not over-dimensioned or under-dimensioned. Over-dimensioning leads to a design that is not affordable, but under-dimensioning makes the roof structure not typhoon resilient. The second recommendation is to look into the SLS requirements regarding maximum deflection of the elements of the roof structure, this way the cross sections can possibly be further optimised.

- Two aspects within the human water system that have a need for additional research are the social approval of the system and the technical capabilities of the designed waste water treatment schedule. The effluent has to meet with the given effluent standards and possibly with the standards for reuse. Therefore, a social study has to be conducted on the acceptance of the current design and water usage, and a study focusing on either modelling or testing of the treatment to assure a healthy effluent

- To finalise the design of the mooring system some choices have to be made regarding several aspects. From the conducted analysis of chapter 5, a favourable length and bending stiffness can be used to find a suitable mooring system. An iterative calculation is still needed to check whether the chosen combination of length and bending stiffness meets the strength requirements. A more optimum design can be obtained by more research of the wave conditions and use of specialised software.

- The construction duration should be determined in more detail, in order to achieve this, a more detailed design should be provided, and choices should be made regarding the materials and construction methods. The construction costs should be added to the project schedule, to acquire a more accurate overview of the entire construction phase. A combined schedule, including time, risk, change and cost management should be developed, used and revised during the entire duration of the pilot project to maintain control over the process.

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Appendices

Appendix A Wind

Appendix A.1: Significant storm events

In this appendix, the significant storm events are chosen from a graphical analysis. Storms from the north western Pacific (NWP) region between 100°E and 180°E from 1955 – 2017 are collected. Storm events are categorized using the Saffir-Simpson Hurricane Wind Scale (SSHWS). Storms that effected The Philippines are selected from this list, from 1980 – 2017. Before 1980 there is little to no information available on whether a storm effected The Philippines. No category 5 typhoon that effected The Philippines is recorded in the period 1980 – 2017. The Philippine, Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) uses a slightly different classification than SSHWS. Both classification systems are shown in Table A.1 Typhoon classification systems .

Table A.1 Typhoon classification systems

Saffir-Simpson Hurricane Wind Scale		PAGASA Classification May 2015	
Category	Wind speeds	Category	Wind speeds
Five	**≥70 m/s**, ≥137 knots, ≥157 mph, **≥252 km/h**	Super Typhoon	**≥61 m/s**, ≥120 knots, ≥137 mph, **≥220 km/h**
Four	**58-70 m/s**, 113-136 knots, 130-156 mph, **209-251 km/h**	Typhoon	**33-61 m/s**, 64-120 knots, 74-137 mph, **118-220 km/h**
Three	**50-57 m/s**, 96-112 knots, 111-129 mph, **178-208 km/h**	Severe tropical storm	**25-32 m/s**, 48-63 knots, 56-73 mph, **89-117 km/h**
Two	**43-49 m/s**, 83-95 knots, 96-110 mph, **154-177 km/h**	Tropical storm	**17-24 m/s**, 34-47 knots, 38-55 mph, **62-88 km/h**
One	**33-42 m/s**, 64-82 knots, 74-95 mph, **119-153 km/h**	Tropical depression	**≤17 m/s**, ≤33 knots, ≤38 mph, **≤62 km/h**
Tropical storm	**18-32 m/s**, 34-63 knots, 39-73 mph, **63-118 km/h**		
Tropical depression	**≤17 m/s**, ≤33 knots, ≤38 mph, **≤62 km/h**		

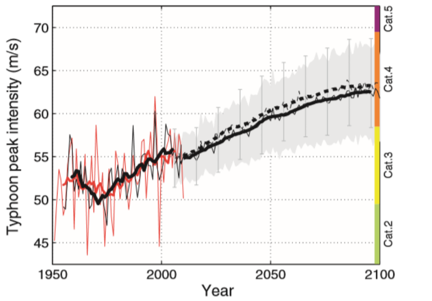


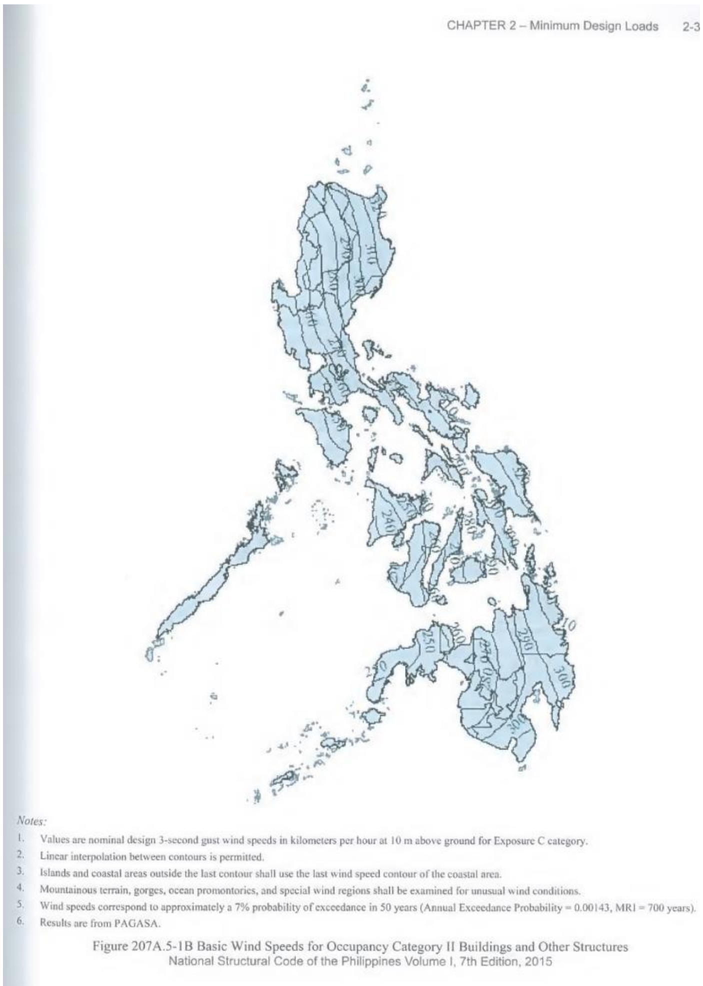
Fig. 4. Observed and projected typhoon lifetime peak intensity. Observed (thin red), predicted (1950–2009; thin black), and projected (2006–2100; thin black) seasonal mean typhoon lifetime peak intensity (m s^{-1}) and their 9-year running means (thick curves). Two projections are given: one (solid) considers both changes in SST and subsurface stratification with continuous gray shading showing error bars, and the other (dashed) ignores changes in subsurface stratification with error bars shown discretely for years 2006, 2016, …, and 2096. See Materials and Methods for details. The colors on the right *y* axis denote the range of typhoon intensity from category 2 up to category 5 based on the Saffir-Simpson hurricane scale.

Figure A.1 (Mei, Xie, Primeau, McWilliams, & Pasquero, 2015) Predicted typhoon intensity increase from 2006 to 2100

Figure A.3 shows the annual number of storms in the NWP region using the PAGASA classification. A 5 period (year) moving average shows that there is no clear trend in the total annual storms. However, from 2010 the total annual storms is increasing. Unfortunately, this period is too short to state that the total number of storms will increase. The storms that effected The Philippines (Figure A.4) show a trend where tropical depressions and severe tropical storms decrease, while tropical storms and typhoons increase. This is an indication of a shift in storm intensity. Tropical depressions are more likely to grow into tropical storms, while severe tropical storms grow into category 1 typhoons. This is better visualised when looking at the intensity of the typhoons. Typhoon classified storms by PAGASA are converted into SSHWS classification. Figure A.5 shows that category 1 and 2 typhoons are decreasing and category 3 and 4 increasing. The increased intensity of NWP typhoons is also researched by Mei et. al. (Mei, Xie, Primeau, McWilliams, & Pasquero, 2015). This research shows that from around 1980 typhoons in the NWP are growing in intensity. In the last two decades typhoon intensity increased by 5 m/s, which is a 33% increase in strength. They discussed that two factors play a large role, intensification rate and duration. Intensification rate is the rate at which a tropical storm can grow in intensity due to interactions between the ocean surface layer and the atmosphere. Intensification duration is the ability of a typhoon to sustain high intensity and reach higher peak intensities. Effected by large climate variability, global warming can potentially cause an increase of tropical storm intensity. The researchers predicted the intensity of typhoons from 2006 to 2100, showing that the mean typhoon intensity will reach category 4 by approximately 2040 (Figure A.1).

The Philippine building code (National Structural Code of The Philippines, 2015) developed wind contour maps for all occupancy categories (Figure A.2). These contour maps show the nominal design 3-second gust winds in kilometres per hour 10 meters above ground level. Residential buildings fall into category II. For the Manila bay region the category II contour map gives a 260 km/h wind speed. This is equal to a 10-minute mean wind speed of 174 km/h, category 2 typhoon on the Saffir-Simpson scale.

Thus although typhoons in the NWP region are increasing in intensity the strongest typhoons do not hit The Philippines very often. This is due to typhoons bending to the north as they move westward. Only some typhoons cross over The Philippines and hit Manila bay. Because of this the Philippine building code is used to determine the significant storm event. This is a category 2 typhoon on the Saffir-Simpson scale with wind speeds up to 177 km/h.

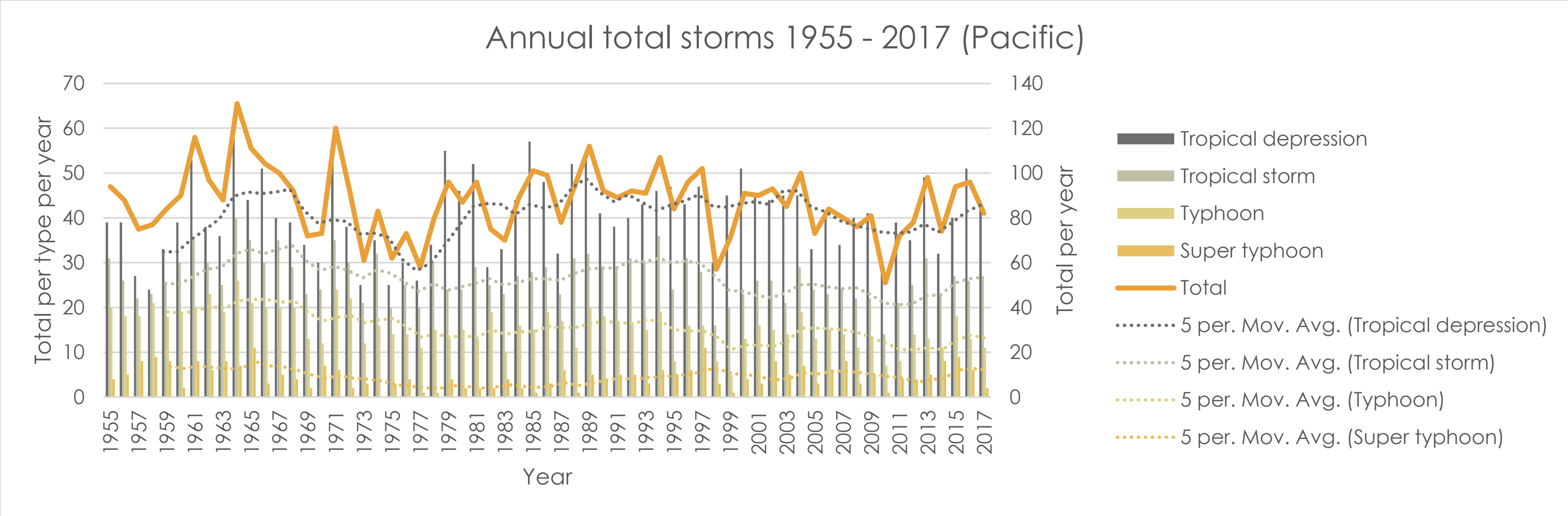

CHAPTER 2 – Minimum Design Loads 2-3

Notes:

1. Values are nominal design 3-second gust wind speeds in kilometers per hour at 10 m above ground for Exposure C category.
2. Linear interpolation between contours is permitted.
3. Islands and coastal areas outside the last contour shall use the last wind speed contour of the coastal area.
4. Mountainous terrain, gorges, ocean promontories, and special wind regions shall be examined for unusual wind conditions.
5. Wind speeds correspond to approximately a 7% probability of exceedance in 50 years (Annual Exceedance Probability = 0.00143, MRI = 700 years).
6. Results are from PAGASA.

Figure 207A.5-1B Basic Wind Speeds for Occupancy Category II Buildings and Other Structures
National Structural Code of the Philippines Volume I, 7th Edition, 2015

Figure A.2 Category II wind speed contour map from the NSCP



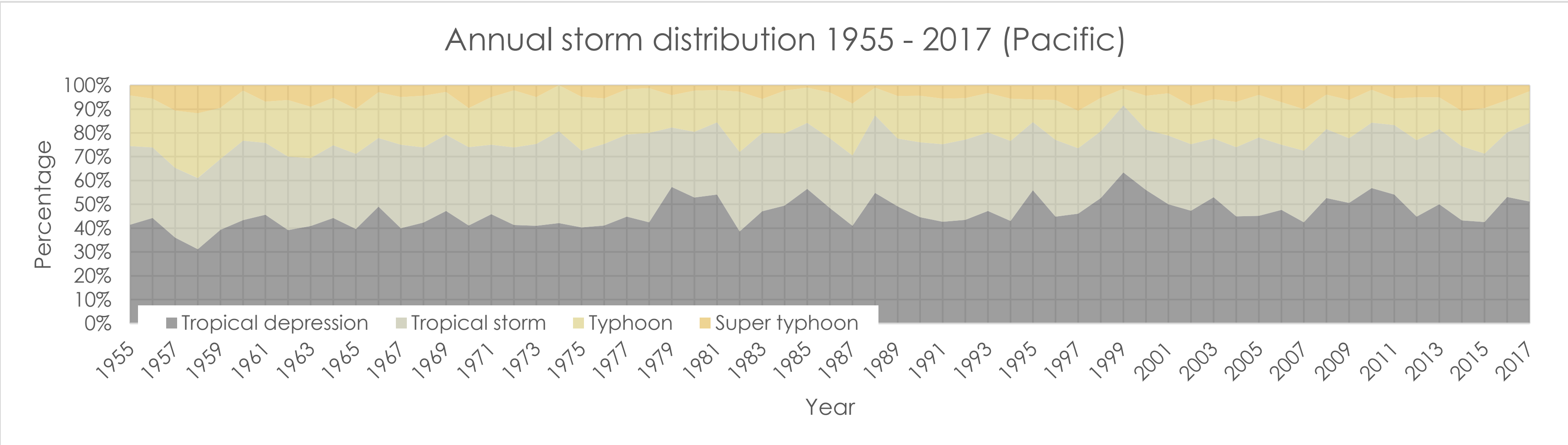
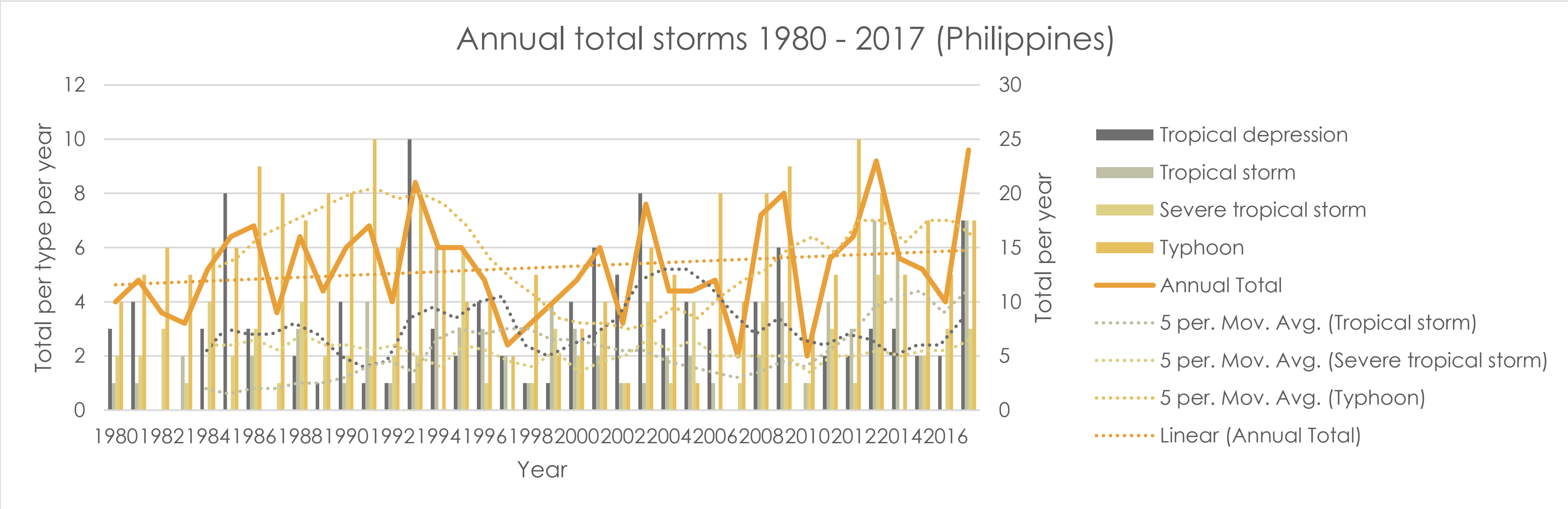


Figure A.3 Annual tropical storm in the north western Pacific region from 1955 to 2017



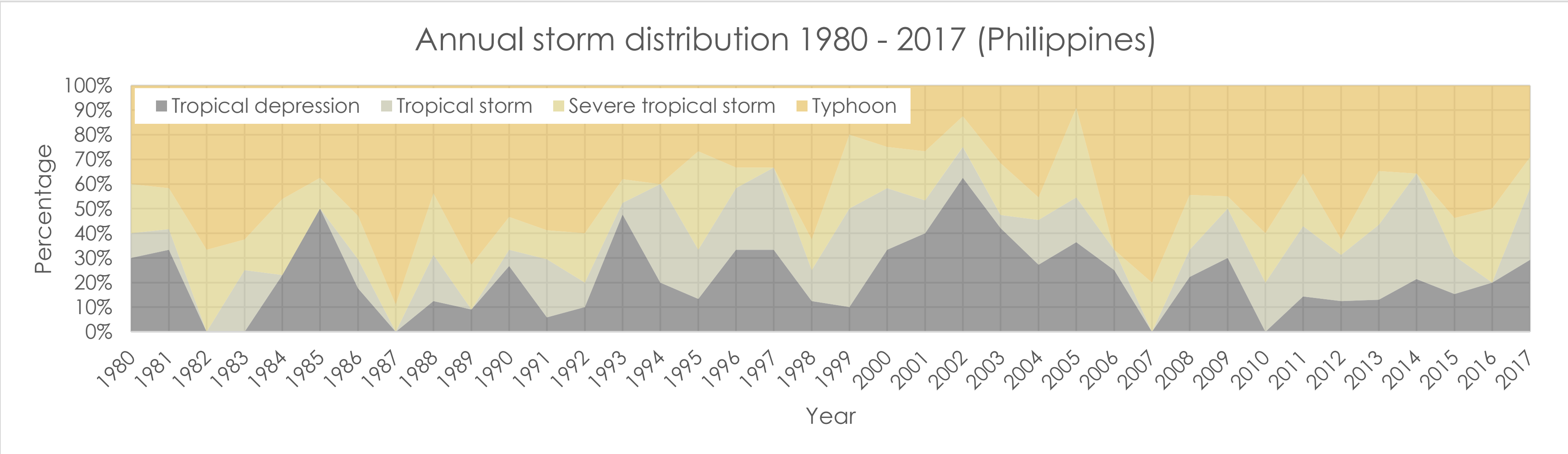


Figure A.4 Annual tropical storms that effected The Philippines from 1980 to 2017

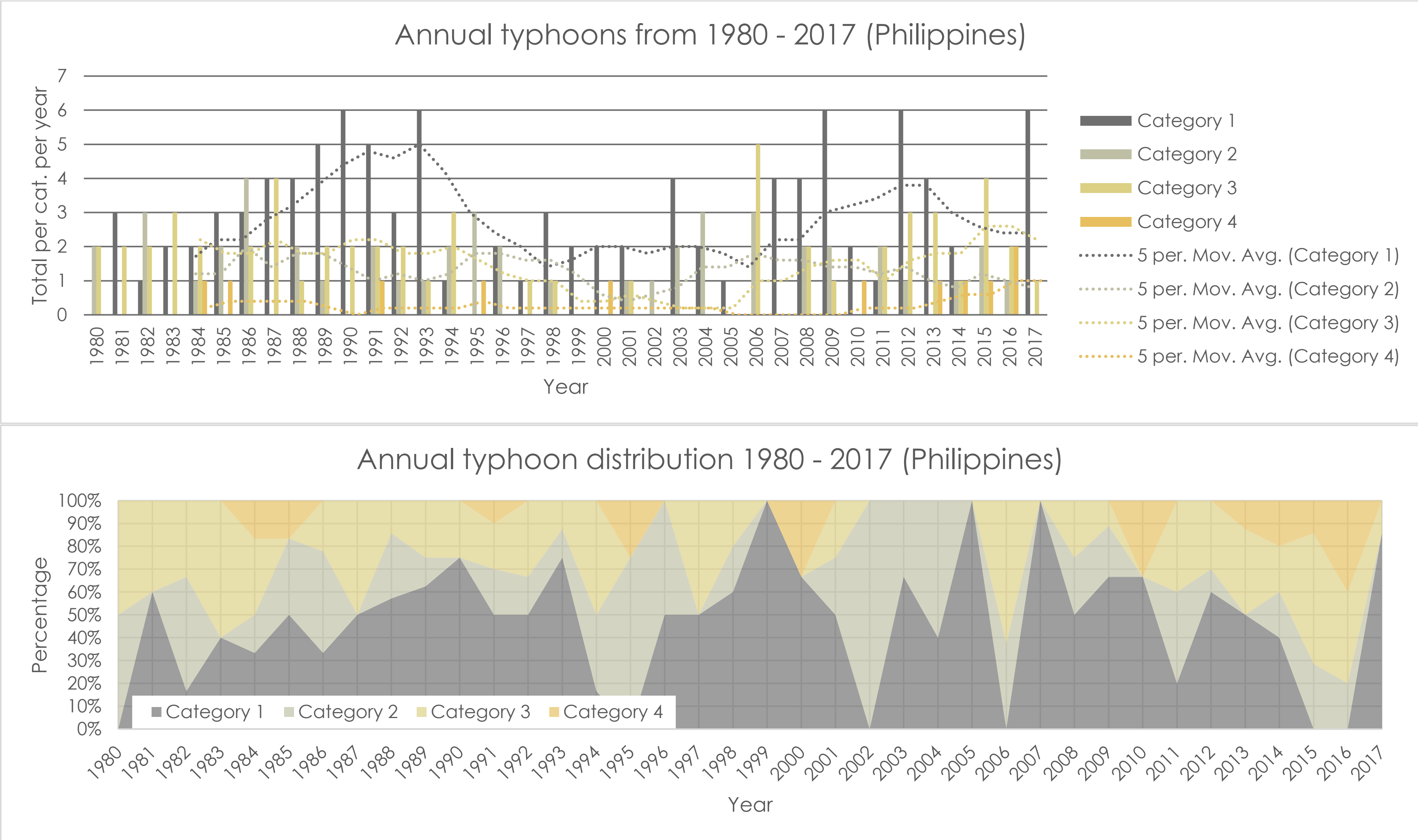


Figure A.5 Annual typhoons that effected The Philippines from 1980 to 2

Appendix A.2: Peak velocity calculation

Using Eurocode 1, the peak velocity pressure for the given wind velocities during a typhoon category 2 and a tropical storm can be calculated. The following formulas need to be used for this calculation:

Terrain factor k_R

$$k_R = 0.19 \frac{z_0}{0.05}^{0.07} \tag{A.1}$$

Basic wind velocity v_b

$$v_b = c_{dir} c_{season} v_{b,0} \tag{A.2}$$

Roughness factor $c_R(z)$

$$c_R(z) = k_R \ln \frac{z}{z_0} \tag{A.3}$$

Mean wind velocity $v_m(z)$

$$v_m(z) = c_R(z) c_{or}(z) v_b \tag{A.4}$$

Turbulence intensity $I_v(z)$

$$I_v(z) = \frac{k_L}{c_{or}(z) \ln \frac{z}{z_0}} \tag{A.5}$$

Peak velocity pressure $q_p(z_e)$

$$q_p(z_e) = \frac{1}{2}(1 + 7I_v(z))\rho_{air} v_m(z)^2 \tag{A.6}$$

The input for these calculations is:

z_0	as given in the Dutch National Annex for terrain category II 0.2 m
c_{dir}	must be taken 1.0
c_{season}	must be taken 1.0
$v_{b,0}$	basic wind velocity, for typhoon category 2 this is 49 m/s and for a tropical storm 32 m/s
$c_{or}(z)$	There are no hills with a slope of more than 5% in Macabebe, so this can be taken 1.0
k_L	must be taken 1.0
ρ_{air}	is 1.2 kg /m^3
z	is taken to be 6.5 m
z_e	is taken to be 6.5 m

Conclusion:
Typhoon category 2: $v_{b,0}$ = 49 m/s gives a peak velocity pressure of $q_{p,ULS}(z_e)$ = 2.40 kN/m^2.
Tropical storm: $v_{b,0}$ = 32 m/s gives a peak velocity pressure of $q_{p,SLS}(z_e)$ = 1.02 kN/m^2.

Appendix A.3: Roof wind load calculation

Wind pressure coefficients for the hip roof are needed for the wind load calculation. The values for each surface can be found in the following table, found in Eurocode 1 for a hip roof of 45 degrees. Positive values represent pressure and negative values represent tension. A distinction is made between global and local force coefficients, the coefficients are dependent on the dimensions of the area undergoing the load. The local force coefficients are meant to be used for calculations of small elements and connections with an area per element equal to or smaller than 1 m². The global force coefficients need to be used for the design calculations of the stability.

Table A.2 Wind load coefficients

		F	G	H	I	J	L	M
Global force coefficient	$c_{pe,10}$	0.0/+0.7	0.0/+0.7	0.0/+0.6	-0.3	-0.6	-1.3	-0.8
Local force coefficient	$c_{pe,1}$	0.0/+0.7	0.0/+0.7	0.0/+0.6	-1.0	-1.0	-2.0	-1.2

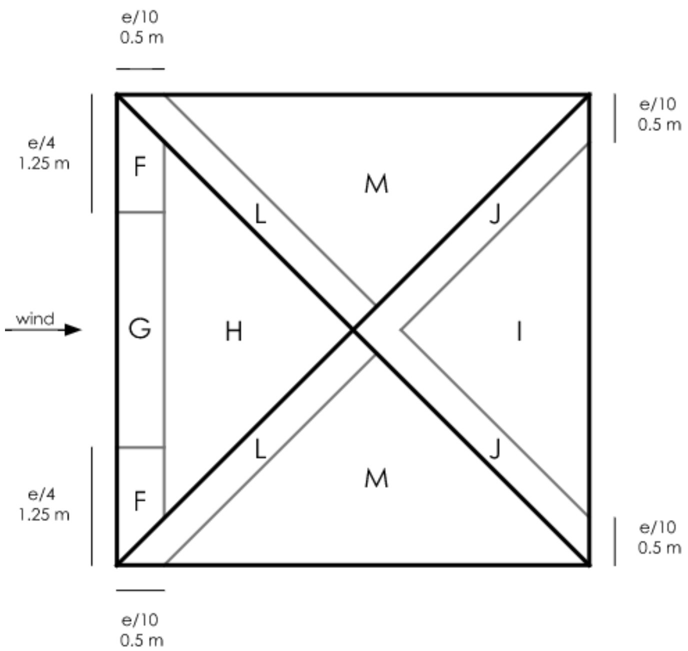


Figure A.7 Wind load surface sections

Using the pressure coefficients and the structural factor, the wind load on each surface can be found:

$$q_w = c_s c_d c_{pe} q_p(z_e) \qquad \text{(A.7)}$$

$c_s c_d$	is 1.0 because the floating houses have a height of less than 15 m
$q_{p,ULS}(z_e)$	is 2.40 kN/m²
$q_{p,SLS}(z_e)$	is 1.02 kN/m²

Ultimate limit state

- Global wind load

The global wind pressure coefficients give the following wind loads on the structure for ULS calculations:

F: $q_w = 1.0 \cdot +0.7 \cdot 2.40 = +1.68\ kN/m^2$
G: $q_w = 1.0 \cdot +0.7 \cdot 2.40 = +1.68\ kN/m^2$
H: $q_w = 1.0 \cdot +0.6 \cdot 2.40 = +1.44\ kN/m^2$
I: $q_w = 1.0 \cdot -0.3 \cdot 2.40 = -0.72\ kN/m^2$
J: $q_w = 1.0 \cdot -0.6 \cdot 2.40 = -1.44\ kN/m^2$
L: $q_w = 1.0 \cdot -1.3 \cdot 2.40 = -3.12\ kN/m^2$
M: $q_w = 1.0 \cdot -0.8 \cdot 2.40 = -1.92\ kN/m^2$

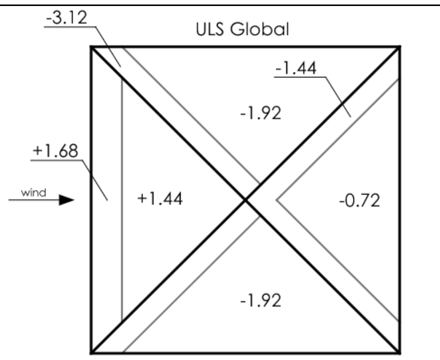


Figure A.10 Global wind pressure ULS

- Local wind load

The local wind pressure coefficients give the following wind loads on the structure for ULS calculations:

F: $q_w = 1.0 \cdot +0.7 \cdot 2.40 = +1.68\ kN/m^2$
G: $q_w = 1.0 \cdot +0.7 \cdot 2.40 = +1.68\ kN/m^2$
H: $q_w = 1.0 \cdot +0.6 \cdot 2.40 = +1.44\ kN/m^2$
I: $q_w = 1.0 \cdot -1.0 \cdot 2.40 = -2.40\ kN/m^2$
J: $q_w = 1.0 \cdot -1.0 \cdot 2.40 = -2.40\ kN/m^2$
L: $q_w = 1.0 \cdot -2.0 \cdot 2.40 = -4.80\ kN/m^2$
M: $q_w = 1.0 \cdot -1.2 \cdot 2.40 = -2.88\ kN/m^2$

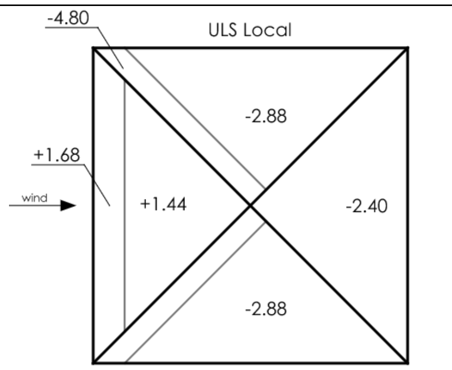


Figure A.11 Local wind pressure ULS

Servicibility limit state

- Global wind load

The global wind pressure coefficients give the following wind loads on the structure for SLS calculations:

F: $q_w = 1.0 \cdot +0.7 \cdot 1.02 = +0.72\ kN/m^2$
G: $q_w = 1.0 \cdot +0.7 \cdot 1.02 = +0.72\ kN/m^2$
H: $q_w = 1.0 \cdot +0.6 \cdot 1.02 = +0.62\ kN/m^2$
I: $q_w = 1.0 \cdot -0.3 \cdot 1.02 = -0.31\ kN/m^2$
J: $q_w = 1.0 \cdot -0.6 \cdot 1.02 = -0.62\ kN/m^2$
L: $q_w = 1.0 \cdot -1.3 \cdot 1.02 = -1.33\ kN/m^2$
M: $q_w = 1.0 \cdot -0.8 \cdot 1.02 = -0.82\ kN/m^2$

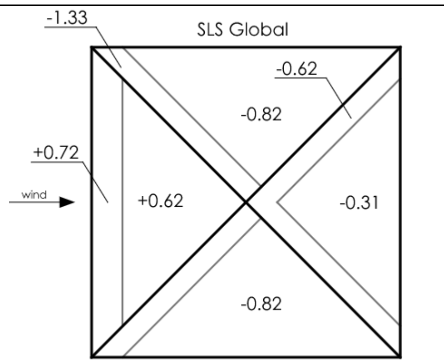


Figure A.12 Global wind pressure SLS

- Local wind load

The local wind pressure coefficients give the following wind loads on the structure for SLS calculations:

F: $q_w = 1.0 \cdot +0.7 \cdot 1.02 = +0.72\ kN/m^2$
G: $q_w = 1.0 \cdot +0.7 \cdot 1.02 = +0.72\ kN/m^2$
H: $q_w = 1.0 \cdot +0.6 \cdot 1.02 = +0.62\ kN/m^2$
I: $q_w = 1.0 \cdot -1.0 \cdot 1.02 = -1.02\ kN/m^2$
J: $q_w = 1.0 \cdot -1.0 \cdot 1.02 = -1.02\ kN/m^2$
L: $q_w = 1.0 \cdot -2.0 \cdot 1.02 = -2.04\ kN/m^2$
M: $q_w = 1.0 \cdot -1.2 \cdot 1.02 = -1.23\ kN/m^2$

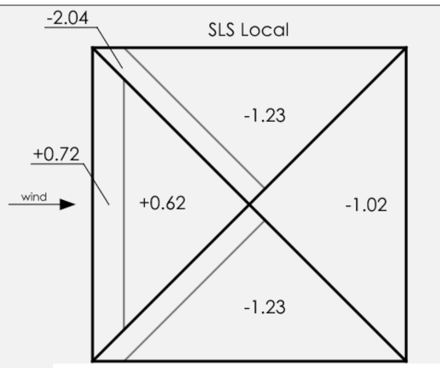


Figure A.13 Local wind pressure SLS

Appendix A.4: Net horizontal wind force

In this appendix the total horizontal wind force will be calculated. The wind force on the roof has been analysed earlier in Appendix A.3. Figure A.11 is copied from that appendix.

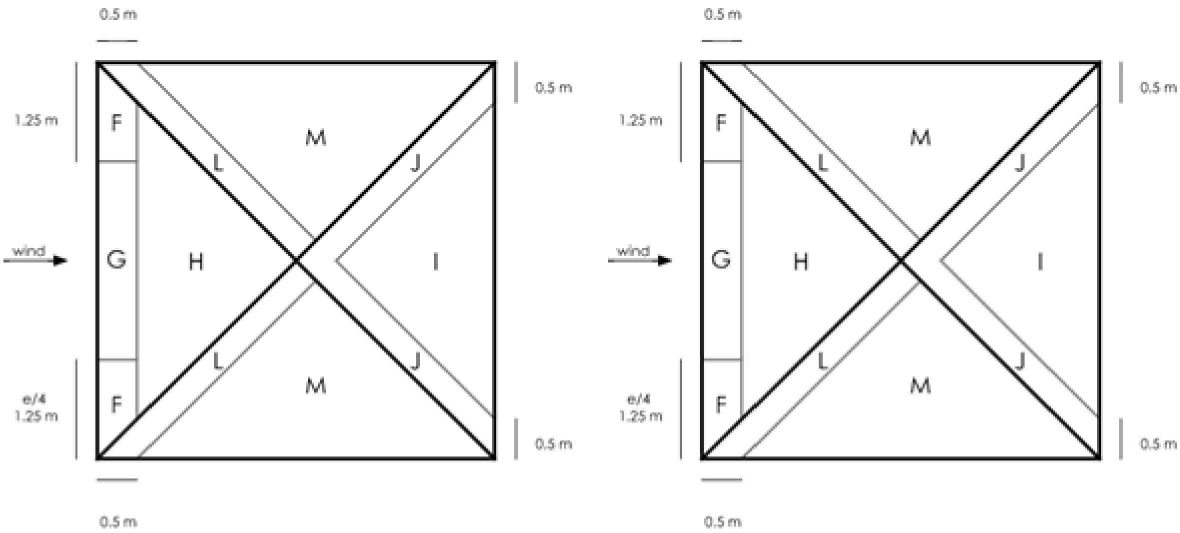


Figure A.14 Global wind coefficients for the roof structure

In the left plot the dimensions of the surfaces are indicated. The numbers in the right plot of Figure A.11 indicate the perpendicular distributed load at that surface. The surfaces L and M are not of interest, since the forces work in perpendicular direction. In Table A.3 Horizontal wind force on the roofthe perpendicular and horizontal wind force of every roof section is calculated. The perpendicular force is taken positive in the case of pressure and negative for suction. All forces work in the same horizontal direction. The direction of the vertical force will differ between the various surfaces. Downward forces are taken positive.

Table A.3 Horizontal wind force on the roof

Surface	Area (m^2)	F_{perp} (kN)	F_{hor} (kN)	F_{ver} (kN)
F	1.41	2.37	1.67	1.67
G	1.63	2.74	1.94	1.94
H	5.11	7.36	5.20	5.20
I	5.11	-3.68	2.60	-2.60
J	3.05	-4.40	3.11	-3.11
Total			14.52	3.11

Table A.4 shows that there is a resulting vertical force. This force is small in comparison with the inertia of the floating structure and will be neglected.

The wind action on the walls and the floating foundation has to be added to the wind force on the roof. The procedure is the same as for the roof, but only horizontal forces will be generated, since the surfaces are vertical. The freeboard of 795 mm during still water will be used. With the help of Eq. A.8 the distributed load on every surface is calculated, similar to the right plot of Figure A.11.

$$q_w = c_s c_d \cdot c_{pe} \cdot q_p(z_e) = 1.0 \cdot c_{pe} \cdot 2.4 \quad \text{(A.8)}$$

In Table A.4 the factor c_{pe} for every surface is presented. Again, side walls are neglected because its force will cancel each other. All resulting horizontal forces work in the same direction.

Table A.4 Horizontal wind force on walls and foundation

Surface	c_{pe}	$q_w\ (kN/m^2)$	Area (m^2)	F_{hor} (kN)
Front wall	+0.8	1.92	14.4	27.65
Back wall	-0.5	-0.96	14.4	13.82
Front foundation side	+0.7	1.68	7.63	12.82
Back foundation side	-0.3	-0.72	7.63	5.50
Total				59.79

The total horizontal wind load is 74.31 kN. The wind load acts at various surfaces with different sizes. This variety in position causes a turning moment on the structure. Beneath the location of the origin of the axis is shown to be able to calculate the total turning moment.

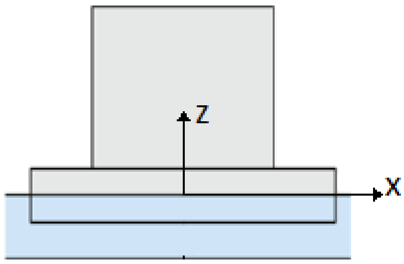


Table A.16 Location of the origin axis

In Table A.5 the turning moment is calculated by multiplication of the z-coordinate and the horizontal force and the x-coordinate and the vertical force of each surface.

Table A.6 Calculation of the turning moment caused by the wind

Surface	x-coordinate (m)	z-coordinate (m)	F_{ver} (kN)	F_{hor} (kN)	T_{wind} (kNm)
F	-2.15	4.105	1.67	1.67	3.26
G	-2.15	4.105	1.94	1.94	3.79
H	-1.27	5.305	5.20	5.20	20.98
I	1.77	4.805	-2.60	2.60	7.89
J	1.2	5.055	-3.11	3.11	11.99
Front wall	-2.4	2.345	0	27.65	64.84
Back wall	2.4	2.345	0	13.82	32.41
Front foundation side	-4.8	0.40	0	12.82	5.10
Back foundation side	4.8	0.40	0	5.50	2.19
Total			3.11	74.31	152.45

Appendix B Roof design

Appendix B.1: Member calculation

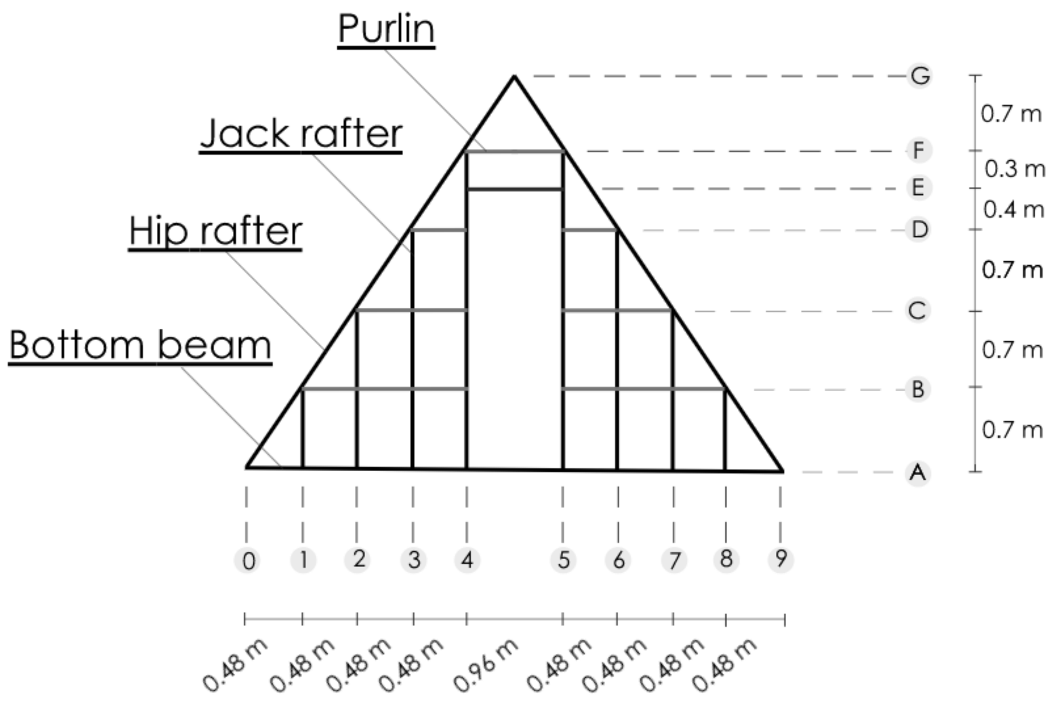


Figure B.1 Roof frame design

Roof sheeting

The maximum wind load that the roof sheeting has to withstand is (-) 4.8 kN/m² (Appendix A.3). This is the wind load for local ULS conditions. For ULS there are no limitations to the deflection.

$$Q_{d,wind} = 1.5 \cdot Q_{k,wind} = 7.2\ kN/m^2 \tag{B.1}$$

Using Puyat Steel Corporation's APO GALFAN CORSPAN corrugated steel roof sheeting (CSRS). The properties of this material is given in Table 3.2:

- thickness = 0.5 mm
- purlin spacing = 0.7 mm
- This gives (following from Table 3.2): **R_d = 7.4 kN/m²**

$$Unity\ check = \frac{R_d}{Q_{d,wind}} = \frac{7.4}{7.2} = 1.02 \tag{B.2}$$

Purlin

Only the governing purlin will be calculated. The governing purlin is the purlin shown on axis F in Figure B.1. This purlin is simply supported on only two supports, is undergoing the governing high wind load for tension from area L and for compression area from area G (Figure A.11) and has the largest length of 0.96 m. The purlins are spaced at a distance of 0.70 m.

The purlins are undergoing wind load perpendicular to the roof surface and permanent load and self-weight pointed downwards in the global coordinate system. The permanent load and self-weight are under an angle of 45 degrees with the local axis of the purlin.

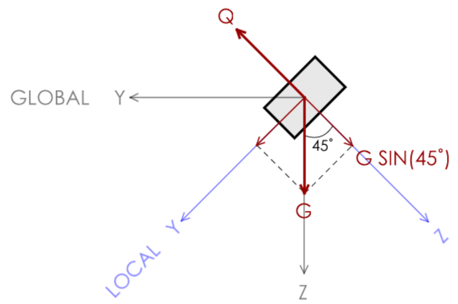


Figure B.2 Purlin orientation

Load combinations and loads
For the purlins in both ULS and SLS, two load combinations will be considered.

ULS:

1. Due to pulling wind (tension). The permanent load works favourable in this case.

$$q_{d,wind,pull} = 1.5 \cdot Q_{k,wind,pull} - 0.9\left[G_{roof} + G_{purlin}\right] \cdot \sin(45) \qquad (B.3)$$

2. Due to pushing wind (compression)

$$q_{d,wind,push} = 1.5 \cdot Q_{k,wind,push} + 1.35\left[G_{roof} + G_{purlin}\right] \cdot \sin(45) \qquad (B.4)$$

SLS:

3. Due to pulling wind (tension). The permanent load works favourable in this case.

$$q_{d,wind,pull} = 1.0 \cdot Q_{k,wind,pull} - 1.0\left[G_{roof} + G_{purlin}\right] \cdot \sin(45) \qquad (B.5)$$

4. Due to pushing wind (compression)

$$q_{d,wind,push} = 1.0 \cdot Q_{k,wind,push} + 1.0\left[G_{roof} + G_{purlin}\right] \cdot \sin(45) \qquad (B.6)$$

Wind ULS: $Q_{k,wind,pull}$ = (-) 4.8 · 0.70 = (-) 3.36 kN/m
$Q_{k,wind,push}$ = (+) 1.68 · 0.70 = (+) 1.18 kN/m
Wind SLS: $Q_{k,wind,pull}$ = (-) 2.04 · 0.70 = (-) 1.43 kN/m
$Q_{k,wind,push}$ = (+) 0.72 · 0.70 = (+) 0.51 kN/m
Permanent: G_{roof} = 0.046 · 0.70 = 0.033 kN/m
G_{purlin} = 10.40 kN/m^3

Cross section
For the cross section of the purlin 38 x 38 mm is chosen. The self-weight of this cross section is:

$$G_{purlin} = 10.40 \cdot 0.038 \cdot 0.038 = 0.015 \text{ kN/m}$$

Calculations

ULS

$q_{d,wind,pull}$ = 1.5 · 3.36 - 0.9 [0.033 +0.015] sin(44) = **5.0 kN/m** (governing)
$q_{d,wind,push}$ = 1.5 · 1.18 + 1.35 [0.033 +0.015] sin(44) = 1.8 kN/m

T_d = ⅛ q l^2 = ⅛ · 5.0 · 0.96^2 = 0.58 kNm = $0.58 \cdot 10^6$ Nmm
W = ⅙ b h^2 = ⅙ · 38 · 38^2 = 9,145 mm^3

$\sigma = T_d/W = 0.58 \cdot 10^6 / 9145 = 63$ N/mm² < f_y = 180 N/mm²

unity check: 180/63 = **2.9**

Support reaction purlins

- Purlin axis F:
  F_s = ½ · 5.0 · 0.96 = 2.4 kN
- Purlin on other axis:
  F_s = ½ · 5.0 · 0.48 = 1.2 kN

SLS

$q_{d,wind,pull}$ = 1.0 · 1.43 - 1.0 [0.033 +0.015] sin(45) = **1.40 kN/m** (governing)
$q_{d,wind,push}$ = 1.0 · 0.51 + 1.0 [0.033 +0.015] sin(45) = 0.54 kN/m

I = 1/12 b h^3 = 1/12 · 38 · 38^3 = 173,761 mm^4
E = 22,000 N/mm²

w = $5ql^4/384EI$ = $5 \cdot 1.40 \cdot 960^4/384 \cdot 22{,}000 \cdot 172{,}761$ = 4.1 mm
w_{max} = 1/250 L = 3.8 mm

Checking SLS requirements: **w > w_{max} -> Chosen cross section does not suffice**

Choosing cross section 38 x 64 mm

I = 1/12 · 64 · 38^3 = 292,651 mm^4
w = $5ql^4/384EI$ = $5 \cdot 1.40 \cdot 960^4/384 \cdot 22{,}000 \cdot 292{,}651$ = 2.4 mm

Checking SLS requirements: **w < w_{max} -> Chosen cross section suffices**

Support reaction purlins

- Purlin axis F:
  F_s = ½ · 1.40 · 0.96 = 0.68 kN
- Purlin other axis:
  F_s = ½ · 1.40 · 0.48 = 0.34 kN

Conclusion

The height of the purlin is 38 mm and the width of the purlin is 64 mm. A larger width makes it easier to connect the purlin to the jack rafters and to connect the roofing material to the purlins.

Jack rafter

The governing jack rafters are the jack rafters on axis 4 and 5. These rafters are the longest with their length of 2.8 m. They undergo load from the purlins and load from the roof openings. The wind load on the roof openings is lower than was used for the purlins, since it is not located in area L. Area M is governing for tension and area G is still governing for compression.

Load combinations and loads

For the jack rafter in both ULS and SLS, two load combinations will be considered. $F_{s,\ purlin}$ is already a design value and can be added to the model.

ULS:

1. Due to pulling wind (tension). The permanent load works favourable in this case.

$$q_{d,wind,pull} = 1.5 \cdot Q_{k,wind,pull} - 0.9 \cdot G_{jack} \cdot \sin(45) \tag{B.7}$$

2. Due to pushing wind (compression)

$$q_{d,wind,push} = 1.5 \cdot Q_{k,wind,push} + 1.35 \cdot G_{jack} \cdot \sin(45) \tag{B.8}$$

SLS

3. Due to pulling wind (tension). The permanent load works favourable in this case.

$$q_{d,wind,pull} = 1.0 \cdot Q_{k,wind,pull} - 1.0 \cdot G_{jack} \cdot \sin(45) \tag{B.9}$$

4. Due to pushing wind (compression)

$$q_{d,wind,push} = 1.0 \cdot Q_{k,wind,push} + 1.0 \cdot G_{jack} \cdot \sin(45) \tag{B.10}$$

Wind ULS: $Q_{k,wind,pull}$ = (-) 2.88 · 0.48 = (-) 1.38 kN/m
$Q_{k,wind,push}$ = (+) 1.68 · 0.48 = (+) 0.81 kN/m
Wind SLS: $Q_{k,wind,pull}$ = (-) 1.23 · 0.48 = (-) 0.59 kN/m
$Q_{k,wind,push}$ = (+) 0.72 · 0.48 = (+) 0.35 kN/m
Permanent ULS and SLS:
$F_{s,\ purlin}$ (See purlins)

Cross section
For the cross section of the jack rafter of 64 x 89 mm is chosen. The self-weight of this cross section is:

$$G_{purlin} = 10.40 \cdot 0.064 \cdot 0.089 = 0.060 \text{ kN/m}$$

Calculations
The calculations for the jack rafters were done for both ULS and SLS in MatrixFrame.

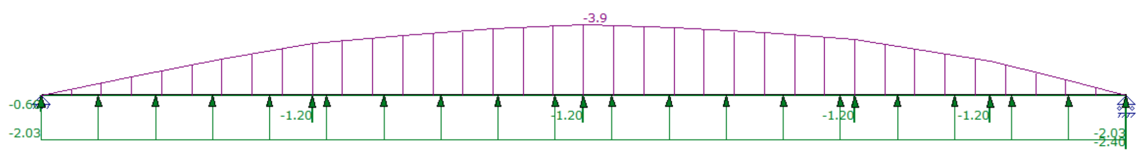


Figure B.3 ULS moment, jack rafter

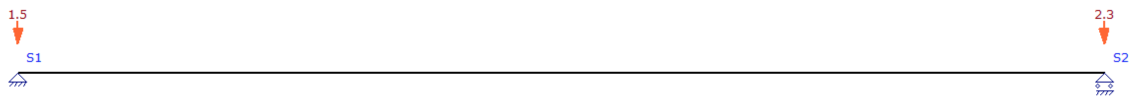


Figure B.4 ULS support reactions, jack rafter

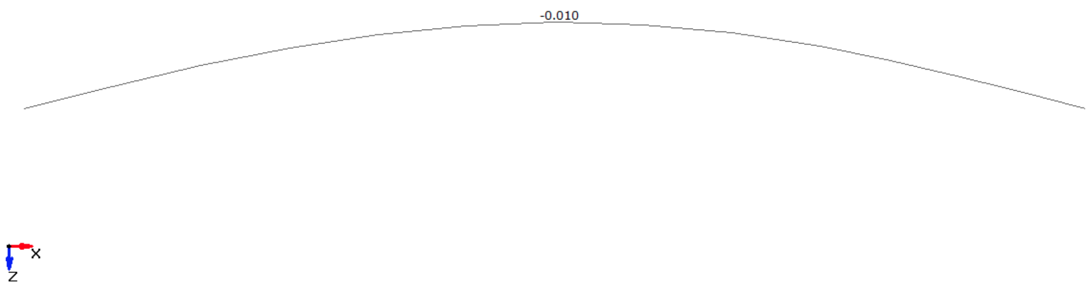


Figure B.5 SLS deflection, jack rafter

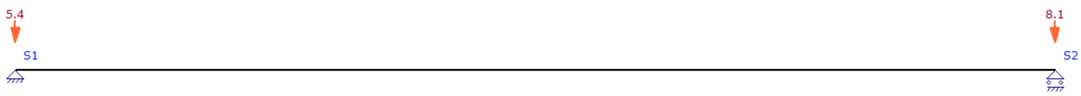


Figure B.6 SLS support reaction

<u>ULS</u>

$q_{d,wind,pull} = 1.5 \cdot 1.38 - 0.9 \cdot 0.060 \cdot \sin(45) = \mathbf{2.03\ kN/m}$ (governing)
$q_{d,wind,push} = 1.5 \cdot 0.81 + 1.35 \cdot 0.060 \cdot \sin(45) = 1.28\ kN/m$

$T_d = 3.9$ kNm (see Figure B.3)
$W = \frac{1}{6} \cdot 64 \cdot 89^2 = 84{,}491\ mm^3$

$\sigma = T_d/W = 3.9 \cdot 10^6 / 84{,}491 = 46\ N/mm^2 < f_y = 180\ N/mm^2$

unity check: 180/46 = **3.9**

<u>Support reaction ULS jack rafter (see Figure B.4)</u>

- Reaction top:
  $\mathbf{F_s} = 8.1$ kN
- Reaction bottom:
  $\mathbf{F_s} = 4.8$ kN

<u>SLS</u>

$q_{d,wind,pull}$ = 1.0 · 0.59 - 1.0 · 0.060 · sin(45) = **0.55 kN/m** (governing)
$q_{d,wind,push}$ = 1.0 · 0.35 + 1.0 · 0.060 · sin(45) = 0.39 kN/m

w = 10 mm (see Figure B.5)
w_{max} = 1/250 L = 11 mm

Checking SLS requirements: **$w < w_{max}$ -> Chosen cross section suffices**

Support reaction SLS jack rafter (see Figure B.6)

- Reaction top
  F_s = 2.3 kN
- Reaction bottom
  F_s = 1.3 kN

Conclusion
The height of the jack rafter is 89 mm and the width of the jack rafter is 64 mm.

Hip rafter

The length of the hip rafters is 4.24 m. As load on the hip rafter, the support reaction of the largest jack rafter will be applied for all the jack rafters. This is conservative, but because the hip rafter will also have a global stability function extra capacity will be needed. The global stability will be determined section 3.4.5 “Global stability”.

Load combinations and loads
The load on the hip rafter due to the jack rafters is already a design value.

- ULS: F_s = 8.1 kN
- SLS: F_s = 2.3 kN

The load due to the self-weight of the hip rafter:

ULS:

1. Due to pulling wind (tension). The permanent load works favourable in this case. It should be directed in opposite direction as the reactions from the jack rafters.

$$q_G = -0.9 \cdot G_{hip} \cdot \sin(45) \quad \text{(B.11)}$$

SLS

2. Due to pulling wind (tension). The permanent load works favourable in this case. It should be directed in opposite direction as the reactions from the jack rafters.

$$q_G = -1.0 \cdot G_{hip} \cdot \sin(45) \quad \text{(B.12)}$$

Cross section
For the cross section of the jack rafter of 140 x 140 mm is chosen. The self-weight of this cross section is:

G_{hip} = 10.40 · 0.140 · 0.140 = 0.21 kN/m

Calculations
The calculations for the jack rafters for both ULS and SLS were done in MatrixFrame.

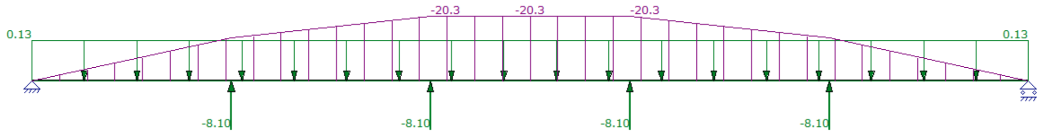


Figure B.7 ULS moment, hip rafter

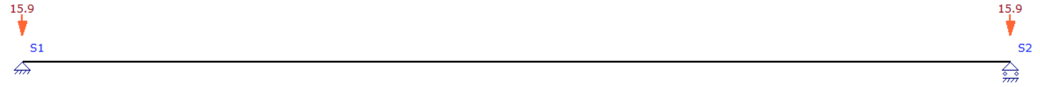


Figure B.8 ULS support reaction, hip rafter

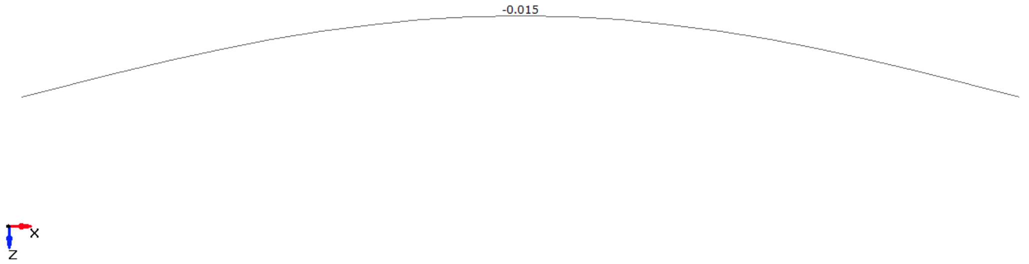


Figure B.9 SLS deflection, hip rafter

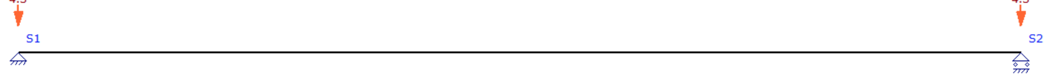


Figure B.10 SLS support reaction, hip rafter

ULS

q_g = - 0.9 · 0.21 · sin(44) = **-0.13 kN/m**

T_d = 20.3 kNm (see Figure B.7)
W = ⅙ · 140 · 140^2 = 457,333 mm^3

σ = T_d/W = 20.3 ·10^6 / 457,333 = 45 N/mm^2
f_y = 180 N/mm

unity check: 180/ 45 = **4**

Support reaction ULS hip rafter

- **F_s** = 15.9 kN (see Figure B.8)

SLS

q_G = - 1.0 · 0.21 · sin(45) = **-0.15 kN/m**

w = 15 mm (see figure Figure B.9)
w_{max} = 1/250 L = 16 mm

Checking SLS requirements: **w < w_{max} -> Chosen cross section suffices**

Support reaction SLS hip rafter

- **F_s** = 4.3 kN (see Figure B.10)

Conclusion

The height of the hip rafter is 140 mm and the width of the hip rafter is 140 mm.

Bottom beam

The bottom beam is loaded by the hip rafters, the jack rafters and self-weight. The bottom beam is supported every 1.20 m by the wall panels. Due to the detailing of the connection of the jack rafter to the bottom beam and the hip rafter to the bottom beam, the width of the beam should be at least 140 mm. The height is free to choose. The local coordinate system of the bottom beam is according to the global coordinate system. This time the load due to wind should be transformed to the global coordinate system. Only the load in the global z axis will be determined, this is governing.

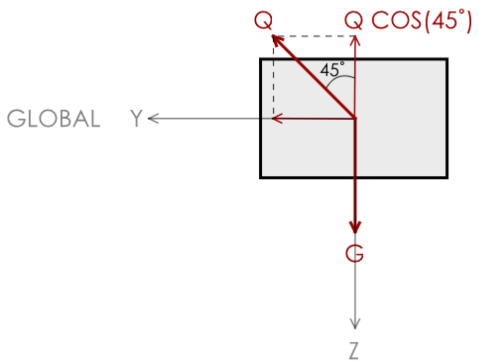


Figure B.11 Bottom beam orientation

Load combinations and loads
The load on the bottom beam due to the jack rafters is already a design value.

- ULS: F = 5.4 · cos(45) = 3.8 kN
- SLS: F = 1.5 · cos(45) = 1.1 kN

The load on the bottom beam due to the hip rafters is already a design value.

- ULS: F = 15.9 · cos(45) = 11.3 kN
- SLS: F = 4.3 · cos(45) = 3.1 kN

The load due to the self-weight of the bottom beam is as follows:

ULS:

1. Due to pulling wind (tension). The permanent load works favourable in this case. It should be directed in opposite direction as the reactions from the jack rafters and hip rafters.

$$q_G = -0.9 \cdot G_{BB} \tag{B.13}$$

SLS:

2. Due to pulling wind (tension). The permanent load works favourable in this case. It should be directed in opposite direction as the reactions from the jack rafters.

$$q_G = -1.0 \cdot G_{BB} \tag{B.14}$$

Cross section
For the cross section of the jack rafter of 140 x 89 mm is chosen. The self-weight of this cross section is:

$$G_{BB} = 10.40 \cdot 0.140 \cdot 0.089 = 0.13 \text{ kN/m}$$

Calculations
The calculations for the jack rafters for both ULS and SLS were done in MatrixFrame.

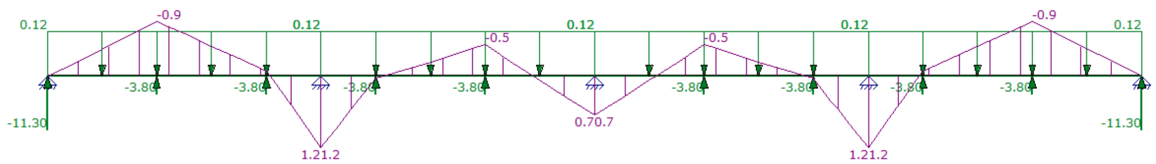


Figure B.12 ULS moment, bottom beam

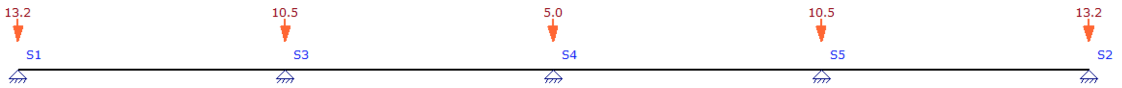


Figure B.13 ULS support reaction, bottom beam

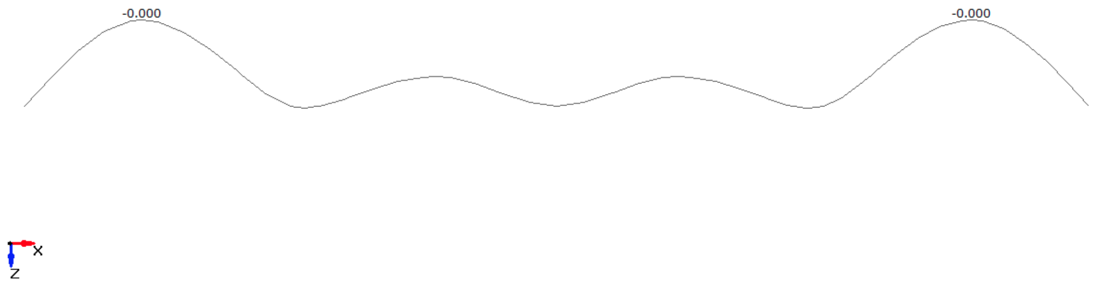


Figure B.14 SLS deflection, bottom beam

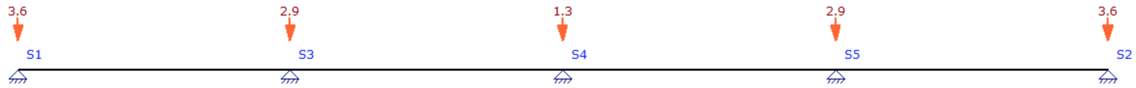


Figure B.15 SLS support reaction, bottom beam

<u>ULS</u>
q_G = - 0.9 · 0.13 = **-0.12 kN/m**

T_d = 1.2 kNm (Figure B.12)
W = ⅙ · 140 · 89^2 = 184,824 mm³

$\sigma = T_d/W = 1.2 \cdot 10^6 / 184{,}824 = 7$ N/mm² < f_y = 180 N/mm²

unity check: 180/ 7 = **26**

<u>Support reactions ULS bottom beam (Figure B.13)</u>

- Corners F_s = 13.2 kN
- Middle F_s = 5.0 kN
- In between F_s = 10.5 kN

<u>SLS</u>
q_G = - 1.0 · 0.13 = **-0.13 kN/m**

w is very small (Figure B.14)

Checking SLS requirements: **w << w_{max} -> Chosen cross section suffices**

Support reactions SLS bottom beam (Figure B.14)

- Corners F_s = 3.6 kN
- Middle F_s = 1.3 kN
- In between F_s = 2.9 kN

Conclusion

The height of the bottom beam is 89 mm and the width of the bottom beam is 140 mm. The detailing of the roof frame defines the dimensions of this bottom beam.

Appendix B.2: Roof opening, openable balconies

The VELUX CABRIO® as introduced by the company Velux group, inspired the concept of the openable balconies. While this product is beautifully designed, it also comes with a price tag beyond the scope of this project. Additionally, the product is not locally available in the Philippines.

Figure B.16 Openable balconies, (left: VELUX CABRIO®. right: wooden concept)

As alternative to the VELUX CABRIO® an own openable balcony framework is designed. The frame uses the same materials as used for the other roof elements, namely Azobé timber beams. Additionally, there are some steel elements which fulfill crucial roles in the design of the framework are:

- Piano hinges:

Figure B.17 Piano hinge

This type of hinge forms the connection between the openable bottom part of the balcony and bottom beam of the roof frame.

- Steel rods:

Figure B.18 Steel rebar

Any type of steel rod strong enough would work, but looking at local availability it seems that steel rebars are the most available type of steel rods. These elements have a double function. In closed position they make sure force transfer is possible between the balcony frame and the roof frame. When the balconies are opened they support the elements in their position.

- Threaded rod with end nuts:

Figure B.19 Threated rod with two end nuts

This combination of a threaded rod and two and nuts combine into the hinged connection for the top part of the balcony.

With the introduction of these additional elements the design of the foldable balcony can now be fully explained.

1. **Bottom section**

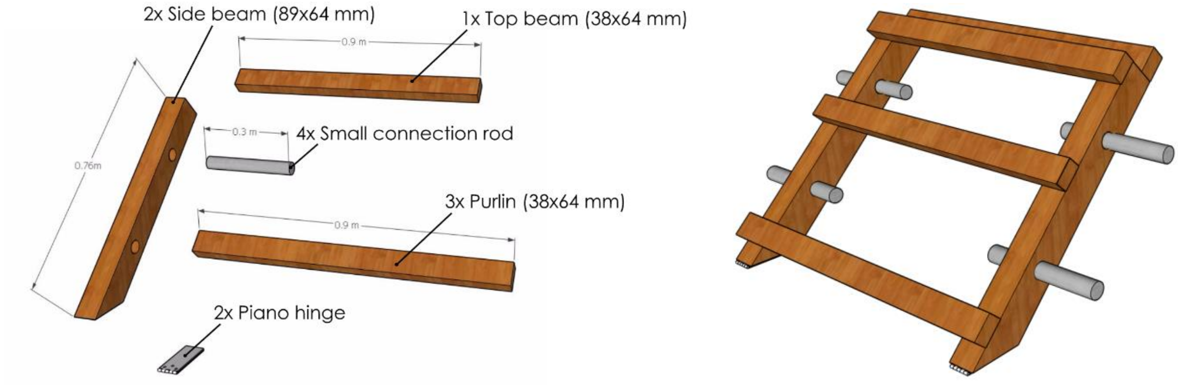


Figure B.20 Bottom section elements

The bottom section of the balcony frame can be prefabricated and installed into the main roof frame as soon as the jack rafters are in place. This section should be installed before the top section of the balcony frame.

2. **Top section**

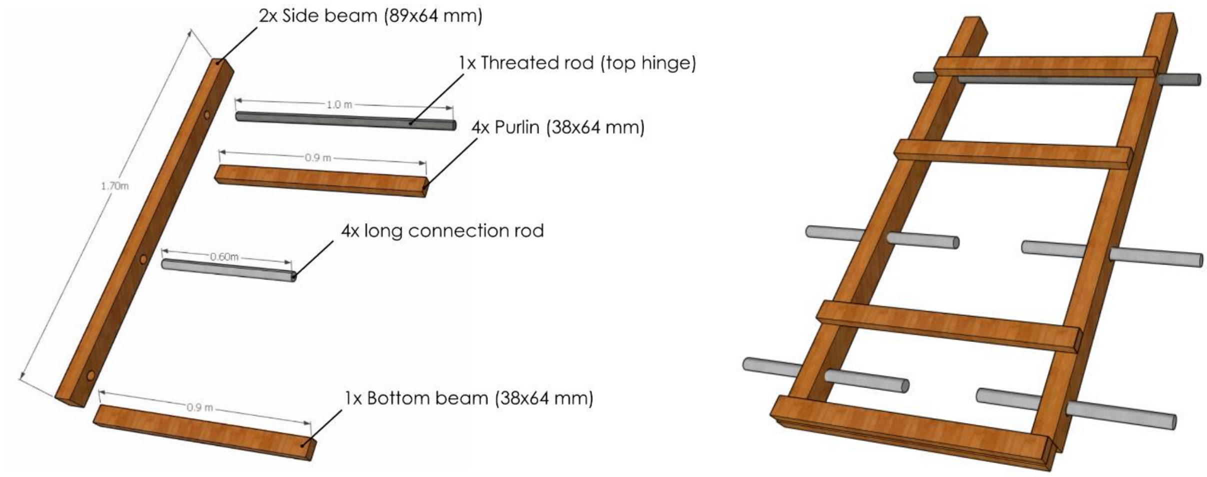


Figure B.21 Top section elements

The top section can be prefabricated using the different components as described in Figure B.21. Notice that compared to the steel connection rods used in the bottom section the connecting elements in the top section are longer. This is due to the double function of these rods. When the balcony is opened two of them support the top section in open position and the other two the bottom section.

The bottom beam as shown in Figure B.21 is on top of the top beam as shown in Figure B.20. This means that top part of the balcony should always be opened first. Using this configuration of interlocking top and bottom sections allows for opening of the top section while the bottom section stays closed. This could be a preferred situation at times when only natural ventilation is wanted, but not the whole balcony setup is required. The designed configuration also prevents leakage of the top section into the bottom section of the opening.

Appendix B.3: Construction manual

In this manual, it will be explained step by step how to construct the roof. Every step is shown by figures of the structure and detail drawings explaining the connections to be made. Constructing the roof consists of three phases:

- Phase 1: Prefabricating the roof frame
- Phase 2: Installing the frames
- Phase 3: Finishing the roof

Phase 1: Prefabricating the roof frame

The prefabrication of the roof frame will be explained in 6 steps. The frame has to be made four times. After prefabricating the frames, the four frames can be transported to the construction site. Table B.1 shows the fasteners that need to be on hand to execute this phase.

Table B.1 Fasteners phase 1

Step	Detail	Fastener type		Amount per detail	Number of details per frame	Total per frame	Total
2	2.1	Screw	#12, 4 1/2	2	2	4	16
	2.2	Bolt	1/4, 3 1/2	3	1	3	12
3	3.1	Screw	#12, 4 1/2	2	8	16	64
	3.2	Screw	#12, 4 1/2	3	8	24	96
4	4.1	Screw	#8, 4	1	2	2	8
	4.2	Screw	#8, 4	2	1	2	8
6	6.1	Screw	#8, 4	2	34	68	272

1. **Saw and predrill the elements**

To make the assembly of the roof structure easy, the elements should be sawn in advance. Also, the bottom beams, hip rafters and jack rafters should be predrilled. The length of each element is given in Table B.2, Figure B.22, Figure B.23, and Figure B.24 show the predrilling and angle at which the bottom beam, jack rafter and hip rafter respectively have to sawn.

Table B.2 Element size and amount

Element type	Dimensions hxb (mm)	Length (mm)	Amount
Bottom beam	89x140	4,800	4
Hip rafter	140x70	4,070	8
Jack rafter	89x64	2,800	8
	89x64	2,100	8
	89x64	1,400	8
	89x64	700	8
Purlins	38x64	1,920	8
	38x64	1,504	8
	38x64	1,024	12
	38x64	544	8
	38x64	890	8
Insulation	5x1000	3,500	12
CSRS	18x1080	3,500	12
Bamboo gutter	Ø100	4,800	2
Bamboo gutter holder	140x76	200	20

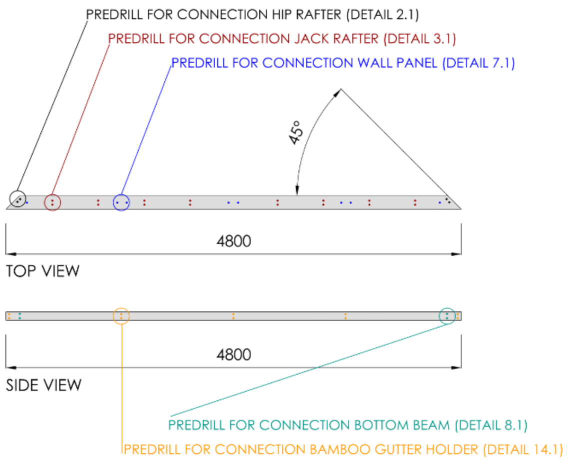


Figure B.22 Bottom beam preparation

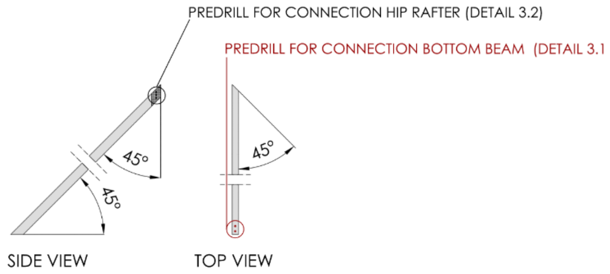


Figure B.23 Jack rafter preparation

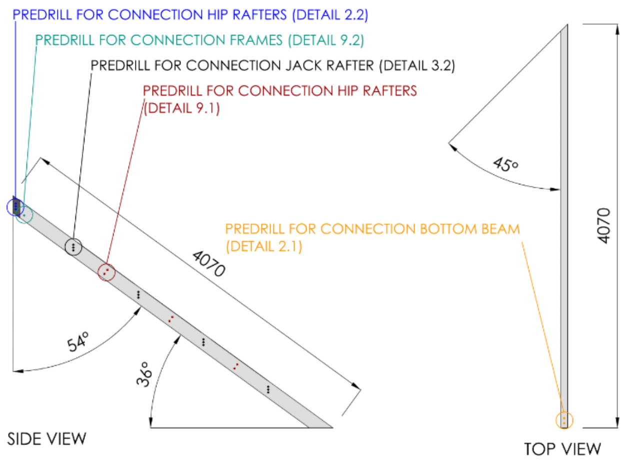


Figure B.24 Hip rafter preparation

2. Connect the hip rafters and the bottom beam

In this step, the outer triangle of the roof frame is made. Start with connecting the two hip rafters to the bottom beam according to detail 2.1. Two screws #12, 4 1/2 are applied through the predrilled holes in the bottom beam. The face of the bottom beam has to remain flat.

After this, connect the two hip rafters to each other according to detail 2.2. This should be achieved by applying three bolts 1/4, 3 1/2 through the predrilled holes.

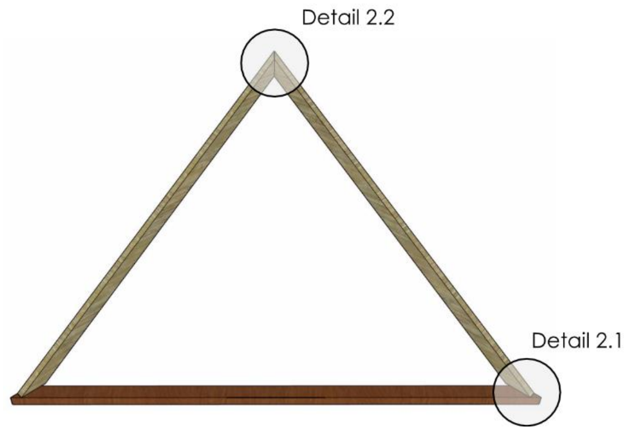


Figure B.25 Hip rafter and bottom beam connection

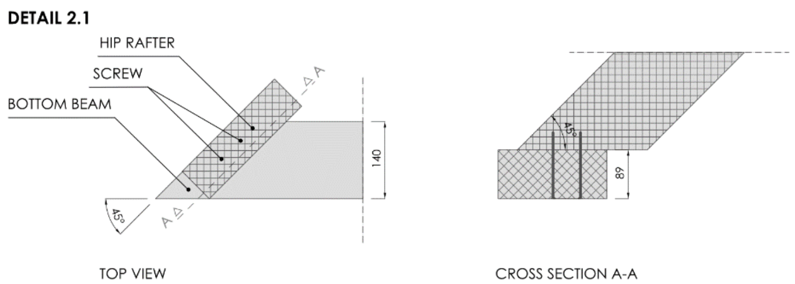


Figure B.26 Detail 2.1, hip rafter to bottom beam

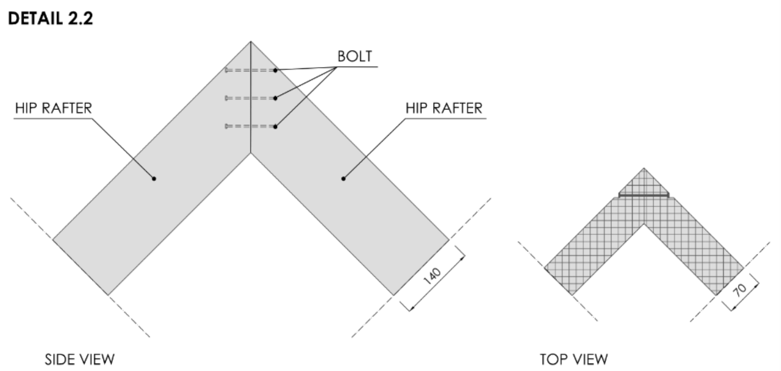


Figure B.27 Detail 2.2, hip rafter to hip rafter

3. Place the jack rafters

Eight jack rafters need to be placed in the outer triangle. First connect them to the bottom beam in a similar matter as the hip rafter was connected to the bottom beam. Two screws #12, 4 1/2 per jack rafter are applied through the predrilled holes in the bottom beam according to detail 3.1. The face of the bottom beam has to remain flat.

After this, connect the jack rafter to the hip rafter according to detail 3.2. Three screws #12, 4 1/2 per jack rafter are applied perpendicular to the face of the hip rafter. The face of the hip rafter has to remain flat, due to the connection of two hip rafters in phase 2.

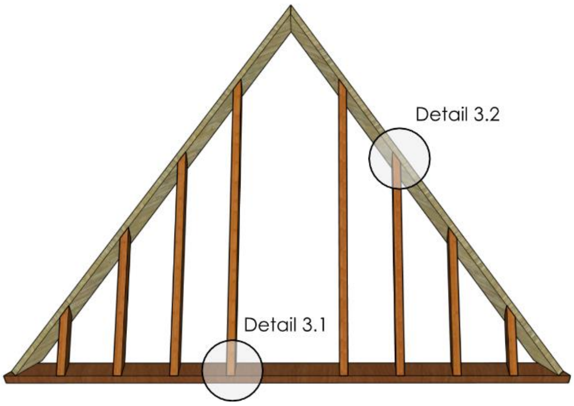


Figure B.28 Jack rafter connections

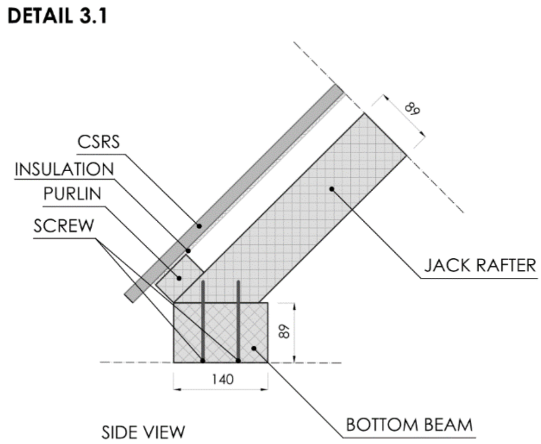


Figure B.29 Detail 3.1, jack rafter to bottom beam

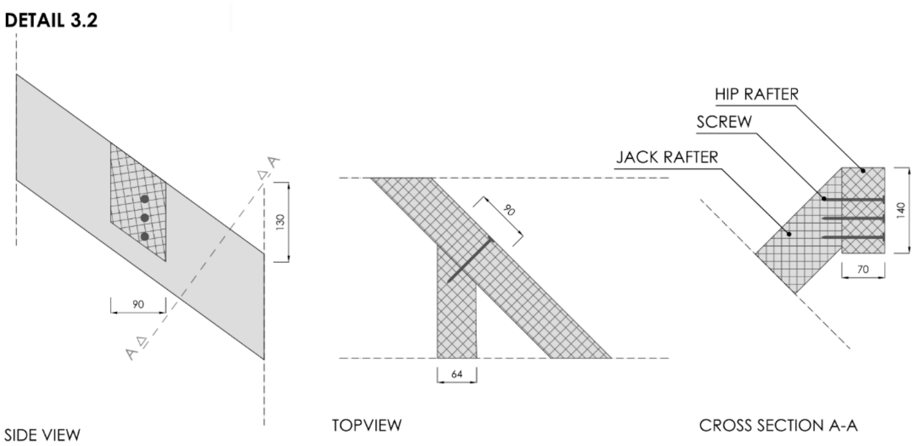


Figure B.30, jack rafter to hip rafter

4. Place the purlin holders

Due to the different orientation of the hip rafters compared to the jack rafters, purlin holders have to be placed to be able to connect the purlins in the corners of the roof frame. The purlin holders can be sawn from left-over material after sawing the purlins.

First apply two purlin holders to the bottom beam according to detail 4.1. Only one screw #8, 4 is needed for each connection.

Then apply the purlin holder at the top of the frame to the two hip rafters according to detail 4.2. This is also done using screw #8, 4, this time two screws are needed.

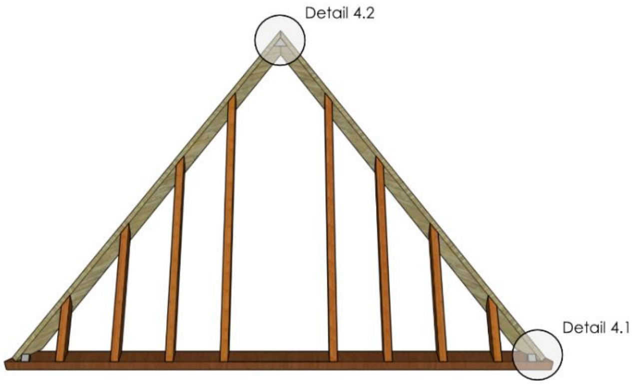


Figure B.31, purlin holders

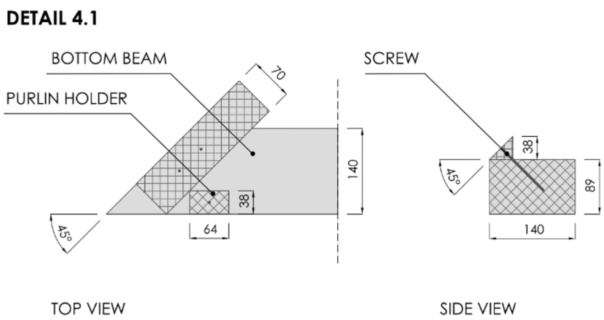


Figure B.32 Detail 4.1, purlin holders

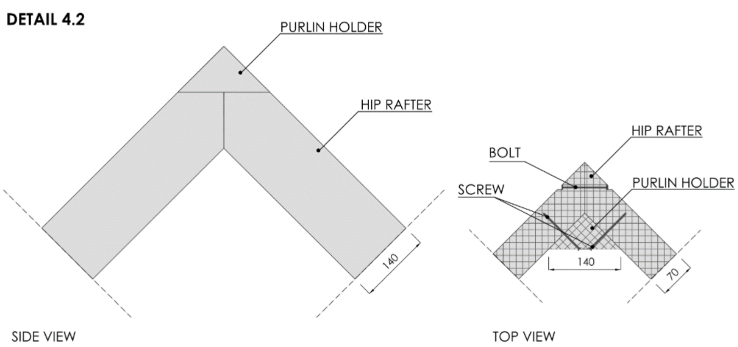


Figure B.33 Detail 4.2, purlin holders

5. Place the opening system

The opening system was produced separately (see Appendix B.2: Roof opening, openable balconies) and can now be attached to the roof frame.

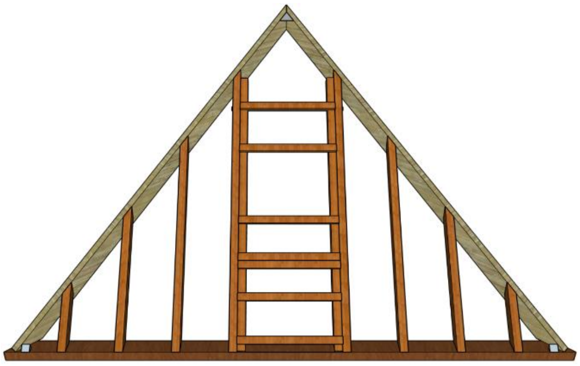


Figure B.34 Opening in closed position

Figure B.35 Opening in open position

6. Place the purlins

Eleven purlins need to be placed on the jack rafters and purlin holders according to detail 6.1. Per connection 2 screws of #8, 4 will be used.

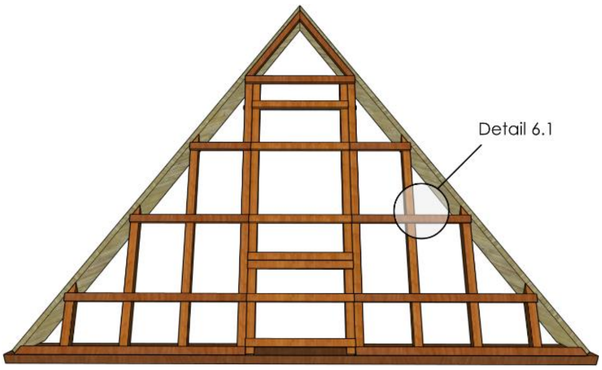


Figure B.36 Purlins

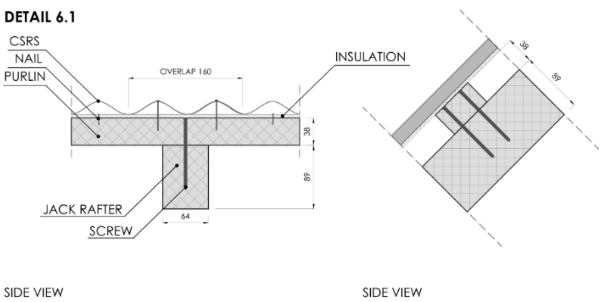


Figure B.37 Detail 6.1, Purlin installation

Phase 2: Installing the frames

After transport, the frames will be placed on top of the house. The frames will be connected to the house and to each other. The frames have to be held in place until all connections from this phase have been executed. Table B.3 shows the fasteners that need to be on hand to execute this phase.

Table B.3 Fasteners phase 2

Step	Detail	Fastener type		Amount per detail	Number of details	Total
7	7.1	Bolt	1/4, 11	2	16	32
8	8.1	Bolt	1/4, 7 1/2	2	4	8
9	9.1	Bolt	1/4, 6	2	12	24
	9.2	Bolt	1/4, 6	4	1	4

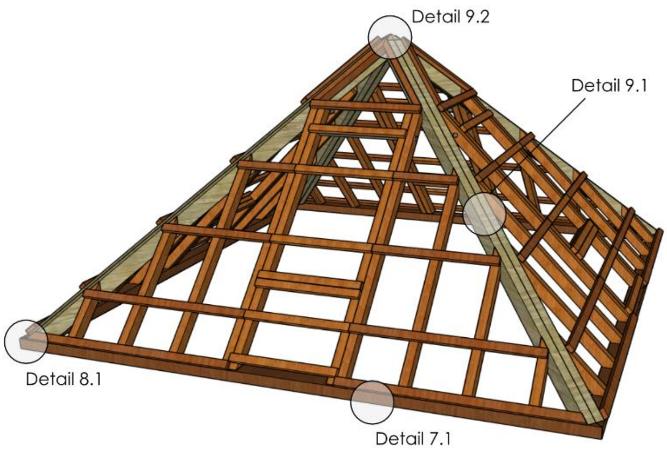


Figure B.38 Assembling of the roof frame

7. Connect bottom beam to wall panels

The bottom beams have to be connected to the wall panels of the floating house. Detail 7.1 has to be applied at every intersection of two wall panels and at the corners. This means that per side the full detail takes place three times and half the detail at both corners. For the connection two bolts 1/4, 11 are used through the predrilled holes.

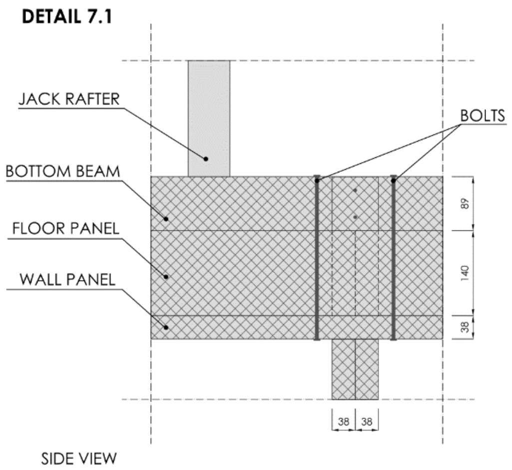


Figure B.39 Detail 7.1, bottom beam to wall panel

8. Connect bottom beams

The next step is to connect the bottom beams to each other. For this connection two bolts 1/4, 7 1/2 will be used according to detail 8.1.

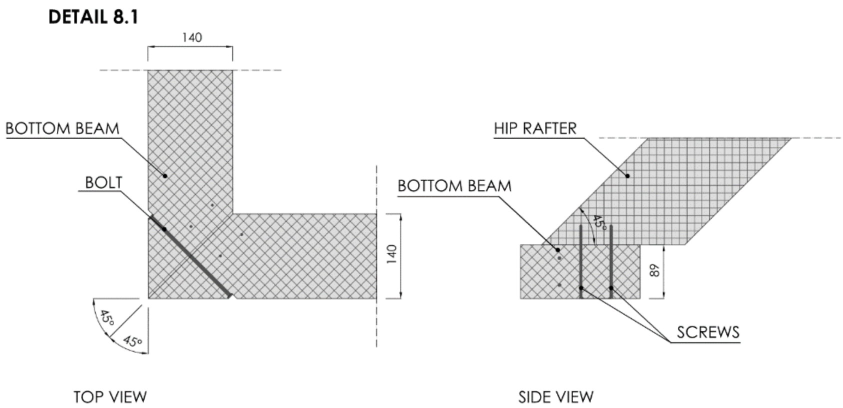


Figure B.40 Detail 8.1, bottom beam to bottom beam

9. Connect hip rafters

The hip rafters will be connected to each other at each span between two jack rafters and at the top of the roof structure.

For the connection at the span two bolts 1/4, 6 will be used per connection. The connection takes place three times per corner. The bolts have to be applied according to detail 9.1.

The connection at the top is also executed using bolts, also with bolts 1/4, 6. They will be applied four times under the purlin holder. Detail 9.2 shows this connection.

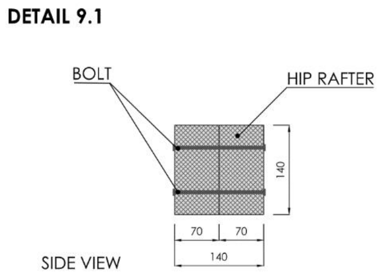


Figure B.41 Detail 9.1, hip rafter to hip rafter

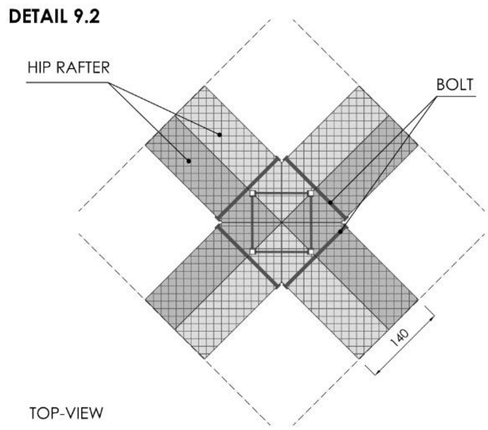


Figure B.42 Detail 9.2, hip rafters connected at crown

Phase 3: Finishing the roof

At this point, the roof structure is put entirely into place. It is time to finish the roof by applying insulation and the corrugated steel roof sheeting. Table B.4 shows the fasteners that need to be on hand to execute this phase.

Table B.4 Fasteners phase 3

Step	Detail	Fastener type		Amount per side	Total
10	11.1	Nail	2d	100	400
11	11.1	Screw	#5, 1 3/4	100	400
12	12.1	Screw	#12, 5	5	20
13	13.1	Screw	#12, 5	1	1
14	14.1	Dowel	5/16, 1 1/2	10	40

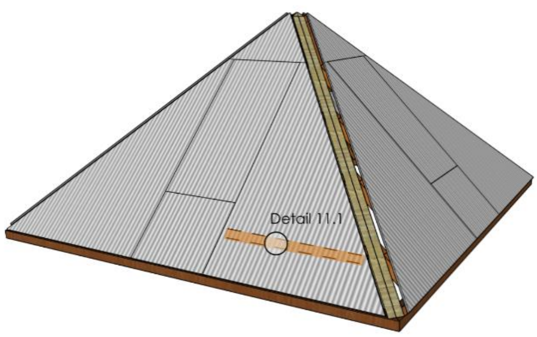


Figure B.43 Roof sheet to purlin

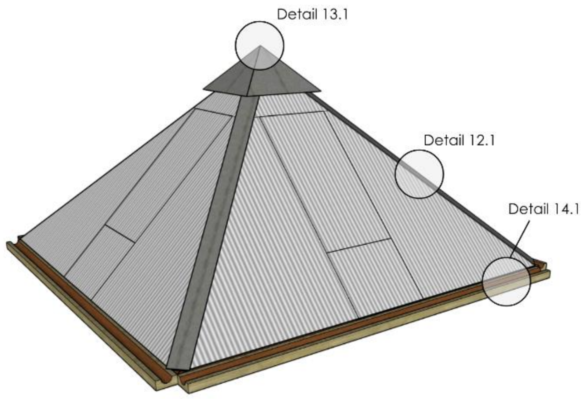


Figure B.44 Roof finishing

10. Apply insulation

The polyethylene foam insulation has to be applied in five strips with a width of 1 meter. The gaps between the strips will be coved using tape. The insulation will be attached to the purlins using small nails 2d with a spacing of 160 mm, which is visible in detail 11.1 in step 11.

11. Place corrugated steel roof sheeting (CSRS)

The corrugated steel roof sheeting can be delivered at a width of 1080 mm. The overlap of 160 mm (see detail 6.1) has to be taken into account. The middle strip with the roof opening has a width of 960 mm and can be covered by one roof sheet. Both sides are 1920 mm in width, two sheets can cover a maximum of 2000 mm. In short, five strips of corrugated roof sheeting are needed. Detail 11.1 shows the connection of the roof sheets to the purlins. A screw #5, 1 3/4 will be applied every 160 mm. A neoprene washer needs to be applied to avoid the inflow of water.

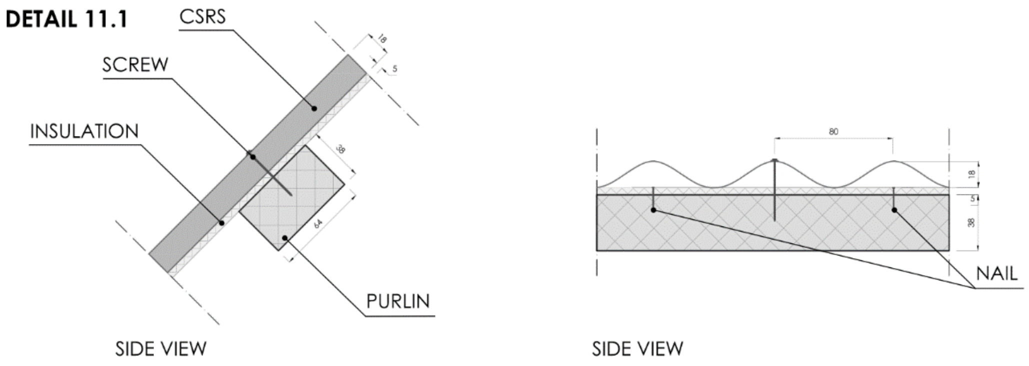


Figure B.45 Detail 11.1, attaching insulation and CSRS to purlin

12. Place hip cover

The corners of the corrugated steel roof sheeting have to be covered by a hip cover to avoid leakage. This cap will be applied according to detail 12.1 using screw #12, 5.

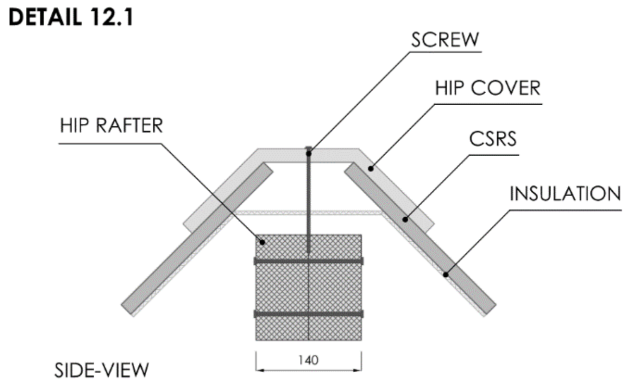


Figure B.46 Detail 12.1, installing hip cap

13. Place crown cover

The top of the roof needs a pyramid shaped cap to avoid leakage. This cap will be applied according to detail 13.1 using screw #12, 5.

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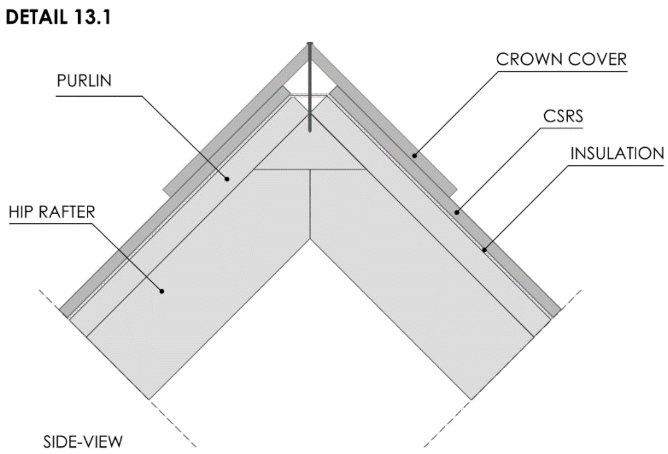


Figure appendix B.47 Detail 13.1, installing crown cover

14. Place bamboo gutter

For rainwater catchment a bamboo gutter will be used on all four sides of the house. The gutter will be carried by timber bamboo gutter holders at every 1.2 m at the location of the intersection of two wall panels. The bamboo gutter and bamboo gutter holder are visible in detail 14.1. The bamboo gutter holder will be connected to the bottom beam using dowels 5/16, 1 1/2 which have to be hammered into predrilled holes.

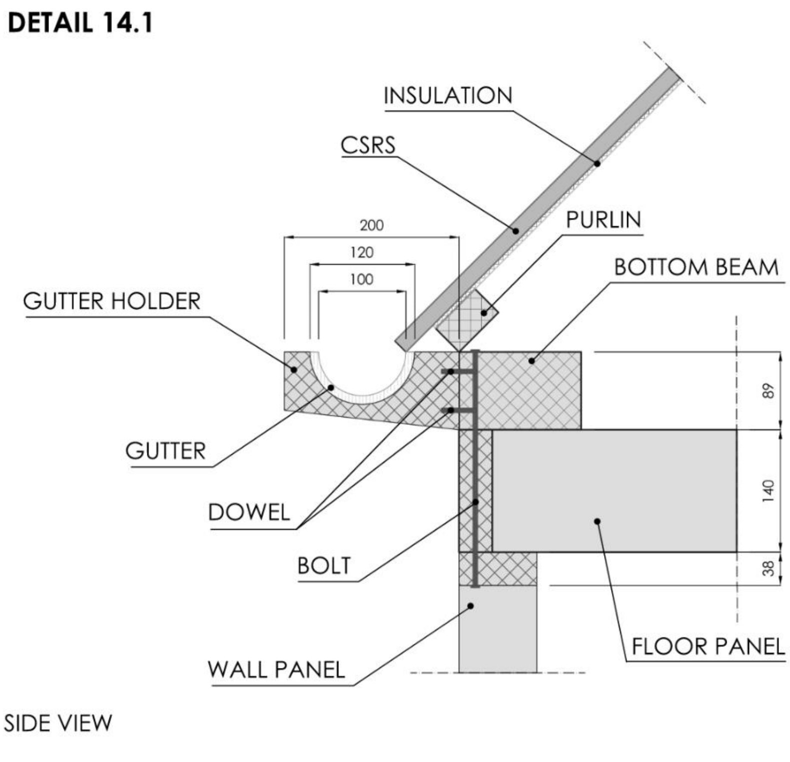


Figure B.48 Detail 14.1, Assembly of rain gutter

Appendix B.4: Fastener types

For the connections in the roof structure, metal and wooden fasteners will be used. The dimensions of these fasteners are according to standard fastener types measured in inches. The dimensions of the fasteners are determined based on detailing, load calculations of the connections still have to be carried out.

Screws

Wood screws will be used for the connections in details 2.1, 3.1, 3.2, 4.1, 4.2, 6.1, 11.1, 12.1 and 13.1. The screws for details 2.1, 3.1, 3.2, 4.1, 4.2 and 6.1, which are wood to wood connections, have a countersunk head with a flat top. The screws for details 11.1, 12.1 and 13.1, which are connecting the CSRS, have a pan head and neoprene washers need to be applied. All screws have an X-shaped Phillips drive (PH). (Bolt Depot Inc., 2017)

The chosen screws are based on Table B.5.

Table B.5 Standard screw types (NAVAL EDUCATION AND TRAINING PROFESSIONAL DEVELOPMENT AND TECHNOLOGY CENTER, 1999)

LENGTH (in.)	SIZE NUMBERS																					
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	20	22	24
1/4	×	×	×	×																		
3/8	×	×	×	×	×	×	×	×	×	×												
1/2		×	×	×	×	×	×	×	×	×	×	×	×									
5/8		×	×	×	×	×	×	×	×	×	×	×	×		×							
3/4			×	×	×	×	×	×	×	×	×	×	×		×		×					
7/8			×	×	×	×	×	×	×	×	×	×	×		×		×					
1				×	×	×	×	×	×	×	×	×	×		×		×		×	×		
1 1/4					×	×	×	×	×	×	×	×	×		×		×		×	×		×
1 1/2					×	×	×	×	×	×	×	×	×		×		×		×	×		×
1 3/4						×	×	×	×	×	×	×	×		×		×		×	×		×
2						×	×	×	×	×	×	×	×		×		×		×	×		×
2 1/4						×	×	×	×	×	×	×	×		×		×		×	×		×
2 1/2						×	×	×	×	×	×	×	×		×		×		×	×		×
2 3/4							×	×	×	×	×	×	×		×		×		×	×		×
3							×	×	×	×	×	×	×		×		×		×	×		×
3 1/2									×	×	×	×	×		×		×		×	×		×
4									×	×	×	×	×		×		×		×	×		×
4 1/2													×		×		×		×	×		×
5													×		×		×		×	×		×
6															×		×		×	×		×
THREADS PER INCH	32	28	26	24	22	20	18	16	15	14	13	12	11		10		9		8	8		7
DIA OF SCREW (in.)	.060	.073	.086	.099	.112	.125	.138	.151	.164	.177	.190	.203	.216		.242		.268		.294	.320		.372

The applied screw types are given in Table B.6.

Table B.6 Applied screw types

Step	Detail	Screw length (mm)	Screw length (inch)	Screw diameter (mm)	Screw diameter (inch)	Screw type (size number, length)
2	2.1	114.3	4 1/2	5.49	0.216	#12, 4 1/2
3	3.1	114.3	4 1/2	5.49	0.216	#12, 4 1/2
	3.2	114.3	4 1/2	5.49	0.216	#12, 4 1/2
4	4.1	101.6	4	4.16	0.164	#8, 4
	4.2	101.6	4	4.16	0.164	#8, 4
6	6.1	101.6	4	4.16	0.164	#8, 4
11	11.1	44.5	1 3/4	3.18	0.125	#5, 1 3/4
12	12.1	127	5	5.49	0.216	#12, 5
13	13.1	127	5	5.49	0.216	#12, 5

Bolts

Besides screws, bolts are also used in the design of the roof structure, especially when connecting the frames.

The chosen bolts were based on Table B.7.

Table B.7 Standard bolt types (NAVAL EDUCATION AND TRAINING PROFESSIONAL DEVELOPMENT AND TECHNOLOGY CENTER, 1999)

LENGTH (INCHES)	DIAMETER (INCHES)				
	1/4, 3/8	7/16	1/2, 9/16, 5/8	1/2, 7/8, 1	1 1/8, 1 1/4
3/4	×	—	—	—	—
1 1/4	×	×	×	—	—
1 1/2, 2, 2 1/2	×	×	×	×	—
3, 3 1/2, 4, 4 1/2, etc., 9 1/2, 10 to 20	×	×	×	×	×
21 to 25	—	—	×	×	×
26 to 39	—	—	—	×	×

The applied bolts are given in Table B.8.

Table B.8 Applied bolt types

Step	Detail	Bolt length (mm)	Bolt length (inch)	Bolt diameter (mm)	Bolt diameter (inch)	Bolt type (diameter, length)
2	2.2	88.9	3 1/2	6.35	1/4	1/4, 3 1/2
7	7.1	279.4	11	6.35	1/4	1/4, 11
8	8.1	190.5	7 1/2	6.35	1/4	1/4, 7 1/2
9	9.1	152.4	6	6.35	1/4	1/4, 6
	9.2	152.4	6	6.35	1/4	1/4, 6

Nails

The connection of the insulation to the purlins in detail 11.1 will be carried out using nails with a spacing of 160 mm.

The chosen nails were based on Table B.9.

Table B.9 Standard nail types (NAVAL EDUCATION AND TRAINING PROFESSIONAL DEVELOPMENT AND TECHNOLOGY CENTER, 1999)

SIZE	LENGTH (IN.)[1]	DIAMETER (IN.)	REMARKS	WHERE USED
2d	1	.072	Small head	Finish work, shop work
2d	1	.072	Large flathead	Small timber, wood shingles, lathes
3d	1 1/4	.08	Small head	Finish work, shop work
3d	1 1/4	.08	Large flathead	Small timber, wood shingles, lathes
4d	1 1/2	.098	Small head	Finish work, shop work
4d	1 1/2	.098	Large flathead	Small timber, lathes, shop work
5d	1 3/4	.098	Small head	Finish work, shop work
5d	1 3/4	.098	Large flathead	Small timber, lathes, shop work
6d	2	.113	Small head	Finish work, casing, stops, etc., shop work
6d	2	.113	Large flathead	Small timber, siding, sheathing, etc., shop work
7d	2 1/4	.113	Small head	Casing, base, ceiling, stops, etc.
7d	2 1/4	.113	Large flathead	Sheathing, siding, subflooring, light framing
8d	2 1/2	.131	Small head	Casing, base, ceiling, wainscot, etc., shop work
8d	2 1/2	.131	Large flathead	Sheathing, siding, subflooring, light framing, shop work
8d	1 1/4	.131	Extra-large flathead	Roll roofing, composition shingles
9d	2 3/4	.131	Small head	Casing, base, ceiling, etc.
9d	2 3/4	.131	Large flathead	Sheathing, siding, subflooring, framing, shop work
10d	3	.148	Small head	Casing, base, ceiling, etc., shop work
10d	3	.148	Large flathead	Sheathing, siding, subflooring, framing, shop work
12d	3 1/4	.148	Large flathead	Sheathing, subflooring, framing
16d	3 1/2	.162	Large flathead	Framing, bridges, etc.
20d	4	.192	Large flathead	Framing, bridges, etc.
30d	4 1/2	.207	Large flathead	Heavy framing, bridges, etc.
40d	5	.225	Large flathead	Heavy framing, bridges, etc.
50d	5 1/2	.244	Large flathead	Extra-heavy framing, bridges, etc.
60d	6	.262	Large flathead	Extra-heavy framing, bridges, etc.

1 This chart applies to wire nails, although it may be used to determine the length of cut nails.

The chosen nails are given in Table B.10.

Table B.10 Applied nail type

Step	Detail	Nail length (mm)	Nail length (inch)	Nail diameter (mm)	Nail diameter (inch)	Nail type	Remark
11	11.1	25.4	1	1.83	0.072	2d	Large flathead

Dowels

For the connection of the bamboo gutter holders to the bottom beam in detail 14.1, wooden dowels were chosen. Dowel connections are needed, because a screw connection is not possible due to the dimensions of the bamboo gutter holder. Contrary to metal dowels, wooden dowels do not corrode. The dimensions of the wooden dowels were chosen from a standard table. (Engineers Edge, LLC, 2018)

The applied dowels are given in Table B.11.

Table B.11 Applied dowel type

Step	Detail	Dowel length (mm)	Dowel length (inch)	Dowel diameter (mm)	Dowel diameter (inch)	Dowel type (diameter, length)
14	14.1	38.1	1 1/2	7.94	5/16	5/16, 1 1/2

Appendix C Human water system design

Appendix C.1: Research approach water management

The floating house has a need for a standalone system that fulfils the needs of drinking water and waste water treatment in any form. The research will be approached and structured as described in the following paragraphs.

Human water system

A first draft of a possible rain and sewage water treatment is made in previous research by Ir. P.H. Ham. (Ham P. H., The design of a modular, amphibious structure for a flood and typhoon-prone municipality; Hagonoy, the Philippines, 2016) This is no more than a conceptual idea what needs to be worked out in detail. Therefore, the scope of the research is to create a social accepted, sustainable and durable solution for the local inhabitants of the Finch Floating Home.

Life itself and the floating house both show interference with water, these components are therefore relevant for this specific research. These components together are the human water system of the house. The components have social and technical interactions on the system, therefore social and technical research will be conducted. This research helps answering the main question that followed from the scope of the project:

How can a socially accepted, sustainable and durable sanitary facility be created?

Sub questions regarding the research are:

What is the current situation of sanitation in the Philippines and what are the corresponding social requirements for the system?

What are the technical constraints of the system for both a single house and a network of houses?

What are the available materials and their characteristics to design the system?

What is the influence of the human water system with the house and how can this be integrated within the structure?

Relation social and technical

The main question can be split in two parts, a technical and a social part, both of these parts have their own requirements. Living on water should be equal to or better than living on land, including all the facilities that are available to the public, like sanitation, energy and safe drinking water. The fact that this research is based upon both social and technical research makes the balance between the two is an important factor. This balance will be addressed throughout the research by designing towards an integrated solution by all means.

Method

The research will first focus on the social wishes and common habits of the local population, secondly research for the possible technical solution, at last the system has to be tested to the requirements stated at the start.

The balance within this design is controlled by the list of requirements which will be set after the analysis of the current situation. The situation itself will be addressed to regional and local, social and technical, and integrated requirements. The requirements will be specified and approached by Wasson's System Engineering method. (Wasson C. , 2005)

The requirements will result in an output in the form of a design for the system. The human water system has to fulfil these requirements and should be verified during the process and adapt before the final design if necessary.

Possible solutions that fall within the scope will be checked with calculations for treatment till the set requirement. Upon the outcome of these calculations and the requirements together will decide which design(s) will be suitable as solution, for both a single house and possible upscaling of the home.

Data

During the research several sources will be applied to enable the research. The sources will either be locally gained data by interviews or data from articles, books or relevant databases.

The social requirements follow from interviews that will clarify the social standards and habits of the local community. The picture given by people will function as a standard example to the human water system of the floating house. The social situation addresses possible problems and functions as input for the requirements.

Articles and books will set requirements for the possible treatment schemes, which as well need input from available databases.

Structure

The research will be structured as followed:

- Introduction
- Analysis, which consists of:
  - Regional analysis;
  - Local analysis;
  - Social analysis;
  - System breakdown;
  - Integration within the system.
- List of requirements
- Possible solutions, which consists of:
  - Rainwater harvesting
  - Watewater collection and treatment
- Final Design
- Conclusion and recommendations

Appendix C.2: Weather influences

In this appendix the additional data for precipitation, temperature and rainfall storage be discussed.

Table C.1 Precipitation, projected and historical monthly data

	Average from 1986-2005	Projected future averages for: 2020-2039	2040-2059	2060-2079	2080-2099
Jan	147.6	142.0	147.8	153.8	155.6
Feb	110.8	114.8	104.6	117.6	91.6
Mar	96.1	119.5	112.2	140.8	105.0
Apr	99.5	139.4	122.8	143.1	107.9
May	192.1	200.6	156.8	182.6	192.5
Jun	276.5	256.9	222.1	223.1	272.1
Jul	314.4	346.2	330.1	306.2	302.5
Aug	285.3	289.1	266.7	271.0	276.7
Sep	267.5	247.6	308.9	307.3	372.5
Oct	267.7	310.5	343.9	282.4	323.5
Nov	241.6	261.5	271.6	254.7	285.9
Dec	202.5	188.4	185.8	200.9	206.2

Table C.2 Precipitation, projected and historical monthly data

	Average from 1986-2005	Projected future averages for: 2020-2039	2040-2059	2060-2079	2080-2099
Jan	24.8	25.5	26.1	26.5	27.5
Feb	24.9	25.6	26.2	26.7	27.7
Mar	25.8	26.3	27.0	27.5	28.3
Apr	26.7	27.4	27.9	28.5	29.3
May	27.1	27.8	28.5	29.0	29.8
Jun	26.5	27.1	27.8	28.4	29.2
Jul	26.1	26.7	27.4	28.0	28.7
Aug	26.1	26.8	27.3	28.2	28.8
Sep	26.0	26.8	27.3	28.1	28.7
Oct	26.0	26.7	27.2	27.8	28.5
Nov	25.7	26.3	26.8	27.5	28.1
Dec	25.0	25.7	26.3	26.9	27.6

Rainfall storage

The rainfall storage is calculated through the approach of an estimated inflow, which is constant for each month, and a daily usage by the user of the system. This resulted in a maximum storage capacity needed for each system. Due the lack of rainfall in several months of the year there could be a shortage in several months. The calculations of the system are based upon a run-off coefficient of 0.85 and start of uptake of water in August, since the home projected handover is in August.

Table C.3 Rainfall storage calculations for 200 L/d

Daily Usage	**200.0**	**[L/d]**		**Year 1**		**Year 2**		**Year 3**		
	Precipitation	Runoff	Inflow daily	V_{stored}	V_{used}	V_{stored}	V_{used}	V_{stored}	V_{used}	Shortage
Month	[mm/month]	[L/month]	[L/d]	[L]	[L]	[L]	[L]	[L]	[L]	[days]
1	149.4	2925.4	96.2			0.0	2885.3	0.0	2885.3	21
2	107.9	2112.9	69.5			0.0	2083.9	0.0	2083.9	26
3	114.7	2246.6	73.9			0.0	2215.8	0.0	2083.9	25
4	122.5	2399.7	78.9			0.0	2366.8	0.0	2083.9	24
5	184.9	3621.7	119.1			0.0	3572.1	0.0	2083.9	16
6	250.1	4898.9	161.1			0.0	4831.8	0.0	4831.8	8
7	319.9	6264.9	206.0			179.0	6000.0	179.0	6000.0	0
8	277.7	5439.4	178.8	0.0	5365	0.0	5543.9	0.0	5543.9	3
9	300.8	5890.1	193.6	0.0	5809	0.0	5809.4	0.0	5809.4	1
10	305.6	5984.7	196.8	0.0	5903	0.0	5902.7	0.0	5902.7	1
11	263.0	5151.4	169.4	0.0	5081	0.0	5080.8	0.0	5080.8	6
12	196.8	3853.4	126.7	0.0	3801	0.0	3800.6	0.0	3800.6	15

Table C.4 Rainfall storage calculations for 180 L/d

Daily Usage	**180.0**	**[L/d]**		**Year 1**		**Year 2**		**Year 3**		
	Precipitation	Runoff	Inflow daily	V_{stored}	V_{used}	V_{stored}	V_{used}	V_{stored}	V_{used}	Shortage
Month	[mm/month]	[L/month]	[L/d]	[L]	[L]	[L]	[L]	[L]	[L]	[days]
1	149.4	2925.4	96.2			0.0	2885.3	0.0	2885.3	14
2	107.9	2112.9	69.5			0.0	2083.9	0.0	2083.9	18
3	114.7	2246.6	73.9			0.0	2215.8	0.0	2215.8	18
4	122.5	2399.7	78.9			0.0	2366.8	0.0	2366.8	17
5	184.9	3621.7	119.1			0.0	3572.1	0.0	3572.1	10
6	250.1	4898.9	161.1			0.0	4831.8	0.0	4831.8	3
7	319.9	6264.9	206.0			779.0	5400.0	779.0	5400.0	0
8	277.7	5439.4	178.8	0.0	5365	743.9	5400.0	743.9	5400.0	0
9	300.8	5890.1	193.6	409.4	5400	1153.3	5400.0	1153.3	5400.0	0
10	305.6	5984.7	196.8	912.1	5400	1656.0	5400.0	1656.0	5400.0	0
11	263.0	5151.4	169.4	592.9	5400	1336.8	5400.0	1336.8	5400.0	0
12	196.8	3853.4	126.7	0.0	3801	0.0	5137.4	0.0	5137.4	1

Table C.5 rainfall storage calculations for 170 L/d

Daily Usage	**170.0**	**[L/d]**		**Year 1**		**Year 2**		**Year 3**		
	Precipitation	Runoff	Inflow daily	V_{stored}	V_{used}	V_{stored}	V_{used}	V_{stored}	V_{used}	Shortage
Month	[mm/month]	[L/month]	[L/d]	[L]	[L]	[L]	[L]	[L]	[L]	[days]
1	149.4	2925.4	96.2			0.0	3343.7	0.0	4422.7	4
2	107.9	2112.9	69.5			0.0	2083.9	0.0	2083.9	18
3	114.7	2246.6	73.9			0.0	2215.8	0.0	2215.8	17
4	122.5	2399.7	78.9			0.0	2366.8	0.0	2215.8	16
5	184.9	3621.7	119.1			0.0	3572.1	0.0	3572.1	9
6	250.1	4898.9	161.1			0.0	4831.8	0.0	4831.8	2
7	319.9	6264.9	206.0			1079.0	5100.0	1079.0	5100.0	0
8	277.7	5439.4	178.8	264.9	5100	1343.9	5100.0	1343.9	5100.0	0
9	300.8	5890.1	193.6	974.3	5100	2053.3	5100.0	2053.3	5100.0	0
10	305.6	5984.7	196.8	1777.0	5100	2856.0	5100.0	2856.0	5100.0	0
11	263.0	5151.4	169.4	1757.8	5100	2836.8	5100.0	2836.8	5100.0	0
12	196.8	3853.4	126.7	458.3	5100	1537.4	5100.0	1537.4	5100.0	0

Table C.6 Rainfall storage calculations for 160 L/d

Daily Usage	**160.0**	**[L/d]**		**Year 1**		**Year 2**		**Year 3**		
	Precipitation	Runoff	Inflow daily	V_{stored}	V_{used}	V_{stored}	V_{used}	V_{stored}	V_{used}	Shortage
Month	[mm/month]	[L/month]	[L/d]	[L]	[L]	[L]	[L]	[L]	[L]	[days]
1	149.4	2925.4	96.2			43.7	4800.0	1454.5	4800.0	0
2	107.9	2112.9	69.5			0.0	2127.6	0.0	3538.4	8
3	114.7	2246.6	73.9			0.0	2215.8	0.0	2215.8	16
4	122.5	2399.7	78.9			0.0	2366.8	0.0	2366.8	15
5	184.9	3621.7	119.1			0.0	3572.1	0.0	3572.1	8
6	250.1	4898.9	161.1			31.8	4800.0	31.8	4800.0	0
7	319.9	6264.9	206.0			1410.8	4800.0	1410.8	4800.0	0
8	277.7	5439.4	178.8	564.9	4800	1975.7	4800.0	1975.7	4800.0	0
9	300.8	5890.1	193.6	1574.3	4800	2985.1	4800.0	2985.1	4800.0	0
10	305.6	5984.7	196.8	2677.0	4800	4087.8	4800.0	4087.8	4800.0	0
11	263.0	5151.4	169.4	2957.8	4800	4368.6	4800.0	4368.6	4800.0	0
12	196.8	3853.4	126.7	1958.3	4800	3369.2	4800.0	3369.2	4800.0	0

Table C.7 Rainfall storage calculations for 150 L/d

Daily Usage	**150.0**	**[L/d]**		**Year 1**		**Year 2**		**Year 3**		
Month	Precipitation [mm/month]	Runoff [L/month]	Inflow daily [L/d]	V_{stored} [L]	V_{used} [L]	V_{stored} [L]	V_{used} [L]	V_{stored} [L]	V_{used} [L]	Shortage [days]
1	149.4	2925.4	96.2			1843.7	4500.0	3854.5	4500.0	0
2	107.9	2112.9	69.5			0.0	3927.6	1438.4	4500.0	0
3	114.7	2246.6	73.9			0.0	2215.8	0.0	3654.2	6
4	122.5	2399.7	78.9			0.0	2366.8	0.0	2366.8	14
5	184.9	3621.7	119.1			0.0	3572.1	0.0	3572.1	6
6	250.1	4898.9	161.1			331.8	4500.0	331.8	4500.0	0
7	319.9	6264.9	206.0			2010.8	4500.0	2010.8	4500.0	0
8	277.7	5439.4	178.8	864.9	4500	2875.7	4500.0	2875.7	4500.0	0
9	300.8	5890.1	193.6	2174.3	4500	4185.1	4500.0	4185.1	4500.0	0
10	305.6	5984.7	196.8	3577.0	4500	5587.8	4500.0	5587.8	4500.0	0
11	263.0	5151.4	169.4	4157.8	4500	6168.6	4500.0	6168.6	4500.0	0
12	196.8	3853.4	126.7	3458.3	4500	5469.2	4500.0	5469.2	4500.0	0

Table C.8 Rainfall storage calculations for 140 L/d

Daily Usage	**140.0**	**[L/d]**		**Year 1**		**Year 2**		**Year 3**		
Month	Precipitation [mm/month]	Runoff [L/month]	Inflow daily [L/d]	V_{stored} [L]	V_{used} [L]	V_{stored} [L]	V_{used} [L]	V_{stored} [L]	V_{used} [L]	Shortage [days]
1	149.4	2925.4	96.2			3643.7	4200.0	6254.5	4200.0	0
2	107.9	2112.9	69.5			1527.6	4200.0	4138.4	4200.0	0
3	114.7	2246.6	73.9			0.0	3743.4	2154.2	4200.0	0
4	122.5	2399.7	78.9			0.0	2366.8	321.1	4200.0	0
5	184.9	3621.7	119.1			0.0	3572.1	0.0	3893.1	2
6	250.1	4898.9	161.1			631.8	4200.0	631.8	4200.0	0
7	319.9	6264.9	206.0			2610.8	4200.0	2610.8	4200.0	0
8	277.7	5439.4	178.8	1164.9	4200	3775.7	4200.0	3775.7	4200.0	0
9	300.8	5890.1	193.6	2774.3	4200	5385.1	4200.0	5385.1	4200.0	0
10	305.6	5984.7	196.8	4477.0	4200	7087.8	4200.0	7087.8	4200.0	0
11	263.0	5151.4	169.4	5357.8	4200	7968.6	4200.0	7968.6	4200.0	0
12	196.8	3853.4	126.7	4958.3	4200	7569.2	4200.0	7569.2	4200.0	0

Table C.9 Rainfall storage calculations for 120 L/d

Daily Usage	**120.0**	**[L/d]**		**Year 1**		**Year 2**		**Year 3**		
Month	Precipitation [mm/month]	Runoff [L/month]	Inflow daily [L/d]	V_{stored} [L]	V_{used} [L]	V_{stored} [L]	V_{used} [L]	V_{stored} [L]	V_{used} [L]	Shortage [days]
1	149.4	2925.4	96.2			7243.7	3600.0	14136.8	17736.8	0
2	107.9	2112.9	69.5			5727.6	3600.0	12620.7	5100.0	0
3	114.7	2246.6	73.9			4343.4	3600.0	11236.6	5100.0	0
4	122.5	2399.7	78.9			3110.2	3600.0	10003.4	5100.0	0
5	184.9	3621.7	119.1			3082.3	3600.0	9975.4	5100.0	0
6	250.1	4898.9	161.1			4314.1	3600.0	11207.2	5100.0	0
7	319.9	6264.9	206.0			6893.1	3600.0	13786.2	5100.0	0
8	277.7	5439.4	178.8	1764.9	3600	8658.0	3600.0	15551.1	5100.0	0
9	300.8	5890.1	193.6	3974.3	3600	10867.4	3600.0	17760.5	5100.0	0
10	305.6	5984.7	196.8	6277.0	3600	13170.1	3600.0	20063.2	5100.0	0
11	263.0	5151.4	169.4	7757.8	3600	14650.9	3600.0	21544.0	5100.0	0
12	196.8	3853.4	126.7	7958.3	3600	14851.5	3600.0	21744.6	5100.0	0

Appendix C.3: Social interview

This appendix describes the social characteristics of the sanitary situation of the local inhabitants. It describes the standards and characteristics of the bathroom and their habits. According this data should the sanitation of the home be designed.

House 1.

A. Household info

House is located close to the pilot location. Middle class family living on family compound. Several houses on compound are not in use anymore because of floods and or typhoons.

Current house is raised twice in order to prevent the home from floods. This is done by construction workers. Inhabitants of the compound don't see the typhoon as a large problem. Of course they do cause large wind forces, however not a lot has been damaged as a result of these loads. However, old houses have been damaged by these typhoons. Not of all them have been rebuilt. The area in the neighbourhood gets flooded during rainy season.

B. Sanitation

D1. Toilet

1. Do you own a toilet?
   a. Yes
   b. No

   If you own a toilet, do you share this with multiple households?
   a. Yes, almost every house
   b. No

   If yes, how many?
   ….. household(s)

2. Is your toilet either inside or outside your house?
   a. Inside
   b. Outside, some small house

3. With how many people do you share a toilet?
   Every family owns toilet

   What would be the maximum amount of users for one toilet?
   1 toilet for … people (hele lastige vraag)

4. Do you flush your toilet with water
   a. Yes, with tap water
   b. Yes, with bottled water
   c. Yes, with collected rainwater
   d. No

5. Do you use toilet paper and how do you dispense it?
   a. Yes, I flush it together with my faeces
   b. Yes, I throw it in a bin
   c. No, I only use a bidet
   d. No, I use a washing cloth with water
   e. No, other (please fill in your habit):
   ____

6. When you clean your toilet what kind of chemical(s) or soap(s) do you use?

   ____

   How often do you clean your toilet?

   …. Times per day/week/month

7. If your toilet is broken, how would you repair it?
   a. Myself or a family member
   b. A maintenance employee
   c. Other: ______________________________________

Shower

1. Do you own a shower?
   a. Yes
   b. No

   If you own a shower, do you share this with multiple households?
   a. Yes
   b. No (bucket shower)

   If yes, How many households do you share your shower with
   …. Households

2. Is your shower either inside or outside your house?
   a. Inside
   b. Outside

3. With how many people do you share a shower?
   …. People
   What would be the maximum amount of users for one toilet?
   1 shower for … people

4. Do you shower with tap water?
   a. Yes, directly from a hose or nozzle
   b. Yes, via a bucket
   c. No, with collected rain water
   d. Other:______________________

5. Do you shower with preheated water?
   a. Yes
   b. No

6. How often do you take a shower and for how long?
   3 times per day/week/month
   … minutes

7. When you clean your shower, what kind of chemical(s) or soap(s) do you use?
   _same as washing clothes and cleaning the toilet.

   How often do you clean you shower?
   ….. times per day/week/month

8. If your shower is broken, how would you repair it?
   a. Myself or a family member (if they know how to)
   b. A maintenance employee
   c. Other:_______________________________

9. Would you be willing to share your bathroom(shower-toilet combination), with multiple households?
   a. Yes
   b. No, only my toilet
   c. No, only my shower
   d. No, not at all

10. Is your toilet/shower connected to the local sewerage?
    a. Yes
    b. No
    If not, where is your wastewater collected?
    septic tank

Cooking

1. How often do you cook at home?
   Every day

2. What heat source do you use? (can select multiple)
- Electrical stove
- Gas stove
- Open fire/wood oven/barbeque
- Microwave

3. How do you do the dishes?
   a. Dishwasher
   b. I don't do the dishes, I use disposables
   c. Handwash with cold water
   d. Handwash with preheated water

4. What do you do with the leftovers
   a. Trashcan
   b. Eat later
   c. Other:____family

House 2

Marvin lives with his mother and brother in one house. On this compound several other family members have their houses. Multiple houses on this plot are not in use anymore, because of typhoons and floods. At some of the older houses, entire roof structures have been blown away. They were not able to rebuild the structure, because of lack of finance.
Only the brother of marvin has a job.
In almost the total area of the plot, water gets in during high tide. Both during rainy season and in dry season. However the situation in rainy season is way worse. That is why they raised the floor for a couple of times, with concrete and timber. They use a lot of sandbags on the plot to move without getting wet feet.

D1. Toilet

8. Do you own a toilet?
    a. Yes
    b. No

    If you own a toilet, do you share this with multiple households?
    c. Yes
    d. No

    If yes, how many?
    ..... household(s)

9. Is your toilet either inside or outside your house?
    a. Inside
    b. Outside

10. With how many people do you share a toilet?
    .... people

    What would be the maximum amount of users for one toilet?
    1 toilet for … people

11. Do you flush your toilet with water
    a. Yes, with tap water
    b. Yes, with bottled water
    c. Yes, with collected rainwater
    d. No

12. Do you use toilet paper and how do you dispense it?
    a. Yes, I flush it together with my faeces
    b. Yes, I throw it in a bin
    c. No, I only use a bidet/(wash it with water)
    d. No, I use a washing cloth with water
    e. No, other (please fill in your habit):
    ____

13. When you clean your toilet what kind of chemical(s) or soap(s) do you use?

    Every day, powder

    How often do you clean your toilet?

    .... Times per day/week/month

14. If your toilet is broken, how would you repair it?
    a. Myself or a family member
    b. A maintenance employee
    c. Other: ______________________________

Shower

11. Do you own a shower?
    a. Yes
    b. No (bucket shower)

    If you own a shower, do you share this with multiple households?
    c. Yes
    d. No

If yes, How many households do you share your shower with
…. Households

12. Is your shower either inside or outside your house?
    a. Inside
    b. Outside

13. With how many people do you share a shower?
    …. People
    What would be the maximum amount of users for one toilet?
    1 shower for … people

14. Do you shower with tap water?
    a. Yes, directly from a hose or nozzle
    b. Yes, via a bucket
    c. No, with collected rain water
    d. Other:________________________

15. Do you shower with preheated water?
    a. Yes
    b. No

16. How often do you take a shower and for how long?
    2 or 3 times per day/week/month
    … minutes

17. When you clean your shower, what kind of chemical(s) or soap(s) do you use?
    ____

    How often do you clean you shower?
    ….. times per day/week/month

18. If your shower is broken, how would you repair it?
    a. Myself or a family member
    b. A maintenance employee
    c. Other:____________________________

19. Would you be willing to share your bathroom(shower-toilet combination), with multiple households?
    a. Yes
    b. No, only my toilet
    c. No, only my shower
    d. No, not at all

20. Is your toilet/shower connected to the local sewerage?
    a. Yes
    b. No
    If not, where is your wastewater collected?
    ____

Cooking

5. How often do you cook at home?
   Every day

6. What heat source do you use? (can select multiple)
   - Electrical stove
   - Gas stove
   - Open fire/wood oven/barbeque
   - Microwave

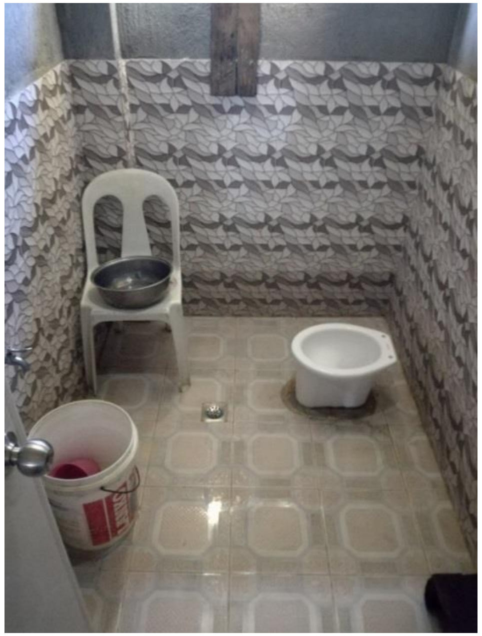
7. How do you do the dishes?
   a. Dishwasher
   b. I don't do the dishes, I use disposables
   c. Handwash with cold water
   d. Handwash with preheated water

8. What do you do with the leftovers
   a. Trashcan
   b. Eat later
   c. Other:____________________________________

House 3 **(difficult conversation because of language differences)**

Ofelia gutierez (woman in green t-shirt) is living with 6 children (and sometimes a grandfather) in one house. Ofelia is housewife and her husband is tricycle driver . The house is built on a family owned compound. Multiple family members are living in the other houses. A lot of the houses on the compound get flooded regularly. Multiple houses are levelled up , several times.

C. Sanitation



D1. Toilet

15. Do you own a toilet?
    a. Yes
    b. No

    If you own a toilet, do you share this with multiple households?
    e. Yes
    f. No

    If yes, how many?
    ….. household(s)

16. Is your toilet either inside or outside your house?
    a. Inside
    b. Outside

17. With how many people do you share a toilet?
    …. people

    What would be the maximum amount of users for one toilet?
    1 toilet for … people

18. Do you flush your toilet with water
    a. Yes, with tap water
    b. Yes, with bottled water
    c. Yes, with collected rainwater
    d. No

19. Do you use toilet paper and how do you dispense it?
    a. Yes, I flush it together with my faeces
    b. Yes, I throw it in a bin
    c. No, I only use a bidet
    d. No, I use a washing cloth with water
    e. No, other (please fill in your habit):
    ____

20. When you clean your toilet what kind of chemical(s) or soap(s) do you use?

    Yes use chemicals; every day

How often do you clean your toilet?

7 Times per day/week/month

21. If your toilet is broken, how would you repair it?
    a. Myself or a family member
    b. A maintenance employee
    c. Other: ______________________________________

Shower

21. Do you own a shower?
    a. Yes
    b. No (bucket shower)

    If you own a shower, do you share this with multiple households?
    e. Yes
    f. No

    If yes, How many households do you share your shower with
    …. Households

22. Is your shower either inside or outside your house?
    a. Inside
    b. Outside

23. With how many people do you share a shower?
    …. People
    What would be the maximum amount of users for one toilet?
    1 shower for … people

24. Do you shower with tap water?
    a. Yes, directly from a hose or nozzle
    b. Yes, via a bucket
    c. No, with collected rain water
    d. Other:______________________

25. Do you shower with preheated water?
    a. Yes
    b. No

26. How often do you take a shower and for how long?
    2 times per day/week/month
    … minutes

27. When you clean your shower, what kind of chemical(s) or soap(s) do you use?
    ____

    How often do you clean you shower?
    ….. times per day/week/month

28. If your shower is broken, how would you repair it?
    a. Myself or a family member
    b. A maintenance employee
    c. Other:___________________________

29. Would you be willing to share your bathroom(shower-toilet combination), with multiple households?
    a. Yes
    b. No, only my toilet
    c. No, only my shower
    d. No, not at all

30. Is your toilet/shower connected to the local sewerage?
    a. Yes
    b. No

    If not, where is your wastewater collected?
    ____

Cooking

9. How often do you cook at home?

7 times per week

10. What heat source do you use? (can select multiple)
- Electrical stove
- Gas stove
- Open fire/wood oven/barbeque
- Microwave

11. How do you do the dishes?
    a. Dishwasher
    b. I don't do the dishes, I use disposables
    c. Handwash with cold water
    d. Handwash with preheated water

12. What do you do with the leftovers
    a. Trashcan
    b. Eat later

Other: give to family

House 4

Miss a Garcia is a (well English-speaking) retired teacher. She lives with 9 people in one house, since other houses on the (family owned) compound are not in use anymore, mainly because of floods. This happened as well to the home of the daughter, so she is now living at Miss Garcia's.
They renewed the house three years ago. The ground floor of the house is not in use anymore. So, they live in the timber first floor, and in the newly built concrete part. They don't experience that much floods in the house itself, however the compound is mostly flooded. Only during a few months in dry season, vegetables can be grown on the lot.

They don't experience a lot of damages by typhoons. However at the house of the neighbours, the roof was blown of, because of the strong winds of Pedring, (2011?)

D1. Toilet

22. Do you own a toilet?
    a. Yes
    b. No

    If you own a toilet, do you share this with multiple households?
    g. Yes
    h. No

    If yes, how many?
    ….. household(s)

23. Is your toilet either inside or outside your house?
    a. Inside
    b. Outside

24. With how many people do you share a toilet?
    …. people

    What would be the maximum amount of users for one toilet?
    1 toilet for … people (hele lastige vraag)

25. Do you flush your toilet with water
    a. Yes, with tap water
    b. Yes, with bottled water
    c. Yes, with collected rainwater
    d. No

26. Do you use toilet paper and how do you dispense it?
    a. Yes, I flush it together with my faeces
    b. Yes, I throw it in a bin
    c. No, I only use a bidet
    d. No, I use a washing cloth with water
    e. No, other (please fill in your habit):
    ____

27. When you clean your toilet what kind of chemical(s) or soap(s) do you use?

____

How often do you clean your toilet?

…. Times per day/week/month

28. If your toilet is broken, how would you repair it?
    a. Myself or a family member
    b. A maintenance employee
    c. Other: ___________________________________

Shower

31. Do you own a shower?
    a. Yes
    b. No

    If you own a shower, do you share this with multiple households?
    g. Yes
    h. No

    If yes, How many households do you share your shower with
    …. Households

32. Is your shower either inside or outside your house?
    a. Inside
    b. Outside

33. With how many people do you share a shower?
    …. People
    What would be the maximum amount of users for one toilet?
    1 shower for … people

34. Do you shower with tap water?
    a. Yes, directly from a hose or nozzle
    b. Yes, via a bucket
    c. No, with collected rain water
    d. Other:_______________________

35. Do you shower with preheated water?
    a. Yes
    b. No

36. How often do you take a shower and for how long?
    … times per day/week/month
    … minutes

37. When you clean your shower, what kind of chemical(s) or soap(s) do you use?

    ____

    How often do you clean you shower?
    ….. times per day/week/month

38. If your shower is broken, how would you repair it?
    a. Myself or a family member
    b. A maintenance employee
    c. Other:_____________________________

39. Would you be willing to share your bathroom(shower-toilet combination), with multiple households?
    a. Yes
    b. No, only my toilet
    c. No, only my shower
    d. No, not at all

40. Is your toilet/shower connected to the local sewerage?
    a. Yes
    b. No
    If not, where is your wastewater collected?
    Septic tank

Cooking

13. How often do you cook at home?
    7 times per week

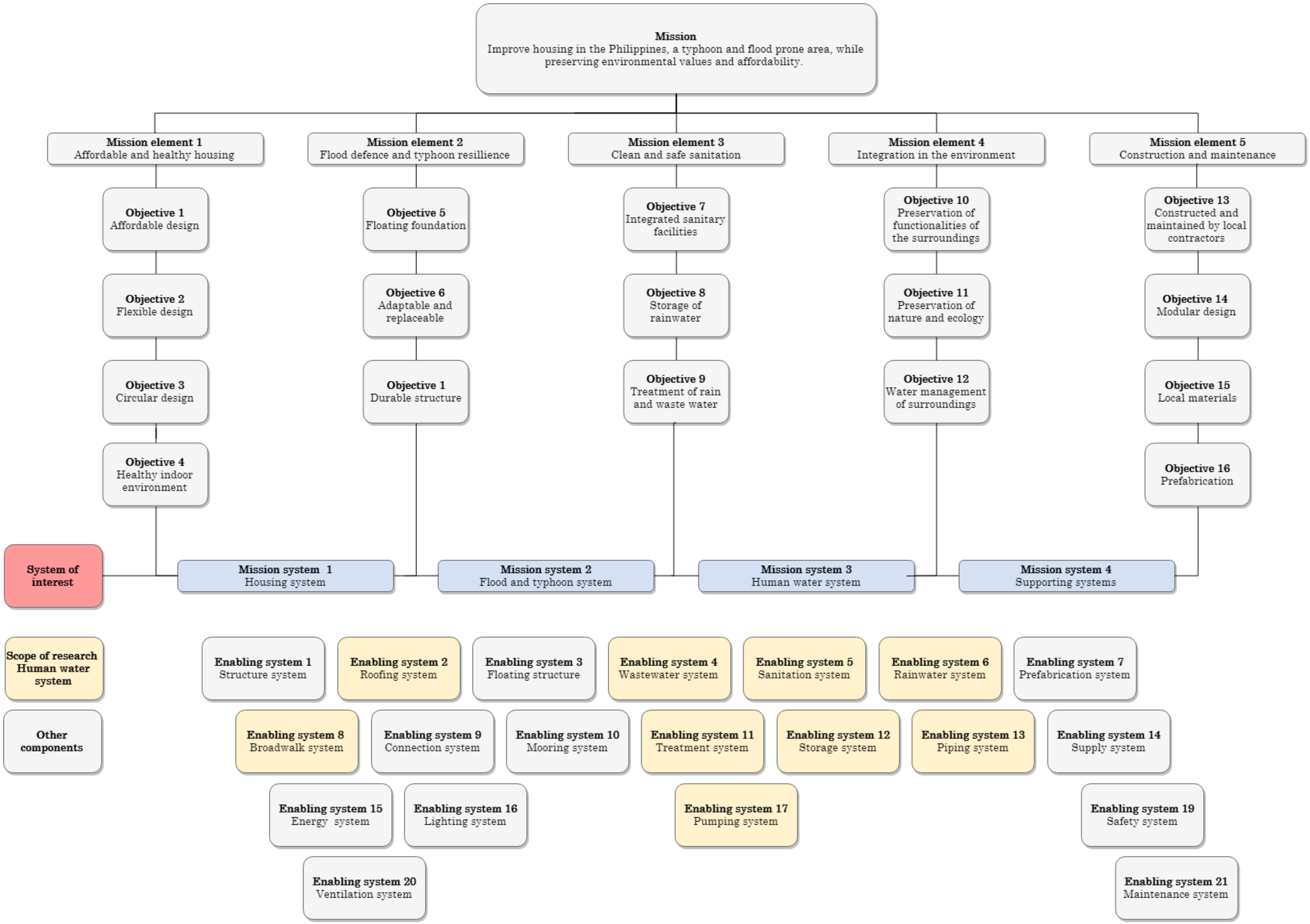
14. What heat source do you use? (can select multiple)
- Electrical stove
- Gas stove
- Open fire/wood oven/barbeque
- Microwave

15. How do you do the dishes?
    a. Dishwasher
    b. I don't do the dishes, I use disposables
    c. Handwash with cold water
    d. Handwash with preheated water

16. What do you do with the leftovers
    a. Trashcan
    b. Eat later

Appendix C.4: System breakdown

See the next page for a complete overview of the system breakdown.


Mission
Improve housing in the Philippines, a typhoon and flood prone area, while preserving environmental values and affordability.
Mission element 1
Affordable and healthy housing
Mission element 2
Flood defence and typhoon resillience
Mission element 3
Clean and safe sanitation
Mission element 4
Integration in the environment
Mission element 5
Construction and maintenance
Objective 1
Affordable design
Objective 2
Flexible design
Objective 3
Circular design
Objective 4
Healthy indoor environment
Objective 5
Floating foundation
Objective 6
Adaptable and replaceable
Objective 1
Durable structure
Objective 7
Integrated sanitary facilities
Objective 8
Storage of rainwater
Objective 9
Treatment of rain and waste water
Objective 10
Preservation of functionalities of the surroundings
Objective 11
Preservation of nature and ecology
Objective 12
Water management of surroundings
Objective 13
Constructed and maintained by local contractors
Objective 14
Modular design
Objective 15
Local materials
Objective 16
Prefabrication
System of interest
Mission system 1
Housing system
Mission system 2
Flood and typhoon system
Mission system 3
Human water system
Mission system 4
Supporting systems
Scope of research Human water system
Other components
Enabling system 1
Structure system
Enabling system 2
Roofing system
Enabling system 3
Floating structure
Enabling system 4
Wastewater system
Enabling system 5
Sanitation system
Enabling system 6
Rainwater system
Enabling system 7
Prefabrication system
Enabling system 8
Broadwalk system
Enabling system 9
Connection system
Enabling system 10
Mooring system
Enabling system 11
Treatment system
Enabling system 12
Storage system
Enabling system 13
Piping system
Enabling system 14
Supply system
Enabling system 15
Energy system
Enabling system 16
Lighting system
Enabling system 17
Pumping system
Enabling system 19
Safety system
Enabling system 20
Ventilation system
Enabling system 21
Maintenance system

Appendix D Wave statistics

Figure D.1 shows the wave height, wave period, wave length and depth over wave length ratio for several depths in SLS and ULS conditions. These results are all obtained with the formulas of Young & Verhagen.

```
                          Storm    Typhoon
Waterdepth = 1.5 m
Significant wave height= 0.557    0.857 m
Peak period            = 2.244    2.723 s
Wavelength             = 7.0    9.137 m
Depth/wavelength ratio = 0.193    0.141

Waterdepth = 1.75 m
Significant wave height= 0.564    0.877 m
Peak period            = 2.245    2.726 s
Wavelength             = 7.278    9.638 m
Depth/wavelength ratio = 0.226    0.164

Waterdepth = 2.0 m
Significant wave height= 0.569    0.89 m
Peak period            = 2.246    2.728 s
Wavelength             = 7.487    10.049 m
Depth/wavelength ratio = 0.258    0.187

Waterdepth = 2.25 m
Significant wave height= 0.573    0.899 m
Peak period            = 2.246    2.729 s
Wavelength             = 7.643    10.39 m
Depth/wavelength ratio = 0.29    0.211

Waterdepth = 2.5 m
Significant wave height= 0.575    0.906 m
Peak period            = 2.246    2.73 s
Wavelength             = 7.757    10.671 m
Depth/wavelength ratio = 0.322    0.234
```

Table D.1 Total wind conditions for SLS and ULS conditions

Appendix E Calculation of wind set-up and current

Appendix E.1: Input parameters of Delft3D calculation

In this appendix the input of Delft3D is presented to be able to redo the calculation. Information about input settings and parameters are obtained from Delft3D FLOW User Manual (Deltares, 2014)

Domain

The bathymetry is uniform with a depth of 2.5m everywhere.

Table E.1 Domain of calculation

	Number of cells	Cell width
m	50	10m
n	2	100m

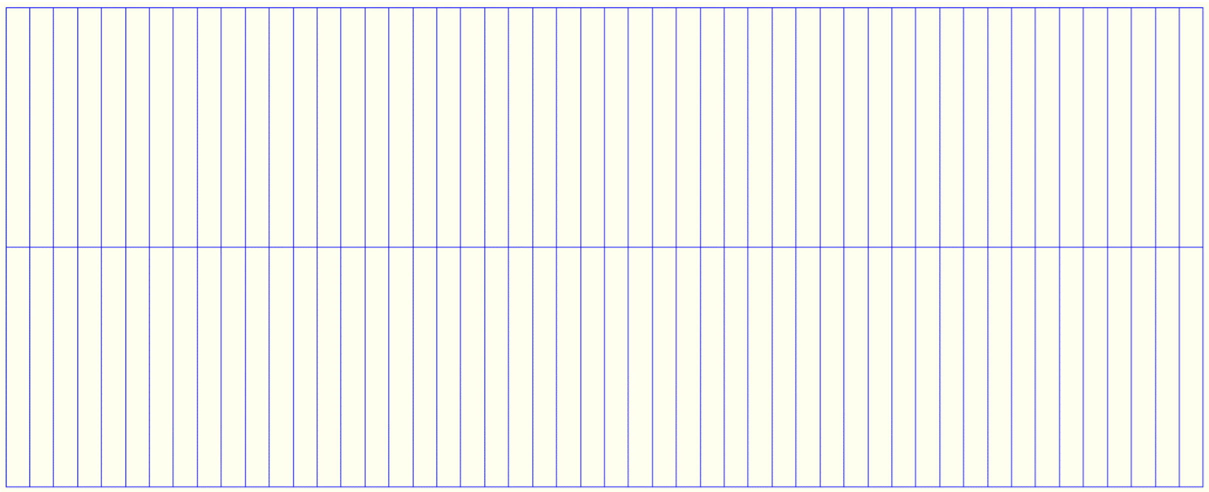


Figure E.1 Top view of the grid

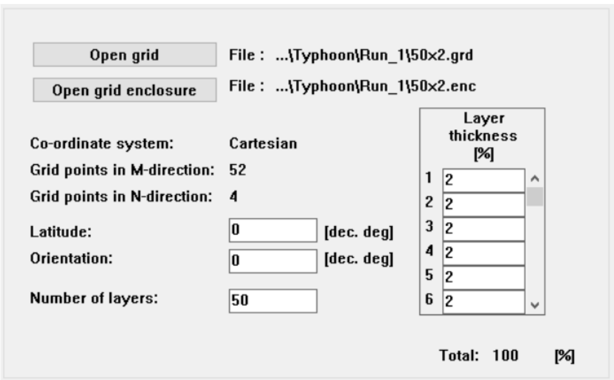


Figure E.2 Grid input

Timeframe

The simulation period is seven hours, with time steps of 30 seconds.

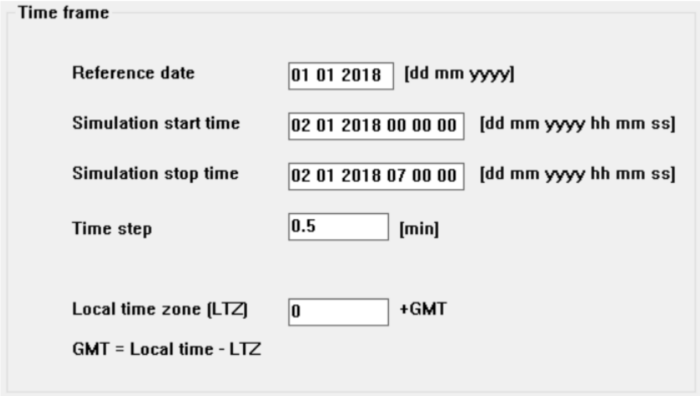


Figure E.3 time frame input

Processes, initial and boundary conditions

The only process enabled is wind, the initial condition is specified by the water level. It is uniform and set to 0 m. No boundary conditions exist as all boundaries are closed.

Constants

Gravity is set to 10 m/s^2 as this is set for all calculations in the project. Water density is set to 1025 kg/m^3. The water in the basin is not fresh but brackish, so seawater density is assumed. Air density is set to 1.2 kg/m^3, the general air density at sea level.

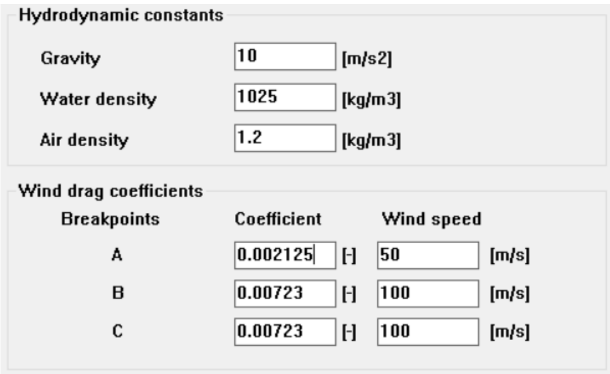


Figure E.4 Hydrodynamic conditions and wind drag coefficients input

The wind drag coefficient is derived from the analytical solution where the wind shear stress at the surface is defined as $|\tau_s| = (0.0505|v|)^2$, whereas in Delft3D it is defined as $|\tau_s| = \rho_{air} C_d |U_{10}|^2$ and thus $C_d = \frac{0.0505^2}{\rho_{air}} = 2.125 \cdot 10^{-3}$.

Roughness and viscosity

The roughness formula is set to Chézy, uniform and set to 65 for both horizontal directions. The slip condition is set to free. Viscosity settings are default.

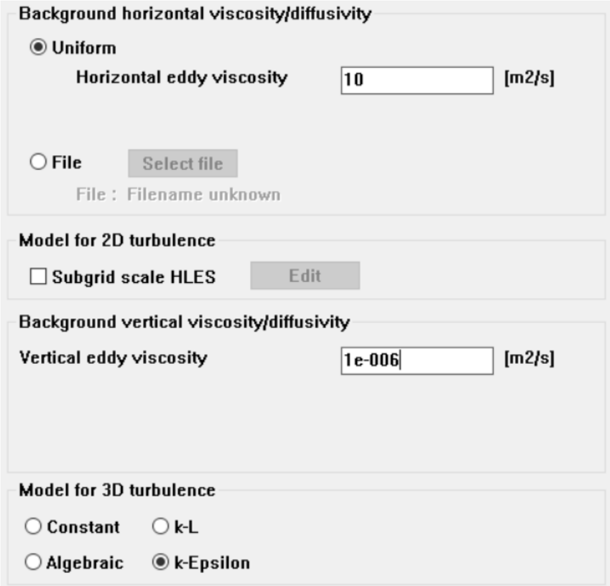
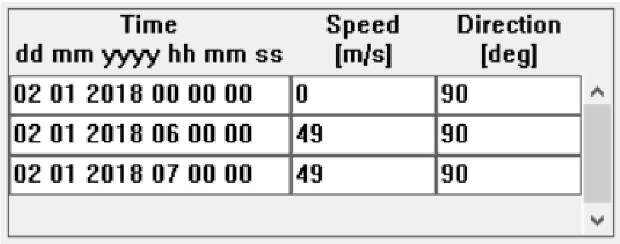


Figure E.4 Viscosity input

Wind

Wind is uniform, linearly interpolated. The first 6 hours the wind velocity increases linearly due to upwinding effects. After the first 6 hours another hour of maximum wind velocity acts on the grid to create a stationary situation. Wind direction is from the east, because this direction has the maximum basin and fetch length.



Time dd mm yyyy hh mm ss	Speed [m/s]	Direction [deg]
02 01 2018 00 00 00	0	90
02 01 2018 06 00 00	49	90
02 01 2018 07 00 00	49	90

Figure E.5 Wind input

Numerical parameters

The default settings are used.

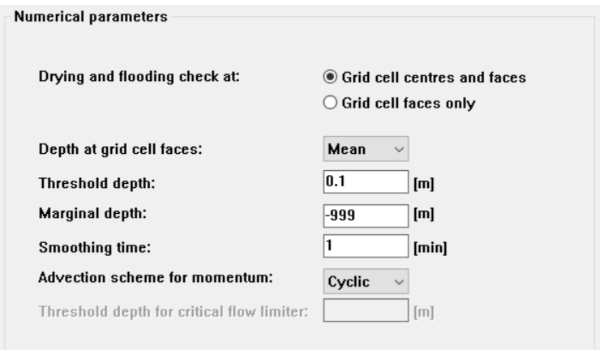


Figure E.6 Numerical parameters input

Appendix E.2: Analytical calculation

In this appendix the solution of Delft3D is approximated by an analytical calculation, (Zitman, 2017).

Water level gradient only

The velocity profile in the stationary, horizontally uniform, gradient driven situation can be determined using the momentum equation for a control volume. This balance consists of three components:

- Hydrostatic pressures left and right F_h
- Shear stress and the surface and the bottom F_w
- Advection horizontally and vertically $F_{a,h}$ and $F_{a,v}$

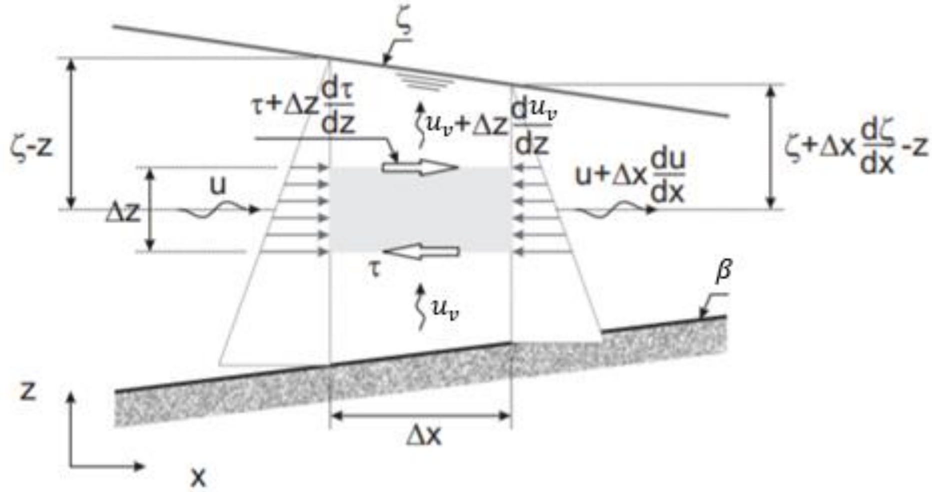


Figure E.6 Balance of forces (Zitman, 2017)

When in balance these forces equal zero.

$$F_h + F_w + F_{a,h} + F_{a,v} = 0 \tag{E.1}$$

This can be written as:

$$2 \cdot u \frac{\partial u}{\partial x} + u \frac{\partial u_v}{\partial z} + u_v \frac{\partial u}{\partial z} = -g \frac{d\zeta}{dx} + \frac{1}{\rho} \frac{d\tau}{dz} \tag{E.2}$$

Assuming an incompressible fluid we know from continuity that:

$$\frac{\partial u}{\partial x} + \frac{\partial u_v}{\partial z} = 0 \tag{E.3}$$

Combined with Eq. E.2:

$$u \frac{\partial u}{\partial x} + u_v \frac{\partial u}{\partial z} = -g \frac{d\zeta}{dx} + \frac{1}{\rho} \frac{d\tau}{dz} \tag{E.4}$$

This is the momentum equation for a **stationary flow in one horizontal direction**. In a closed rectangular basin with constant depth the term on the left hand side equals zero (horizontally uniform). The resulting equation is the **stationary, horizontally uniform momentum equation**.

$$0 = -g \frac{d\zeta}{dx} + \frac{1}{\rho_w} \frac{d\tau}{dz} \tag{E.5}$$

To get the velocity profile from Eq. E.5 a relation is needed between velocity and shear stress. This relation is found in eddy viscosity. Using Reynolds decomposition the shear stress can be related to the turbulent fluctuations in velocity, known as Reynolds shear stress.

$$|\tau| = \rho_w \overline{u'w'} \tag{E.6}$$

Prandtl defined that the turbulent fluctuation is proportional to a **depth-averaged velocity gradient** (e.g. a water column is divided in multiple layers each with their own average flow velocity). The proportionality is related to the mixing length $l_{mix} = \kappa(z - \beta)$ where $\kappa \approx 0.41$, the Von Karman constant.

$$u' = l_{mix}^2 \frac{d\overline{u}}{dz} \tag{E.7}$$

Prandtl also stated that fluctuations are equal in all directions, $|u'| = |w'|$. Combined with Eq. E.7:

$$\tau = \rho_w l_{mix}^2 \frac{d\overline{u}}{dz}\left|\frac{d\overline{u}}{dz}\right| \tag{E.8}$$

This can be written as:

$$\frac{\tau}{\rho} = \nu_t \frac{d\overline{u}}{dz} \qquad \nu_t = l_{mix}^2 \left|\frac{d\overline{u}}{dz}\right| \tag{E.9}$$

Eq. E.9 and $l = \kappa(z - b)$ is applicable for distances close to the bottom. Further from the bottom the turbulent character causes the mixing length to grow non-linearly. Also the free surface influences the mixing length. Therefore, for a stationary, gradient-driven, horizontally uniform flow the mixing length is defined as:

$$l_{mix} = \kappa(z - \beta)\sqrt{\frac{\zeta - z}{d}} \tag{E.10}$$

From now on the depth-averaged velocity $(\overline{u})$ will simply be (u). Combining Eq. E.5 and Eq. E.9 with the boundary condition in Eq. E.12:

$$0 = -g\frac{d\zeta}{dx} + \frac{d}{dz}\left(\nu_t \frac{du}{dz}\right) \tag{E.11}$$

$$\nu_t \frac{du}{dz}\bigg|_{z=\zeta} = 0 \tag{E.12}$$

The equation can be integrated to z and using Eq. E.10:

$$\frac{du}{dz} = \pm\frac{1}{\kappa}\sqrt{gd\left|\frac{d\zeta}{dx}\right|}\frac{1}{z - \beta} \tag{E.13}$$

The $\pm$ notation is required for the direction of flow, dependent on $d\zeta/dx$, which is absolute in the square root. Using boundary condition $u(z_0) = 0$ and integrating to z again the velocity profile is described as:

$$u = \pm\frac{1}{\kappa}\sqrt{gd\left|\frac{d\zeta}{dx}\right|}\ln\left(\frac{z - \beta}{z_0}\right) \quad z \geq z_0 + b \tag{E.14}$$

Substituting Eq. E.13 and Eq. E.10 in Eq. E.8 an expression for the bottom shear stress is found.

$$\frac{\tau_b}{\rho_w} = -g(d - z_0)\frac{d\zeta}{dx} \approx -gd\frac{d\zeta}{dx} \tag{E.15}$$

The solution for the eddy viscosity and velocity profile for a **water level gradient only** is found using Eq. E.13 and Eq. E.10 in Eq. E.9 and remembering Eq. E.15:

$$\nu_t(z) = \kappa \frac{(\zeta - z)(z - \beta)}{d} u_* \qquad u_* = \sqrt{\frac{|\tau_b|}{\rho_w}} \tag{E.16}$$

$$u(z) = \frac{u_*}{\kappa} \ln\left(\frac{z - \beta}{z_0}\right) \qquad z \geq z_0 + b \tag{E.17}$$

Where u_* is the shear velocity.

Including wind shear stress

In Eq. E.12 the boundary conditions at the water surface states that there is no shear stress. When wind blows over a water surface it generates a shear stress at the water surface. The eddy viscosity profile **no longer only depends** on the shear velocity u_*. The eddy viscosity profile changes slightly from the logarithmic profile. This can be compensated by adjusting the eddy viscosity profile. A variable, **the depth-averaged eddy viscosity** ($\nu_{t,avg}$), represents the influence of the bottom shear velocity and wind shear stress but is unknown. Implementing this variable into Eq. E.16 gives:

$$\nu_t(z) = \nu_{t,avg} \frac{(\zeta - z)(z - \beta)}{d^2} \tag{E.18}$$

The velocity profile can be considered as a superposition of the gradient driven (u_p) and wind driven components (u_W). The gradient driven component follows from Eq. E.11 and boundary conditions Eq. E.12 (including $u(z_0) = 0$) and using the newly defined viscosity profile Eq. E.18:

$$u_p(z) = -g \frac{d\zeta}{dx} \frac{d^2}{\nu_{t,avg}} \ln\left(\frac{z - \beta}{z_0}\right) \tag{E.19}$$

Similarly, the wind driven component can be derived. The momentum equation with boundary conditions are given below.

$$0 = \frac{d}{dz}\left(\nu_t \frac{du_w}{dz}\right) \tag{E.20}$$

$$u_w\,(z_0 + \beta) = 0 \qquad \nu_t \frac{du_w}{dz}\bigg|_{z=\zeta} = \frac{\tau_s}{\rho} \tag{E.21}$$

Wind shear stress is related to the wind velocity according to:

$$\tau_s \approx \left(0.0505 v_{b,0}\right)^2 \rho_{air} \tag{E.22}$$

Where W is the wind velocity at 10 m above ground level and ρ_{air} the density of air at sea level (1.2 kg/m^3) (Garrat, 1977). Integration of Eq. E.20 with boundary conditions Eq. E.21 leads to the wind driven velocity profile.

$$u_{w(z)} = \frac{\tau_s}{\rho_w} \frac{d}{\nu_{t,avg}} \ln\left(\frac{z - \beta}{z_0} \cdot \frac{\zeta - (z_0 + \beta)}{\zeta - z}\right) \tag{E.23}$$

For every wind velocity this profile is known, while the gradient driven profile changes in time as the gradient grows. However, for the stationary situation the depth-averaged flow velocity equals zero.

$$\int_{z_0+b}^{\zeta} u_p\, dz + \int_{z_0+b}^{\zeta} u_p\, dz = 0 \tag{E.24}$$

By substituting Eq. E.19 and E.23 into Eq. E.24, using Eq. E.22.

$$gd \frac{d\zeta}{dx} = v_{b,0}^2 \cdot 0.0505^2 \frac{\rho_{air}}{\rho_w} \frac{\int_{z_0+b}^{\zeta} \ln\left(\frac{z - \beta}{z_0} . \frac{\zeta - (z_0 + \beta)}{\zeta - z}\right) dz}{\int_{z_0+b}^{\zeta} \ln\left(\frac{z - \beta}{z_0}\right) dz} \tag{E.25}$$

And

$$gd\frac{d\zeta}{dx} = v_{b,0}^2 c_W \quad \Leftrightarrow \quad \frac{d\zeta}{dx} = c_W\frac{v^2}{gd} \tag{E.26}$$

The dimensionless coefficient c_W is dependent on z_0. Practical implementation of this coefficient usually states $c_W \approx 3.5 \cdot 10^{-6}$.

The velocity profile is found using Eq. E.23 and E.19.

$$u(z) = \frac{d^2}{\nu_{t,avg}}\left(\frac{\tau_s}{\rho_w}\ln\left(\frac{z-\beta}{z_0}\cdot\frac{\zeta-(z_0+\beta)}{\zeta-z}\right) - gd\frac{d\zeta}{dx}\ln\left(\frac{z-\beta}{z_0}\right)\right) \tag{E.27}$$

And with Eq. E.22 and E.26.

$$u(z) = v_{b,0}^2\frac{d^2}{\nu_{t,vag}}\left(\frac{0.0505^2\rho_{air}}{\rho_w}\ln\left(\frac{z-\beta}{z_0}\cdot\frac{\zeta-(z_0+\beta)}{\zeta-z}\right) - c_W\ln\left(\frac{z-\beta}{z_0}\right)\right) \tag{E.28}$$

Note that the wind velocity is only a scale factor of the velocity profile. This is a result of the use of the depth-averaged eddy viscosity profile defined earlier. The profile is independent of the wind velocity.

The components and resulting velocity profile shapes are shown in Figure E.9.

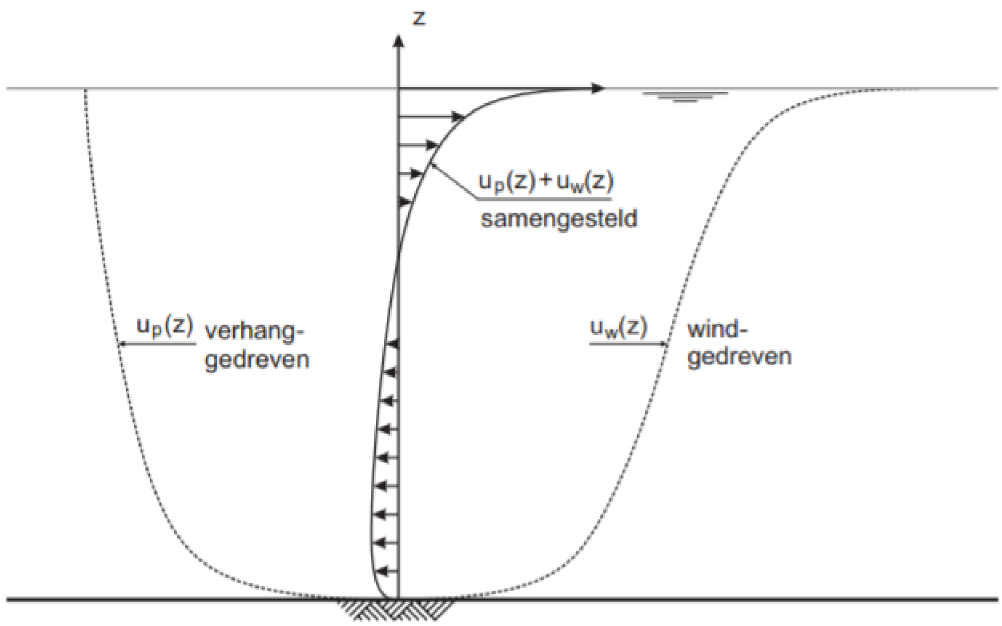


Figure E.9 Resulting velocity profile

The water surface gradient generated by the wind can be approximated. The water depth can be written in a water surface and bottom level component.

$$\frac{dh}{dx} = \frac{d\zeta}{dx} - \frac{d\beta}{dx} \tag{E.29}$$

With Eq. E.26 this becomes:

$$\frac{dd}{dx} = c_W\frac{v^2}{gd} - \frac{d\beta}{dx} \tag{E.30}$$

No analytical solution exists for this equation for a random bottom profile. However a solution exists when the bottom profile is considered flat, $d\beta/dx = 0$

$$\frac{1}{2}d^2 = c_W\frac{v_{b,0}^2}{g}x + I \tag{E.31}$$

Where I is an integrationconstant. This can be found by defining a boundary condition. The boundary condition is defined as a **known water depth** d_0 at location x_0.

$$d(x_0) = d_0 \tag{E.32}$$

The solution then becomes:

$$d(x) = \sqrt{2c_W \frac{v_{b,0}^2}{g}(x - x_0) + d_0^2} \tag{E.33}$$

For a closed basin the boundary condition follows from the **centre of gravity** of the basin. The water level at this point will be constant and equal to the initial water level as the water surface gradient grows in time. For other basin configurations this is more complicated. For simplicity, a closed rectangular basin is defined: 20 x 500 m.

Parameter estimation

An attempt is made to confirm the Delft3D output with the analytical approximation. From the Delft3D FLOW User Manual (Deltares, 2014) and analytical approximation some parameters can be estimated. These are given in Table E.3 for the depth-averaged turbulent viscosity.

Table E.2 Estimation parameters

Parameter		Value	Determined from	Input for
Chézy coefficient	C_{2D}	$65\ \sqrt{m}/s$	Estimation	Delft3D
Bed roughness length	$z_0 = \frac{d}{e^{1+\frac{\kappa C_{2D}}{\sqrt{g}}} - e}$	$2.0125 \cdot 10^{-4}\ m$	Delft3D	Analytical calculation
Wind drag coefficient	$C_d = 0.0505^2$	0.0025505	Analytical calculation	Delft3D
Depth-averaged turbulent viscosity	$\nu_{t,avg} = \kappa d \sqrt{\frac{gu^2}{C_{2D}^2}}$	Dependent on the velocity $[m^2/s]$	Derived from analytical calculation and Delft3D, see below.	Analytical calculation
Dimensionless coefficient	c_W	Practical value: $3.5 \cdot 10^{-6}$	Estimation	Analytical calculation

The depth-averaged turbulent viscosity, $\nu_{t,avg}$ derived from the analytical approximation combining Eq. E.16 and E.18 and the definition for bottom shear stress used in Delft3D are presented in Eq. E.34 and E.35 respectively.

$$\nu_{t,avg} = \kappa d \sqrt{\frac{|\tau_b|}{\rho_w}} \tag{E.34}$$

$$|\tau_b| = \frac{\rho g u^2}{C_{2D}^2} \tag{E.35}$$

Where u is the depth-averaged velocity and C_{2D} is the 2D Chézy coefficient. Combining Eq. E.34 and E.35:

$$\nu_{t,avg} = \kappa d \sqrt{\frac{gu^2}{C_{2D}^2}} \tag{E.36}$$

The value for U is difficult to determine. The steady state condition implies that the depth-averaged velocity equals zero. Also the analytical velocity profile is dependent on $\nu_{t,avg}$. However, $\nu_{t,avg}$ was introduced to correct the gradient driven velocity profile for influence of the wind shear stress. Recall Eq. E.14 and notice that the pressure term $gd\left|\frac{d\zeta}{dx}\right|$ can be rewritten using Eq. E.26 the following velocity profile is obtained.

$$u = \pm \frac{v_{b,0}}{\kappa} \sqrt{c_W} \ln\left(\frac{z-\beta}{z_0}\right) \quad z \geq z_0 + \beta \tag{E.37}$$

The depth-averaged velocity can be determined from this profile and used in Eq. E.36 to determine $v_{t,avg}$. The computed values are given in table E.3

Table E.3 Calculated depth-averaged velocity and viscosity

	Storm	Typhoon
Depth-averaged velocity	$1.22\ m/s$	$1.87\ m/s$
Depth-averaged turbulent viscosity	$6.084 \cdot 10^{-2}\ m^2/s$	$9.316 \cdot 10^{-2}\ m^2/s$

The parameters are substituted in Eq. E.28 and E.33, the results are plotted in Figure E.10.

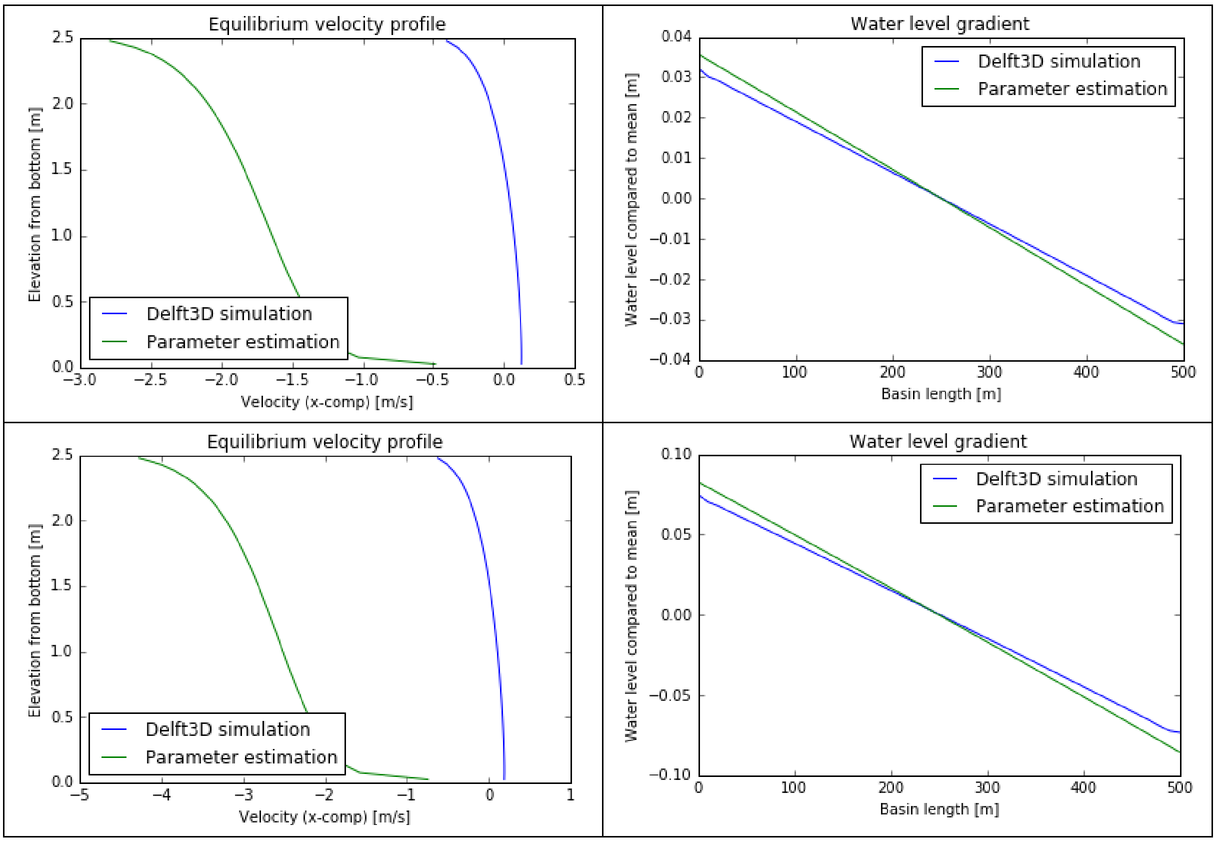


Figure E.10 Resemblance of Delft3D and analytical solution without best fit

It is clear that the analytical approximated velocity profile shows **no resemblance** with the Delft3D profile. On the other hand, the water level gradient shows **good resemblance** with the Delft3D outcome. The depth-averaged turbulent viscosity parameter is only a **scaling factor** for the velocity profile, while the dimensionless coefficient has influence on the **shape**. From this it can be concluded that the dimensionless coefficient for the velocity profile is incorrect, see Eq. E.28. A best fit for c_W is done for both the velocity profile and the water level gradient, see Table E.4 and Figure E.11.

Table E.4 Best fit values of dimensionless coefficient c_w

	Storm	Typhoon
$c_{W,w}$	$8.48 \cdot 10^{-6}$	$8.49 \cdot 10^{-6}$
$c_{W,p}$	$3.09 \cdot 10^{-6}$	$3.1 \cdot 10^{-6}$

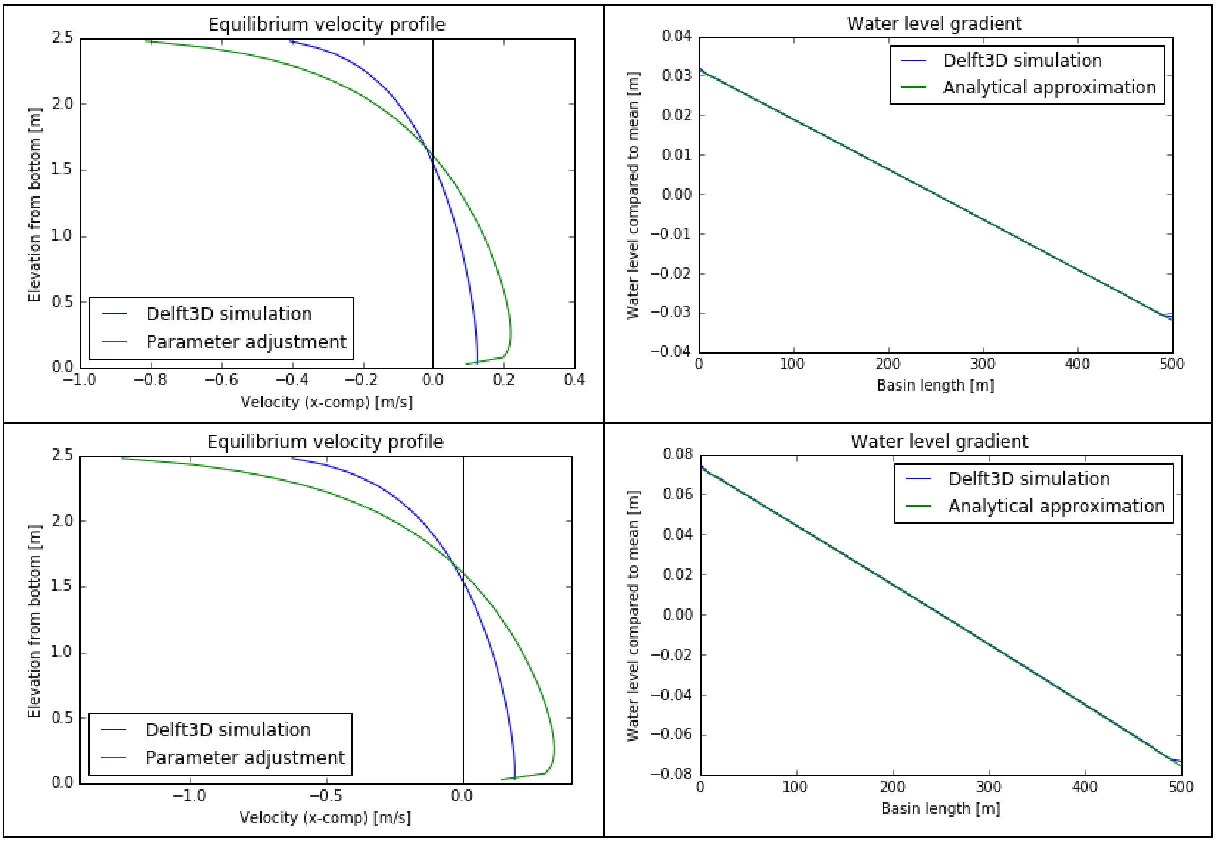


Figure E.11 Resemblance of Delft3D and analytical calculation with best fit of only c_w

The shape of the velocity profile is more as expected, but the magnitude of the velocities are too large. For both profiles the average difference between Delft3D and the analytical solution is approximately 1.8. Another best fit can be done for $\nu_{t,avg}$. The results are given in Table E.5 and Figure E.12.

Table E.5 Best fit values of depth-averaged turbulent viscosity v_(t,avg)

	Storm	Typhoon
$\nu_{t,avg}$	0.13	0.20

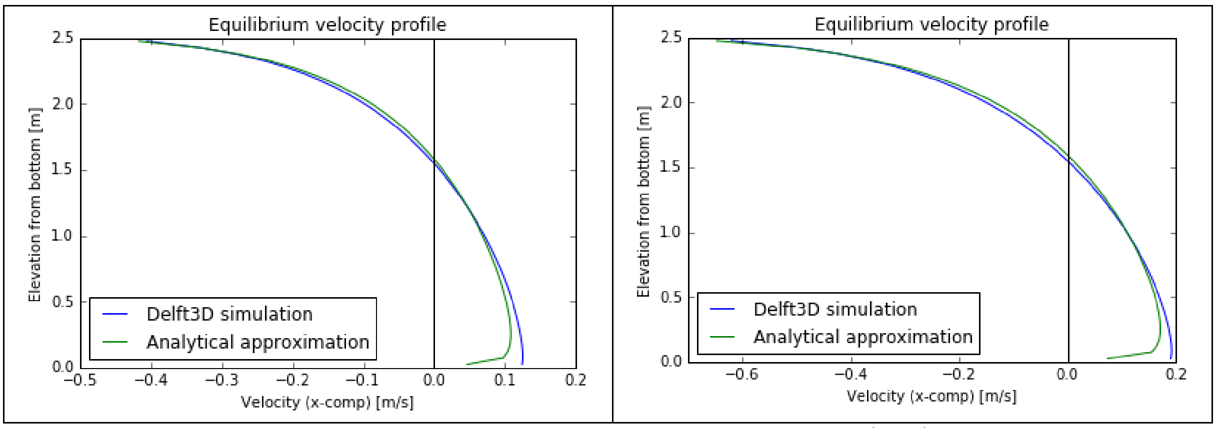


Table E.17 semblance of Delft3D and analytical calculation with best fit of c_w and v_(t,avg)

Remarks

As it is unknown if $c_W = 8.5 \cdot 10^{-6}$ should always be used when describing the velocity profile. It is recommended to simulate wind set-up with Delft3D when one wants to determine the velocities. The analytical approximation of the velocity gradient is too dependent on unknown parameters that are difficult to determine. The water level gradient, however, can be approximated with good accuracy when using $c_W = 3.5 \cdot 10^{-6}$ in the analytical derivation. Also, the formula derived for $\nu_{t,avg}$ gives a value that is half of the best fit value. The value can be determined with more accuracy if the Chézy coefficient is decreased to 30 (meaning higher resistance). However, the Chézy coefficient is difficult to determine beforehand.

Appendix F Forces in the equation of motion

Appendix F.1: Froude-Krilov force

The undisturbed wave force, called the Froude-Krilov force, is calculated with potential flow theory. Potential flow theory is based on linear wave theory, so viscous effects are neglected and the flow is thought to be incompressible and irrotational. The waves are presented as harmonic functions with constant wave amplitude. A wave potential is a mathematical function with the property that the derivative is equal to the flow velocity.

The calculation starts with the potential function of the incoming waves. The general form of this potential is shown in Eq. F.1

$$\Psi_0 = \frac{\zeta_a g}{\omega} \cdot \frac{\cosh(k_w(d+z))}{\sinh(k_w d)} \cdot \sin(k_w x - \omega t) \tag{F.1}$$

In this equation 'z' is a parameter proportional to the height. It is equal to zero at the water surface and –h at the bottom. The derivative of the potential function results in the velocity. From the velocity the pressure can be obtained by the following equation.

$$p = -\rho_w u = -\rho_w \cdot \frac{\partial \Psi_0}{\partial t} = \omega \rho_w \zeta_a g \cdot \frac{\cosh(k_w(d+z))}{\sinh(k_w d)} \cdot \cos(k_w x - \omega t) \tag{F.2}$$

The pressure calculated with Eq. F.4 is only the fluctuating pressure due to the waves. The static pressure does not result in a dynamic force, because this is a constant hydrostatic force. The fluctuating pressure can be calculated at every point at the hull of the structure. Integration over the entire wetted area of the structure results in the loads and moments in every direction.

$$F_{FK} = -\iint (p \cdot \bar{n}) dS_0 \tag{F.3}$$

$$T_{FK} = -\iint (p \cdot (\bar{r} \cdot \bar{n}) dS_0 \tag{F.4}$$

The n-vector defines the surface of the hull. By including this vector in the integral the resulting force in that specific point will have a direction perpendicular to the hull. The r-vector takes into account the distance between the point of interest and the origin of the axis. This origin is located in the middle of the floating structure at the water surface. In the table below the resulting Froude-Krilov forces and moments are presented.

Table F.1 Froude-Krilov force

Direction of the force	Froude-Krilov force
Horizontal	$$\frac{2 \cdot b_s \rho_w g \omega \zeta_a}{k_w \cdot \sinh(2.5 k_w)} \cdot \sin(0.5 \cdot b_s k_w) \cdot \big(\sinh\big((d-D)k_w\big) - \sinh\big((d-D)k_w\big)\big) \cdot \sin(\omega t) \tag{F.5}$$
Vertical	$$\frac{2 \cdot b_s \rho_w g \omega \zeta_a}{k_w} \cdot \frac{\cosh((d-D)k_w)}{\sinh(d k_w)} \cdot \sin(0.5 \cdot b_s k_w) \cdot \cos(\omega t) \tag{F.6}$$
Turning moment	$$\frac{2 \cdot b_s \rho_w g \omega \zeta_a}{k_w^2} \cdot \frac{\cosh((d-D)k_w)}{\sinh(d k_w)} \cdot (\sin(0.5 \cdot b_s k_w) - 0.5 \cdot b_s k_w \cos(0.5 \cdot b_s k_w)) \cdot \sin(\omega t) \tag{F.7}$$

The Froude-Krilov force is often presented by an amplitude times a harmonic function, like Eq. F.8.

$$F = F_a \cdot \cos(\omega t + \varepsilon) \tag{F.8}$$

The harmonic function can be recognized by its dependency on time. The amplitude of the force is not a function of time, but as can be seen in Table F.1 it is dependent on the wave frequency, wave number, water depth and wave amplitude.

Appendix F.2: Analysis of various forces

In this appendix the three situations are analysed from which the total force can be determined.

- Situation 1: no waves and no motion. This is the static behaviour of the structure. This has already been used by calculating the mass of the structure. The forces in this situation are the downward gravity force and the upward buoyancy force according to Archimedes' principle. These forces cancel each other, so they do not influence the motions of the structures.
- Situation 2: no waves and motion. In this situation the structure has an initial displacement. The structure is released and will perform a vibration. The incoming waves are neglected; all forces on the structure are a result of the motion of the structure itself. These hydromechanical forces successively are split into hydrostatic and hydrodynamic forces. The hydrostatics will generate a restoring force. For example, when the structure is heaving upwards, the buoyancy force will get less. The gravity force becomes larger than the buoyancy force, creating a net downward force. A characteristic of the restoring force is that it is linearly dependent on the displacement and works in the opposite direction of the displacement.
  The hydrodynamic forces are more complicated. Due to the motions of the structure, waves radiate from it. These radiating waves present the dissipation of energy. Viscous effects create more damping into the system, but since they are usually small and non-linear it is neglected in this analysis. In the equation of motion, damping is expressed in the multiplication of the damping coefficient and the velocity of the motion. Besides damping, extra mass is introduced as well in case of vibrations in water. The water surrounding the structure is put in motion when the structure moves. This water leads to extra inertia, which explains why the mass of the structure has to be increased by the so-called added mass (Journée & Massie, 2008).
  Summing up the forces in situation 2 results in the hydromechanical forces.

$$F_h = -a\ddot{x} - c\dot{x} - kx \tag{F.9}$$

- Situation 3: waves and no motion. The structure is not able to move in this situation, while incoming waves hit the structure. The force consists of two parts: the undisturbed incoming wave force and diffraction force. The diffraction force are from now on. The undisturbed wave force, called the Froude-Krilov force, was already calculated in Appendix F.1. The horizontal force is causing surge motion, the vertical force heave and the turning moment pitch.

Appendix G Conditional use of added mass and damping graphs

In this appendix, the use of the added mass and damping graphs are explained, since these graphs cannot always be used. The graphs are produced namely by a flow analysis introducing an infinitely long cylinder. In the length direction of the cylinder the flow does not vary. The three-dimensional flow problem is reduced to a two-dimensional problem. The potential functions are also reduced to two-dimensional functions, but still it is complicated to solve them with the help of the six boundary conditions.

However, the flow problem is solved for an infinitely long cylinder, which is not the case for the floating house. So first, the rectangle cross-section of the foundation has to be mapped into an equivalent circular cross-section. This is not possible for every arbitrary floating structure. With the following equations it can be checked if the foundation can be mapped into a circular cross-section (Journée & Massie, 2008).

$$H_0 = \frac{b/2}{D} = \frac{9.6/2}{0.314} = 15.3 \tag{G.1}$$

$$For\ H_0 \geq 0:\ \frac{3\pi}{32}\left(2 - \frac{1}{H_0}\right) \leq \frac{A}{bD} \leq \frac{\pi}{32}\left(10 + H_0 + \frac{1}{H_0}\right) \tag{G.2}$$

Eq. G.3 shows that Eq. G.2 is fulfilled.

$$0.57 \leq 1 \leq 2.49 \tag{G.3}$$

Concluding, the flow potentials around the foundation can be calculated by neglecting the third dimension. The results of the two-dimensional flow potentials are shown in the graphs, which will be used later on to determine the motions.

Appendix H Analysis of motions (without mooring system influence)

Appendix H.1: Added mass and damping heave motion

As mentioned in the main report, the added mass and damping coefficients have to be determined by calculating discrete values. In this appendix the factors of added mass and damping are guesstimated. For completeness the figures from the main report are shown again.

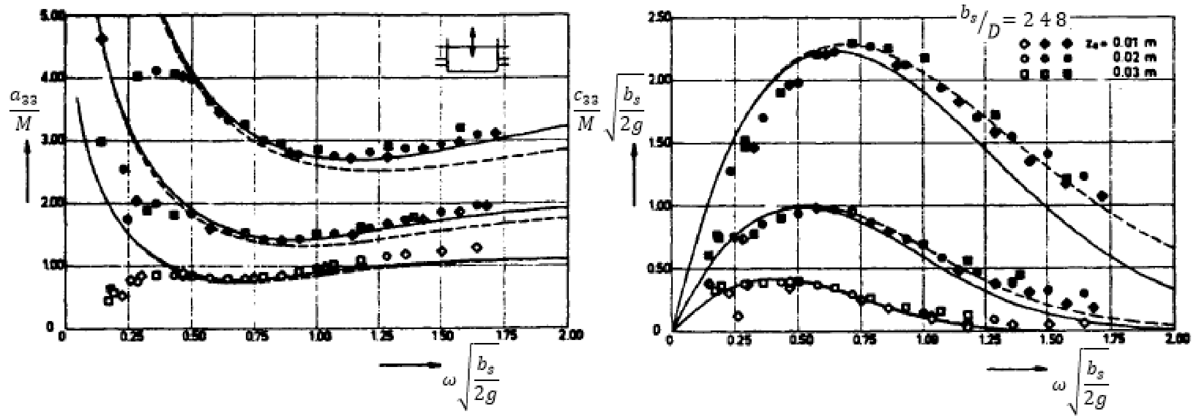


Figure H.1 Added mass (left) and damping (right) graphs for heave motion (Lewis, 1989)

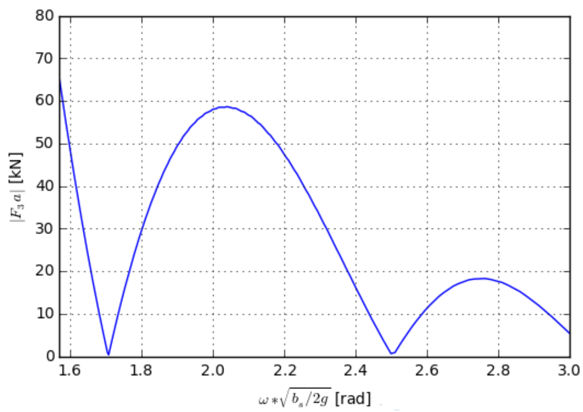


Figure H.2 Force amplitude as function of the modified wave frequency

First, the added mass coefficients that result in resonance, will be determined. Therefore Eq. H.1 is needed:

$$z(t) = \frac{F_{3a}}{\sqrt{(k_{33} - (M + a_{33})\omega^2)^2 + (c_{33}\omega)^2}} \cos(\omega t + \varepsilon) \tag{H.1}$$

Resonance will occur when the denominator will become small or even zero, since dividing by approximately zero will result in a large motion amplitude. Analysing the terms in the square root concludes that it cannot become zero when there is some damping. The terms are minimal when Eq. H.2 is valid.

$$k_{33} - (M + a_{33})\omega^2 = 0 \tag{H.2}$$

The restoring coefficient and mass are constants. Solving for factor a_{33} leads to Eq. H.3

$$a_{33} = \frac{k_{33}}{\omega^2} - M \tag{H.3}$$

It is known that the frequency of the waves is larger than 2.30 rad/s. In Table H.1 the added mass values are calculated which fulfil Eq. H.3. The last columns show the modified frequency and the dimensionless added mass factor, which are the same as the horizontal and vertical axis of Figure H.1.

Table H.1 Added mass causing resonance

ω (in rad/s)	a_{33}(in kg)	$\omega\sqrt{\frac{b_s}{2g}}$ (in rad/s²)	$\frac{a_{33}}{M}$ (-)
2.30	126501	1.59	6.81
2.80	79310	1.94	4.27
3.30	51891	2.29	2.79
3.80	34564	2.63	1.86
4.30	22922	2.98	1.23

In the graph of Figure H.1 it can be seen that the added mass is larger for larger width over draft ratios. Probably the minimum of the curve of the floating house (b/D=30) will lie above five. For small frequencies the added mass will be enormous, but as mentioned before these do not occur in the fishpond. For large frequencies the added mass will also be higher, because it is likely that the asymptote of the curve lies higher than 5. From this it can already be concluded that for frequencies larger than 2.7 rad/s no resonance will occur. However, for frequencies between 2.3 rad/s and 2.7 rad/s resonance may be an issue. This does not need to be a problem provided that the system is damped enough. From Eq. H.1 it can be seen that the damping coefficient is beneficial for the motion amplitude. To be conservative a low damping coefficient is taken.

In Table H.2 the motion amplitude is calculated for the lowest frequencies that can appear in the fishpond. These frequencies include the resonance frequencies and the frequencies that lead to the highest vertical excitation force according to Figure H.2. The first three added mass coefficients are chosen such that resonance occurs. For the last coefficients this is not realistic, because the added mass coefficients at which resonance occurs are too low. A value of 5.3 is guesstimated as the most unfavourable but still realistic value. It is chosen to use the double of the damping coefficient of the curve for a ratio of eight.

Table H.2 Calculation of motion amplitude

ω (in rad/s)	$\omega\sqrt{\frac{b_s}{2g}}$ (in rad/s²)	$\frac{a_{33}}{M}$ (-)	$\frac{c_{33}}{M}\sqrt{\frac{b_s}{2g}}$ (-)	$\lvert F_{3a}\rvert$ (in kN)	ζ_a (in m)	z_a (in m)
2.30	1.59	6.81	1.72	51.9	0.227	0.49
2.40	1.66	6.17	1.48	17.3	0.206	0.18
2.50	1.73	5.61	1.26	8.9	0.188	0.11
2.60	1.80	5.3	1.08	30.4	0.171	0.38
2.70	1.87	5.3	0.92	44.8	0.156	0.41
2.80	1.94	5.3	0.74	54.3	0.143	0.34
2.90	2.01	5.3	0.58	58.3	0.132	0.26
3.00	2.08	5.3	0.41	57.5	0.122	0.20

The motion amplitude does vary a lot. This is mainly caused by the variation in force amplitude. Due to the introduced damping, the motion amplitude does not go to infinity, but still the amplitudes are quite large. The amplitudes of the waves are indicated in the same table to make comparison with the resulting motion amplitude easier.

The calculated amplitudes are the results of the most unfavourable, yet realistic combination of the added mass and damping coefficients. To get insight into the influence of the choice of these parameters, a sensitivity analysis is performed. In Figure H.3 the motion amplitudes are shown for four different wave frequencies. The motion amplitude is large for only a few combinations of the added mass and damping coefficient. A slightly other choice can result in amplitudes halve of the ones in Table H.2. Another observation from Figure H.3 is that the motion amplitude increases with increasing wave frequency, which is logical because the force increases with increasing wave frequency. A more careful view shows that the maximum of the motion amplitude shifts to the lower added mass values for higher frequencies. Eq. H.3, which is used to calculate the added mass coefficient that causes resonance, is in accordance with this observation.

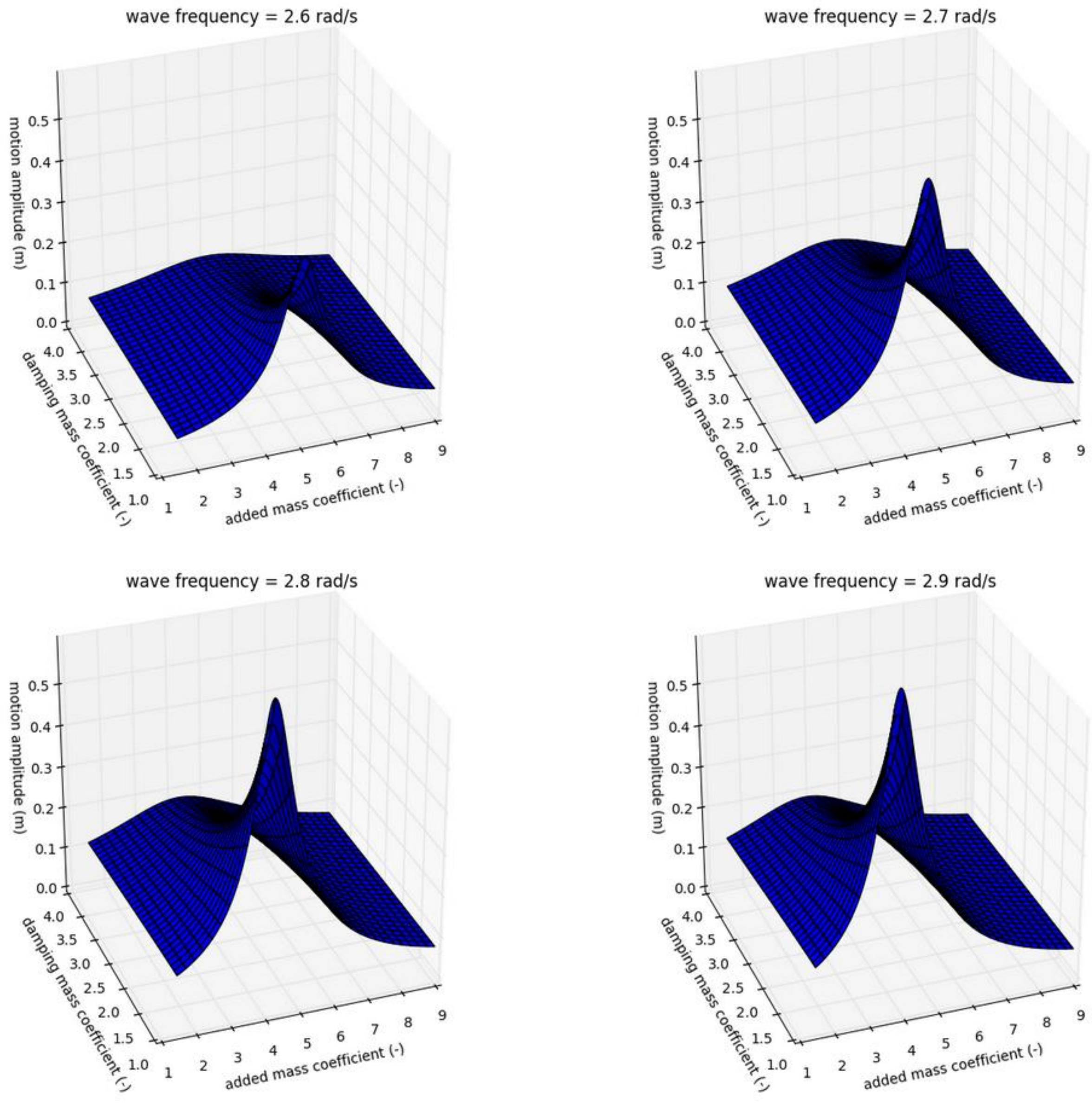


Figure H.3 The motion amplitude for varying added mass and damping coefficients

Appendix H.2: Restoring coefficient surge motion

This appendix is a sort of repetition of appendix H.1. Instead of the heave motion the surge motion is analysed. For the heave motion the restoring coefficient was known, for the surge motion it depends on the mooring system, which has to be designed in a later stage. The aim of this appendix is to investigate which stiffness of mooring system is desired or which is not desired. Once more, it is started by repeating the needed graphs, see Figure H.4 and Figure H.5.

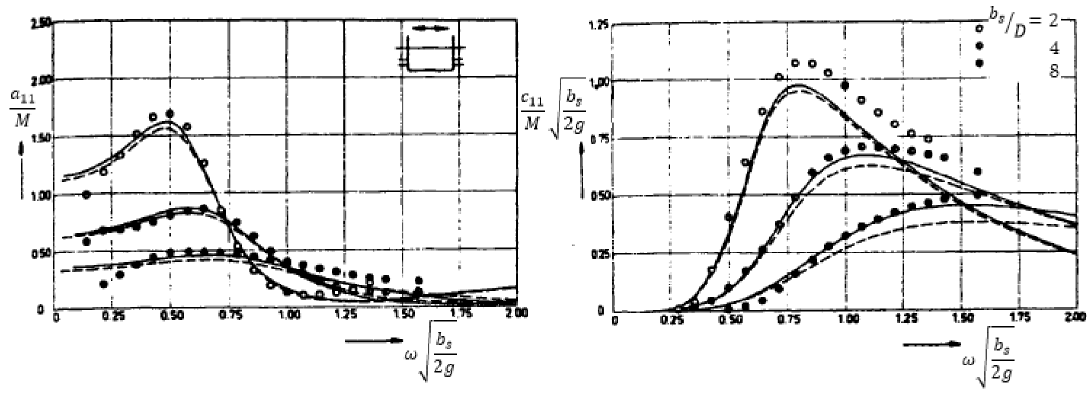


Figure H.4 Added mass (left) and damping (right) graphs for surge motion (Lewis, 1989)

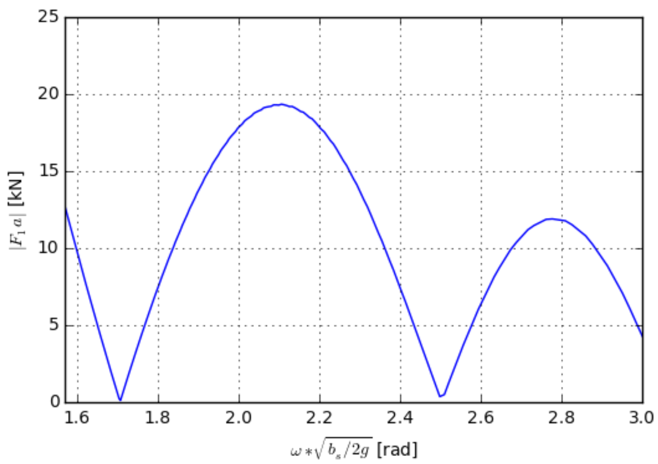


Figure H.5 Force amplitude for surge motion

Also, the equation with which resonance can be determined is the same.

$$x(t) = \frac{F_{1a}}{\sqrt{(k_{11} - (M + a_{11})\omega^2)^2 + (c_{11}\omega)^2}} \cos(\omega t + \varepsilon) \tag{H.4}$$

The added damping is beneficial for the motion amplitude, so it is taken conservative at 0.25. In Table H.3 the restoring coefficients that cause resonance are calculated. The added mass coefficient is neglected (set to zero), so the restoring coefficient has to fulfil Eq. H.5 to cause resonance.

$$k_{11} = M\omega^2 \tag{H.5}$$

Table H.3 Restoring coefficient causing resonance

ω (in rad/s)	k_{11}(in N/m)
2.30	98331
2.80	145730
3.30	202423
3.80	268411
4.30	343692

As expected, the restoring coefficient is growing with increasing wave frequency. If the added mass were taken into account, the restoring coefficients causing resonance would become even larger. The design of the mooring system is partly based on the desired restoring coefficient. In Table H.4 the motion amplitude is calculated in case of a restoring coefficient of 90 kN/m to get a feeling about the order of magnitude of the horizontal motion.

Table H.4 Calculation of motion amplitude

ω (in rad/s)	$\frac{c_{11}}{M}\sqrt{\frac{b}{2g}}$ (-)	k_{11}(in N/m)	$\lvert F_{1a} \rvert$ (in kN)	ζ_a (in m)	x_a (in m)
2.30	0.25	90000	10.4	0.227	0.60
2.40	0.25	90000	3.7	0.206	0.16
2.50	0.25	90000	2.1	0.188	0.07
2.60	0.25	90000	7.6	0.171	0.19
2.70	0.25	90000	12.0	0.156	0.24
2.80	0.25	90000	15.7	0.143	0.27
2.90	0.25	90000	18.1	0.132	0.26
3.00	0.25	90000	19.2	0.122	0.24

Appendix H.3: Added mass and damping pitch motion

In this appendix the added mass and damping for the pitch motion is elaborated. This results in the pitch motions of the floating structure.

Again the needed figures are shown below.

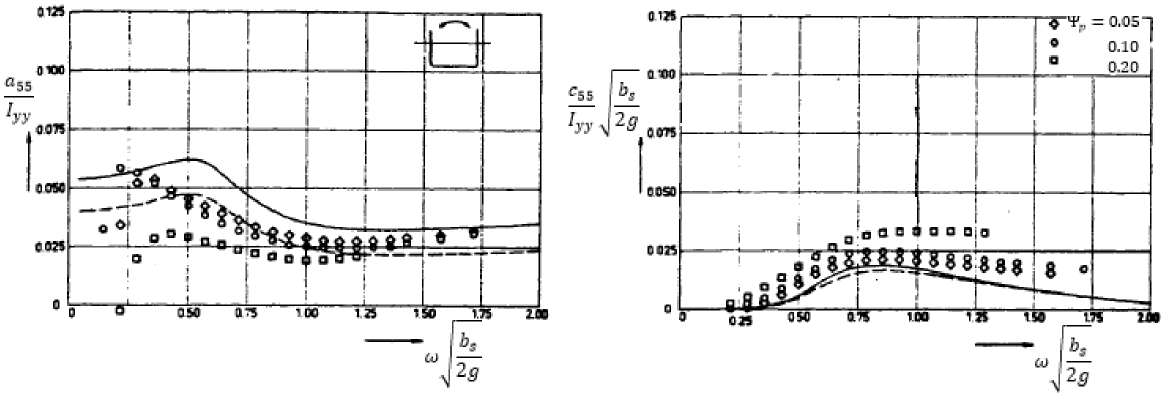


Figure H.6 Added mass (left) and damping (right) graphs for pitch motion (Lewis, 1989)

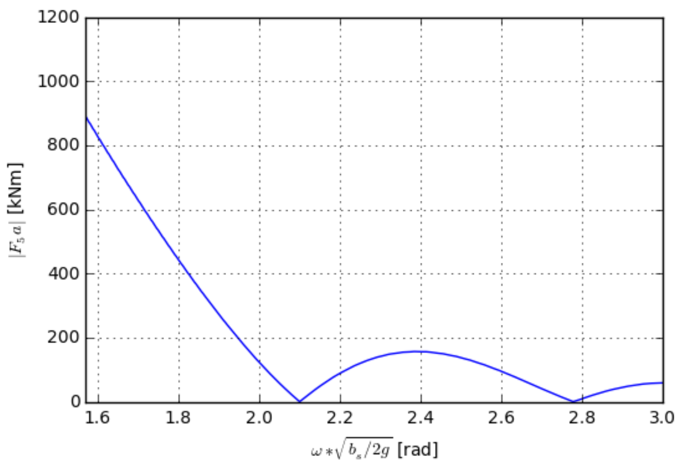


Figure H.7 Force amplitude as function of the modified wave frequency

Also, the equation for the pitch motion is the same as for the other motions:

$$\Psi_p(t) = \frac{F_{5a}}{\sqrt{\left(k_{55} - (I_{yy} + a_{55})\omega^2\right)^2 + (b_{55}\omega)^2}} \cos(\omega t + \varepsilon) \qquad \text{(H.6)}$$

The restoring coefficient can be obtained from Eq H.7 ($k_{55} = 5302\ kNm/rad$). The mooring system will probably add some restoring force, but this is neglected for now. The added mass coefficient that causes resonance is calculated for a range of frequencies in Table H.5 with the help of Eq. H.7.

$$a_{55} = \frac{k_{55}}{\omega^2} - I_{yy} \qquad \text{(H.7)}$$

Table H.5 Added mass causing resonance

ω (in rad/s)	a_{55}(in kgm²)	$\omega\sqrt{\frac{b_s}{2g}}$ (in rad/s²)	$\frac{a_{55}}{I_{yy}}$ (-)
2.30	860554	1.59	6.07
2.80	534539	1.94	3.78
3.30	345131	2.29	2.44
3.80	225436	2.63	1.59
4.30	145011	2.98	1.03

Obviously, resonance does not occur during typhoon or storm conditions. Taking an added mass coefficient of 0.050, it turns out that resonance occurs at waves with a frequency of 6.0 rad/s. At this frequency the most common wave height, wave length and exciting wave force are very small, so resonance will not be a problem. The resulting motion amplitude expressed in radians can be found in Table H.6.

Table H.6 Calculation of motion amplitude

ω (in rad/s)	$\omega\sqrt{\frac{b_s}{2g}}$ (in rad/s²)	$\frac{a_{55}}{I_{yy}}$ (-)	$\frac{c_{55}}{I_{yy}}\sqrt{\frac{b_s}{2g}}$ (-)	$\lvert F_{5a}\rvert$ (in kNm)	$\Psi_{p,a}$(in rad)
2.30	1.59	0.035	0.010	841.0	0.186
2.40	1.66	0.035	0.010	699.2	0.154
2.50	1.73	0.035	0.010	570.0	0.126
2.60	1.80	0.035	0.005	437.8	0.097
2.70	1.87	0.035	0.005	391.8	0.087
2.80	1.94	0.035	0.005	206.4	0.046
2.90	2.01	0.035	0.005	108.4	0.024
3.00	2.08	0.040	0	21.1	0.005

Appendix I Matrix solution to the equations of motion

In this appendix the matrix equation is solved for the coupled system (fixed rotation). The matrix equation and test equations are first repeated.

$$\begin{bmatrix} (M+a_{11})\frac{\partial^2}{\partial t^2}+c_{11}\frac{\partial}{\partial t}+k_{trans} & k_{coupled} \\ k_{coupled} & (I_{yy}+a_{55})\frac{\partial^2}{\partial t^2}+c_{55}\frac{\partial}{\partial t}+k_{55}+k_{rot} \end{bmatrix} \cdot \begin{bmatrix} x \\ \Psi_p \end{bmatrix} = \begin{bmatrix} F_{wind}+F_{1a}\sin(\omega t) \\ T_{wind}+F_{5a}\sin(\omega t) \end{bmatrix} \tag{I.1}$$

$$x = C_1\sin(\omega t)+C_2\cos(\omega t)+C_3 \qquad \Psi_p = D_1\sin(\omega t)+D_2\cos(\omega t)+D_3 \tag{I.2}$$

The matrix equation, Eq. I.1, can be expanded as shown below.

$$\begin{bmatrix} M+a_{11} & 0 \\ 0 & I_{yy}+a_{55} \end{bmatrix}\begin{bmatrix} \ddot{x} \\ \ddot{\Psi}_p \end{bmatrix}+\begin{bmatrix} c_{11} & 0 \\ 0 & c_{55} \end{bmatrix}\begin{bmatrix} \dot{x} \\ \dot{\Psi}_p \end{bmatrix}+\begin{bmatrix} k_{trans} & k_{coupled} \\ k_{coupled} & k_{55}+k_{rot} \end{bmatrix}\begin{bmatrix} x \\ \Psi_p \end{bmatrix}=\begin{bmatrix} F \\ T \end{bmatrix} \tag{I.3}$$

Inserting the test equations, Eq. I.2, solve for x and Ψ_p respectively results in the following equations.

$$\begin{gathered} -(M+a_{11})\omega^2C_1+c_{11}\omega C_2+k_{trans}C_1+k_{rot}D_1=F_{1a} \\ -(M+a_{11})\omega^2C_2-c_{11}\omega C_2+k_{trans}C_1+k_{rot}D_1=0 \\ k_{trans}C_3+k_{rot}D_3=F_{wind} \\ -(I_{yy}+a_{11})\omega^2D_1+c_{55}\omega D_2+k_{rot}C_1+k_{coupled}D_1=F_{5a}-k_{55}D_1 \\ -(I_{yy}+a_{11})\omega^2D_2-c_{55}\omega D_1+k_{rot}C_2+k_{coupled}D_2=-k_{55}D_1 \\ k_{rot}C_3+k_{coupled}D_3=T_{wind}-k_{55}D_3 \end{gathered} \tag{I.4}$$

With six equations and six unknowns the coefficients C1 to D3 can be determined. This is done using Maple 2017. The output is not presented in this appendix as it is too large. Instead the solution to the equations is presented for free rotation, where k_{rot} and $k_{coupled}$ are zero.

$$C_1 = \frac{-F_{1a}(M\omega^2+a_{11}\omega^2-k_{trans})}{M^2\omega^4+2Ma_{11}\omega^4+a_{11}^2\omega^4-2Mk_{trans}\omega^2-2a_{11}k_{trans}\omega^2+c_{11}^2\omega^2+k_{trans}^2} \tag{I.5}$$

$$C_2 = \frac{F_{1a}c_{11}\omega}{M^2\omega^4+2Ma_{11}\omega^4+a_{11}^2\omega^4-2Mk_{trans}\omega^2-2a_{11}k_{trans}\omega^2+c_{11}^2\omega^2+k_{trans}^2} \tag{I.6}$$

$$C_3 = F_{wind}/k_{trans} \tag{I.7}$$

$$D_1 = \frac{F_{5a}\omega(I_{yy}+a_{55})}{I_{yy}^2\omega^3+2I_{yy}a_{55}\omega^3+a_{55}^2\omega^3-I_{yy}k_{55}\omega-a_{55}k_{55}\omega+c_{55}^2\omega-c_{55}k_{55}} \tag{I.8}$$

$$D_2 = \frac{F_{5a}(c_{55}\omega-k_{55})}{\omega^3(I_{yy}^2\omega^3+2I_{yy}a_{55}\omega^3+a_{55}^2\omega^3-I_{yy}k_{55}\omega-a_{55}k_{55}\omega+c_{55}^2\omega-c_{55}k_{55})} \tag{I.9}$$

$$D_3 = T_{wind}/k_{55} \tag{I.10}$$

The now known coefficient can be inserted into the test equations, Eq I.2. The horizontal displacements and rotations are now determined for any ω, but dependent on time. Only the maximum values are of significance. Setting both sine and cosine function to one the amplitudes of the motions can be summed, see Eq. I.11.

$$x_a = \sqrt{C_1^2+C_2^2}+|C_3| \qquad \Psi_{p,a} = \sqrt{D_1^2+D_2^2}+|D_3| \tag{I.11}$$

Taking the maximum amplitude for each mooring pile stiffness (EI) results in the 2D figures shown in the main document.

Appendix J Soil stiffness

Table J.1 is literally copied from (Ham P., 2016). The horizontal modulus for subgrade reactions is calculated for each layer. The last column gives the result in kN/m³.

Table J.1 Horizontal modulus of subgrade reactions for each layer

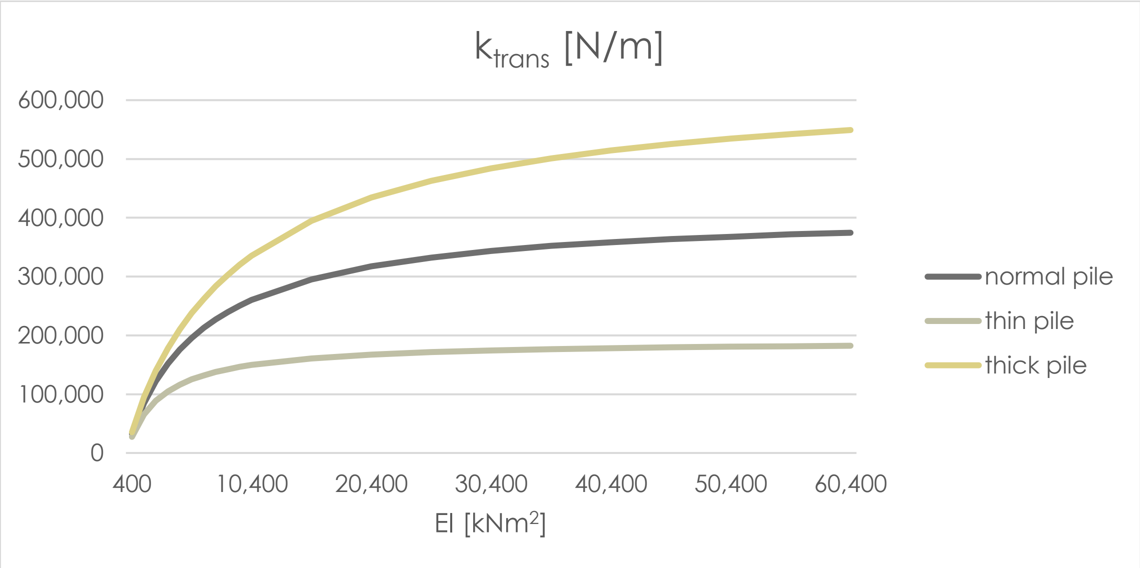
from (m)	to (m)	material	consistency	Nvalue	qc/nvalue	qc (kpa)	β	α	R0	R	Ep	1/kh	kh	kh
0	1	silty sand	loose	3	0,3	900	0,5	0,25	0,3	0,15	5800	7,86079E-05	12721,36499	11154,49
1	2	silty sand	loose	3	0,3	900	0,6	0,3	0,3	0,15	4500	0,000104301	9587,624636	11154,49
2	3	silty sand	loose	3	0,3	900	0,8	0,4	0,3	0,15	720	0,000689537	1450,248785	1450,249
3	4	silty sand	loose	3	0,3	900	0,8	0,4	0,3	0,15	720	0,000689537	1450,248785	1450,249
4	5	silty sand	loose	3	0,3	900	0,8	0,4	0,3	0,15	720	0,000689537	1450,248785	1450,249
5	6	silty sand	loose	6	0,3	1800	0,8	0,4	0,3	0,15	1440	0,000344768	2900,49757	3263,06
6	7	silty sand	loose	7	0,3	2100	0,8	0,4	0,3	0,15	1680	0,000295516	3383,913831	3263,06
7	8	silty sand	loose	7	0,3	2100	0,8	0,4	0,3	0,15	1680	0,000295516	3383,913831	3263,06
8	9	silty sand	loose	7	0,3	2100	0,8	0,4	0,3	0,15	1680	0,000295516	3383,913831	3263,06
9	10	silty sand	medium	20	0,3	6000	0,8	0,4	0,3	0,15	4800	0,000103431	9668,325232	6888,682
10	11	silty sand	medium	15	0,3	4500	0,8	0,4	0,3	0,15	3600	0,000137907	7251,243924	6888,682
11	12	silty sand	medium	12	0,3	3600	0,8	0,4	0,3	0,15	2880	0,000172384	5800,995139	6888,682
12	13	silty sand	medium	10	0,3	3000	0,8	0,4	0,3	0,15	2400	0,000206861	4834,162616	6888,682
13	14	silty sand	loose	8	0,3	2400	0,8	0,4	0,3	0,15	1920	0,000258576	3867,330093	3383,914
14	15	silty sand	loose	6	0,3	1800	0,8	0,4	0,3	0,15	1440	0,000344768	2900,49757	3383,914
15	16	silt with sand	very loose	6	0,3	1800	0,9	0,5	0,3	0,15	1620	0,00032341	3092,053213	1958,3
16	17	silt with sand	very loose	3	0,3	900	0,9	0,5	0,3	0,15	810	0,000646819	1546,026607	1958,3
17	18	silt with sand	very loose	4	0,3	1200	0,9	0,5	0,3	0,15	1080	0,000485115	2061,368809	1958,3
18	19	silt with sand	very loose	4	0,3	1200	0,9	0,5	0,3	0,15	1080	0,000485115	2061,368809	1958,3
19	20	sandy silt	very loose	3	0,2	600	0,9	0,5	0,3	0,15	540	0,000970229	1030,684404	1958,3
20	21	sandy silt	loose	4	0,2	800	0,9	0,5	0,3	0,15	720	0,000727672	1374,245873	2061,369
21	22	sandy silt	loose	5	0,2	1000	0,9	0,5	0,3	0,15	900	0,000582137	1717,807341	2061,369
22	23	sandy silt	loose	7	0,2	1400	0,9	0,5	0,3	0,15	1260	0,000415812	2404,930277	2061,369
23	24	sandy silt	loose	8	0,2	1600	0,9	0,5	0,3	0,15	1440	0,000363836	2748,491745	2061,369

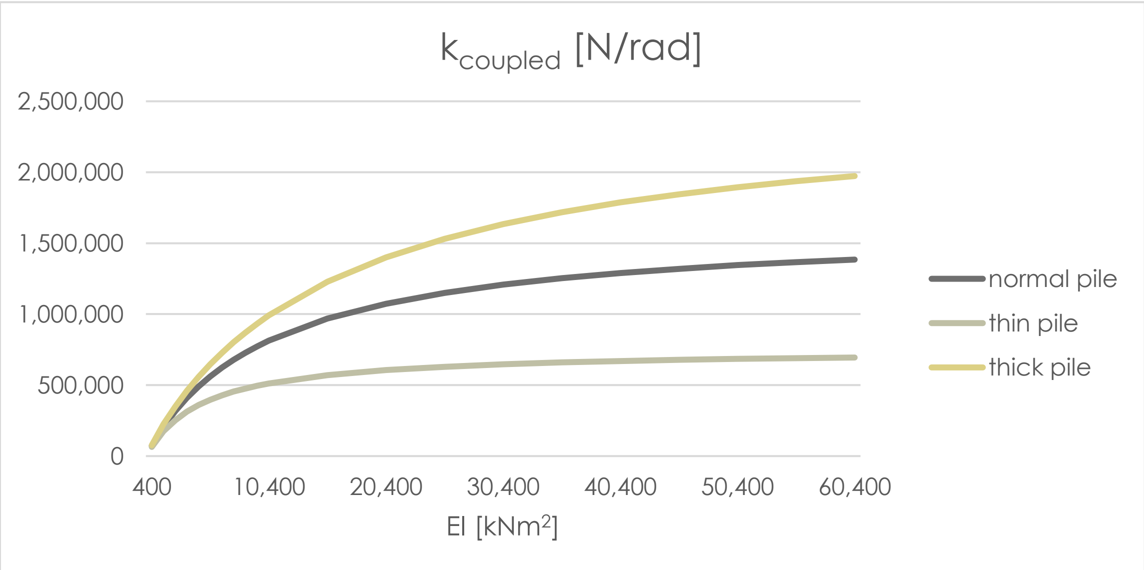
Appendix K Sensitivity of solution

Appendix K.1: Sensitivity of pile diameter

For the calculation of the total pile stiffness, circular piles with a diameter of 325 mm are chosen. This diameter follows from taking the average of 150 and 500 mm thick piles. These two dimensions are set as boundaries, so the mooring piles should have a diameter between these two values. However, the calculation is done with a diameter of 325 mm, so with the help of this sensitivity analysis it is determined if another pile diameter has large influence on the total pile stiffness.

In this sensitivity analysis a pile length of four meters is chosen. Resulting stiffness is calculated for a pile width of 150, 325 and 500 mm. The bending stiffness EI of the pile should not change due to the change in width. The thicker pile has a larger moment of inertia, so the modulus of elasticity of the thicker pile should be smaller. The only effect that is determined is the area which is supported by the soil. This area determines the soil stiffness, since the values of the last column in appendix J have to be multiplied by the diameter of the pile. The spring constant of the soil is smaller in the case of thin pile than for the 'normal' pile. The effect of this spring constant can be seen in figure K.1.





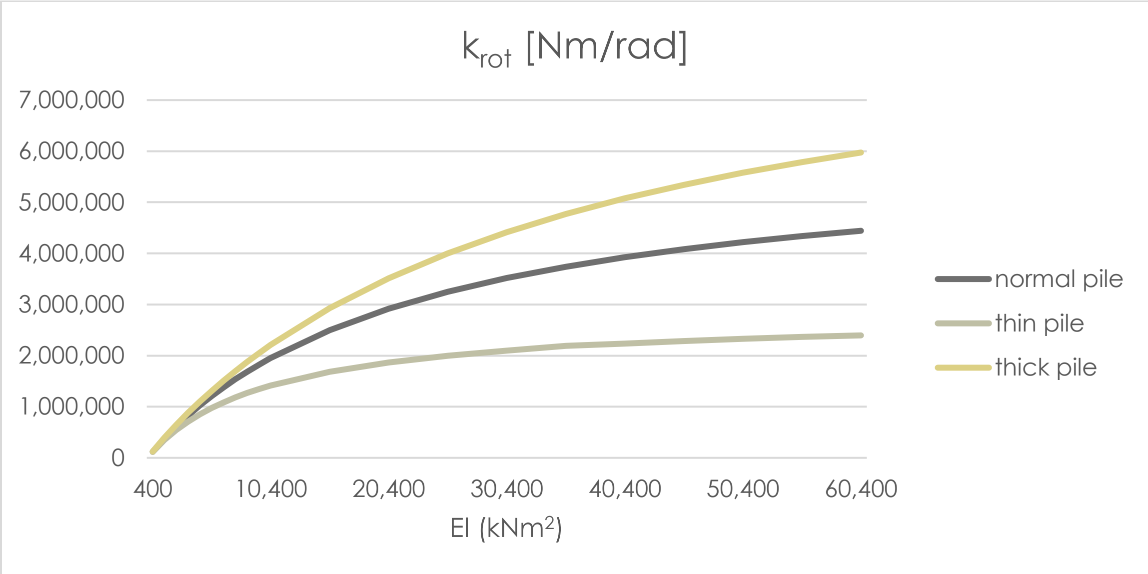


Figure K..1 Matrixframe results for stiffness parameters for various pile diameters

As is shown, the differences in stiffness are quite significant. The diameter of the pile and thus the spring constant of the soil turn out to be of large influence. Therefore, it is concluded that the resulting total pile stiffness for a width of 325 mm is only valid for this specific width. If a pile with a different width has to be designed, the values of the k_{trans}, $k_{coupled}$ and k_{rot} should be adapted to this width.

Appendix K.2: Sensitivity analysis of mass due to water storage

Possible rainwater storage is applied from rainwater harvesting. Moreover, some barrels are filled for water treatment. These applications will lead to extra weight of the total structure for some time. At the beginning of the typhoon season the rainwater storage will be quite empty. When a typhoon at the end of this season will hit the area, the mass of the structure will be larger than the 18,588 kg, which is used until now. The mass moment of inertia will also increase, though the extent of increase will depend on the position of the filled barrels.

Firstly, the extra mass will lead to a larger draft, which causes more waves to overtop the foundation. The significant wave height amounts 0.91 m, the freeboard circa 0.79 m. So the corresponding significant wave amplitude is 0.45 m, which is much lower than the freeboard. Assuming that 32 barrels of 200 L will be filled with water, the resulting extra mass is 6,400 kg. The freeboard will decrease to 0.68 m. This is still 0.23 m above the significant wave amplitude. Large increase of the number of overtopping waves is not expected.

The extra mass and inertia do change the input of the equations of motions as well. The extra mass amounts approximately 6,400 kg. The mass moment of inertia is depending on the position of the filled barrels. Placing the filled barrels underneath the house will lead to 17,597 kgm^2 extra inertia. Placing the filled barrels at the edges of the platform leads to 201,403 kgm^2 extra inertia, an increase of almost 150%. First the solutions of the free motion is analysed, after that the solution of the fixed motion will be investigated.

Free motion

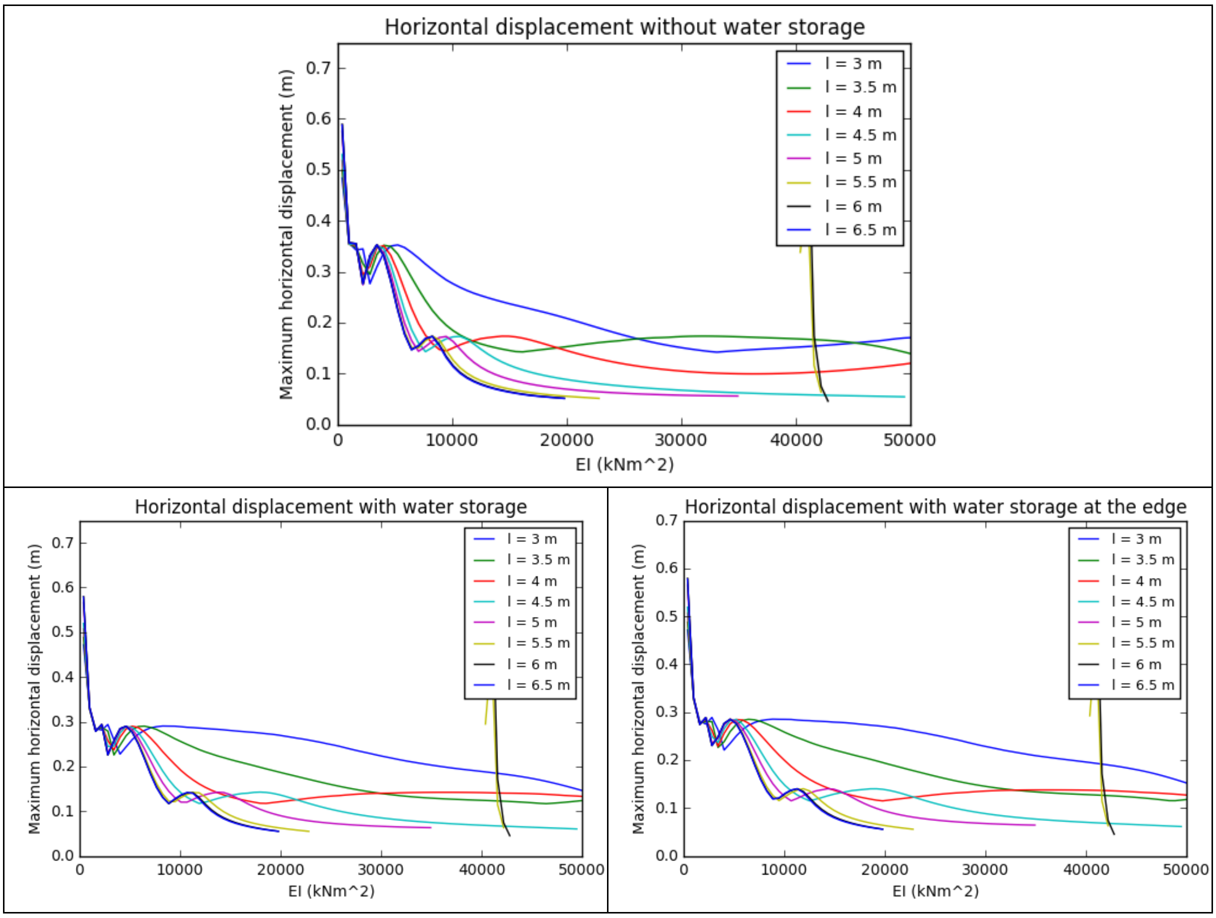


Figure K.2 Influence of water storage on horizontal motion in case of free motion

Figure K.2 shows the horizontal displacements for the different water storage options. For free motion the position of the water storage does not have influence on the horizontal motions. Comparison with the situation without water storage leads to the conclusion that especially the motions with shorter piles are increasing by the increased mass.

In free motion the rotation is not restricted by the piles. Therefore, the result is not a function of the length of the pile and the bending stiffness of the pile. Figure K.3 below shows this clearly.

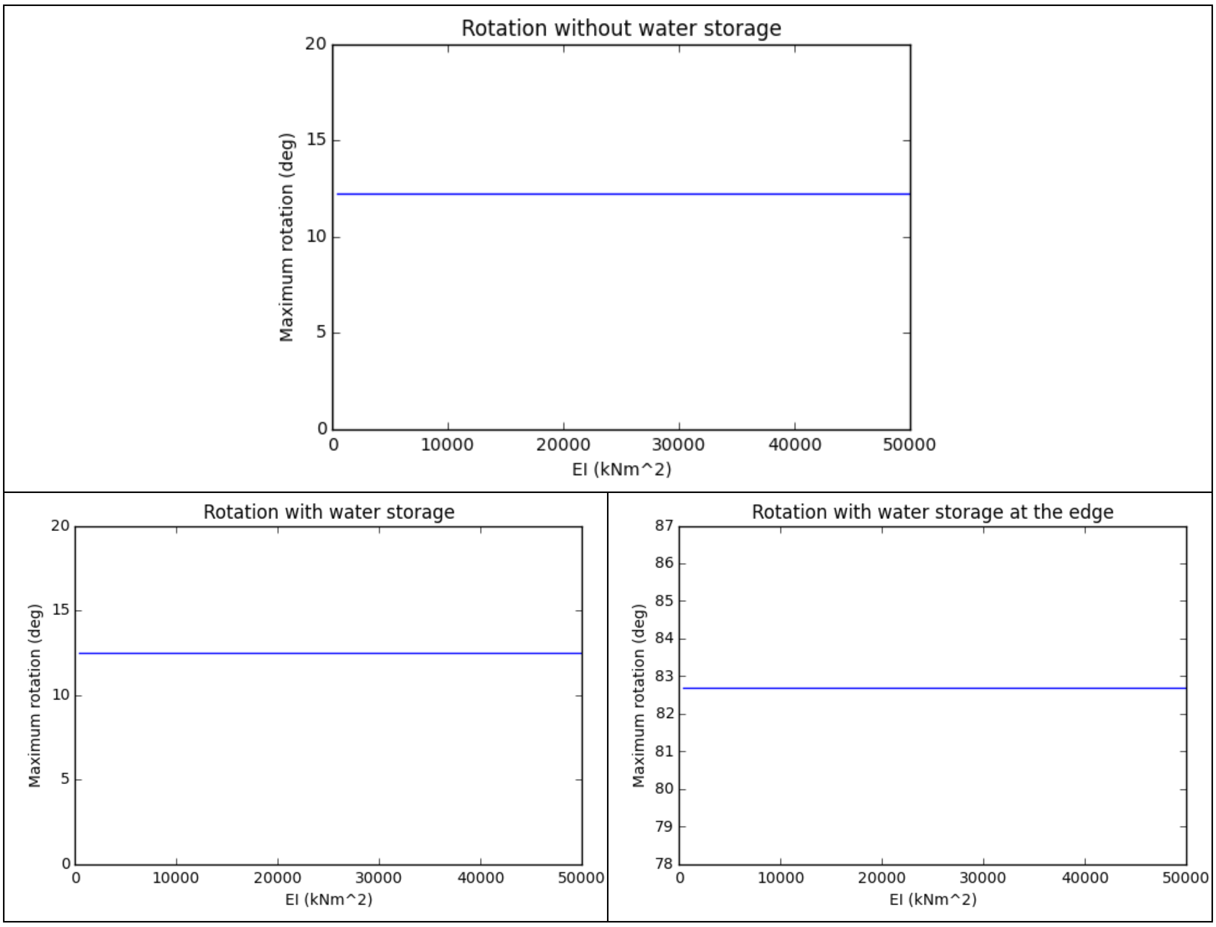


Figure K.3 Influence of water storage on rotation in case of fixed motion

Water storage in the middle of the platform does not have much influence on the maximum heeling angle. However, water storage at the edge of the platform in combination with free motion is strongly discouraged.

Fixed motion

For the fixed motion, the horizontal motions regardless of the applied the pile length will increase by the application of water storage. Again, water storage at the edge will enlarge the motion.

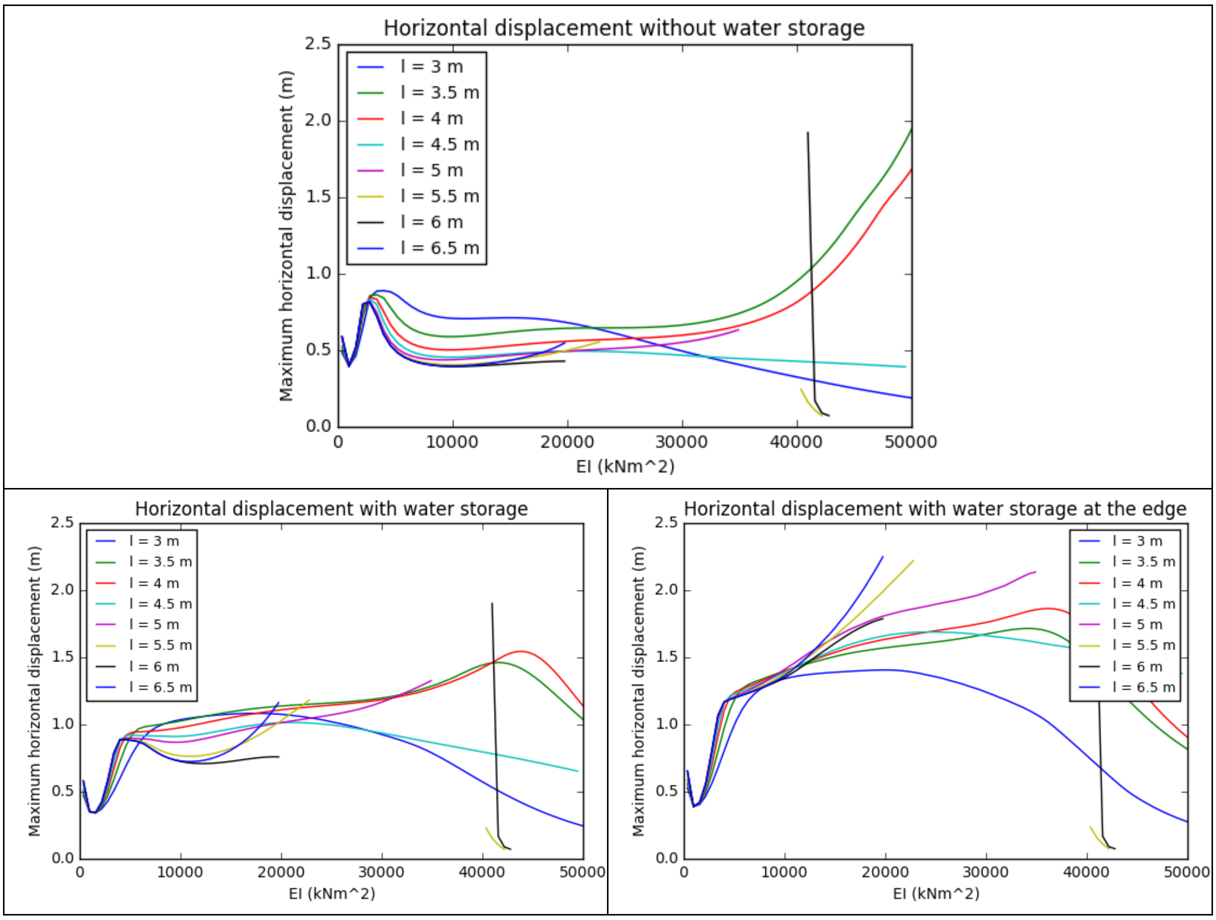
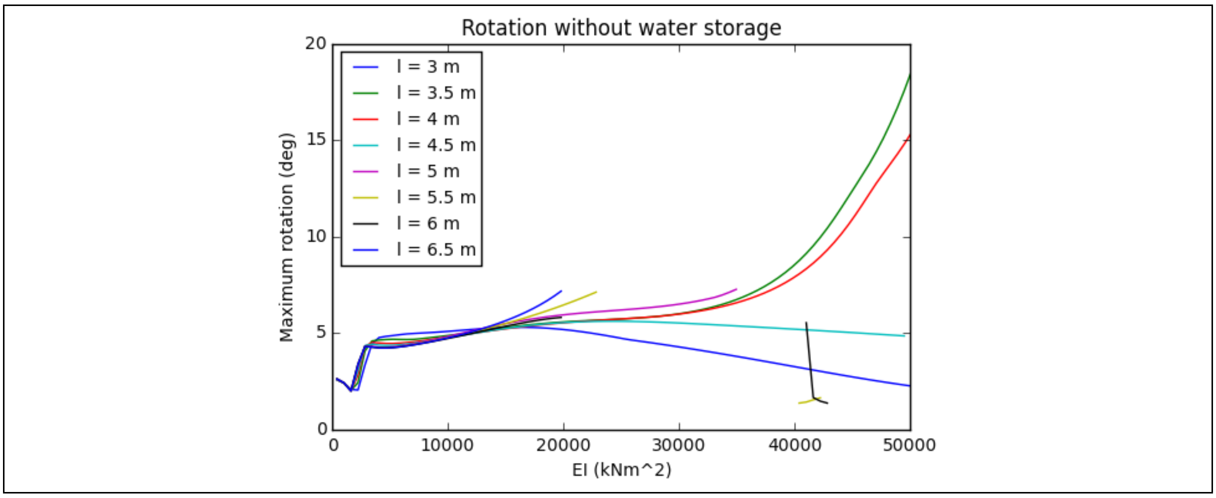


Figure K.4 Influence of water storage on horizontal motion in case of fixed motion

For the fixed motion the rotation is a function of the total pile stiffness. Figure K.5 shows the influence of water storage on the rotation. The effect is the same as for the horizontal motions in the fixed system. Regardless of the pile length, the rotation increases with water storage and water storage at the edge is worse.



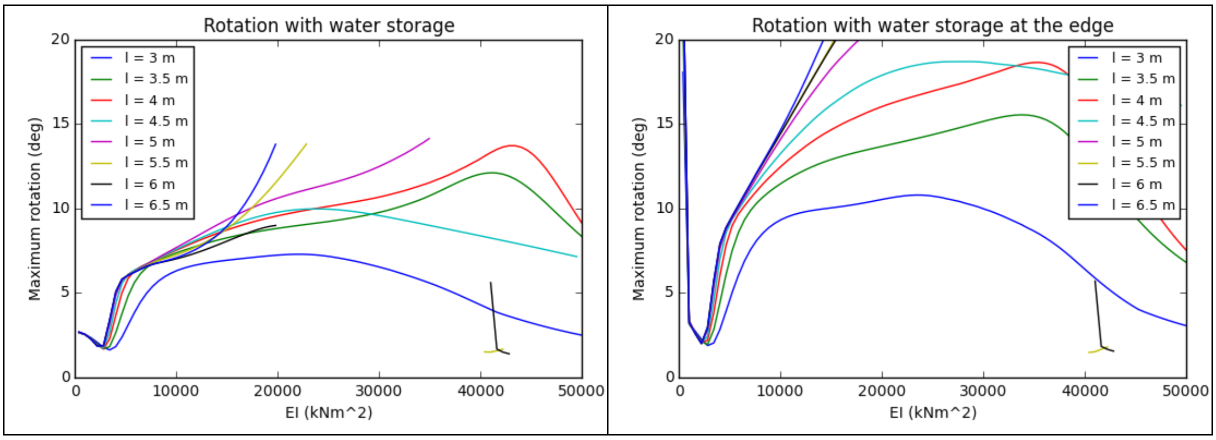


Figure K.5 Influence of water storage on rotation in case of fixed motion

From all the figures above it can be concluded that rain water storage at the edges is no option. The storage in the foundation underneath the house can be applied, but a consideration has to be made between storing much rain water and the disadvantageous effects on the horizontal motions and rotations.

Appendix L Results as function of the wave frequency

In this appendix the results of a pile with a length of four meter are shown. In contrast to the graphs of Figure 5.23, not only the maximum displacement and rotation for each bending stiffness is shown. For each bending stiffness the displacement and rotation for every wave frequency is shown.

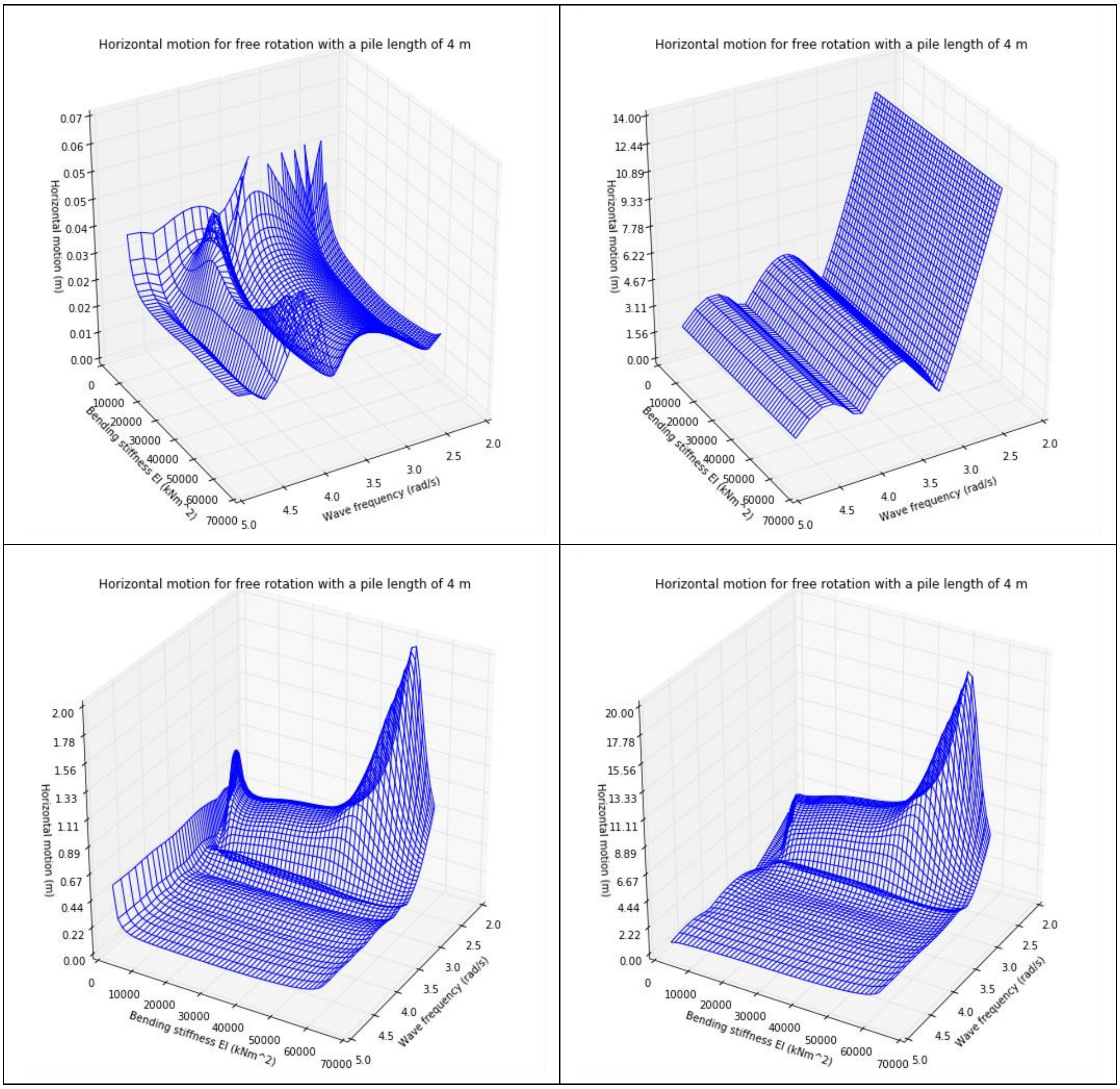


Figure L.1 Motion amplitude for all frequencies. Top graphs for free motion, bottom graphs for fixed motion.

In the upper left graph of Figure 5.23 it can be seen that for a pile length of 4 m, the horizontal displacement is large for a very large bending stiffness. In the upper left graph of figure L.1 this can be seen too. Surprisingly, this large displacement does not occur during waves with a frequency of 2.3 rad/s, which represent typhoon conditions. They occur during waves with a frequency of 3.5 rad/s. This is an undesirable situation, because people will live in the floating house while resonance occurs. The combination of a bending stiffness of 60,000 kN/m^2 and a pile length of 4 m is an undesirable combination. For the rotation in free motion it can be seen that the bending stiffness does not influence the rotation of the platform. The maximum rotation always occurs during typhoon conditions. The pattern looks very similar to the pattern of the excitation force in Figure 5.7 (Left) Dynamic horizontal and vertical force due to waves (Right) Turning moment due to waves

For the fixed motion resonance also occurs at a high bending stiffness. In contrast to the free motions, resonance now occurs during typhoon conditions. The graphs for horizontal motion and rotation look similar due to the coupling of the equations of motions.

Appendix M Project construction plan

Appendix M.1: Survey

Pilot project resources

In order to create a construction plan for the first pilot of the floating house, I am looking for some information on materials, labour and transport. Please answer the following questions with text or by checking the boxes that apply to the construction of a small house in Macabebe. Note: this is solely for university research and planning of the one pilot project in Macabebe, by filling in this survey no ties are made to the project.

<u>LOCATION OF THE PILOT HOUSE</u>

<u>INFORMATION ABOUT THE SURVEYEE:</u>

Type of job:………

Years of experience:……………………………………………………………………………………………………

Main location of projects:……………………………………………………………………………………………..

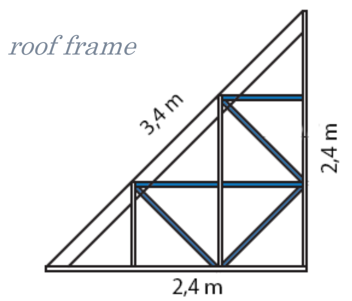
<u>MATERIALS AND EQUIPMENT</u>

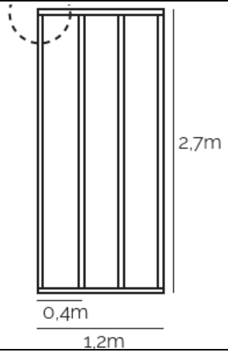
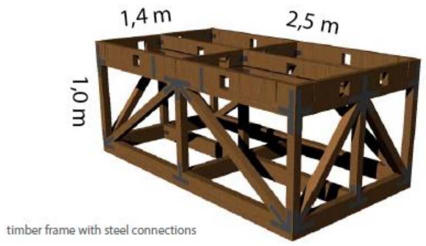
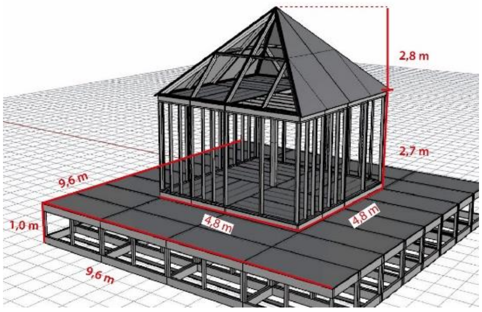
Survey page 2 of 3

1. What are the most common building materials used in Pampanga?
2. What is the best building material to use in Pampanga?
3. What is the worst building material to use in Pampanga?
4. Where do the materials come from?
   ☐ Macabebe ☐ Pampanga ☐ Luzon/Manila ☐ other part of Philippines ☐ abroad ☐ other: …
5. What type of equipment is used for construction in towns like Macabebe?
   - ☐ heavy machinery (excavators, pumping equipment)
   - ☐ light machinery (sanding, welding, drilling)
   - ☐ generator / pump (electricity and water)
   - ☐ containers (storage units, construction waste)
   - ☐ crane
   - ☐ scaffolding and weather covers
   - ☐ safety and support equipment (fences, rails, fall/traffic protection)
   - ☐ hand tools (hammer, shovel, saw and other)
6. Where does the necessary equipment come from?
   ☐ own equipment ☐ rent in Macabebe ☐ rent in Pampanga ☐ rent from far away ☐ Other: …
7. Where do you store the materials and equipment?
8. Where do you assemble the materials?
   ☐ factory ☐ own shop ☐ manufacturing site ☐ construction site ☐ Other: …

<u>LABOUR</u>

9. Where do construction workers for projects in Macabebe come from?
   ☐ Macabebe ☐ Pampanga ☐ Luzon/Manila ☐ Other part of Philippines ☐ Abroad ☐ Other: …
10. Are the construction workers unskilled / semi-skilled / skilled?
    ☐ unskilled ☐ semi-skilled ☐ skilled
11. What is the average cost in PHP for the construction worker?
    Cost per hour for an *unskilled* worker: ₱ ………..
    Cost per hour for a *semi-skilled* worker: ₱ ………..
    Cost per hour for a *skilled* worker: ₱ ………..
12. How do the workers get to the construction site?
    ☐ walk ☐ bike/tricycle ☐ own car ☐ jeepney/bus ☐ Other: …

13. How many hours will assembling this roof frame take for one person? material = Eucalyptus Grandis, construction method = standard		Approximately ……….. hours for the roof frame.

14. How long will assembling this wall frame take for one person? material = Eucalyptus Grandis, construction method = standard	*wall frame* 	Approximately ………… hours for the wall frame.
15. How long will assembling this foundation frame take? material = Eucalyptus Grandis and stainless steel Construction method = manual provided		Approximately …… days with …… construction workers.
16. Approximately how long will assembling this construction take? Material = Eucalyptus Grandis, stainless steel, screws/nails *walls*: wood fibre cement board, *floor*: OSB *roof*: corrugated bamboo sheets		Approximately …… days with …… construction workers.

TRANSPORTATION

17. What type of transport is commonly used for materials and equipment?
    - ☐ Heavy trucks (garbage truck, concrete transport truck, freight truck)
    - ☐ Medium trucks (flatbed truck, fire truck, van, jeepney)
    - ☐ Light trucks (pickup truck, car)
    - ☐ Small vehicle (tricycle, motorbike)
    - ☐ No vehicle (bike, carry trolley, by foot)
18. Where does the transport come from?
    ☐ own vehicle ☐ rented vehicle ☐ no vehicle ☐ Other: …
19. How do you get the materials and necessary equipment in Macabebe?
20. What does the transport from outside of Macabebe to Macabebe cost?
    ₱ ………... per delivery
21. How long does the transport from outside of Macabebe to Macabebe take?
    ………... days / ………... weeks / ………... months
22. How do you transport the material / assembled parts to the construction site?
23. What does the transport from Macabebe to the construction site cost?
    ₱ ………... per delivery
24. How long does the transport from Macabebe to the construction site take?

………... days / ………... weeks / ………... months

THANK YOU.

Appendix M.2: Sequence of Erection

Sequence of erection according to the 2016 Master thesis of J.W.J. van Schaik. Used as design where the project time and risk management plans are based on.

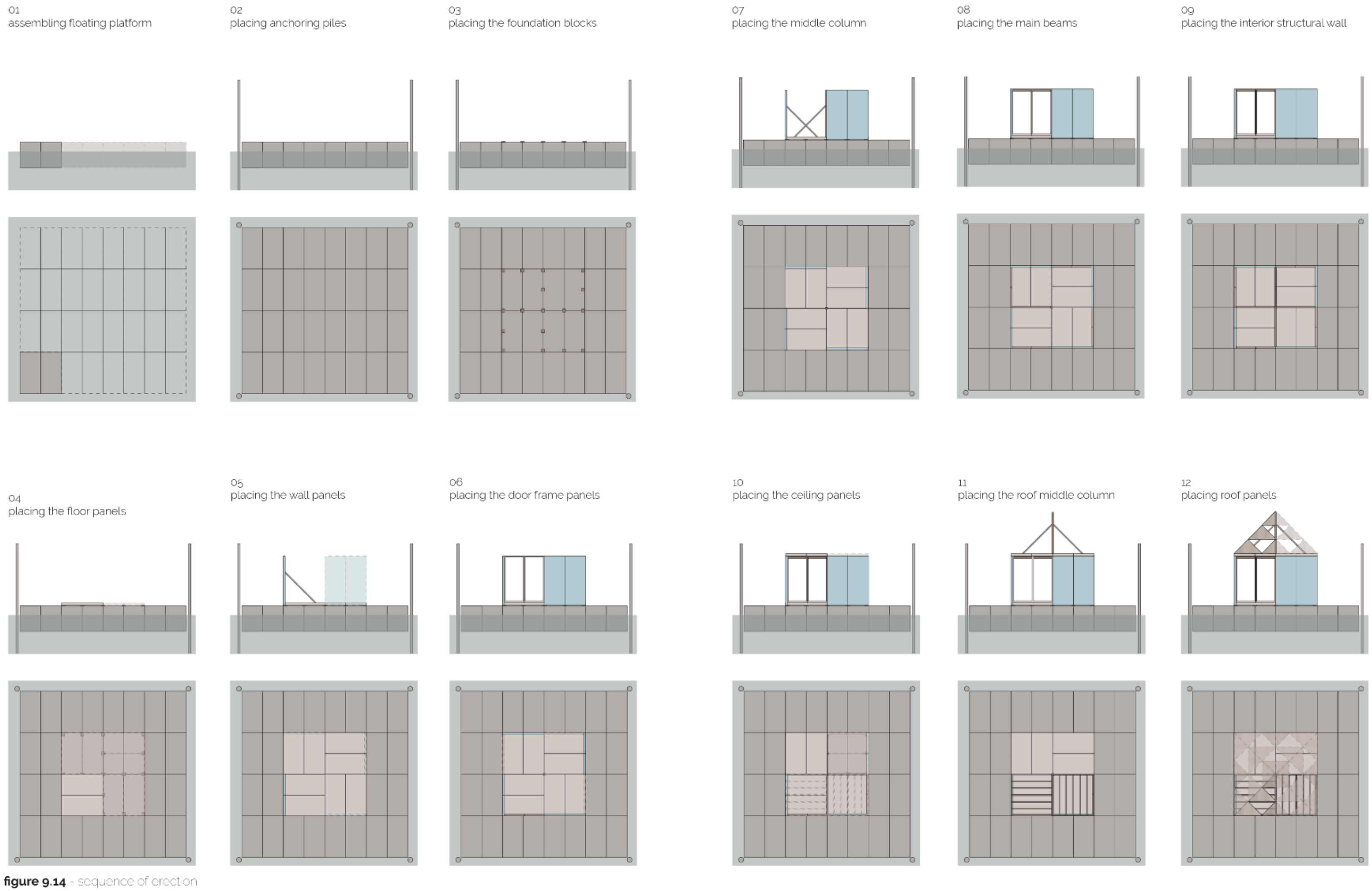


Figure M.1 Pilot design (Schaik, 2016)

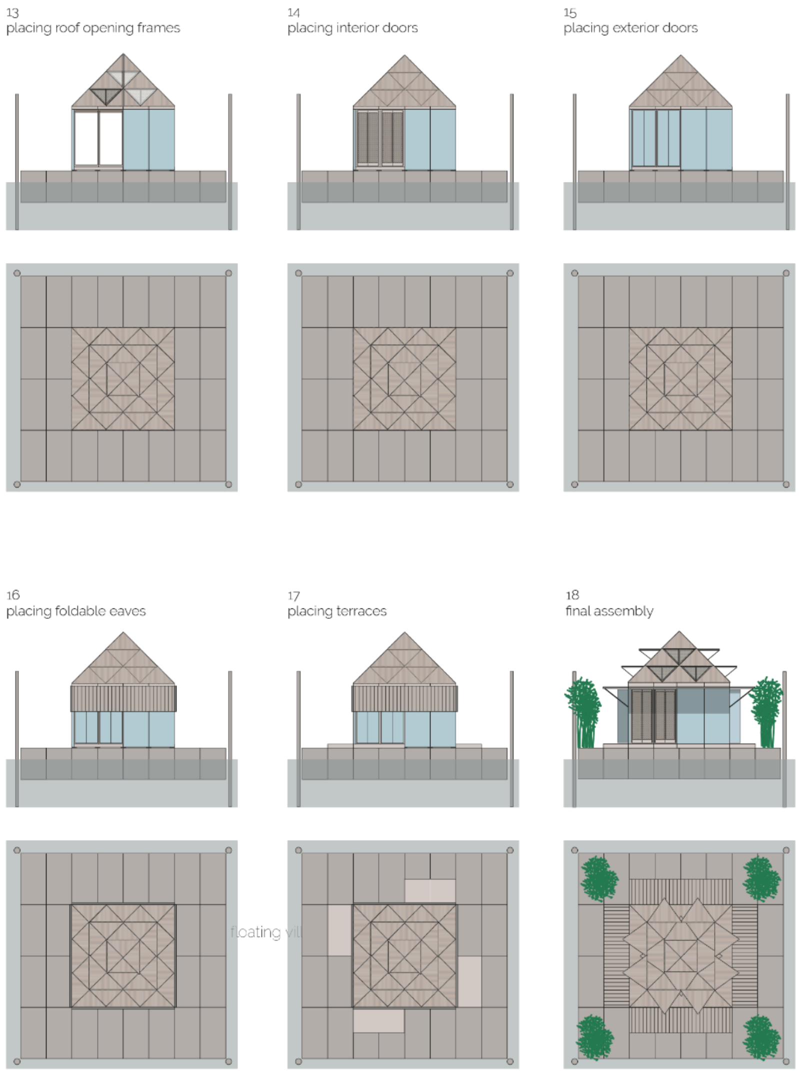


figure 9.14 - sequence of erection

Appendix M.3: Work breakdown structure

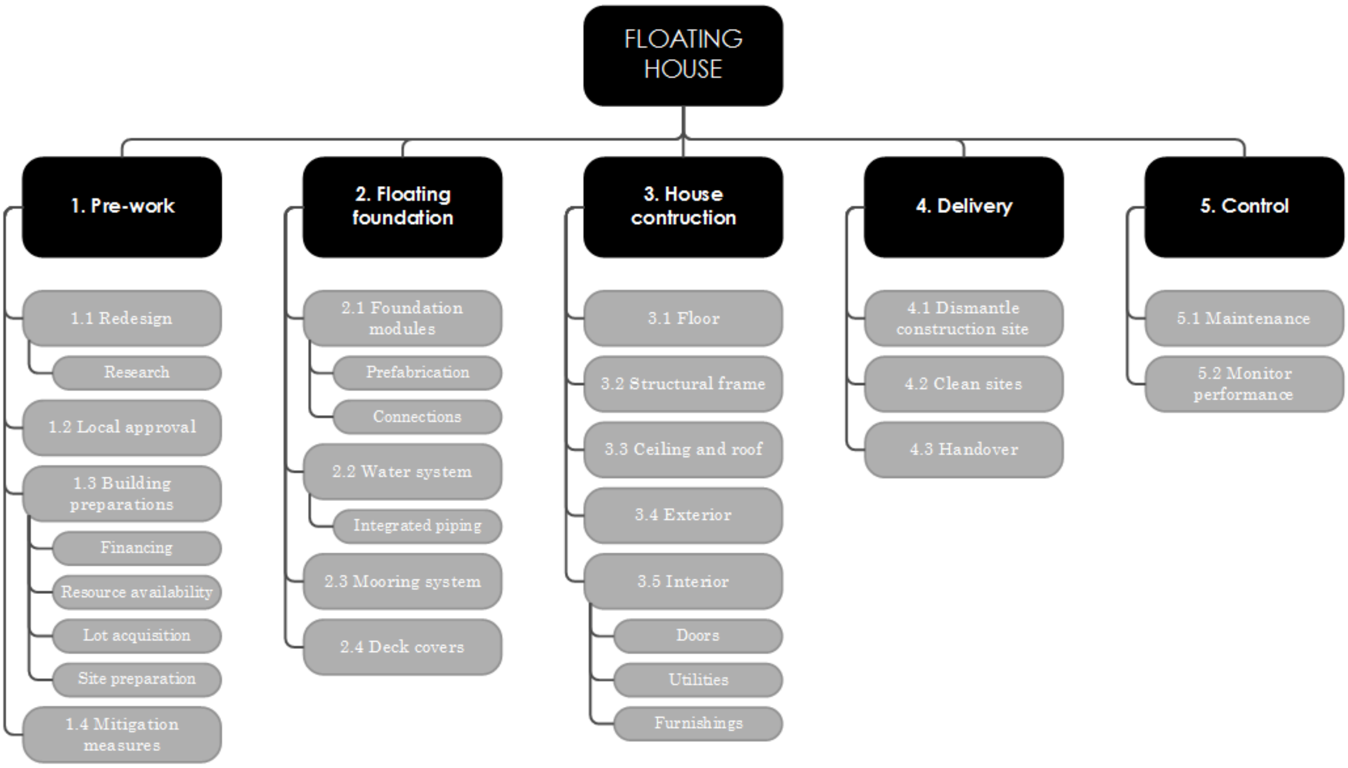


Figure M.2 Diagram of the Work Breakdown Structure (own illustration)

Table M.1 Construction process activities and their description

	activity	**description**
1	**Pre-work**	
1.1	Redesign	A more detailed design will be made by Finch Floating Homes.
	research	the multidisciplinary team provides advice and alternatives for the design of the floating home.
1.2	Local Approval	the local people and authorities should be informed about and supportive of the project well in advance of the start of construction. The project is realised in collaboration with the municipality, so not much action is required regarding their support.
	Obtain permits	permits should be obtained through the municipal engineering office. Documents required for construction should be ready at this point.
1.3	Building Preparations	
	Financing	the financing of the project needs to be completed to set the budget and cost estimation. The pilot project is financed through a crowdfund, which was accomplished prior to the redesign phase.
	Resource availability	resources are scarce and take time to be delivered to the pilot location. Materials and equipment should be ordered three weeks in advance to prevent delays.

	Lot acquisition	the project owner does not possess a piece of water for the floating house, the municipality has provided a location where the house can stand, so no acquisition is required
	Site preparation	the construction site needs to be prepared, roads needs to be cleared so transportation can pass through, workstations need to be set up at the construction site and pilot location.
1.4	Mitigation Measures	the project risks need to be mitigated and monitored to prevent delays and cost overruns.
2	**Floating foundation**	
2.1	Foundation modules	
	Prefabrication	the frame of the modules will be constructed from raw materials at the construction site, then transported to the pilot location for assembly.
	Connections	the modules have lower and upper connections to form the floating foundation and house connections to secure the house, these need to be added to the frame for assembly.
2.2	Water system	piping for sanitary and drink water will be placed in pre-made positions in the modules, located in the upper part of the foundation.
2.3	Mooring system	the foundation will be secured by a mooring system, the four piles will be constructed at the construction site and placed in the water at the pilot location. The foundation will be attached to the mooring piles.
2.5	Deck covers	the foundation will be finished with deck covers whereon can be walked.
3	**House construction**	
3.1	Floor	floor frames are constructed from raw materials at the construction site, then transported to and assembled at the pilot location.
3.2	Structural frame	
	Wall panels	wall panels are constructed from raw materials at the construction site, then transported to and assembled at the pilot location
	Open Wall panels	wall panels are constructed from raw materials at the construction site, then transported to and assembled at the pilot location
	Middle column	the middle column is sawn to the correct dimensions and secured into its final location in the floating house.
	Main beams	the main beams are sawn to the correct dimensions and connected to the middle column and wall panels in the outer part of the house.
3.3	Ceiling and roof	ceiling panels and roof frames are constructed from raw materials at the construction site, transported to the pilot location and placed on top of the main beams to finalise the house.
3.4	Exterior	
	Foldable eaves	foldable eaves are constructed from raw materials at the construction site, then transported to and assembled at the pilot location.
3.5	Interior	

	Doors	the doors are bought as a whole, delivered to the construction site and assembled in its correct place within the house frame.
	Doors closed - in panels	*The closed doors in the façade, bought as a whole.*
	Doors open - in panels	*The open doors in the façade, bought as a whole.*
	Doors - bathroom special	*The special bathroom doors, bought as a whole.*
	Utilities	utilities like water, gas, electricity and sewage are connected on the inside and outside of the house.
	Furnishings	final furnishings, such as the kitchen, bathroom tiles, the ladder, are placed in the house.
4	**Delivery**	
4.1	Dismantle construction site	the construction site is dismantled and organised, scaffolding and work stations are cleared out.
4.2	Clean sites	excess materials and the equipment is emptied out the construction and assembly site, waste is cleared out and the sites are cleanly left behind.
4.3	Handover	the house is presented to the municipality and the first volunteers move in.
5	**Control**	
5.1	Maintenance	the house and its materials need to be maintained to ensure prolonged quality and increase feasibility of success of the pilot project.
5.2	Monitor performance	the performance of the house should be monitored and documented for research purposes and to improve the design for succeeding floating houses.

Appendix M.4: Network diagram

The activity sequence in an activity-on-node network diagram, including narrative of special elements.

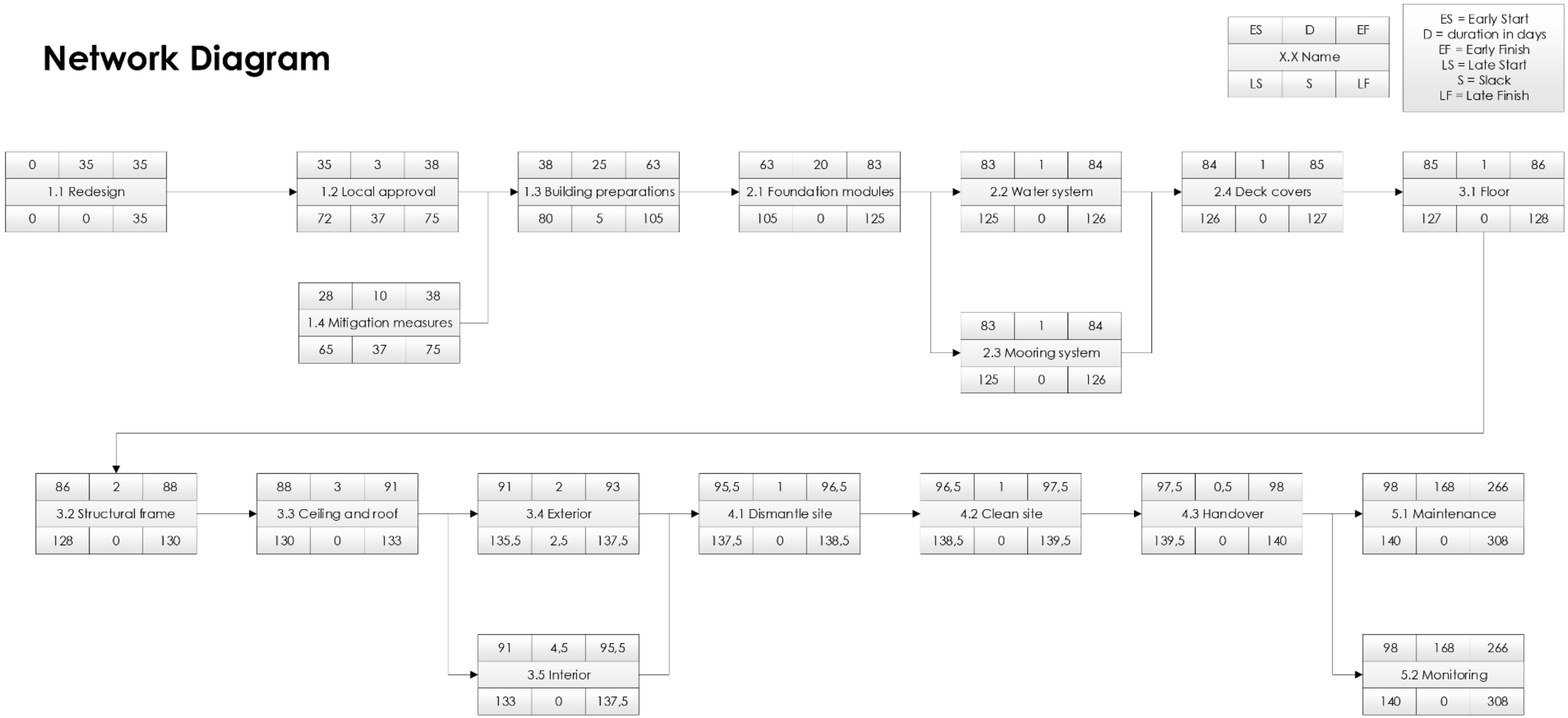


Figure M.3 Activity-On-Node-Diagram

Activity sequencing

As can be seen in the diagram, many activities are succeeding one another in this project, with two exceptions in the process where the activities can be constructed concurrently. The project starts with the redesign and is followed by a 7 week break. This is due to the fact that the research for the redesign is carried out by the multidisciplinary team in the months of February and March, and the construction will start when the project owner is at location, which is in the first week of June 2018. During the break, the technical drawings for construction should be made for the contractors to work with, and contracts with local contractors and suppliers should be established to prepare for the construction phase. Not having the drawings in full detail in time is a risk which can lead to problems, these are described in section Construction risks. The break can also be called slack, the allowable deviation between the activities that has been taken into account, which is 37 days. The activities can also immediately follow one another, if the project owner could be on site at that time or allows commencement without his presence.

As mentioned above, most activities are constructed in sequence, which means they have a finish-to-start relationship. The start of the succeeding activity can only commence when the preceding activity has been finished (Project Management Institute, 2004). This is most evident in the construction of the house itself, where the structural frame can only be built once the floor is finished, given that the wall frames are fastened onto the floor frames (Schaik J. , 2016). An exception to the start-to-finish relationships is the activity *1.4 mitigation* measures. This activity has a finish-to-finish relationship with activity *1.2 local approval*, since both activities should be completed before the building preparations start, however, the mitigation measures can be started whenever desirable as long as they are completed once the permits are approved and building preparations start. If needed, the mitigation measures can already start before completion of the redesign. This finish-to-finish relationship is established so the project owner knows what risks can be expected and the necessary measures can be taken well in advance to prevent delays and cost overruns by foreseen risks. Timely completion of the activity 1.4 should be controlled to keep the process in compliance with the schedule. Then between the local approval and the start of the building preparations is another 5 day slack to allow for a longer processing time for the permits and more risk monitoring. Experience with the Filipino culture has proven that activities such as applying for a building permit can take longer than the communicated processing time.

Once the project owner arrives at the project location in the first week of June, the building preparations can start. There is a small window in which the materials should be ordered, delivery of the materials is approximately three weeks, but the materials should not be ordered too much in advance, since they will have to be stored in a secure place and security will have to be hired to prevent the materials from getting stolen. When the preparations are complete and the materials are delivered, construction can start. As stated above, all frames will be prefabricated in a secure building and then transported to the pilot location. In this diagram, all activities are first prefabricated, then transported to the site and assembled before prefabrication of the next activity starts. Realistically, the prefabrication of the next activity can start as soon as the prefabrication of the first activity is complete and the frames are being transported. If closely managed, the duration between activities can be shortened through overlapping of construction. Note that extra construction workers will be needed in that case. The foundation modules form the base, it should be completed before it can be moored and the house can be placed on top. The foundation modules are the main work of the project. They will be constructed separately, including the connections to fasten the modules to one another and to fasted the house to the base. The modules will be placed and then connected in the water, after which the mooring system can be put in place and the water system can be laid in the upper part of the base. The mooring system and water system can be constructed simultaneously since they take place on different parts of the base. The construction workers can work aside each other for completion of the two systems. Once this is in place, the base can be covered with boards and the assembly of the house can start. The house will be constructed from the bottom to the top. The frames for the floor and wall panels will be prefabricated, including part of the cladding to provide stability. They are not completely clad to allow enough space for assembly. The frames are transported to the pilot location and then assembled, first the floor is fastened to the base, then the walls are fastened to the floor and the middle column and main beams are placed to complete the structural frame. After this, the ceiling and roof are placed on top, similarly prefabricated like the floor and wall panels.

Once the house is completed the interior and exterior can be assembled, which can be done concurrently because the activities do not require the workers to work in the same spot. While the eaves are constructed at the secure location, transported to the pilot location and assembled onto the exterior of the house, the doors, utilities and furnishings are placed in the interior of the house. The interior is defining the critical path, since it takes longer to construct than the exterior. The activity *3.4 exterior* has a slack of 2.5 days, the project owner can choose to construct the eaves immediately after completion of activity *3.3 ceiling and roof*, or he can wait 2.5 days. When using the slack of 2.5 days, the risk of delay arises. If the eaves are constructed immediately and there is a delay, it will not affect the total construction time. However, if the slack is used and construction of the eaves starts 2.5 days after completion of activity 3.3 and there is a delay, the entire project will be delay by the same amount of days as the delay of activity 3.4. It is advised to construct the eaves immediately after the completion of the ceiling and roof, to prevent delay of the entire project.

When the exterior and interior are completed, the construction is finished, and the sites can be dismantled, cleaned and the handover can take place. It is important that the sites are left clean and all waste is properly disposed of. Proper waste disposal is not a common practice in the Philippines, but due to its sustainable nature it is essential that the project sets an example by cleaning the sites completely and causing no pollution during construction. After handover, maintenance and monitoring have to be performed to ensure the quality of the house and to use its data and experience for further research.

Appendix M.5: Project schedule

A schedule for the pilot project has been developed, to give an estimation of when the project can be finished. In order to determine the end date, an estimate has been made for the duration of the activities. Usually, the project team member who is most familiar with the type and specifics of the activity, will estimate the duration. In the case of the pilot project, that would be a local contractor. However, no contractor is connected to the project yet and there are no usable drawings of the schematic design, so it is not feasible to acquire a contractor to estimate the duration. Use of historical information would have been possible if the pilot project was not of the innovative and "state of the art" nature that it is. The duration of every separate activity has been estimated based on the survey outcome, conversations with local experts and knowledge of the industry in the Netherlands.

Work breakdown structure Floating Homes Philippines

nr.	activity	most likely duration (days)	Predecessors					
1	**Pre-work**	**73**						
1.1	Redesign	35		-				
1.1.1	research	35		7	weeks	6	students	280 hours of work for MDP project
1.2	Local Approval	3	1.1	-				
1.2.1	Obtain permits	3		3	days	1	person	1 day for processing, 2 days for obtaining required documents
1.3	Building Preparations	25	1.1, 1.2	-				
1.3.1	Financing	-		*already available*				
1.3.2	Resource availability	15	1.3.1	3	weeks	1	person	15 days, order on time - delivered on required day. Limited availability
1.3.3	Lot acquisition	-	1.3.1	*already approved by mayor*				
1.3.4	Site preparation	10	1.3.1, 1.3.3	2	weeks	4	workers	10 days, clearance of roads, construction site, signage, set up of workstations
1.4	Mitigation Measures	10	1.1	1	unit	1	person	10 days, risk prevention, perform measures and inform relevant stakeholders
2	**Floating foundation**	**23**						
2.1	Foundation modules	20	1.1, 1.2, 1.3, 1.4	-				
2.1.1	Prefabrication	17,00		32	modules	6	workers	1 day per module per 3 workers + 1 day transportation
2.1.2	Connections	3,00	2.1.1	32	modules	8	workers	0,5 day to connect 4 modules, 4 workers + 1 day to install upper&houseconnections
2.2	Water system	1	2.1	1	unit	4	workers	1 day to lay piping in the pre-made positions on the modules
2.3	Mooring system	1	2.1	4	piles	4	workers	1 day for 4 piles with 4 workers.
2.5	Deck covers	1	2.1, 2.2, 2.4	176	covers	8	workers	3 covers per worker per hour
3	**House construction**	**12,50**						
3.1	Floor	1	2.1, 2.2, 2.3, 2.4, 2.5	8	panels	8	workers	0,5 day per panel per worker + 0,5 day transportation
3.2	Structural frame	2,00	3.1	-				1,5 day for frames + 0,5 day transportation
3.2.1	Wall panels	0,63		10	panels	6	workers	0,125 day per panel per 3 workers
3.2.2	Open Wall panels	0,50		8	panels	6	workers	0,125 day per panel per 3 workers
3.2.3	Middle column	0,13		1	column	4	workers	0,125 day per column per 4 workers
3.2.4	Main beams	0,25		4	beams	4	workers	0,5 beam per worker per hour (1 beam, 1 hour, 2 workers)
3.3	Ceiling and roof	3	3.2	8	panels	6	workers	0,5 day per panel per worker + 0,5 day for 4 ceiling panels + 0,5 day transportation
3.4	Exterior	2	3.1, 3.2, 3.3, 3.4	-				
3.4.1	Foldable eaves	2,00		4	eaves	3	workers	0,5 day per eave per 3 workers
3.5	Interior	4,50	3.1, 3.2, 3.3, 3.4	-				
3.5.1	Doors	2,50		-				
3.5.1	*Doors closed - in panels*	*1,00*		8	doors	3	workers	0,125 day per door per 3 workers
3.5.1	*Doors open - in panels*	*1,00*		8	doors	3	workers	0,125 day per door per 3 workers
3.5.1	*Doors - bathroom special*	*0,50*		2	doors	3	workers	0,25 day per door per 3 workers
3.5.2	Utilities	1,0		1	unit	2	workers	1 day connecting water, gas electricity to the house
3.5.3	Furnishings	1,0	3.6.1, 3.6.2, 3.6.3	1	unit	3	workers	1 day, kitchen, bathroom (tiles!), ladder etc
4	**Delivery**	**2,5**						
4.1	Dismantle construction site	1,0	3.1, 3.2, 3.3, 3.4, 3.5, 3.6	1	unit	8	workers	1 day
4.2	Clean sites	1,0	4.1	1	unit	8	workers	1 day
4.3	Handover	0,5	4.2					
5	**Control**	**168**						
5.1	Maintenance	168	4.3	1	unit	1	person	168 days, 6 month maintenance
5.2	Monitor performance	168	4.3	1	unit	1	person	168 days, 6 month monitoring

	Total duration	
1	pre-work	73
2, 3, 4	construction, delivery	38
5	control	168

Figure M.4 Elaborated Work Breakdown Structure

The project schedule depicted in a Gantt Chart.

ID		Element	Task Mode	Task Name	Duration	Start	Finish	Predecess	Qtr 1, 2018 Jan Feb Mar
1		1.1		Redesign	35 days	Mon 12-2-18	Wed 4-4-18		Redesign
2		1.2		Local approval	3 days	Wed 23-5-18	Fri 25-5-18	1	
3		1.3		Building preparations	25 days?	Mon 4-6-18	Mon 9-7-18	2	
4		1.4		Mitigation measures	10 days	Mon 14-5-18	Fri 25-5-18	2FF	Mitiga
5		2.1		Foundation modules	20 days	Tue 10-7-18	Mon 6-8-18	3	
6		2.2		Water system	1 day	Tue 7-8-18	Tue 7-8-18	5	
7		2.3		Mooring system	1 day	Tue 7-8-18	Tue 7-8-18	5	
8		2.4		Deck covers	1 day	Wed 8-8-18	Wed 8-8-18	7	
9		3.1		Floor	1 day	Thu 9-8-18	Thu 9-8-18	8	
10		3.2		Structural frame	2 days	Fri 10-8-18	Mon 13-8-18	9	
11		3.3		Ceiling and roof	3 days	Tue 14-8-18	Thu 16-8-18	10	
12		3.4		Exterior	2 days	Fri 17-8-18	Mon 20-8-18	11	
13		3.5		Interior	4,5 days	Fri 17-8-18	Fri 24-8-18	11	
14		4.1		Dismantle construction site	1 day	Fri 24-8-18	Tue 28-8-18	13	
15		4.2		Clean sites	1 day	Tue 28-8-18	Wed 29-8-18	14	
16		4.3		Handover	0 days	Wed 29-8-18	Wed 29-8-18	15	
17		5.1		Maintenance	168 days	Wed 29-8-18	Wed 24-4-19	16	
18		5.2		Monitor	168 days	Wed 29-8-18	Wed 24-4-19	16	

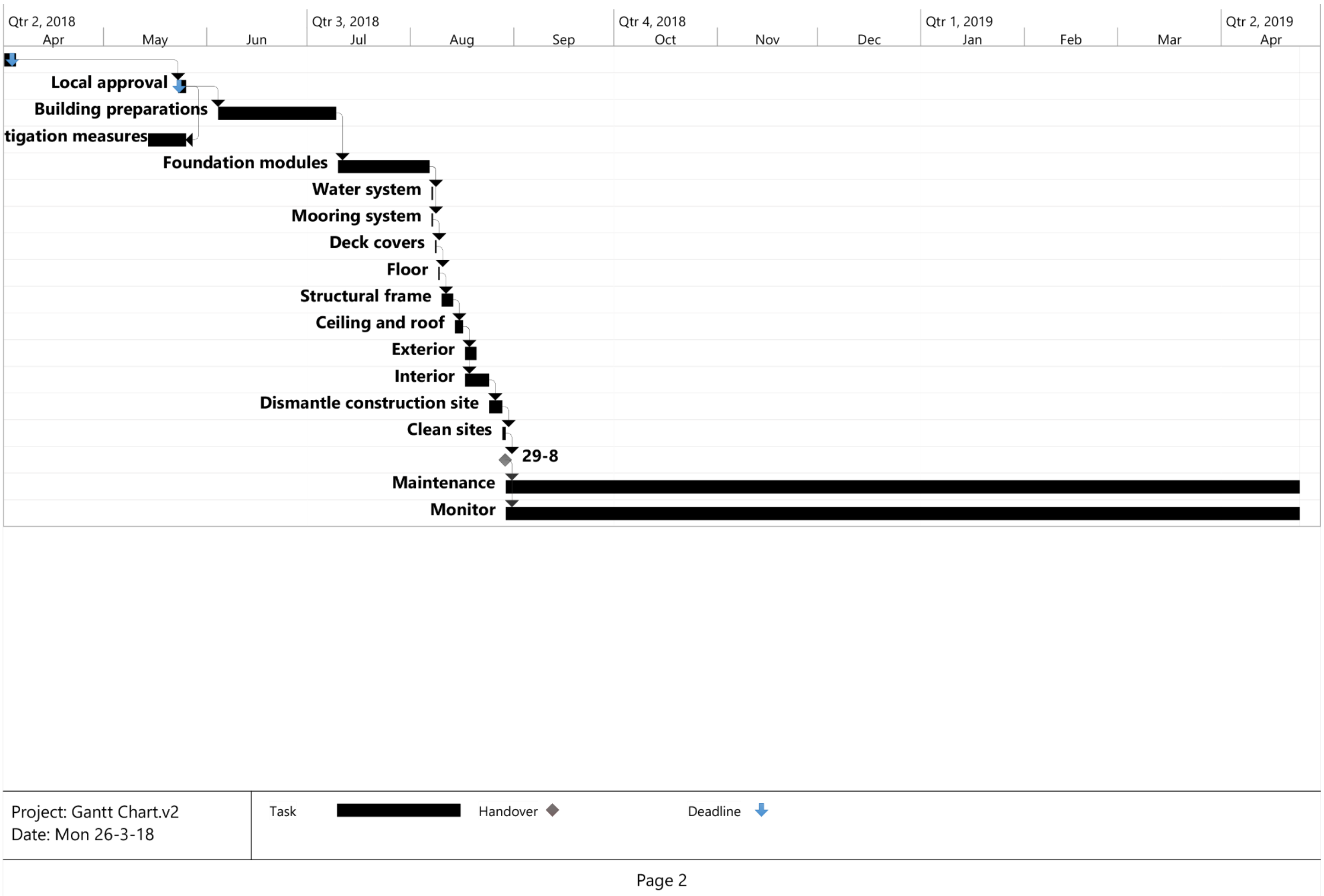


Figure M.5 Pilot project construction schedule

Appendix N Risk analysis

In this appendix the full risk analysis is shown. A division is made in the different phases of risk management. Namely, identification, analysis, and response to the risk.

Identification

To identify the risks, the cause of the risk should be identified first. The risk cause is an uncertain factor that can impact the outcome of the project (Nicholas & Steyn, 2012). Once the cause is known, the risk event and the consequence can be identified to describe the full risk. In order to identify the risks for the construction process of the floating home, the work breakdown structure described in section 6.2.1 has been analysed on possible risks for every of its components. The network diagram has been used to identify the risks related to merge bias. As can been seen from the network diagram, there are some components of the construction process which are executed concurrently. These components merge together at one point and are followed by the next component, for example the components 2.2 water system, 2.3 mooring system and 2.4 house connections all need to be completed before the construction of component 2.5 deck covers can start. This merge point can be the source of risks. Thirdly, a brainstorm has been held with the multidisciplinary team to identify category-specific risks. The elements described above have been analysed on both internal and external risks. The internal risks commence inside the project and can be controlled to some extent. Whereas the external risks have to do with factors that lie outside the project and a project manager has little to no control over these risks (Nicholas & Steyn, 2012). The risks that have been identified were documented in the risk register in several categories. For the categorisation a PESTLE framework has been used, to ensure that risks were checked in different angles and the whole environment of the project had been taken into account. The categories in the PETSLE framework are; Political, Economic, Social, Technical, Legal and Environmental (PESTLE analysis, 2015). Added to the risks in these categories are the categories Issue, Black Swan and Opportunity. The issue is a fact that can cause problems within the project. If an issue remains unresolved throughout the project, it can delay the project and it grows more complicated and becomes harder to deal with (Nicholas & Steyn, 2012). The Black Swan is an event which is extremely rare to occur, carries enormous impact and is only predictable in retrospect (Taleb, 2007). Risks, issues and Black Swan events are examples of threats. An opportunity is an upside risk, an event that might happen and if it does, the outcome has a positive impact on the project.

Analysis

There are several aspects of importance prior to the start of the analysis. These aspects, such as project status, project type, data precision, scales and assumptions, are the input for the qualitative risk analysis and will influence the analysis (Project Management Institute, 2004). The ***project status*** determines the likeliness of whether the risks can be identified. This project is in its early stages; the research and design are not complete yet, there are no contracts between the project owner and any contractors or suppliers and the construction process is not fully determined. This results in a higher uncertainty of the risks. For the early stage that the project is in, the most important risks have been identified and assessed. The further the project develops, these risks should be monitored and new risks will be discovered and assessed. Adding to the uncertainty of the risks is the ***project type***. The floating house project is an innovative project, providing new solutions for problems in a third world country like the Philippines. Construction technology in project location is not yet developed to the level of the Dutch standard, however, the floating house is designed according to Dutch knowledge. Being first of its kind, using foreign knowledge, the probability and occurrence of the risks are harder to predict. This uncertainty described above contributes in the ***data precision***. Combined with the fact that little data is available, the sources and data that were found, cannot be blindly relied upon. The sources for the input of the analysis are the local people. The knowledge required to execute the analysis is obtained through a survey and conversations with local contractors, engineers and architects. The risk analysis is an estimation based on these sources and should be monitored and adjusted as the project develops.

In order to assess the risk, scales had to be set. The risks are assessed on probability of occurrence and severity of the impact, both with a qualitative rating. The range of rating is as shown in Table N.1.

Table N.1 Scales of probability and impact

Probability	very low	low	medium	high	very high
Impact	very low	low	medium	high	very high

The qualitative rating in the form of a five point scale has been chosen due to the fact that the available data is not sufficient enough to give precisely calculated ratings to the risk probability and impact. In this phase of the project, it is important identify the most important risks in order to create a mitigation plan. By giving the probability and impact of the risks a rating from very low to very high in the risk register, an overview is created and the risk who have the most influence on the project can be determined. Normally, the assessment depends on the expertise and culture of the assessor, it can never be completely rational. Thus it is advised to base the assessment upon the opinions of many experts in a wide range of disciplines (Nicholas & Steyn, 2012). However, for this project, that is not possible. As mentioned above, the risks have been assessed based on the knowledge gained from the survey and conversations with local experts. It was not possible to let these experts assess the risks, since they do not know the project well enough. It is advised to do a reassessment by other experts within the project in addition to reassessments when the project is further developed. The output of the analysis is the risk register with a list of all the risks including the assessment on the probability and impact. Based on this, the risk response can be planned.

Response

For the response planning, the risk register is supplemented with the risk owner, response action including implementation advice, and a post-response assessment. In this case, the responsibility of many risks lie with one person, since the organisation behind the project is small. The different roles of project manager, PR-manager, marketing, designing and more, belong to only a few people. The project owner carries the most responsibility, this person makes the most decisions and fully dedicates his time to the project. Others involved are the organisation Finch Floating Homes, local contractors and suppliers, the local municipalities and people with interest in the project. Apart from being responsible for risks, these actors have some other responsibilities, see Table N.2.

Table N.2 Project team and their responsibilities

Project team member	Responsibility
Project owner	• project management • design • analyses • technical expertise • asset management • contract management
Finch Floating Homes	• business plan • design • social network • marketing • financial management
Local contractors and suppliers	• building the pilot • providing materials and equipment • hiring construction workers
Local municipalities	• providing data and information • providing the pilot location
People with interest	• financing (crowdfund)

These team members can be assigned to take responsibility for the project risks. By assigning a team member to the risk and risk response, the risks can be monitored, and responses can be executes. If this would not be done, the outcome of the project can be jeopardised. Despite being the risk owner, the team member can delegate the implementation of the risk response to another team member or an external party.

The risk response can be done with different strategies, depending on whether it is a risk or an opportunity. The most suitable response should be chosen to deal with the risk. If the response is successful, it will change the course of the risk and its exposure will be eliminated. However, eliminating all threats is not possible, they should be documented after identification, so the project team can be aware of the existing threats (Minnesota Department of Transportation). The response strategies are described in Table N.3 (Project Management Institute, 2004).

Table N.3 Risk response strategies

Threats		**Opportunities**	
Avoid	Avoid the risk by changing the project plan, the cause will be eliminated, or the project will be protected from the impact.	Exploit	Exploit the opportunity by eliminating uncertainties. The probability increases, and realisation of the opportunity can be ensured.
Transfer	Transfer the risk by shifting responsibility and consequence of the risk to a third party. The risk will still exist, but the ownership lies with another party.	Share	Share the opportunity by shifting responsibility to a third party which is able to increase the probability and maximise the benefits of impact. Benefits are shared between the parties.
Reduce	Reduce the probability and / or impact of the risk by taking action in an early stage of the project. It is more effective than repairing the damage after impact. Costs of mitigating the risk versus the likely probability and impact should be taken into account	Enhance	Enhance the probability and / or impact of the opportunity by in an early stage of the project. With a higher probability and higher impact, the benefits will be greater. This is similar to the exploit strategy if the probability can be increased to 100 percent.
Accept	Accept the risk by not changing the project plan or dealing with the risk in advance. Accepting can be active or passive. Active acceptance includes the development of a contingency plan for if the risk occurs. Passive acceptance means doing nothing and only dealing with the consequences after the risk has occurred.	Accept	Accept the opportunity by not changing the project plan or dealing with the benefits in advance. The probability and / or impact of the upside risk are not increased, but the benefits are taken as is, if the upside risk occurs.

Table N.1 The Risk Register including risks, consequences, risk owner and risk response.

		Risk Description			Pre-response Assessment		Response			Post-Response Assessment**		
Nr.	**Category**	**Cause**	**Risk Event**	**Consequence**	**Probability***	**Impact***	**Risk owner**	**Risk Response**	**Response action implementation**	**Probability***	**Impact***	**Secondary risk**
1	POLITICAL	The higher authorities have no knowledge of the project	higher authorities might not approve of the project	the project will be cancelled	low	high	project owner	transfer	The municipality has more leverage with higher authorities, through agreements and networking the probability and impact can be reduced.	very low	medium	
2		the current mayor is soon to end her period as mayor of Macabebe	a new mayor might disapprove of the project	the project will be cancelled	low	high	project owner	transfer	the counsellors fully support the project, they can convince a new mayor of the benefits of the project.	very low	high	the counsellors might be convinced by the mayor to stop the project.
3	ECONOMIC	there is limited information available on the material and construction costs	the total costs might get higher than the budget	the project will be delayed	low	medium	project owner / financial manager	reduce	by conducting extensive research or hiring a local cost consultant a better cost estimation can be made to ensure the total costs stay within the budget.	very low	medium	
4		the price of land is raising rapidly	the municipality sees different opportunities for the land purpose of the pilot location	there is no location for the pilot project	high	medium	project owner	accept - active	A contingency plan should be made; if the pilot cannot be built in Macabebe. another location can be found in surrounding municipalities, which have expressed great interest in the project.	high	low	the locals might protests if the pilot suddenly changes locations.
5		the contractors have contracts with specific suppliers	a supplier might run out of business close to the start of construction	the project will be delayed	low	medium	project owner / contract manager	transfer	by choosing the right contract, the contractor is responsible for the subcontractors and supplier he hires. E.g. a Fixed Price contract will make the contractor responsible for this risk.	very low	low	
6	SOCIAL	local people do not trust the materials	the locals lose faith in the project	the project will fail	medium	high	project owner / marketing	reduce	Ensure good quality and suitable materials for the specific situation to prove success of the project. A marketing strategy could be created.	low	medium	
7		several Filipino volunteers will live in the house to test it	monitoring is not according to standard	the data is unusable for further research	high	medium	project owner	reduce	construct a meeting with the volunteers and brief them about the responsibilities of living in the pilot house.	low	medium	
8		proper maintenance is not a common practice in the Philippines	materials or components of the house might deteriorate faster than expected	the project will fail after a certain period of time	high	high	project owner	reduce	construct a meeting with the volunteers and brief them about the responsibilities of living in the pilot house. Monitor the maintenance extensively.	low	medium	the locals might not volunteer if they think it is too much work to live in the pilot house.
9	TECHNICAL	little known specifications about the materials in the local environment	the materials might not comply with the requirements of the floating house	the project will fail after a certain period of time	medium	high	designers	reduce	use materials of which the specifications are known or test the new materials to ensure good quality of the floating house.	low	medium	
10		timber materials are not readily available in the Philippines	the materials could not be delivered to the site in time	the project will be delayed	high	medium	supplier	reduce	order the materials in advance with enough contingency allowance and store them in a secure site.	medium	medium	
11		wood is an unfavourable, expensive and not sustainable material	a different material might be chosen for the pilot	Finch Buildings does not approve of the design	medium	high	designers	avoid	the pilot house is a test, the desired materials which are in line with the Finch Buildings Principles, can be chosen to avoid conflict.	very low	medium	the materials are not right for the floating house, the pilot will fail after a certain period of time
12		construction workers need to be hired on single project basis	labour might not be available at the desired time	the project will be delayed	very low	medium	constructor	accept - passive	the probability is very low due to abundant availability of construction workers in the region of the pilot location.	very low	medium	
13		construction workers are unfamiliar with the construction methods	the construction workers might not carry out the work as designed	the house will not be as designed and calculated	medium	medium	contractor	reduce	explain the construction method to the main construction workers. Supervise the workers and helpers during construction.	very low	medium	
14		prefabrication is an uncommon construction method	the construction workers might be slowed down by the new technique	the project will be delayed	low	medium	contractor	reduce	explain the construction method to the main construction workers. Supervise the workers and helpers during construction.	very low	low	
15		the project consists of many interrelated components	one of these components might be absent or delayed	the project will be delayed	medium	medium	contractor	reduce	order the materials in advance with enough contingency allowance and store them in a secure site.	low	medium	the materials might get stolen from the site where they are stored.
16		many components are scheduled to be constructed sequentially	one or more components might be delayed	the project will be delayed	medium	medium	contractor	reduce	With the use of prefabrication the on-site construction works can be reduced, there is more contingency allowance between components.	low	low	prefabrication of the components might cause delay due to the innovative technique for the locals.
17		some components are scheduled to be constructed concurrently	it might not be possible to construct these components concurrently	the project will be delayed	low	medium	contractor	accept - active	this concerns a few components which are likely possible to be constructed concurrently. A prefabrication plan can be made to ease the on-site construction works.	low	low	prefabrication of the components might cause delay due to the innovative technique for the locals.

18		good building equipment is not always easily obtainable	the required building equipment cannot be available at the construction site	the project will be delayed	medium	medium	contractor	transfer	hire subcontractors who have the equipment readily available. Establish the correct contracts in time.	low	medium	the subcontractors might need to be monitored, causing more work and possibly a delay
19		the design is not drawn in full detail	the design might not be producible as desired	the pilot house will be different from the intended design	low	low	designers	reduce	hire more designers to ensure there is a full set of construction documents prior to the start of construction.	very low	very low	
20		the multidisciplinary research will change several parts of the design	the research might impose significant changes to the design	the design needs to be altered in a short period of time	low	medium	designers	avoid	the new designs should only be implemented for the pilot if the design changes are feasible for the pilot house. Any other design changes should be implemented in succeeding houses.	very low	low	
21	LEGAL	the Philippine building code, laws and required permits are unclear documents and not strictly followed by the locals	the project might not comply to the current laws and regulations	the project will be cancelled	low	high	Finch Floating Homes	reduce	hire experts to research the laws and regulations regarding the floating house.	very low	medium	
22		materials get stolen from construction sites	construction materials might get stolen from the construction site	the project will be delayed	high	medium	contractor	reduce	store the materials in a secure site and hire security to protect the site and materials which cannot be stored in a secure site.	low	medium	
23	ENVIRONMENTAL	typhoons occur during the rainy season	a typhoon might occur during the construction period	the project will be destroyed	low	very high	project owner	accept - active	the project location is less prone to typhoons, even during the rainy season. The chances on a devastating typhoon are low enough to accept. A contingency plan can be made on what to do with the materials during a typhoon.	low	very high	
24		floods occur during the rainy season	a flood might occur on the construction site, during the construction period	the project will be destroyed	very high	very high	project owner	avoid	lots of floods occur at the project location during the rainy season. Construction should take place during the dry season.	very low	very high	
25		floods occur during the rainy season	transportation of building materials is impossible	the project will be delayed	very high	medium	contractor	avoid	lots of floods occur at the project location during the rainy season. Construction should take place during the dry season.	very low	medium	
26	BLACK SWAN environmental	Earthquakes occur in Pampanga, the project location	the project location and surroundings might be destroyed beyond repair	the project will be cancelled	very low	very high	project owner	accept - passive	the probability of an earthquake occurring in the project area is very low. The risk can be accepted.	very low	very high	
27	BLACK SWAN economic	exchange rates between Euro and Philippine Peso fluctuates	the value of the Euro might drop significantly, while the value of the Philippine Peso rises significantly	there will not be enough money to finance the pilot project	very low	very high	project owner / financial manager	accept - passive	the probability of a significant value change of both the Euro and the Philippine Peso are very low. The risk can be accepted.	very low	very high	
28	ISSUE	the design of Finch Floating Homes has to comply with the Finch Principles of the company Finch Buildings		the design is not the most optimal for the local situation		Medium	Finch Floating Homes	reduce	different alternatives should be analysed to find the most optimal design which complies with the Finch Principles as well as offers the best solution for the local circumstances.		low	
29	OPPORTUNITY political	the local authorities support the project	other municipalities might want the next house to be built in their town	there will be an abundance of new locations for succeeding houses to choose from	medium	medium	Finch Floating Homes	exploit	agreements can be made with surrounding municipalities to build succeeding pilots for the project, in order to expand and grow the support of the locals	high	high	
30	OPPORTUNITY social	the local people are extremely enthusiastic about the project	the project might become very popular	the demand for the houses increases drastically	high	low	Finch Floating Homes	exploit	the popularity of the project can be used for the upscaling of the project. The design of succeeding houses can be improved according to the wishes of the interested locals.	high	medium	