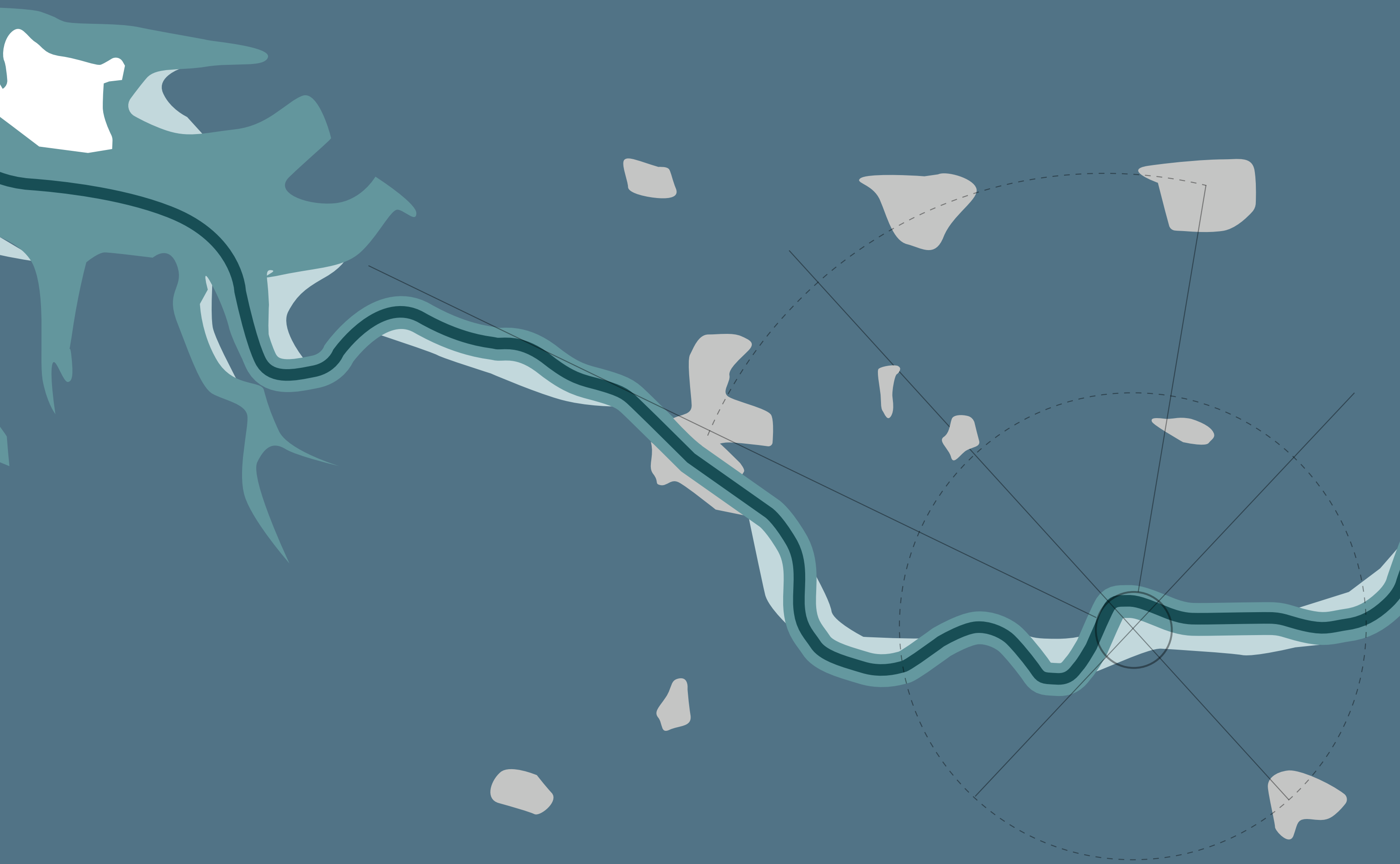
Flood-proof living at the riverside

The development of a lightweight amphibious building concept that responds dynamically to changing water levels in the flood-prone wetlands of Groningen



Master Thesis

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TU Delft

Flood-proof living at the riverside

The development of a building concept that responds dynamically to changing water levels in the future wetlands of Groningen and incorporates a lightweight biobased construction.

Delft University of Technology

Faculty of Architecture and the Built Environment
MSc Architecture, Urbanism and Building Sciences
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MSc Thesis - Research Report

Abstract

In the face of changing climate and the increasing threats of flooding in low-lying Dutch polder landscapes, the demand for new development in adaptive residential architecture becomes crucial. This research explores the development of a lightweight amphibious building concept, designed to dynamically respond to changing water levels in the flood-prone wetlands of Groningen. The study delves into living with water typologies, construction techniques for amphibious buildings, and the utilization of paper and wood as a building material in lightweight constructions. The central hypothesis posits that a combination of a dynamic semi-floating foundation, coupled with paper as a sustainable and lightweight building material, offers new possibilities for future buildings in the floodplains of rivers. The research question addresses how buildings can effectively adapt to fluctuating water levels in Dutch polder landscapes through the incorporation of a lightweight biobased building construction and an adaptable dynamic floating foundation.

The objective is to identify key elements by forming a series of design requirements for an amphibious building concept that tackles climate challenges by new construction techniques and biobased building materials. The thesis is carried out by a literature study of floating constructions and paper constructions, a precedents study and an experimenting phase through research by design. The findings indicate that an amphibious construction could be implemented in various ways, depending on the situation and location. When the river's floodplain is submerged, the building will start to float. It should be considered that everything is connected flexibly, and access roads remain accessible. Paper constructions contribute to a stable, more sustainable, and cheaper building, enabling larger-scale buildings to be executed amphibiously. Paper constructions, with the right design, can meet the construction standards of traditional building materials and also score well in terms of recyclability and disassembly. However, paper as a building material poses additional risks in comparison with the traditional building materials. Also, the practical longevity of such structures remains a matter of debate. For an amphibious building that is specifically aimed at adapting to the future, it is important that the building materials can last a long time. Paper as a building material is a good alternative, but in the application of amphibious living it could be inadequate due to its lifespan.

These research results are used in the design assignment of an amphibious housing complex in a water-rich neighborhood in the Reitdiep area in Groningen. This building implements aspects such as sustainability, technical features, adaptability to climate change and collective living community.

Keywords

Sea level rise, adaptable building, amphibious buildings, floating structure design, paper constructions, sustainable architecture

Preface

During my academic career in architecture, I developed a great interest in construction techniques and the architectural design challenges that coincide with them. I was constantly seeking innovative applications to achieve future-proof results and designs. During the exploration of an alternative and biobased building material my interest grew in cardboard constructions, a material that was minimally used in load-bearing structures. This interest aligned with a strong vision that a solution must be found to build differently in flood-prone areas, enabling homes to withstand high water and adapt to environmental changes. The hypothesis emerged that dynamic semi-floating foundations and lightweight paper-based constructions could complement each other, forming an innovative building concept that is solution-oriented and future-proof. This ultimately led to the concept of “Flood-proof living at the riverside.”

During the research, my focus initially centered on various ways to live with water. After careful consideration, I delved into analyzing and developing foundations for amphibious buildings, which are structures that stand on the ground during dry periods and float during floods, by adjusting to the water level. To determine the necessary pontoon and foundation for this building type, I further explored the advantages of lightweight constructions using cardboard, comparing it with traditional building methods.

This research provided me with numerous new insights, and I thoroughly enjoyed conducting it. It allowed me to further develop within my field of interest, and I really enjoyed the design phase where the research results began to take shape. This research report was written during the first semester of my graduation year, after which the results were applied in a design project during the second semester. I would like to express my gratitude to my tutors for guiding my research and the brainstorming sessions we conducted.

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

In the low-lying expanses of the Dutch landscapes, the water is becoming an increasingly important element, which will be almost impossible to ignore if we don't change anything about the landscape, our protective waterworks or our architecture. The water level keeps rising and flooding is nowadays a common problem in low lying areas near rivers (Ter Steege, 2022). A potential solution lies in adaptive architecture that harmonizes with these fluctuating water levels. This approach challenges architects to deal with climate change by leading the use and implementation of innovative technologies in the built environment. A solution for building in flood-prone areas would make the riversides attractive again for housing, which currently involves too much risk and leads to the cancellation of many housing projects (Haasnoot & Diermanse, 2022).

Another global challenge is reducing the environmental impact of the construction industry for architectural applications. What if paper and cardboard, which are primarily known as everyday materials for packaging, printing papers, tissues and paper towels, can also be used in architectural constructions? Paper is highly recyclable, cheap, made from a renewable source and it is more lightweight and more ecofriendly than other building materials like wood, steel or concrete (Latka et al., 2022). It contributes to achieving carbon-neutral and sustainable architecture. Currently, building with paper is not yet widely applied, because there is a scarcity of defined technical possibilities and validated evidence on its endurance when used in the building industry that can be verified scientifically.

"Flood-proof living at the riverside" seeks to tackle these pressing architectural challenges by embracing climate adaptability and biobased materials. This innovative concept combines the integration of a lightweight paper-based construction method with an adaptable floating foundation, resulting in a new architectural approach for the water-rich Dutch landscapes.

Illustration of the proposed challenges; floods in the built environment and environmental impact of construction industry (Own work)

1.2 BACKGROUND

Landscape of Groningen

The focus area of this research and design project is the Hunze river valley between the city of Groningen and Lauwersoog. This area has undergone significant changes over time and mainly evolved into a human-crafted agricultural landscape, while losing its characteristics like the old dikes, the wierden, old riverbeds and the pattern of ditches (Het Groninger Landschap, 2015). Also, the landscape has continuously evolved due to the influences of ebb and flow, floods, and the construction of dikes and sluices, where managing water has been a continuous challenge. This changing landscape is part of an ancient cultural landscape that traces its origins back to the 6th century. In the last two decades a renewed vision emerged for 2030, aiming to restore the Hunze valley to its original state: a natural landscape characterized by meandering rivers within a wetland area (see figure below). This direction results in a water-rich, dynamic landscape, capable of adapting to rising sea levels, wherein some areas could be intentionally flooded during times of high water (Het Groninger Landschap, 2015). This entails adopting the vision of living with the water rather than solely focusing on defending against it. The next challenge is to make these water-rich areas usable, while remaining as guests in the landscape.

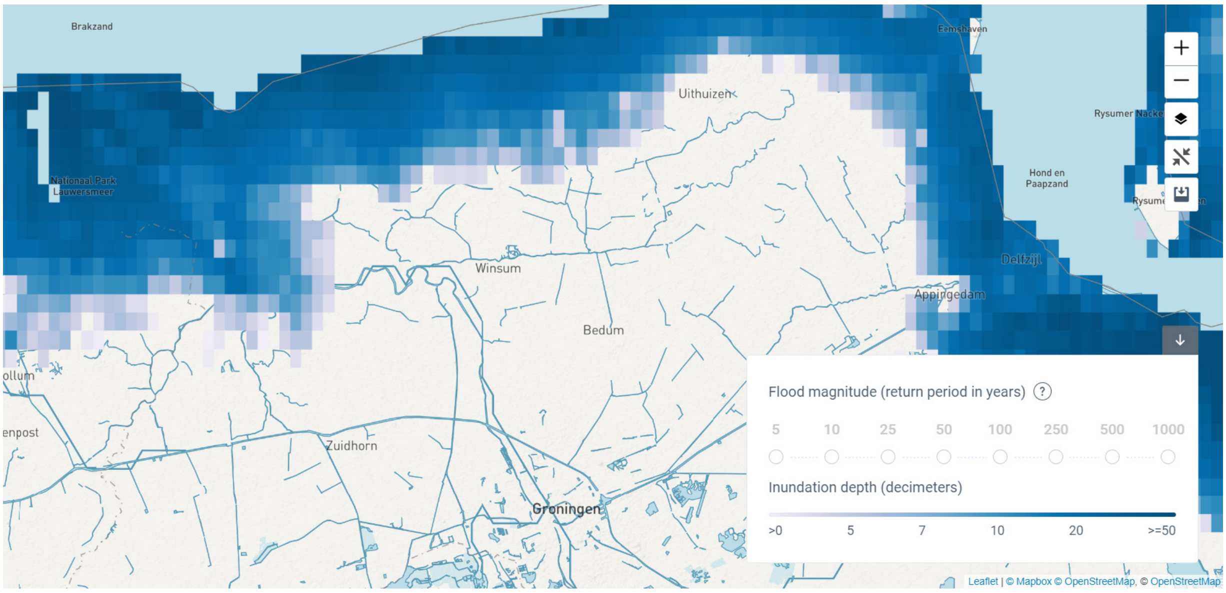
Map of the Hunze river valley, showing the interventions in the meandering of the river (Het Groninger Landschap, 2015)

Dike in Zoutkamp and flooded landscape in Ezinge, Groningen (Own images, 2023)

Flood risk Groningen

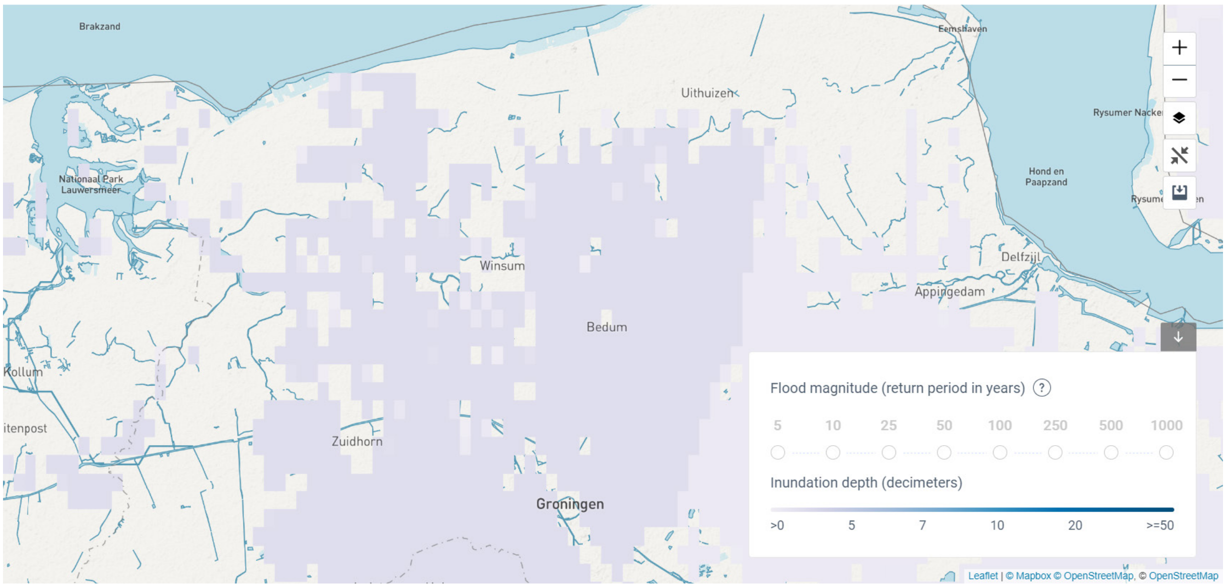
The province of Groningen is located near the sea and is crossed by the river The Hunze, which makes the area at higher risk for floods. Especially because this area is mainly below sea level and the ground continues to sink. The land keeps dry feet through an extensive complex of dunes, dikes, waterways, locks, and pumping stations. But it is becoming increasingly challenging for these defense works to continue holding back the water as it rises. Additionally, these kinds of projects cost a tremendous amount of money (Haasnoot & Diermanse, 2022). The following maps show future scenarios of the flood risk in the Hunze river valley for the year 2080, assuming the scenario that there will be a continuing climate change and land subsidence (World Resources Institute, 2023).

Coastal flood risk



Affected areas: Lauwersoog, Zoutkamp, Kloosterburen, Pieterburen
Average inundation depth: 150 cm

River flood risk



Affected areas: Zoutkamp, Ezinge, Oldehove, Warfhuizen, Bedum, Garnwerd, Winsum
Average inundation depth: 50 cm

"...een zeespiegelstijging van 10 of zelfs 15 meter in de komende paar eeuwen niet uitgesloten."
"...a sea level rise of 10 or even 15 meters in the coming centuries is not excluded.
source: RTL Nieuws (2022)

"Provincie Groningen staat in 2050 regelmatig onder water."
"By 2050, the province of Groningen will regularly be underwater."
source: Omroep Groningen (2021)

"Zo'n 50.000 woningen zouden door een hoog overstromingsrisico bijna de helft minder waard worden"
"About 50.000 homes could lose nearly half of their value due to a high risk of flooding."
source: AD (2023)

Minister: "goed nadenken over woningbouw in lage polders"
Minister: "carefully consider housing development in low-lying polders"
source: AD (2022)

"820.000 woningen gepland in gebied dat kwetsbaar is door klimaatverandering"
"820,000 homes planned in areas vulnerable to climate change."
source: NOS (2021)

"In de lange historie van overstromingen in Nederland is de strijd tegen het water een terugkerend fenomeen"
"In the long history of floodings in the Netherlands, the battle against water is a recurring phenomenon"
source: NOS (2023)

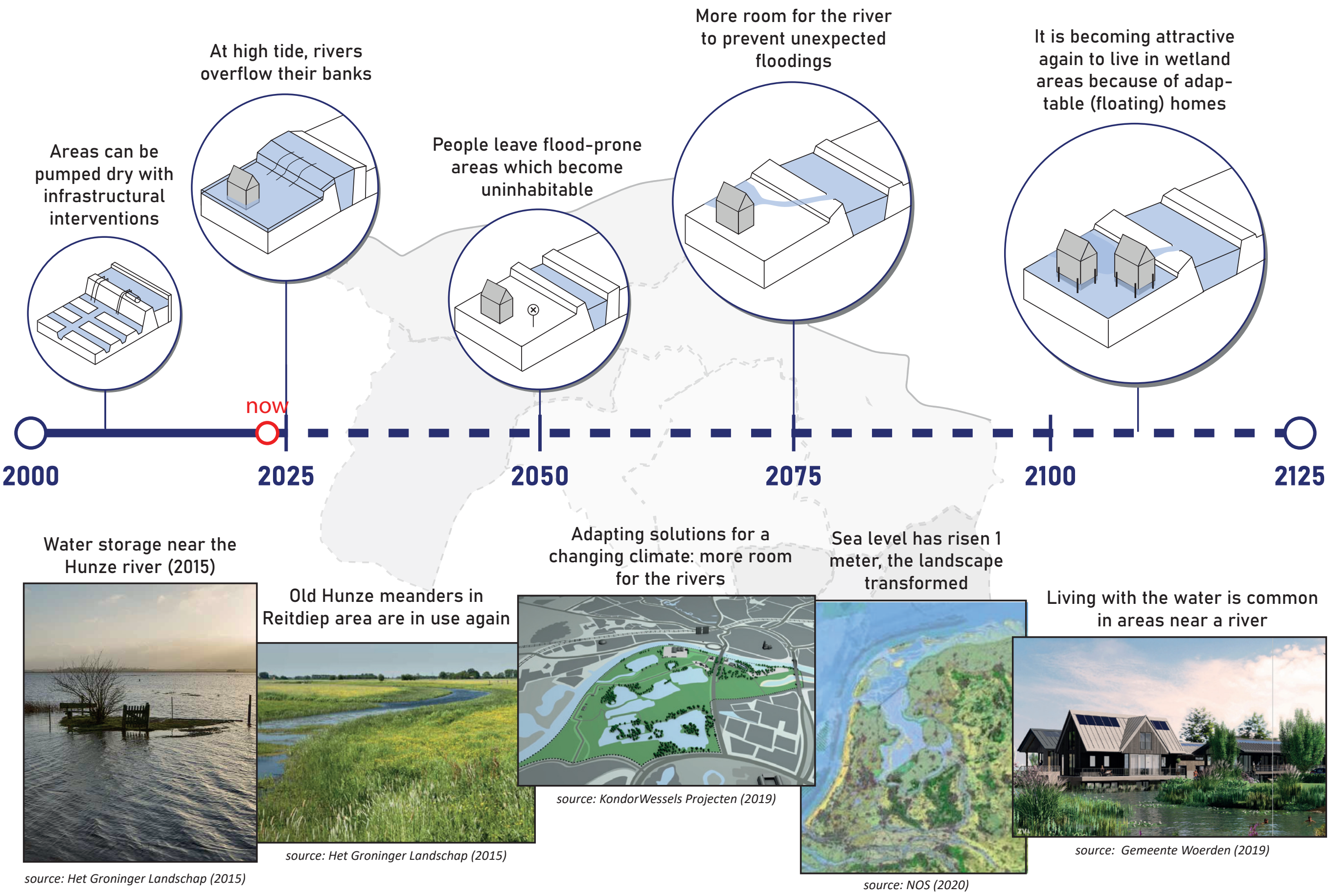
Quotes from Dutch news websites showing the current urgency of the water problem for the built environment in The Netherlands (2021-2023)

Future scenario Groningen and vision

Because of environmental changes, the landscape is constantly changing. The landscape of Groningen faces pressing challenges of climate change, particularly in its interaction with water management, which is influenced by the Reitdiep River and the North sea. As visible in the flood risk maps, Groningen has many areas in danger zones. To protect the built environment from floods, people depend on riverbank defenses, infrastructural interventions and tidal barriers (Varkey & Philbin, 2022). This makes it possible to keep living and developing in flood zones. However, there is a limit in continuing to defend the water problem. In the Netherlands, more and more floods have occurred in the last few years. The primary issue with floodings is that it causes loss of life, properties, land, and it takes a long time to recover the damage of buildings and the environment (Varkey & Philbin, 2022).

My vision for the future scenario of the province of Groningen is that the landscape has undergone a transformation, by embracing a new way of coexisting with the water. Adaptation and integration is chosen over constant defense. This affects the habitability of various areas close to the river. The vision is to give space to the water when it is needed while maintaining the safety of the inhabitants. This can be done by creating adaptable and dynamic residential areas. It will ensure that people stop continue to leave these flood-prone areas and that the river areas become more vibrant.

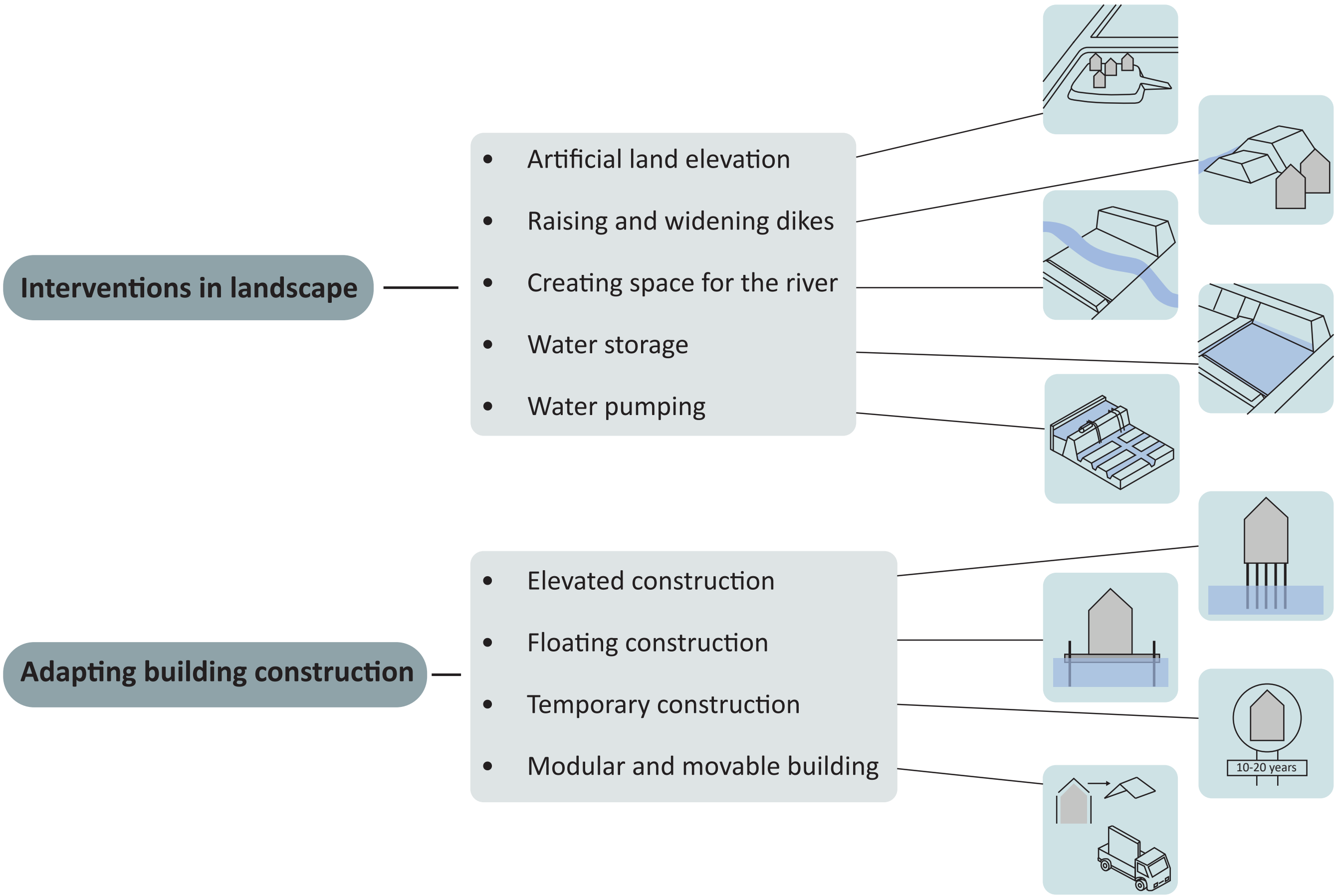
The following figure gives an overview of my vision on the future scenario of the province Groningen, for the coming 100 years. This scenario is the underlying starting point for the rest of the research and the design phase.



Timeline of future scenario for the province of Groningen (Own work)

Solutions for future scenario Groningen

Ultimately, there are various possibilities to deal with the changes in this landscape and the consequences for building in these areas (Haasnoot & Diermanse, 2022). The following figure provides an overview of long-term solutions for living in areas at risk of flooding.



This thesis will further focus on a combination of the approach of 'elevated construction and floating construction,' aiming to prevent costly interventions in the characteristic landscape. This entails a vision that assumes that the Hunze river once in a while will overflow its banks and that a strategy like ‘moving along’ is open to that situation. Now it is the role of the architect to think about a solution of building in this type of changing wetlands and flood areas. As quoted by The American Institute of Architects (2018): **“Resilient and adaptable buildings are a community’s first line of defense against disasters and changing conditions of life and property.”**

That is why this thesis focuses on a building principle with a lightweight construction which can adapt its height to the level of the water, which means it has the possibility to float during floods and to stand on the ground during dry periods. In this way, the character of the Groningen landscape can remain intact and a new type of architecture arises.

1.3 PROBLEM STATEMENT

The two global challenges which this research adresses are being able to deal with the rising water level in the built environment and reducing the environmental impact of the construction industry.

The first challenge focuses on the deal of how to navigate and adapt to the constant rise in water levels. This is a critical concern that directly influences how we design, construct and inhabit our spaces. As water levels continue to rise and flood events happen more frequently, it's imperative to reimagine our approach to architecture in a way that harmonizes with these fluctuations while ensuring safety, sustainability, and resilience in the building structures.

The second challenge revolves around rethinking the commonly used building materials as a first step of a transition from a linear to circular and sustainable built environment. The traditional materials like steel and concrete are energy intensive materials and have negative environmental impacts (Latka, 2017). Biobased materials are raw materials which are derived from renewable biological sources like trees, plants or animal biomass and can be used as material in construction (Stahl, n.d.). These types of building materials can be recycled and process less CO_2 during their life cycle. Such a material is paper, which has a natural composition, made of fibers from wood pulp, rags, straw or other fibrous materials (Knaack et al., 2022). Paper or cardboard are historically not typically used as primary structural building material due to its limitations in sensitivity to moisture and fire and its questionable lifespan when compared to other materials. However, recent researchers have been exploring paper in architecture which resulted in experiments with cardboard panels, paper tubes, papercrete and even 3D printing with paper pulp (Knaack et al., 2022). In the case of a floating building, this lightweight material can offer new opportunities.

High water in the river Dinkel that overflows its bank in Losser, NL (ANP, 2023)

1.4 OBJECTIVE

The primary objective of this research is to explore innovative solutions that enable buildings to effectively adapt to the dynamic challenges posed by fluctuating water levels in Dutch polder landscapes. To specify, the building solution provides an adaptable and flexible floating house concept in an area which has dry periods and flood periods, where the construction of housing is currently a challenge. The main focus revolves around incorporating two key elements into an architectural concept: an adaptable and dynamic floating foundation and a lightweight paper-based construction. Through the examination of experiments and research that discovers a range of design possibilities with paper constructions in combination with dynamic floating systems, this thesis can offer valuable insights for architects, engineers and designers who are developing in flood risk areas with an innovative and sustainable approach. To achieve this aim, the following objectives are formulated:

- To understand the importance of building responsibly in wetland areas.
- To investigate the basic fundamentals of floating systems and flood conscious architecture.
- To introduce and test a new approach of dynamic floating systems, capable of adjusting to varying water conditions while maintaining stability and functionality.
- To explore the opportunities of lightweight sustainable constructions with paper.
- To strive for improved living conditions in flood-prone locations in a sustainable way.

1.5 RESEARCH QUESTION

The main research question of this thesis is:

“How can buildings effectively adapt to fluctuating water levels in Dutch polder landscapes by incorporating an adaptable dynamic floating foundation and a lightweight biobased construction?”

Sub questions:

1. What are the current typologies of living with the water in wetlands?

2. What technical principles are there for amphibious constructions that can dynamically accommodate varying water levels while ensuring stability and structural safety?

3. Why and how to enhance constructional and load-bearing purposes with the biobased material paper when applied to architectural building structures?

4. How can the principles of amphibious foundations and paper-based constructions be applied innovatively in a residential building design for a floodplain in the Reitdiep area?

1.6 METHODOLOGY

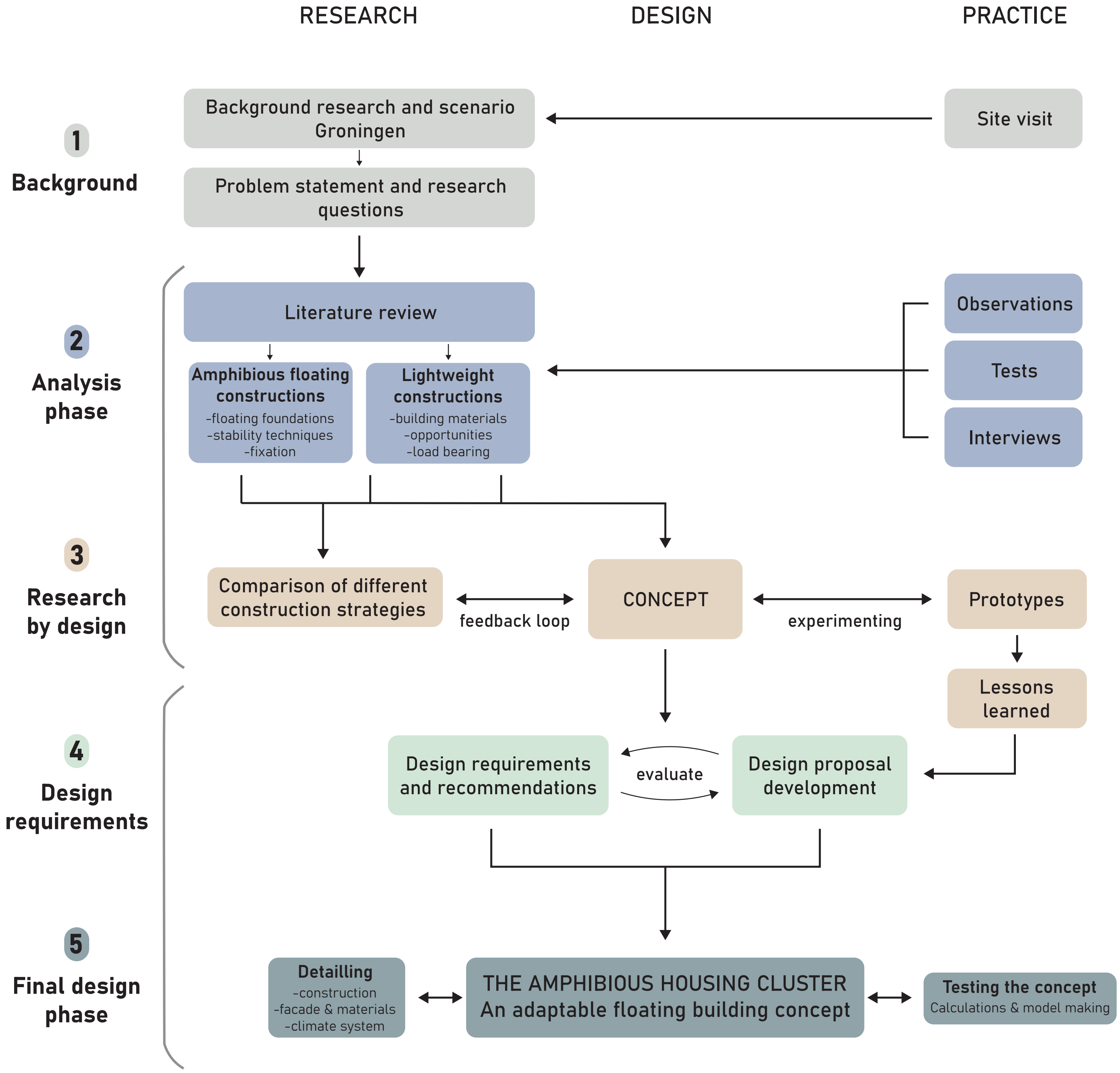
This thesis will be carried out using a variety of research methods, including an analysis of case studies, a literature review of floating constructions and paper constructions, material studies by testing, and an experimenting phase through research by design. In the end the research will result in a list of preconditions for a design proposal, which is a basis for further development of an amphibious housing project.

Multiple case studies are selected to provide insight into specific topics. Three of these case studies are described in chapter 2 and give insight in floating building constructions. In chapter 4, there are studied paper construction case studies to learn more about the techniques and applications of paper-based constructions in architectural projects over recent decades. The advantages and limitations of these projects will be evaluated.

Furthermore, a comprehensive literature review will be conducted to analyze the techniques of amphibious foundations. Because an amphibious construction is a new development, many techniques can be researched from floating buildings as they have many similarities. The literature is additionally utilized to understand the methodologies for calculations on the floating platform and the weight of the building which can be used during the design phase. The focus of the research is on achieving stability within the construction, looking into the depth and size of the pontoon, the fixation of the building and the possible size for this type of construction. In addition to literature research, tests are used for these subjects.

Next, the focus shifts to lightweight constructions, investigating paper structures. This exploration delves into the potential of paper-based materials for sustainable structural applications. The experimenting phase represents the practical application and testing of the constructional properties of the material. It relies on the insights gained from material research, including the structural, environmental, and design aspects of using paper in construction. The experiments can consist of testing the strength of paper construction prototypes, trying out different tube joining techniques, and testing it weathering circumstances. During this experimenting phase, I will investigate the potential benefits, challenges, and innovations of using paper-based materials in architecture. A comparison with traditional building materials as wood and steel is made to give a complete overview of the material's potential.

In the following figure the structure of the research is elaborated, showing the research by design approach.



Conceptual framework of research - Research by design workflow (Own work)

1.7 HYPOTHESIS

The hypothesis for this study is that a amphibious housing constructions can offer new opportunities for building in wetlands in the future. Moreover, paper as a lightweight material is expected to offer sustainable and innovative solutions for structural architectural applications in floating architecture. In case studies, it has turned out that wood is the most common building material for floating architecture. To test the potential of paper constructions instead of wood, a comparison will be done. The research aims to contribute to the understanding of paper's potential in the realm of architecture and construction design, taking into account its advantages, limitations, and real-world applicability. To evaluate the potential of floating constructions in combination with a paper-based load bearing construction, the following performance standards and criteria are set up:

- An integrated construction of a floating and fixed foundation should offer a practical and safe system for building in wetlands, which effectively adjusts to various water levels.
- In a high water situation, the system should meet the building standards of stability, strength and comfort.
- Skeleton frame structures from paper tubes or paper-based wall components should meet the load-bearing standards which are typically applied to construction materials like wood or steel. A middle-scale low-rise building must be among the possibilities of the construction.
- The construction methods with paper should withstand environmental factors, including exposure to moisture, temperature fluctuations or weather influence, so it can function as a permanent building.

The hypothesis assumes that paper can be a viable building material, because of its lightweight properties and sustainable characteristics, but its inherent limitations, such as sensitivity to moisture and fire, may hinder its applicability in certain contexts. Moreover, challenges related to structural and load-bearing capacities may pose significant threats to the feasibility of paper-based constructions, or it could result in a limitation of the maximum building scale. And contrary to the sustainability argument, concerns about the environmental impact of paper production may undermine the hypothesis. If the results indicate that paper is not a viable structural building material based on predetermined criteria and that a combined structure for floating and fixed buildings is not a practical solution, the hypothesis would be falsified.

CHAPTER 2

LIVING WITH WATER

2.1 Effect of changing water level on buildings
2.2 Flood proof construction for Groningen: amphibious living
2.3 Case studies building on water

2.1 EFFECT OF CHANGING WATER LEVEL ON BUILDINGS

Floods are happening more frequently in The Netherlands as a result of the rising sea level (Haasnoot & Diermanse, 2022). Next to damage to the public spaces and infrastructure, it poses significant risks to buildings. It causes compromising structural integrity and the aftermath of a flood can lead to water infiltration, which permeates walls, floors and foundations (Roos, 2003). This results in a structural weakening, rot and deterioration of materials. Furthermore, prolonged exposure to water can result in mold growth, compromising indoor air quality and posing health hazards. Electrical systems and appliances within buildings are also at risk, leading to potential short circuits or total malfunction.

After several major floods in the Netherlands and surrounding areas, like the recent river floodings in Limburg in 2021 and in Dordrecht in 2020 (see images), many people have become more aware of the high-risk areas in which we as Dutch citizens live. More and more areas are being designated as uninhabitable, and the value of houses in flood-prone areas is decreasing, which could amount to a depreciation of 325 billion euros due to climate change (Calcasa, 2023).

When looking back to the historical landscape of Groningen, we see already that the water is a difficult element to deal with and for which protective elements have been built for centuries. During the Middle Ages, the northern regions of the Netherlands experienced frequent floods due to the absence of substantial sea dikes. During the years the dikes improved and Groningen had a unique solution for dealing with the water. The landscape is known from its "wierden", which are man-made earthen mounds which provided protection to buildings and settlements from floods during high water levels (Ter Steege, 2022).

Meanwhile, we have again reached a period where the question arises whether the dikes provide sufficient protection (Haasnoot & Diermanse, 2022). Recently, in February 2022, Groningen had to deal with lots of rainfall and high water. This has led to the construction of additional emergency dikes and additional pumping stations that were added, but still it was not possible to prevent many crawl spaces from flooding (Ter Steege, 2022). This shows that conventional dikes will not solve these water problems, so it is important to look at other solutions. In addition to interventions in our water management, adapting the landscape and continuing to raise the dikes, it is also a solution to explore architectural approaches, such as adaptable building constructions which can live with the water, instead of fighting against the water. Climate-adaptive construction is the next step towards a more secure future.

Flood in Limburg in 2021 (NU.nl, 2022)

Flood in Dordrecht in 2020, water level of 2,24m above NAP (Knobbe, C., 2020)

2.2 FLOOD PROOF CONSTRUCTION FOR GRONINGEN: AMPHIBIOUS LIVING

Already, several solutions and strategies to live with the water are applied in Dutch architecture to address the challenges posed by floodings and high water. The most commonly known ways of living with the water are the elevated and floating building types (Haasnoot & Diermanse, 2022). Buildings on stilts or pilings are useful to elevate a building above potential flood levels. Floating structures can rise and fall with water levels and make use of a floating pontoon and flexible floating infrastructural connections. A third and less common solution is an amphibious construction. This system is meant to float only during floods and functions as a static building on the ground during dry periods. The figure below shows schematically the differences between these three living with water typologies.

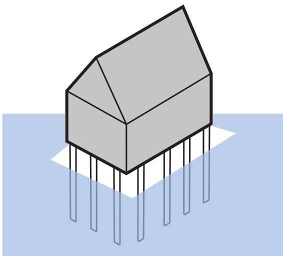
In Groningen, with its low-lying polder landscapes and meandering river, an approach is demanded of constructions that ensures both safety and sustainable development (Haasnoot & Diermanse, 2022). Among the available options of statically elevated buildings and permanent floating structures, the choice of amphibious buildings emerges as the most fitting solution, poised to address the unique challenges and opportunities this region faces in the next hundred years. This approach not only mitigates risk but also opens up previously untouched regions for habitation, thereby optimizing land use. The following reasons will substantiate this choice.

Statically elevated buildings, while providing a certain degree of protection, face limitations in design and functionality. Elevating structures to extreme heights alters the landscape, impacting aesthetics and creating a disconnection between the inhabitants and the environment. Moreover, the need for elevated access routes introduces infrastructural complexities and visual disturbances. Furthermore, buildings on stilts still have the risk of water damage when the water rises above the lifted ground level.

Permanent floating buildings, confined to water bodies, fail to cater to dry but flood-prone areas, limiting their applicability within Groningen's diverse landscape. Moreover, floating buildings are mostly scale-limited, because they must have the possibility to be transferred by the water (Witsen, 2012). Furthermore, floating buildings indeed offer numerous new possibilities to render wet areas habitable and effectively withstand flooding. However, in the context of future construction in Groningen, the problem lies in the fact that floating buildings can only be implemented on open waters, leaving out areas next to the water that equally deals with water-related issues. While there are specific locations where floating construction could prove viable, on a larger scale, amphibious building presents a broader spectrum of opportunities.

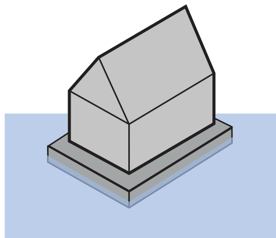
Next to maximize land use and adaptability to water levels, amphibious constructions offer also other advantages that make them a compelling choice for flood-prone areas. Unlike other flood-proofing methods, such as elevating buildings on stilts or constructing permanent floating structures on open waters, amphibious buildings maintain a relatively natural and visually appealing appearance. This helps in preserving the aesthetic integrity of the surrounding landscape. Moreover, residents can continue to live and work in these areas without the constant threat of displacement.

So in conclusion, this research will continue to focus on floating techniques for amphibious constructions, aiming to explore the potential of this new technique and what it means for a new architectural typology.



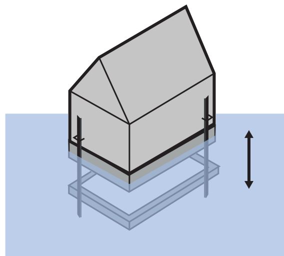
Statically elevated building

- \+ Practical and cheap solution
- \+ Stable
- — Not flexible, water level can reach the maximum allowed height
- — Connections to infrastructure are limited
- — Has a striking expression and can feel disconnected to the environment



Permanent floating building

- \+ Flexible, it can be moved to other places
- \+ It can withstand rising sea levels
- \+ New (wet) areas can be used for living, useful when land is limited
- — Limited scale, must be transfered by the water
- — Stability can be challenging
- — Increased corrosion due to its constant submergence in water



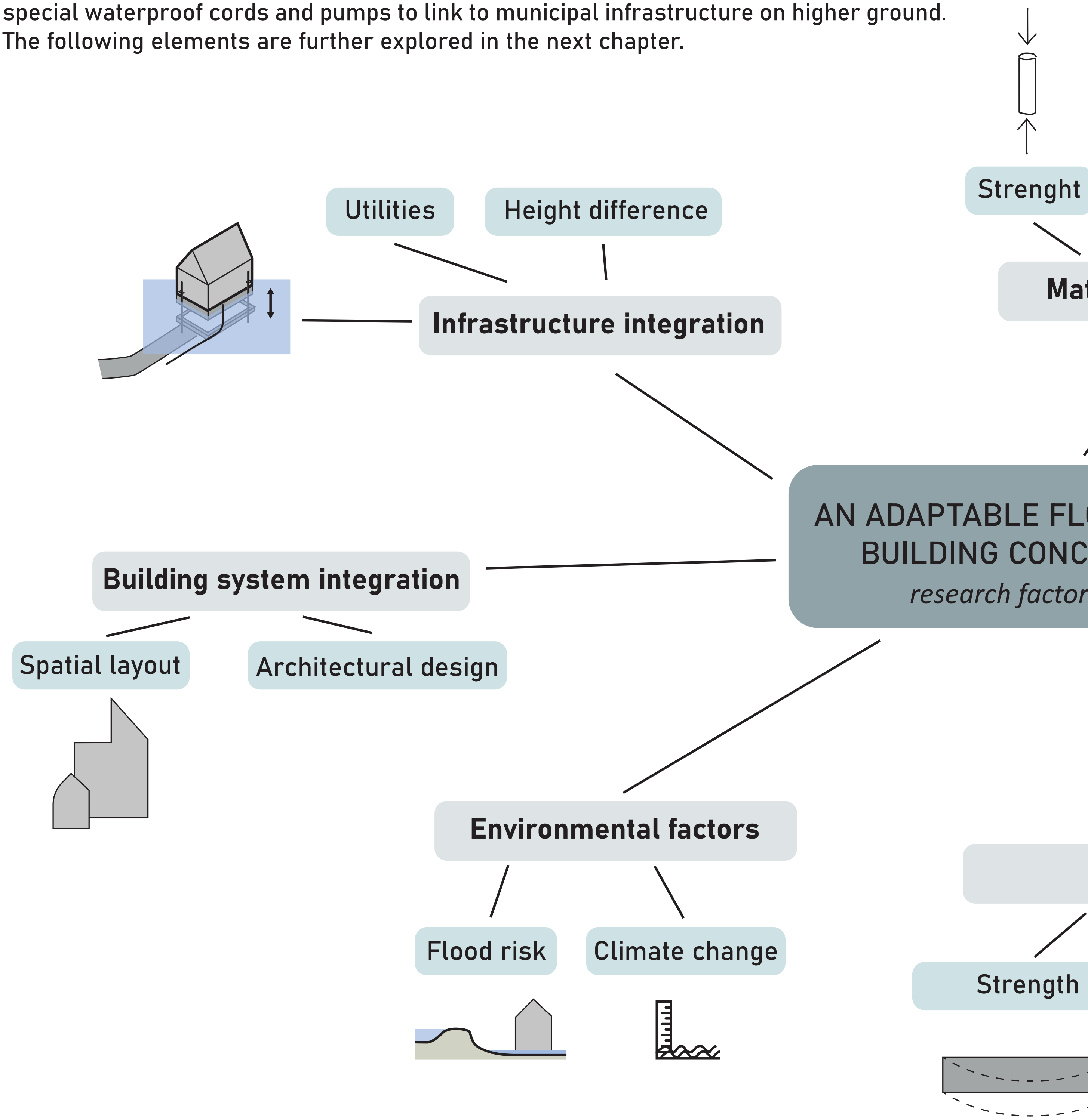
Amphibious building; only floats during floods

- \+ Makes flood prone areas attractive again, which are now unattractive to live in
- \+ Adapts to the changes in the water level, makes it future proof
- \+ Also functions if an area is not under water
- — Double foundation, makes it expensive and uses more material
- — Stability can be challenging

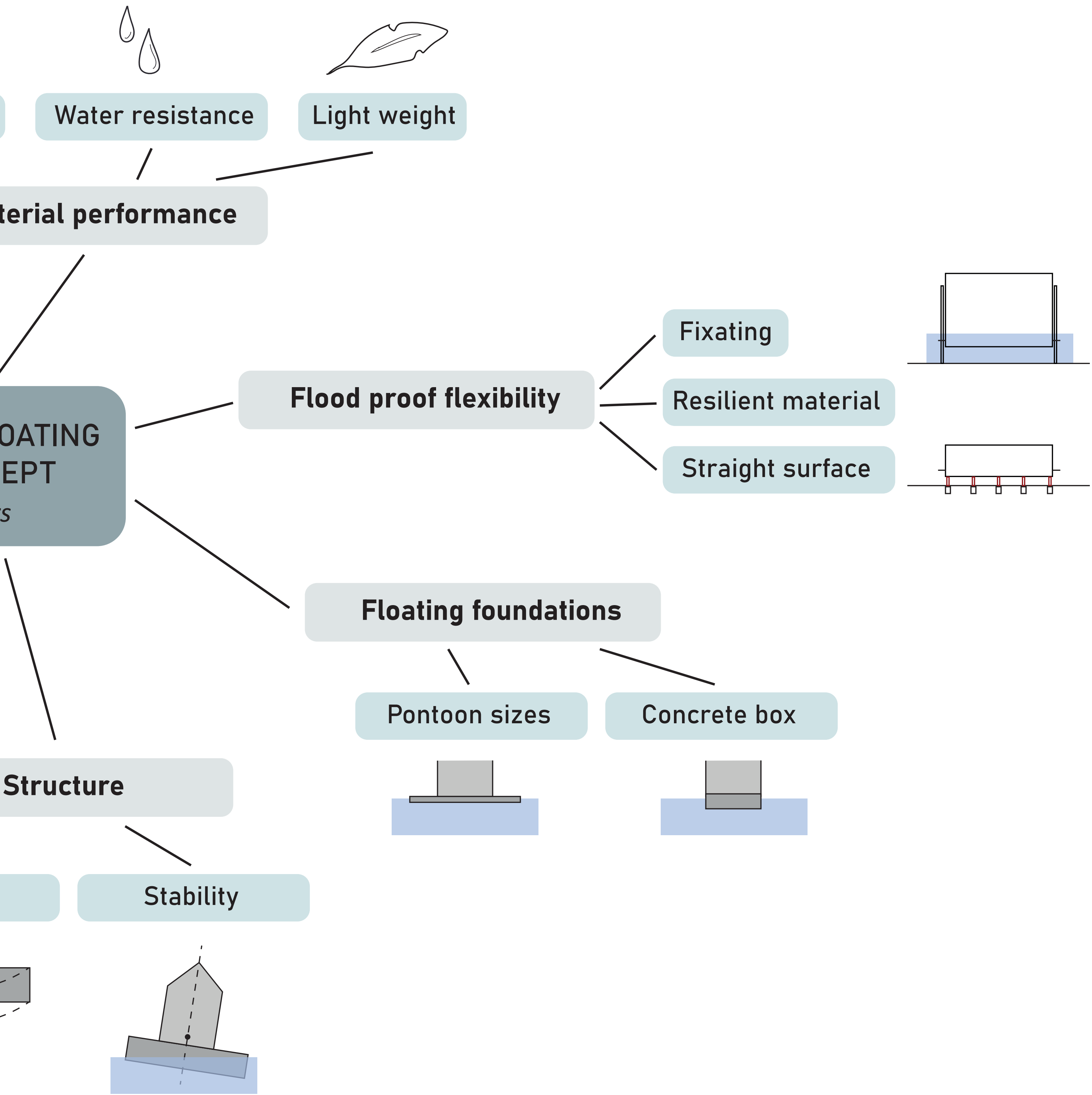
Solution-oriented building types for wetlands (Own work)

Research factors for adaptable floating buildings

The following figure provides an overview of factors which are influencing a building's comfort and a stable construction in case of an amphibious house. These factors are important considerations which have to be integrated to achieve a well-functioning flood-proof design. In terms of utilities for example, such as connection to the electricity grid and sewer system, amphibious houses require more infrastructure and effort than regular houses. As they are below the level of regular municipal services, they require special waterproof cords and pumps to link to municipal infrastructure on higher ground. The following elements are further explored in the next chapter.



Research factors amphibious buildings (Own work)


Water resistance
Light weight
terial performance
Fixating
Flood proof flexibility
Resilient material
Straight surface
OATING
EPT
Floating foundations
Pontoon sizes
Concrete box
Structure
Stability

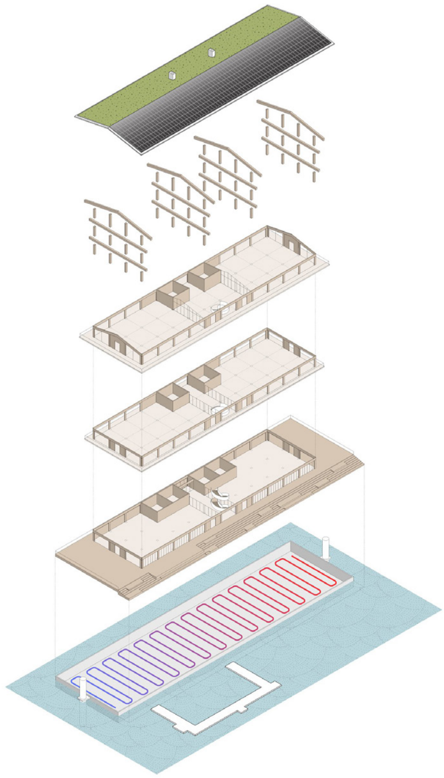
2.3 CASE STUDIES BUILDING ON WATER

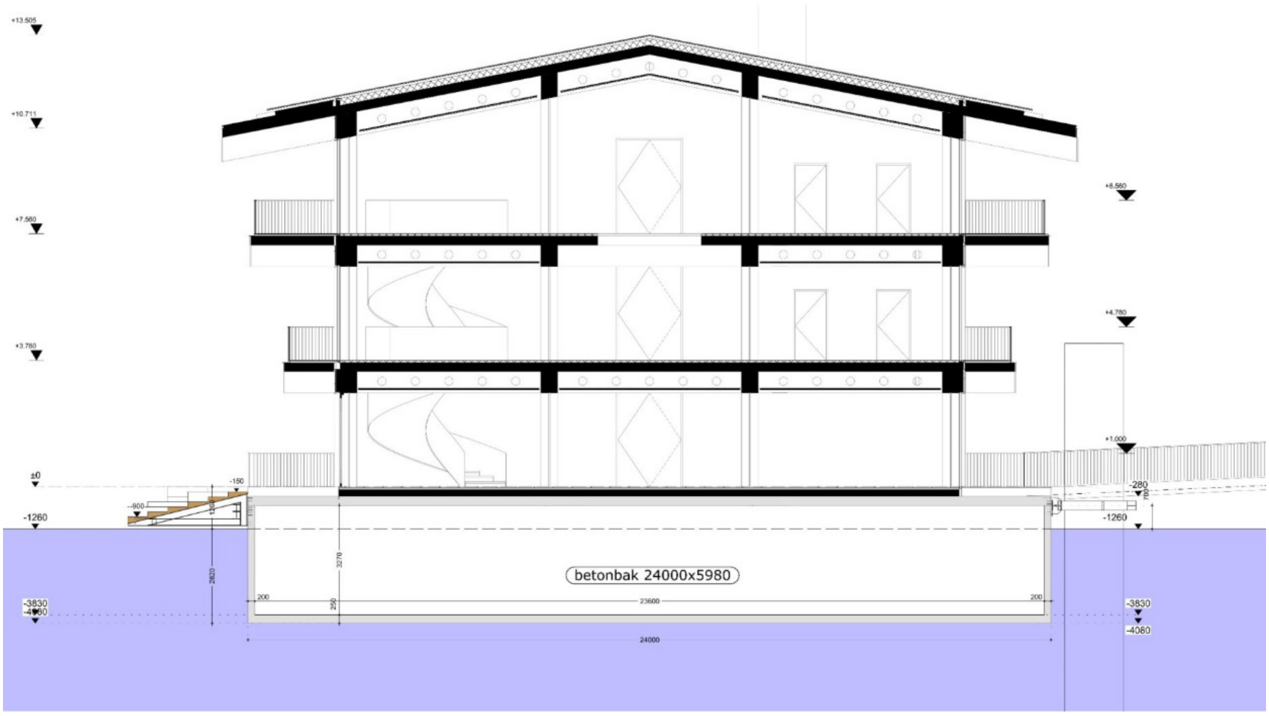
Global center on adaptation, Rotterdam - floating office

This office building for the Global Center on Adaptation in Rotterdam completely floats on its foundation. The scale of this building makes it a special project, since it is the largest floating office building in the world, of 4500 m2. Moreover, it is a self-sufficient and climate-resilient design. A heat exchange system generates energy from the river, which works like a home floor heating system, where heat pumps take energy from the water and use it to heat or cool the building. The pipes are placed into the concrete walls. More energy is produced by the solar panels on the roof. MEP machinery is placed in the hollow floating pontoons. From there it runs through the shafts and ceiling, to then be distributed around the building.

The building consists of a wooden structure situated on 15 concrete pontoons. The wood structure can easily be demounted and re-used. These concrete pontoons provide the building to float. The concrete pontoons are connected to each other with tension cables. Two mooring poles are anchored to the building for fixation. For access, a floating pier with small bridges has been implemented (Bartels, Vedder, 2021).

In conclusion, the case study of the Global Center on Adaptation's floating office building in Rotterdam stands as a groundbreaking example of innovative and sustainable construction. Its sheer scale as the world's largest floating office building showcases the feasibility of large-scale floating structures. This project's self-sufficiency and climate-resilient design set a new standard. Looking ahead, this case study serves as an inspiration for this research in floating construction methodologies and sustainable architecture.



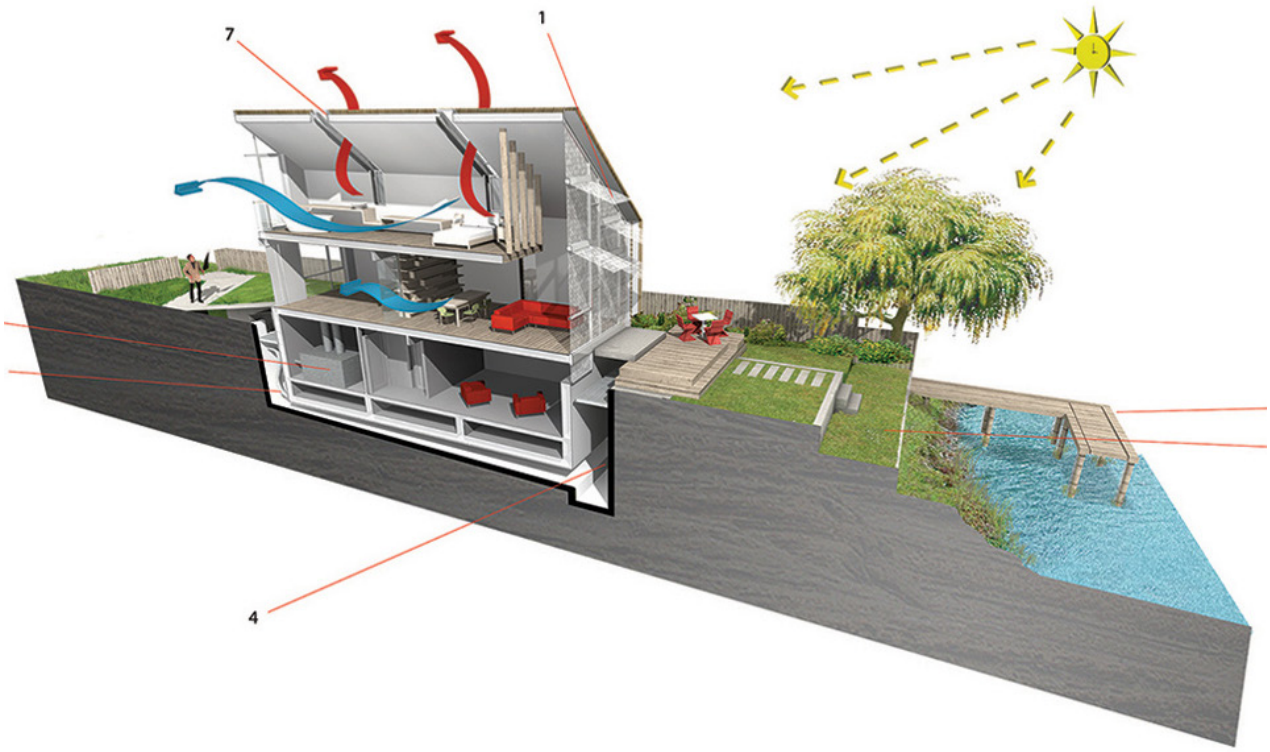


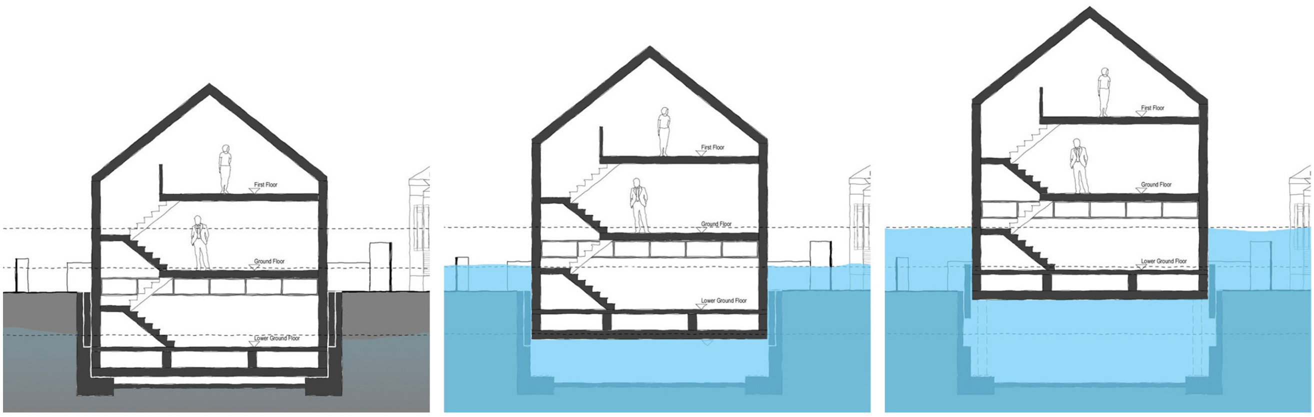
Global center on adaptation, Rijnhaven, Rotterdam (Bartels & Vedder, 2021)

Amphibious house UK

In 2015 Baca architects developed UK's first amphibious house, which is located in an area with high flood risk on the banks of the river Thames. When the river overflows, the building can float upwards with its own floating foundation. The water pushes the house upward while floodwaters fill the dock underneath it. This floating base is almost invisible from the outside. The dwelling has an area of 225 m2. In order to prevent the house from floating away, it is fastened to four guideposts that provide a floodwater clearance of 2.5 meters. Connections to utilities are carried out flexibly and they can extend up to three meters. The house itself is made from a timber frame, which is attached to the top of the concrete structure. The ground floor, which sinks into the dock, functions both as a living area and as a floating foundation (Baca architects, 2015).

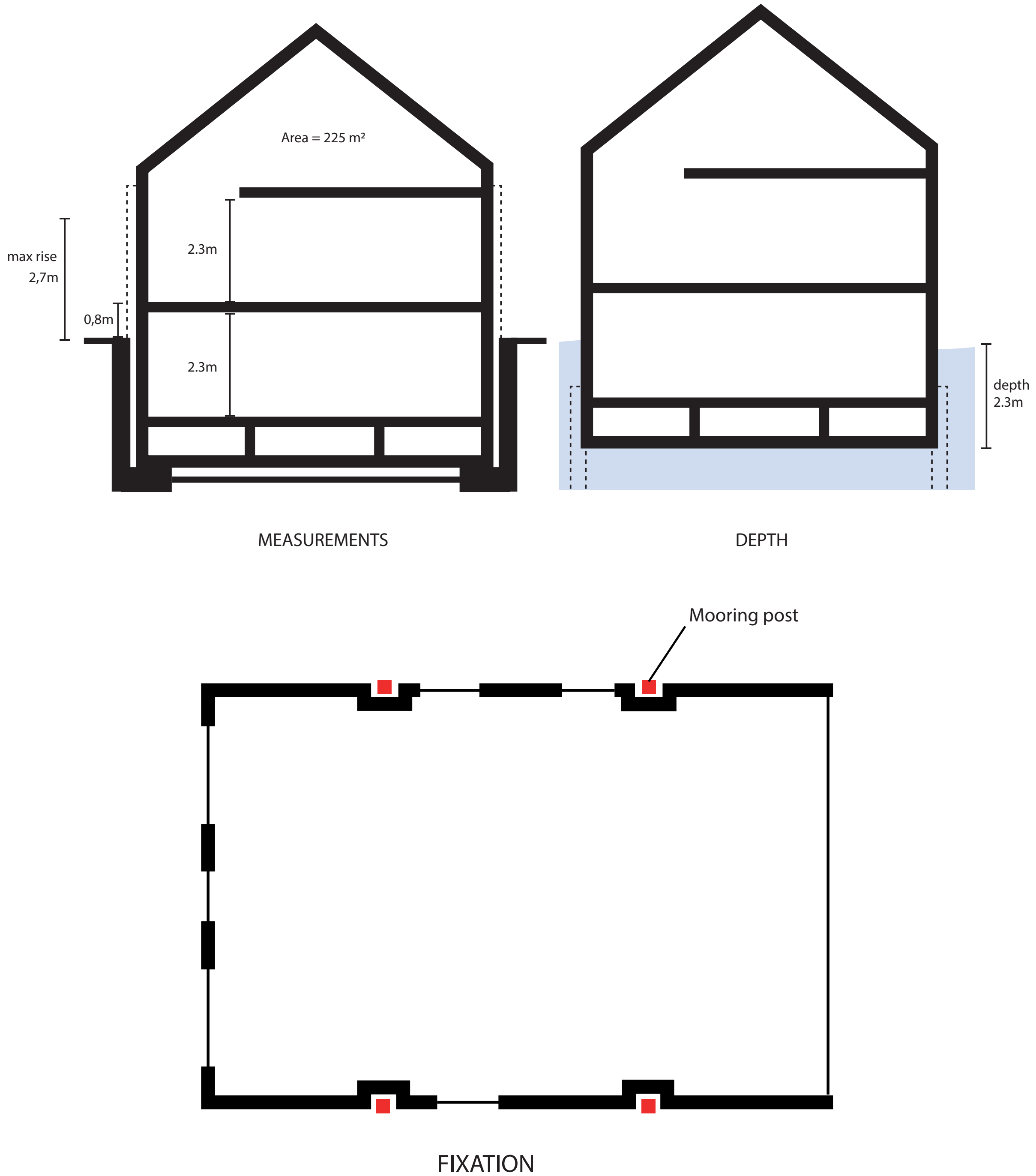
Looking forward, this project serves as a base for further exploration into flood-resilient amphibious housing solutions, with its innovative design principles and adaptability. The next step is to look into the long-term performance, functionality and scalability of such amphibious structures.



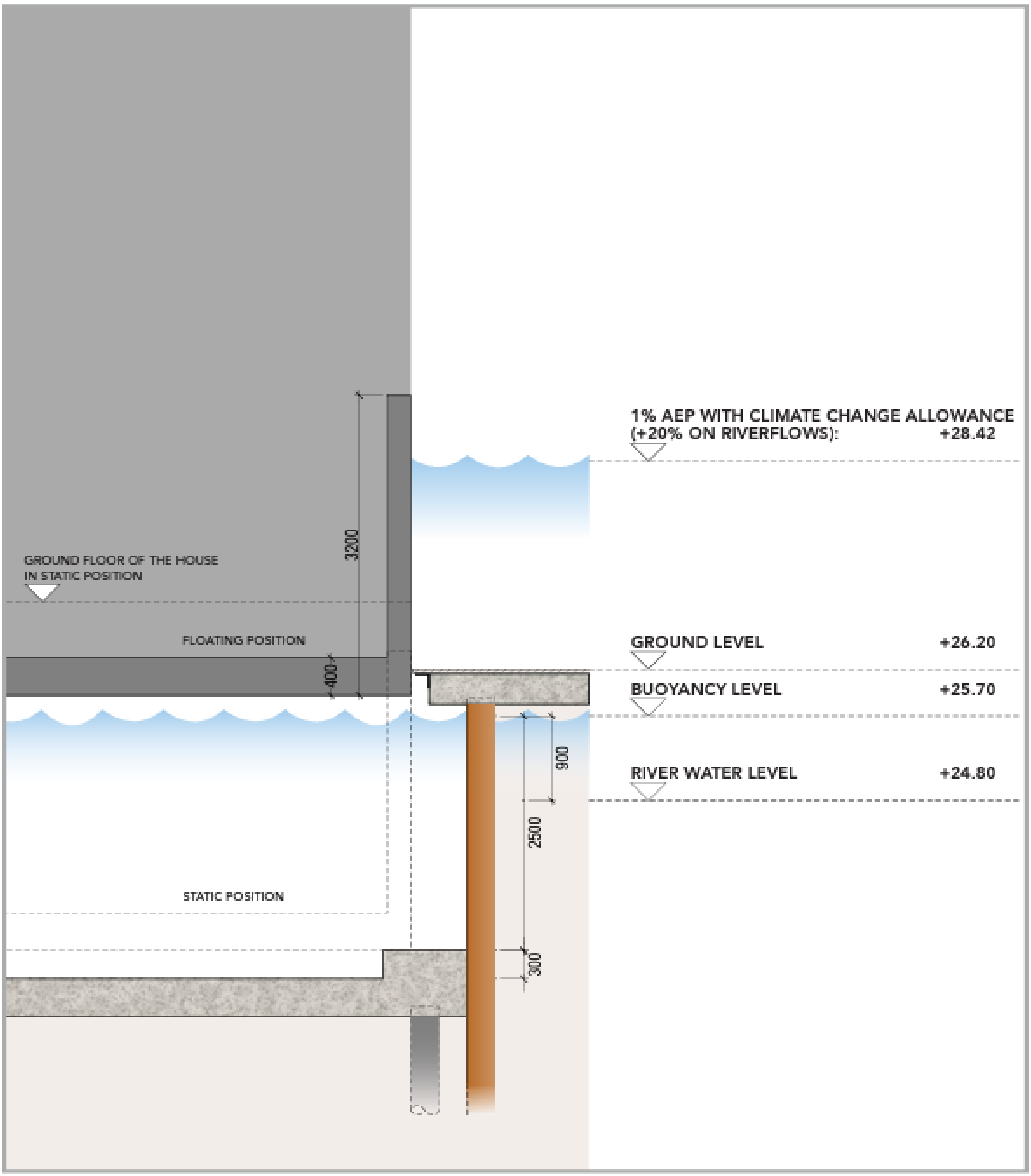


Amphibious house in Buckinghamshire, UK (Baca architects, 2015)

To get a clear overview of the working of its construction, these analytical schemes are made to understand the amphibious principle. Actually, the system consists of two foundations, one static foundation in the ground and one dynamic floating foundation of the house. The floating foundation can be seen as a concrete box, of which the space is used as living space. This also lowers the center of gravity, because the rest of the building is made of timber, which is more lightweight than concrete. The depth of the building in floating condition is 2,3 meters. Above this height there are situated windows, to get light into the basement. For fixation, four mooring posts are integrated into the building's design.



Analysis Amphibious house UK (Own work)



Construction detail of foundation (Baca architects, 2015)

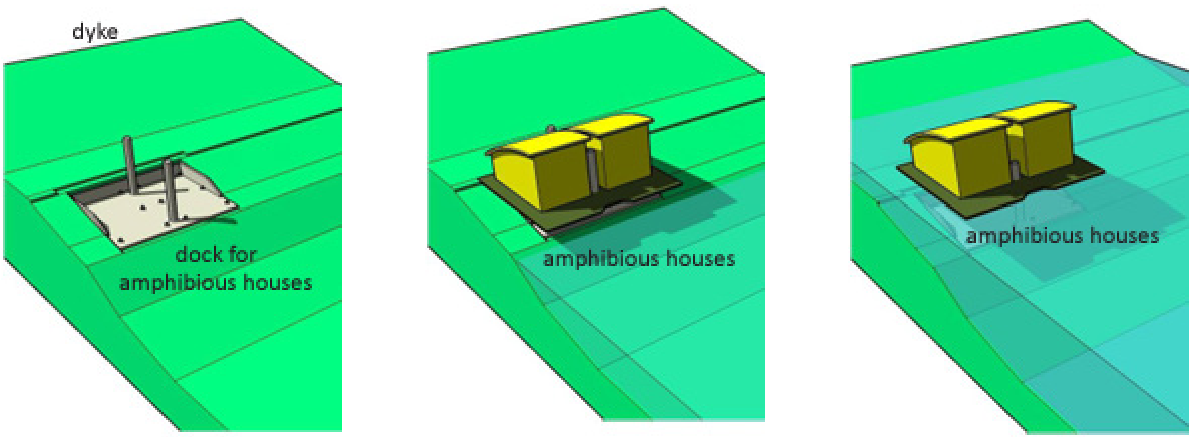
Amphibious housing project - Maasbommel, NL

The Netherlands also has experience with amphibious housing and has been one of the pioneers with this technique. In the flood-prone city Maasbommel, near the river "the Maas", 32 amphibious houses were realized in 2005 by Factor architecten and Dura Vermeer. Due to their adaptability to water levels during floods, amphibious houses do not impede the area's capacity for water storage. This was the primary reason for Rijkswaterstaat to agree with this concept. In 2011 the first flood encountered the houses and the buildings floating without any issues and resettled seamlessly afterward. The project aimed to envision a future where hydrological living becomes feasible in flood-prone areas (Factor Architects, 2011).

The amphibious houses in Maasbommel keep floating during a flood due to the concrete base with a lightweight house of wood on top of it. The concrete box works as an underwater air buoyancy chamber to keep the building afloat, just like the hull of a boat. The hollow concrete hull must have a minimal thickness of 20 cm to achieve watertightness (Factor Architects, 2011). The 23 cm thick concrete hulls of the Maasbommel project weigh over 70 tons per hull and were prefabricated on site. The house can rise up to a maximum of 5,5 meters.

Fixation is done by iron posts in between the houses. Flexible pipes are adapted to connect the house to utilities and building services and they can move with the force of the water. Another advantage of this type of housing is that a garden is still possible to realize.

During the realization of the project, it was unclear how this type of building could be classified and how the legislation could be applied. This legal issue is also the reason why no other amphibious housing projects are realized in the Netherlands after this successful project. Moreover, developers are not interested in the extra costs of these types of projects. However, when amphibious living becomes more widespread, the benefits may probably outweigh the costs.

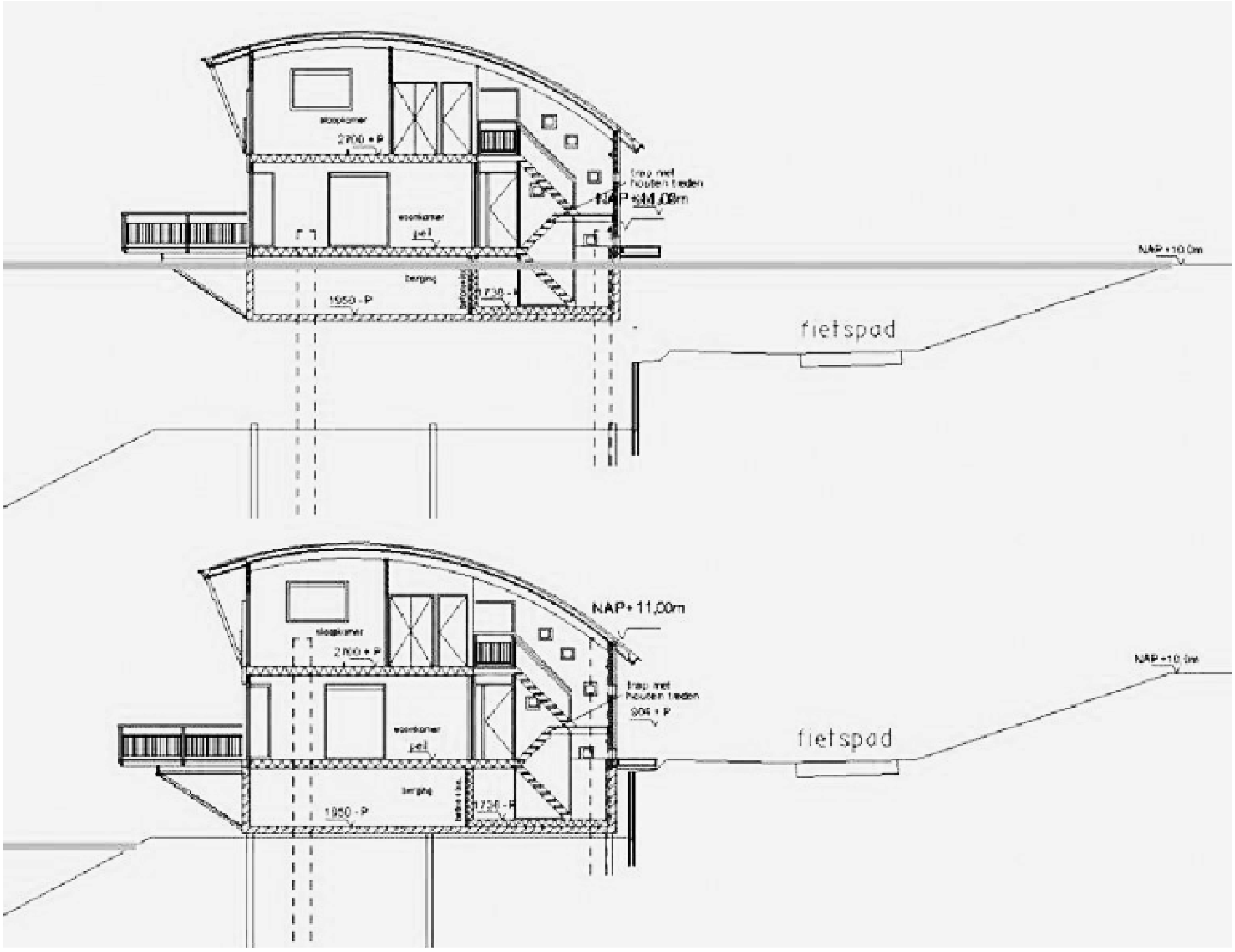


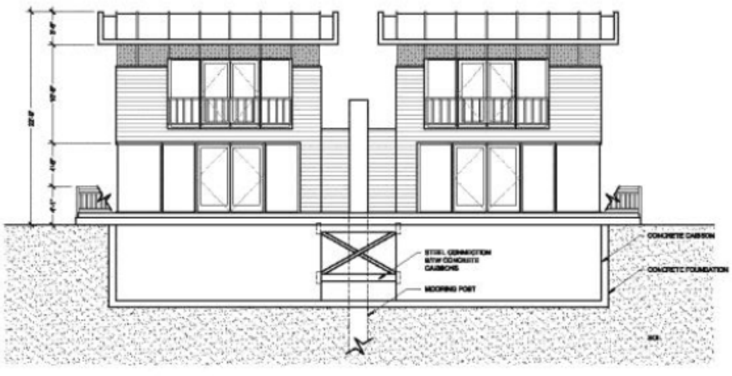
Amphibious housing system
(Factor architects, 2011)

Low water level

High water level

Amphibious houses in Maasbommel during dry period and during high water
(Factor architects, 2011)





Technical details of amphibious houses in Maasbommel, NL (Factor architects, 2011)

Summary of precedent studies

	Floating office Rotterdam	**Amphibious house** UK	**Amphibious housing** Maasbommel
Typology	Floating	Amphibious	Amphibious
Size	4500 m²	225 m²	120 m²
Maximum vertical rise	n/a	2,5 m	5,5 m
Foundation system	15 concrete pon-toons, used for installations	Concrete box, used as living space	Concrete box, used as living space
Building material	CLT, modular	Timber frame	Timber frame
Weight of building construction	Unknown	250.000kg	97.000 kg (of which 70% is the concrete foundation)
Advantages	+ Self sufficient + Always accesible + Energy neutral + Heat exchange system generates energy from the river	+ Occupants can still use their garden + Looks like a nor-mal house + Makes living near the river possible again + The concrete ‘ground floor’ has been recessed out of sight	+ Attached houses minimize runout of waves + Always accesible, because of floating infrastructure + Safety during floods
Disadvantages	- Building can not be moved to another place because of its size - The space in the pontoons are not used as living space	- Dirt can get into the container, ma-king the house unstable -During a flood a boat is needed to access the house - Costs around 20% more than a similar sized house	- The concrete ‘ground floor’ doesn’t look attractive - Small terrace - No windows in the concrete basement, which makes this space unlivable

Table 1: Analytical overview of three floating or amphibious buildings (Own work)

2.4 SUB-CONCLUSION

The chapter "Living with Water" explained the pressing architectural challenges posed by a changing climate and the resulting floods in the Netherlands, particularly regarding the vulnerability of buildings and infrastructure. As floods compromise structural integrity, the aftermath can result in significant damage, including water infiltration, material deterioration, and health hazards due to mold growth. The impact on property value and uninhabitable zones due to these risks highlights the urgency of exploring innovative strategies to tackle these issues.

Reflecting on Groningen's historical issues with water management reveals a longstanding battle with flood threats, showcasing the evolution of protective measures like the "wierden." Despite significant advancements in dike systems, recent flood events signify the limitations of conventional defense strategies.

To answer the sub-research question, “What are the current typologies of living with water in wetlands?”, there are explored various types of living with water, such as statically elevated buildings, permanent floating structures, and the less common amphibious constructions. While each approach offers qualitities, the analysis substantiates the adaptability and viability of amphibious buildings in Groningen's landscape. These amphibious constructions emerge as an optimal choice due to their capacity to mitigate risks while harmonizing with the environment and coexist with nature. Unlike elevated structures or permanent floating buildings, amphibious constructions minimize landscape alterations, preserve aesthetics, and assure continuous inhabitability despite water fluctuations. It also offers a solution to the shortage of land available for housing, especially on riverbanks.

The third paragraph delved deeper into floating techniques and amphibious constructions by getting inspiration from innovative projects like the Global Center on Adaptation's floating office in Rotterdam, the UK's first amphibious house by Baca Architects, and the Dutch amphibious housing experience in Maasbommel. Analyzing these projects showed how to achieve long-term performance and scalability with floating structures. It also concluded the factors influencing comfort and stability in an amphibious house. The case study analysis also shows that the advantage of amphibious living is that it offers a solution to manage floods without evacuation or damage, providing flexibility and a sustainable building. Challenges for amphibious houses are the affordability, laws and regulations and accessibility during high water.

In short, it can be concluded that specific innovations in architecture can significantly contribute to tackling environmental problems, from which the details and potential will be further explored in the following chapters.

CHAPTER 3

CONSTRUCTION TECHNIQUES FOR AMPHIBIOUS BUILDINGS

3.1 PRINCIPLES OF CONSTRUCTIONS WHICH CAN ADAPT TO THE CHANGING WATER LEVEL

This paragraph further elaborates on different amphibious construction techniques. Five concepts are developed and compared, which resulted in an overview of advantages and disadvantages of the different concepts (see figure). These conditions are useful for the decision-making process during the design phase of an amphibious housing project. Furthermore, a certain typology can be identified within this construction principle. The technical aspects to make these principles work will be further elaborated in the following paragraphs.

The first concept consists of a concrete box which functions both as living space and as a floating waterproof pontoon. To keep the building consistently upright on its ground, a small elevation with concrete foundation piles has been constructed upon which the building stands.

The second principle is based on the construction technique of the previous discussed case study from Baca Architects. This system works with a sunken cellar in a pit in the ground, which fills with water during floods. In practice, with this system it could be difficult to clean the pit if residue falls into it after a high water level. The stability is here achieved with mooring posts.

For the third amphibious system, the pontoon consists of hollow tubes, instead of a concrete box. Around the house, a platform is attached, which also contributes to balance. The advantage of this platform is that you will always have dry feet when stepping out of the house during high water. As a disadvantage, this system always is in the situation where the house is higher and the ground floor cannot be used.

In the fourth design, fixation is achieved using poles embedded in hollow guidance poles in the ground to manage stability, instead of the mooring posts from the previous concepts. The advantage of this principle is that the construction is relatively out of sight. However, it can be difficult to provide maintenance to the guide posts when this may be necessary after prolonged use. It is also not known whether the poles will release smoothly when the building starts to float. Instead of a concrete box, a box filled with styrofoam is applied in this design.

The last concept involves again a floating concrete box. The fixation takes place by poles which disappear into hollow guidance poles in the ground, but this time on the side of the building. A wider foundation is expected to provide a more stable structure.

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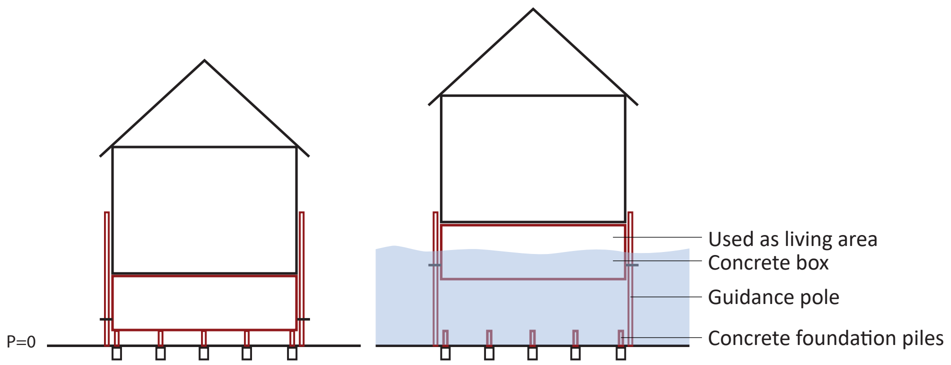

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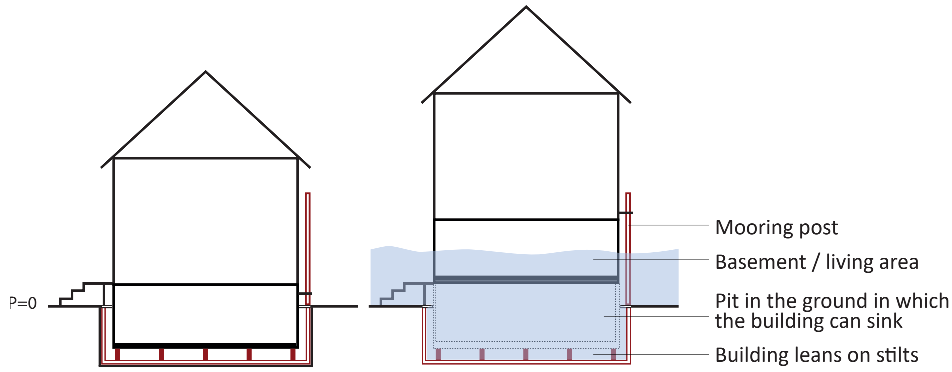

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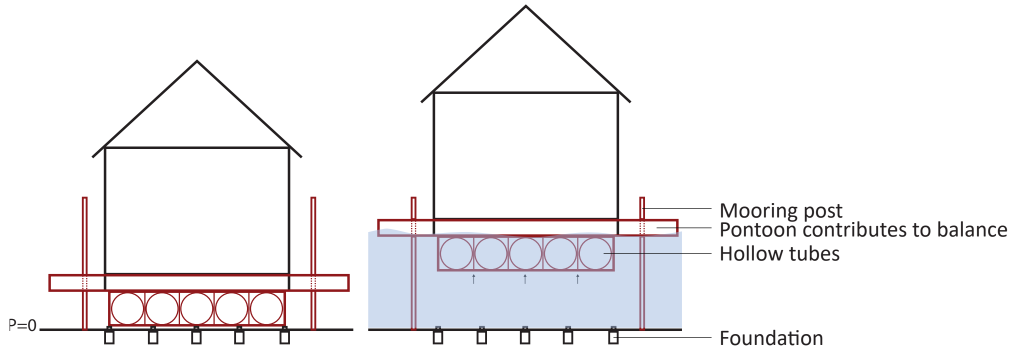

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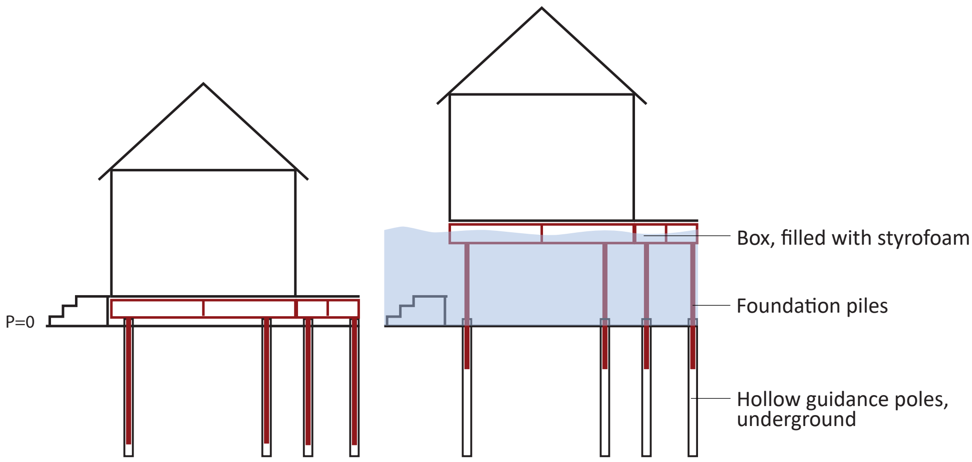

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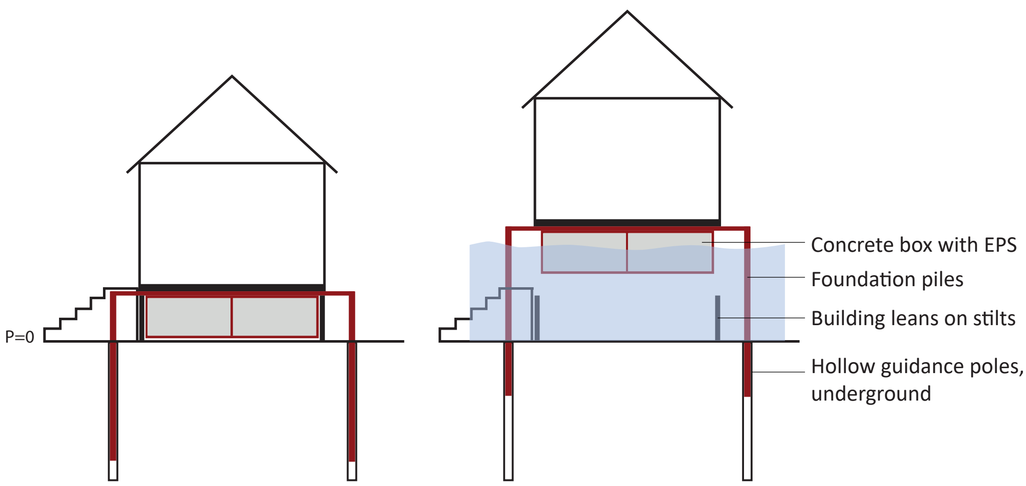


Amphibious construction concepts (Own work)

Comparison amphibious foundations

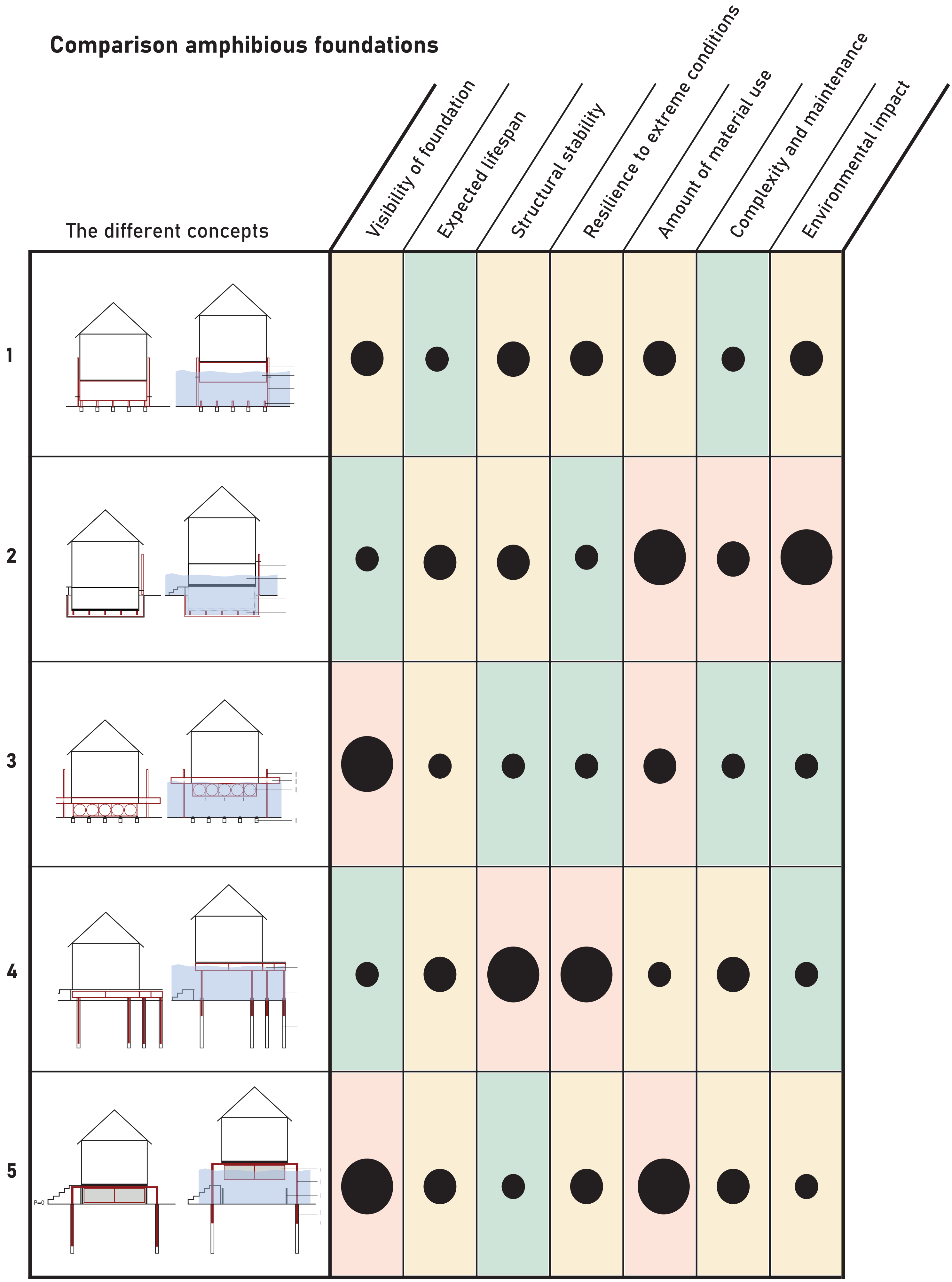
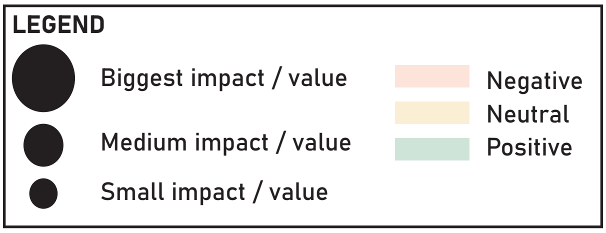
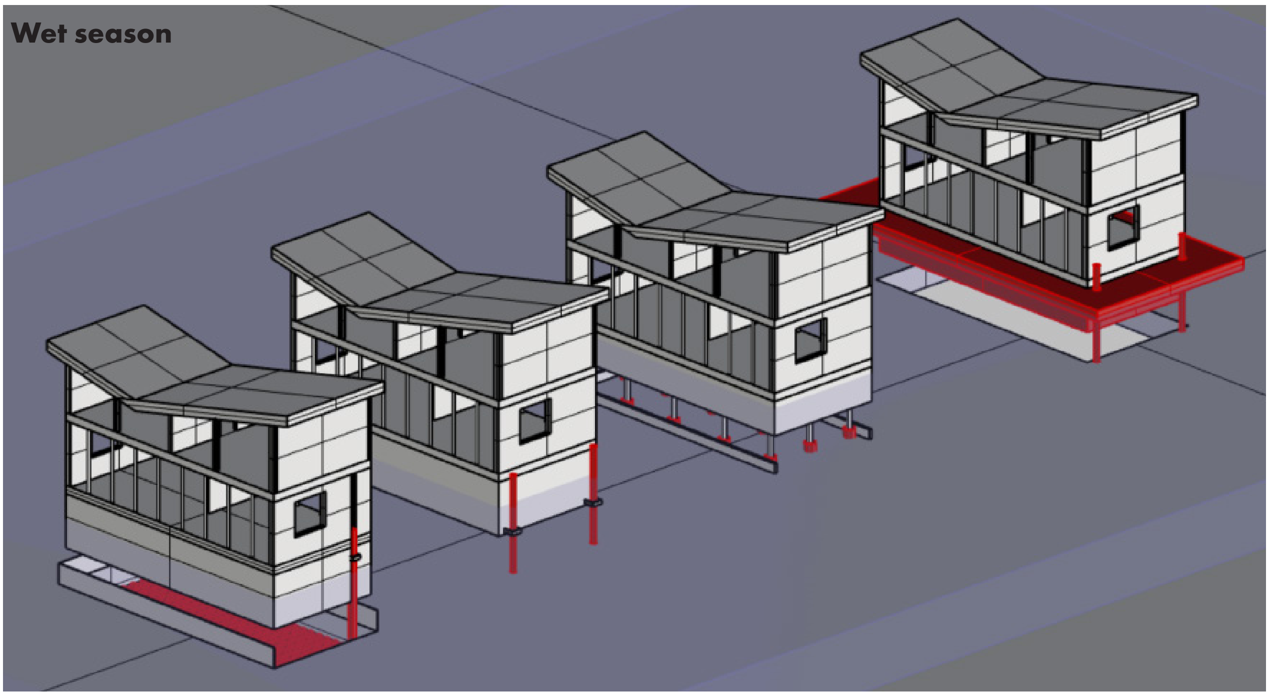


Table 2: Value analysis of amphibious foundation concepts

Table 2 gives an overview of a comparison between the five different concepts for amphibious foundations. The concepts are compared on multiple measurable values. The results are based on estimates, technical insights and experiences from case studies. From this comparison, it can be concluded that each concept for amphibious foundations presents distinct strengths and considerations based on the evaluated values. The structural stability stands out in concept 3 and 5, where a wider pontoon has been used, which also results in a better resilience to extreme weather conditions. Additionally, concept 4 emerges as the most eco-friendly choice, promoting habitat preservation and minimal disturbance to the surroundings. Concept 2 stands out for its minimal visibility of the amphibious construction, because the building is sunk into the ground. This also contributes to higher community acceptance. In principle, several concepts could be implemented using a submerged foundation in the ground, but this consideration is weighed against the complexity and cost of the system and its impact on nature. Later on, this consideration is related to other specific design requirements.

These comparisons emphasize the need for a holistic approach, considering specific project requirements and environmental considerations to select the most suitable amphibious foundation for a design. Different techniques from these concepts could also be combined to achieve the best result, such as a wider pontoon in combination with a concrete box. The individual techniques are further discussed in more detail in the following paragraphs.





3D visualisation of some amphibious construction concepts (Own work)

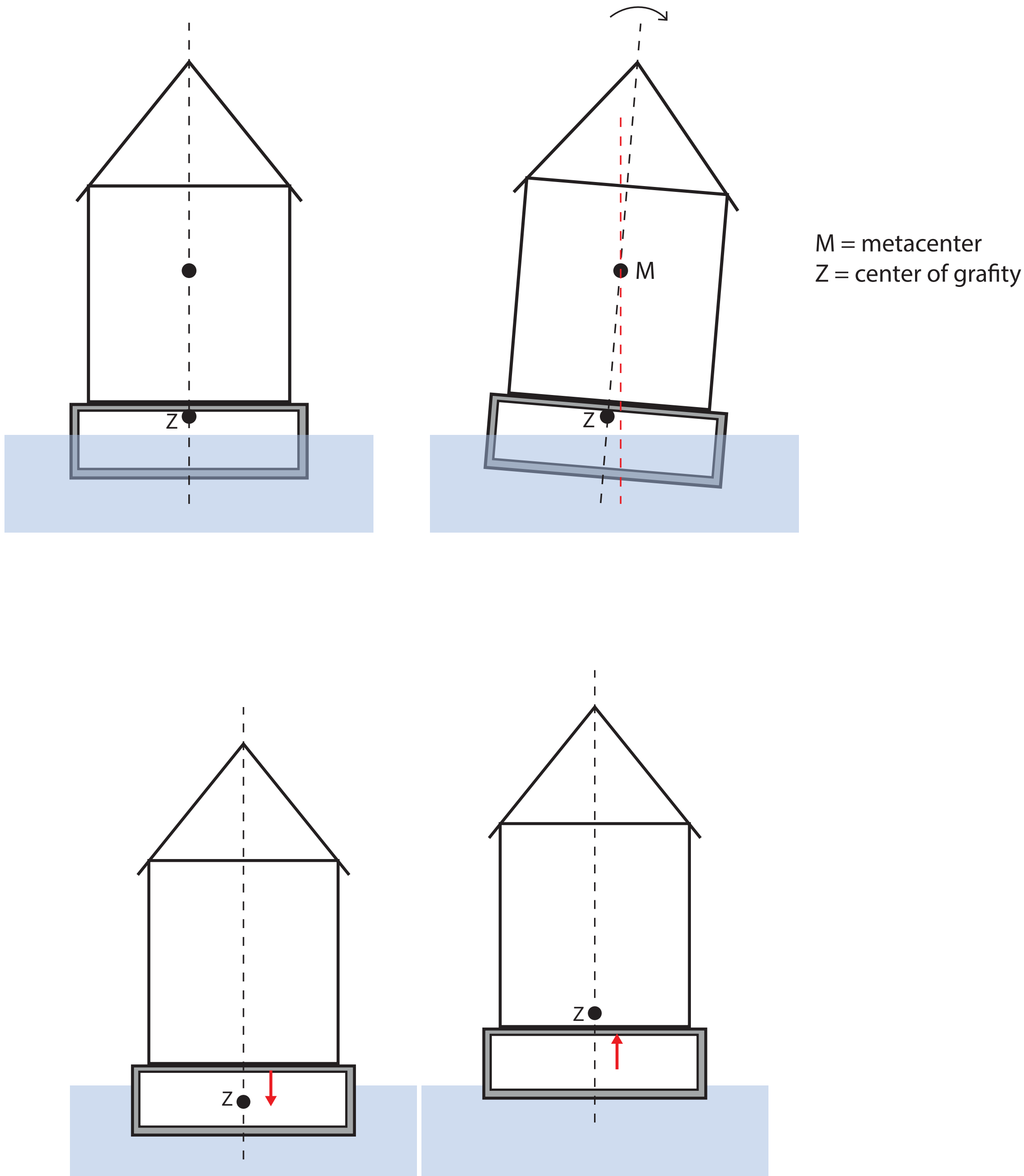
3.2 STABILITY AND CENTER OF GRAVITY

The stability and center of gravity of floating pontoons in buildings are crucial aspects that determine the safety and functionality of amphibious structures (Van Winkelen, 2007). Floating pontoons serve as the foundation for amphibious buildings. Their stability is paramount to ensure the overall stability of the structure, especially during fluctuations in water levels. The design and buoyancy of these pontoons must provide adequate stability to support the weight of the building above and withstand external forces like currents or waves without tilting or capsizing. The main factors for a stable pontoon are the shape, size and the material of which it is made. A wider pontoon for example promotes better balance. The material is important for the weight of the structure, because a heavier pontoon lies deeper in the water and is more stable, which is shown in the figure below (Witsen, 2012).

The center of gravity is the point where the entire weight of the building and pontoons can be considered to act (Van Winkelen, 2007). For stability, the center of gravity should align with the geometric center of the pontoons. Any shift in the center of gravity, especially towards the edges of the pontoons, could lead to instability (see figure). The ratio between height and width of the building is important here. Also, the maximum height of a building can be calculated on the basis of the position of the meta center towards the center of gravity (Van Winkelen, 2007). The position of the center of gravity is determined by the mass of the building structure and the mass of the floating foundation. The best option for a stable construction is a heavy foundation and a lightweight building structure, which results in a low center of gravity. The higher you build, the higher is the center of gravity, which has larger consequences when the center of gravity moves.

Another influencing aspect for the stability of the floating building is the furniture. Especially, the kitchen and sanitary facilities are of relatively large weight. This can be compensated by making specific walls thicker or by making counterweight in the concrete foundation (Witsen, 2012).

Furthermore, the movements of waves affect stability. Particularly the wavelength of the waves is crucial. It refers to the distances between two wave peaks where you aim to prevent an object from moving along with the wave (Vedder, 2023). Ideally, you want the object to always have at least two wave peaks underneath it. This ensures that the wave rolls beneath it, anchoring the object consistently on two wave peaks. If the object is smaller, it may move with the wave, depending on the wave height and the weight of the building. The most effective way to counter this is by increasing the surface area, so the width of the floating body.



Low grafity center (heavy foundation + light building)
+better stability
+less rotations
-more likely to sink

High grafity center (light foundation + heavy building)
-less stable
-change on rotation
+will not sink

Stability figure (Own work)

3.3 DEPTH, SIZE AND MATERIAL OF PONTOON

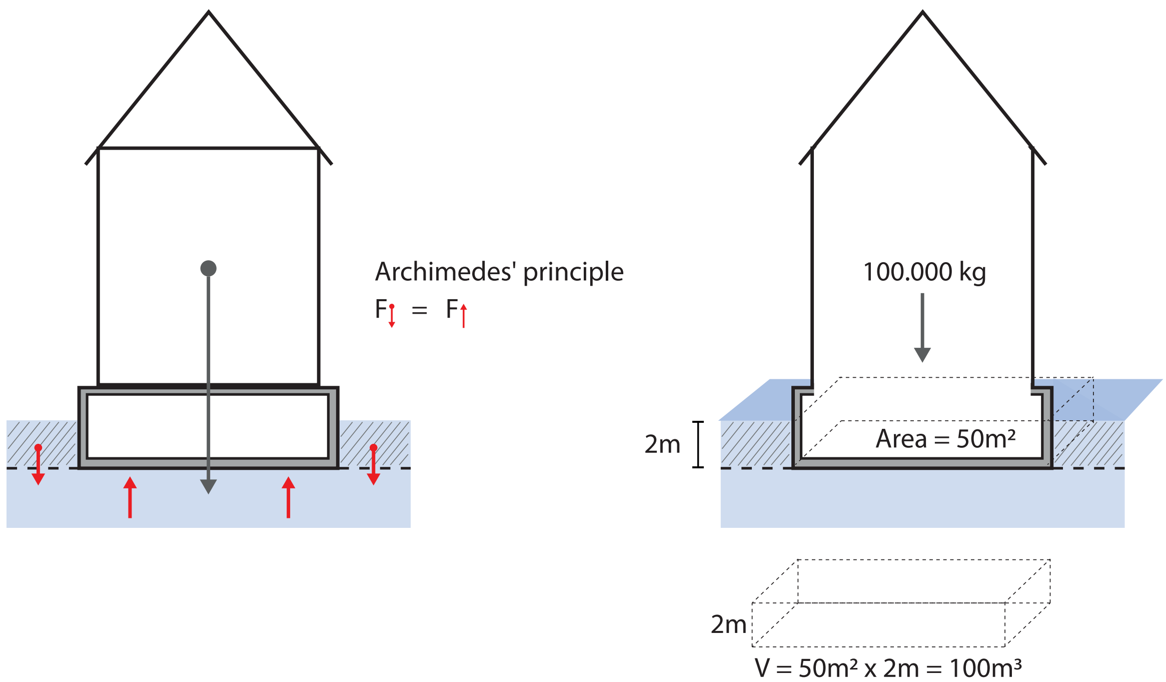
The floating capacity and the depth of the pontoon can be calculated by a physical principle. A house weighing 100.000 kg displaces precisely the same weight of water. This fact dates back to Archimedes' principle, which states that the upward force is equal to the weight of the volume of fluid displaced (Witsen, 2012). 100.000 kg mass which pushes the water equals 100 m² water which is pushed aside. When distributed across an area of 50 m², this results in a depth of two meters. Consequently, the house will not sink deeper. This is shown in the diagram on the next page.

Based on this principle, it means that a lighter construction requires a less deep pontoon. The same occurs with a larger surface area, resulting in a shallower depth. The other way around, it can be concluded that a heavier building lies deeper in the water or also needs a higher pontoon.

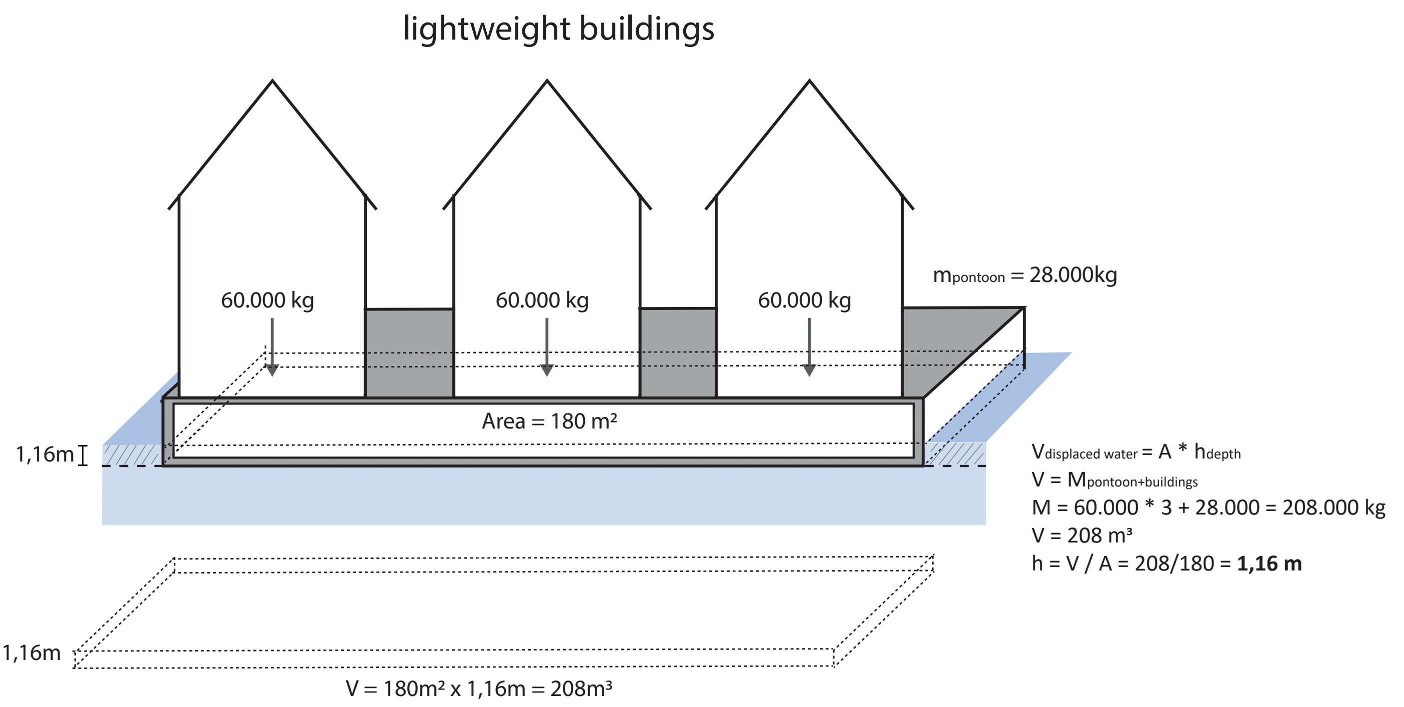
We will go through another calculation example to see what happens on a much larger scale. The two situations both consist of three buildings of the same size and a similar pontoon. The only difference is the weight of the buildings. In the first situation, the buildings have a mass of 60.000 kg and in the second situation the buildings are 120.000kg. The lightweight situation results in a depth of 1,16m. The second situation has a depth of 2,15m (see figure).

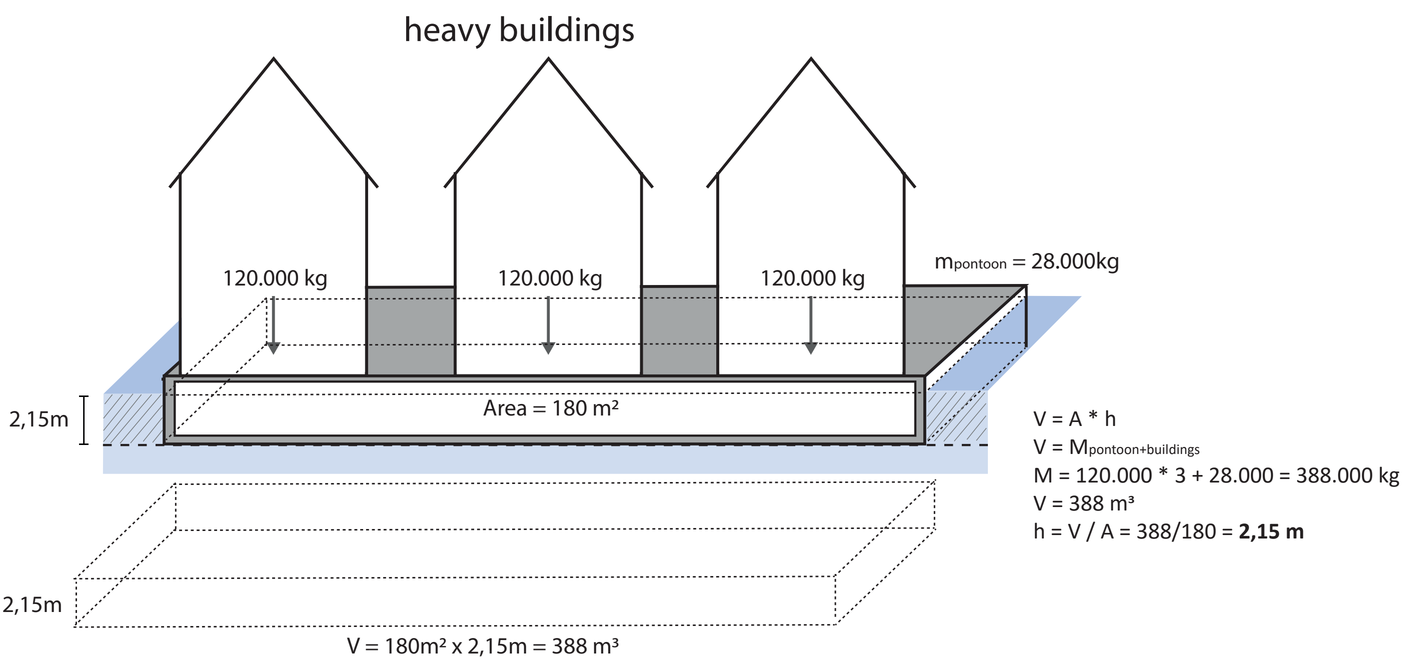
In the ideal situation the pontoon can be used as living space, which means it requires windows. The preconditions are therefore that the maximum draft is 1.6 m. The challenge is how high and large you can build to meet these conditions and also guarantee stability.

In addition to the dimensions of the pontoon and the weight of the building structure, there is another aspect that influences the draft. That is the material and type of pontoon. On the next page, these different floating structures are explained.



Floating capacity, based on Archimedes' principle (Own work)





Comparison depth of pontoon by lightweight and heavy buildings (Own work)

Floating pontoons do exist in various types, each designed to serve specific purposes and accommodate different environments. These are some of the most common types:

Closed concrete pontoon: These are durable and heavy, often used for larger structures or in areas with harsh conditions. They provide stability and can be interconnected to create larger floating platforms. This floating body has a large mass, which has two consequences. The system has a low center of gravity and therefore a good stability. However, the building on top of the pontoon is limited in its weight, because otherwise the whole structure has a possibility of sinking too deep into the water. The pontoon itself can be used as living space.

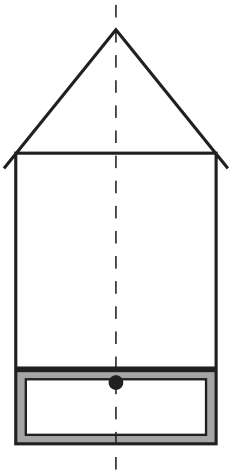
Open concrete pontoon: This system comprises a concrete box that is open at the top. The walls and the base of this type of floating body experience significant pressure from the water, due to the relatively substantial draft and the low center of gravity (Van Winkelen, 2007). A draft between 0,75 meters and 2 meters is common. The space within the box can serve for technical installations, piping, and potentially as usable space. An advantage of this type of floating body is the possibility of installing and inspecting connections between floating bodies from the inside. It's also technically feasible to install connections below the waterline.

EPS core: These pontoons consist of a concrete box filled with EPS. The system offers buoyancy while being lightweight. They are commonly used for docks, terraces and in smaller recreational floating (Vedder, 2023). The system is useful when the space within the foundation is not necessarily required to use. The pontoon is mostly shallower and lies higher in the water surface. The benefit of filling with EPS is that it allows to reduce the concrete thickness, leading to cost savings.

Hollow tubes: A system with air-filled tubes offers buoyancy to keep the structure afloat. These systems commonly feature tubes made of materials like high-density polyethylene (HDPE) or other lightweight yet durable materials (Varkey & Philbin, 2022). An advantage of this system is that it often incorporates modular elements, which makes it easy to adapt. A consideration is that the load capacity of these systems might have limitations compared to heavier, solid pontoon systems. Also, extreme weather conditions or prolonged exposure to UV rays might affect the durability of certain materials over time.

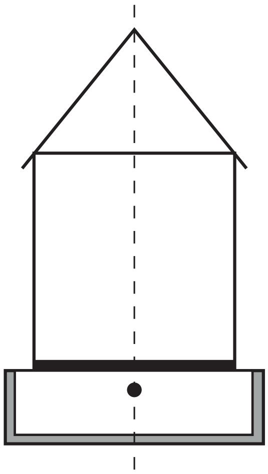
Catamaran pontoon: These pontoons consist of two parallel hulls connected by a deck or a structure. The wider separation between hulls lowers the center of gravity, contributing to improved stability. Moreover, the dual double pontoon allows for a larger surface area, enabling greater load-bearing capacity and accommodating heavier structures. (Van Winkelen, 2007)

In conclusion, expanding the pontoon's width rather than its depth is preferable if the floating body's capacity needs to be increased (Van Winkelen, 2007). This also means that a higher building is achievable. Additionally, a higher building can be achieved by bringing the material to the outside of the floating body. Choosing the best pontoon type depends on factors like the intended use, weight considerations, space requirements, and environmental conditions. It's crucial to weigh these factors against the advantages and limitations of each pontoon type to make an informed decision for the specific project.



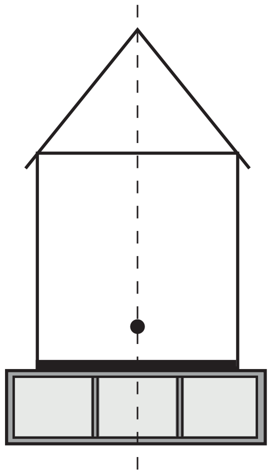
Closed concrete box

Can be used as basement or installation room. Air in the box makes the system float. Large mass.
Depth = 1 - 2m



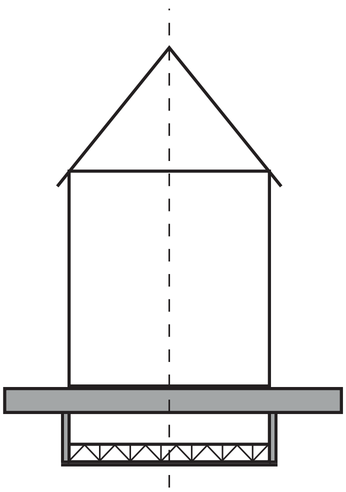
Open concrete box

Has a lower center of gravity
Depth = 0,75 - 2 m



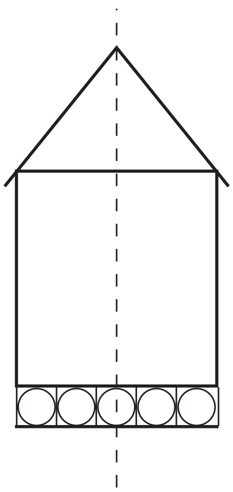
EPS core

Instead of air this concrete box is filled with EPS, results in a thinner concrete shell and a lighter system, which is unsinkable.
Depth = +- 0,5m

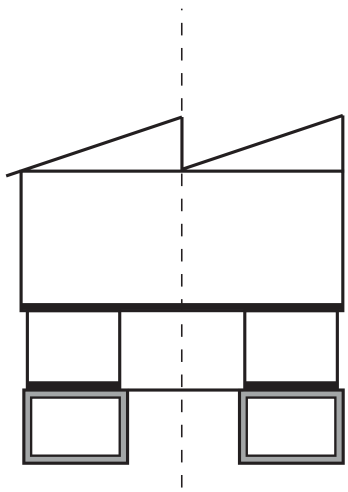


Floating platform

Steel frame for stiffness.
A wider pontoon means a higher achievable building height



Hollow tubes



Catamaran construction

Less rotation sensitive.
Needs a connecting construction.

Floating structures for architectural applications (Own work)

3.4 FIXATION OF AMPHIBIOUS BUILDINGS

Horizontal fixation of a floating or amphibious building is a critical aspect to ensure its safety in water environments and it contributes to improved stability by securing against external forces like waves or wind. There are different types of fixation methods for buildings, like a mooring system, piles, tension cables, integrated support structures or dynamic fixation systems. The methods must strike a balance between securing the structure and allowing controlled movement in response to natural forces (Witsen, 2012).

In traditional static houses, utility connections are typically rigidly established, maintaining a fixed position throughout the building's lifespan. The utilities consist of water, sewage and electricity. However, in buildings designed to adjust in height, the utilities must be flexible and move along with the building's fluctuations. Because of the permanent location of an amphibious building, it can still connect their utility services to municipal pipes for convenience, in contrast to houseboats which need to internally contain all essential utilities within their structure due to their mobile nature and varied mooring locations (Anderson, 2014). One possible way of applying an adaptable utility system can be done with pipelines which break on their own when the building rises (Varkey & Philbin, 2022). Another option involves extended, coiled lines that can stretch as the house adjusts in height (Anderson, 2014).

A system utilized in floating homes in Amsterdam involved a special attachment system in the concrete foundation: a type of rail to which the cables and pipes could be attached, preventing them from being loosely positioned while allowing ample space for maintenance work (Witsen, 2012).

A flexible pipe connection for floating and amphibious buildings (Witsen, 2012)

Mooring posts of amphibous houses in Maasbommel (Dura Vermeer, 2005)

3.5 SUB-CONCLUSION

The exploration of construction techniques for amphibious buildings has resulted into a nuanced interplay of essential principles for structures adaptable to changing water levels while ensuring stability and structural integrity.

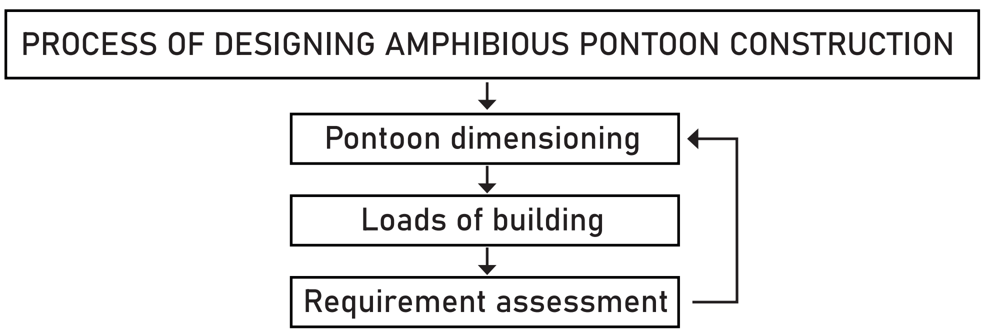
The subquestion of this chapter was "What technical principles are there for amphibious constructions that can dynamically accommodate varying water levels while ensuring stability and structural safety?".

One of the key findings is that stability is the most important aspect to tackle. To keep a floating building steady, it is most useful to design a lightweight top part and a heavy and strong pontoon. This creates a low center of gravity. Ideally, the concrete basin can be used as a residential function, which is realistic if the maximum draft of the pontoon is 1,6 meters to facilitate windows at eye level.

Another aspect which is discussed is the scalability of the building. Hereby, the relation of the height of the building and the width of the pontoon is important. Making the pontoon's surface area bigger contributes to improved stability, which allows larger buildings to build on top of the pontoon. When the footprint of the building is smaller compared to its height, it negatively affects the stability. So this sets limitations for the form of an amphibious building. Another way of creating a larger surface area and better stability is using a catamaran pontoon or U-form pontoon. These pontoons can significantly contribute to larger-scale building because it offers increased stability compared to single-hull pontoons. The wider separation between hulls distributes the weight of the structure more effectively, minimizing tilting or instability. Furthermore, less material has to be used for the pontoon, while the same or even better results are achieved.

Attaching the structure to mooring poles ensures that the building is completely fixed. It's also crucial to make sure that the metacenter remains above the center of gravity, otherwise the building will tilt. Extra effort to connect the waterproof utilities and extra infrastructure must be taken into account. This can also lead to higher costs.

The technical principles uncovered here are useful for future innovations in amphibious constructions. These principles, as stability, adaptability, and safety, propel the evolution of structures resilient to water-level dynamics, promising a sustainable and versatile future for amphibious architecture. Overall, the benefits of amphibious buildings outweighs the challenges and it can save a lot of flood damage to buildings and more available land to build on.



CHAPTER 4

PAPER AS BUILDING MATERIAL IN LIGHTWEIGHT CONSTRUCTIONS

4.1 The advantages of paper in constructions
4.2 Load bearing purposes
4.3 Paper construction techniques
4.4 Paper, wood or steel construction for amphibious architecture

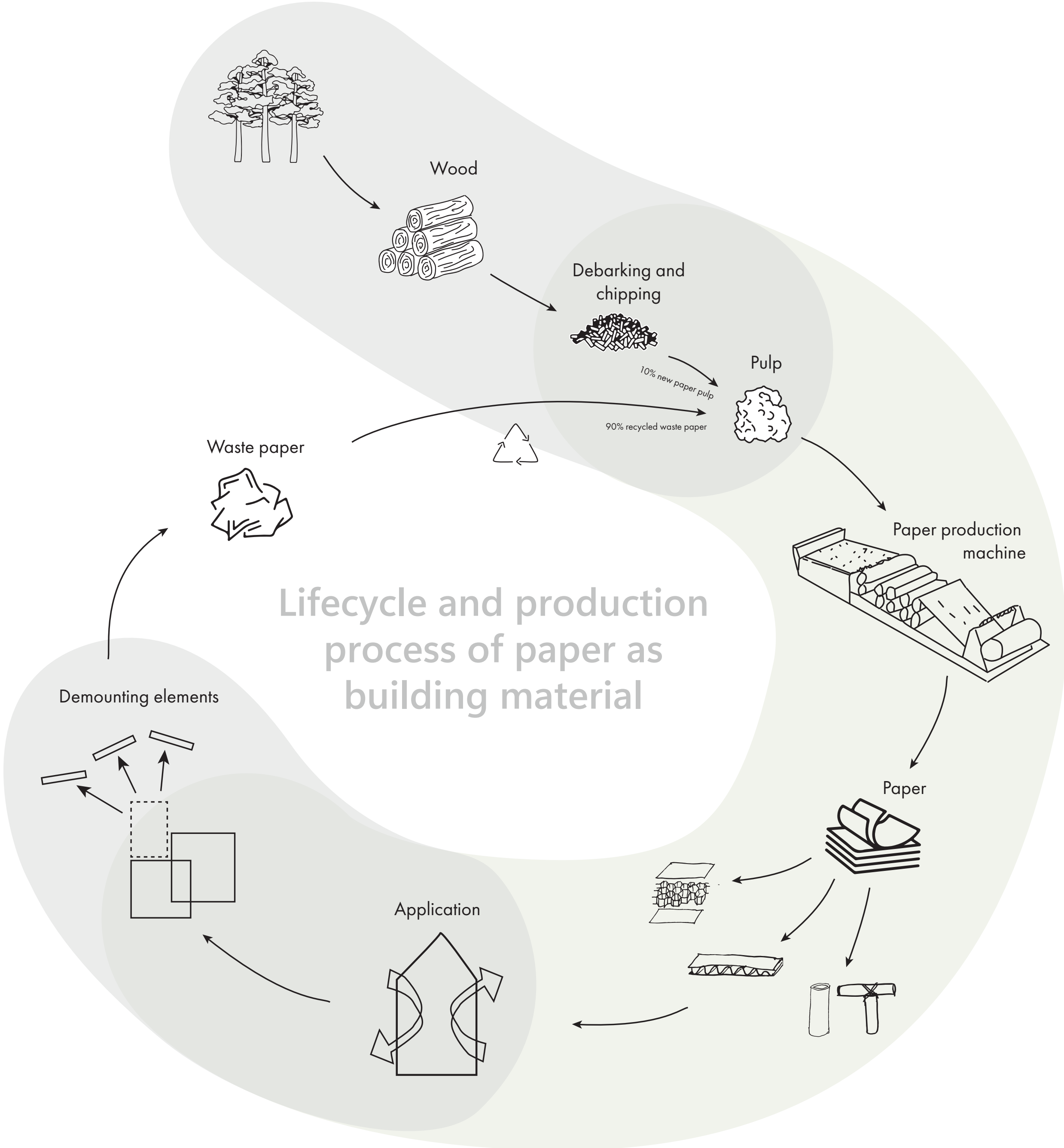
4.1 THE ADVANTAGES OF PAPER IN CONSTRUCTIONS

From the previous chapters, it has emerged that for optimal stability, a lightweight building is desired on the heavy basement/pontoon. In floating building reference projects, a timber frame is often used for the construction of the house. To see if we can go even lighter, this chapter explores the possibilities of building with paper and cardboard. The hypothesis of this thesis was that paper can offer probably new opportunities for floating or amphibious architecture. The question is to what extent paper constructions are useful for amphibious building and if it could meet the load-bearing and insulation purposes.

Paper as a building materials contributes to achieving carbon-neutral and sustainable architecture. This type of architecture can be defined as “buildings designed to limit humanity's impact on the environment and enhance human well-being” (Vaccari, 2008). The 21st century has made a significant contribution to the development of building materials, mostly because of the emergence of sustainable construction as a result of growing environmental concerns. Nevertheless, building with paper is not yet widely applied, because there is a scarcity of defined technical possibilities and validated evidence on its endurance when used in the building industry that can be verified scientifically.

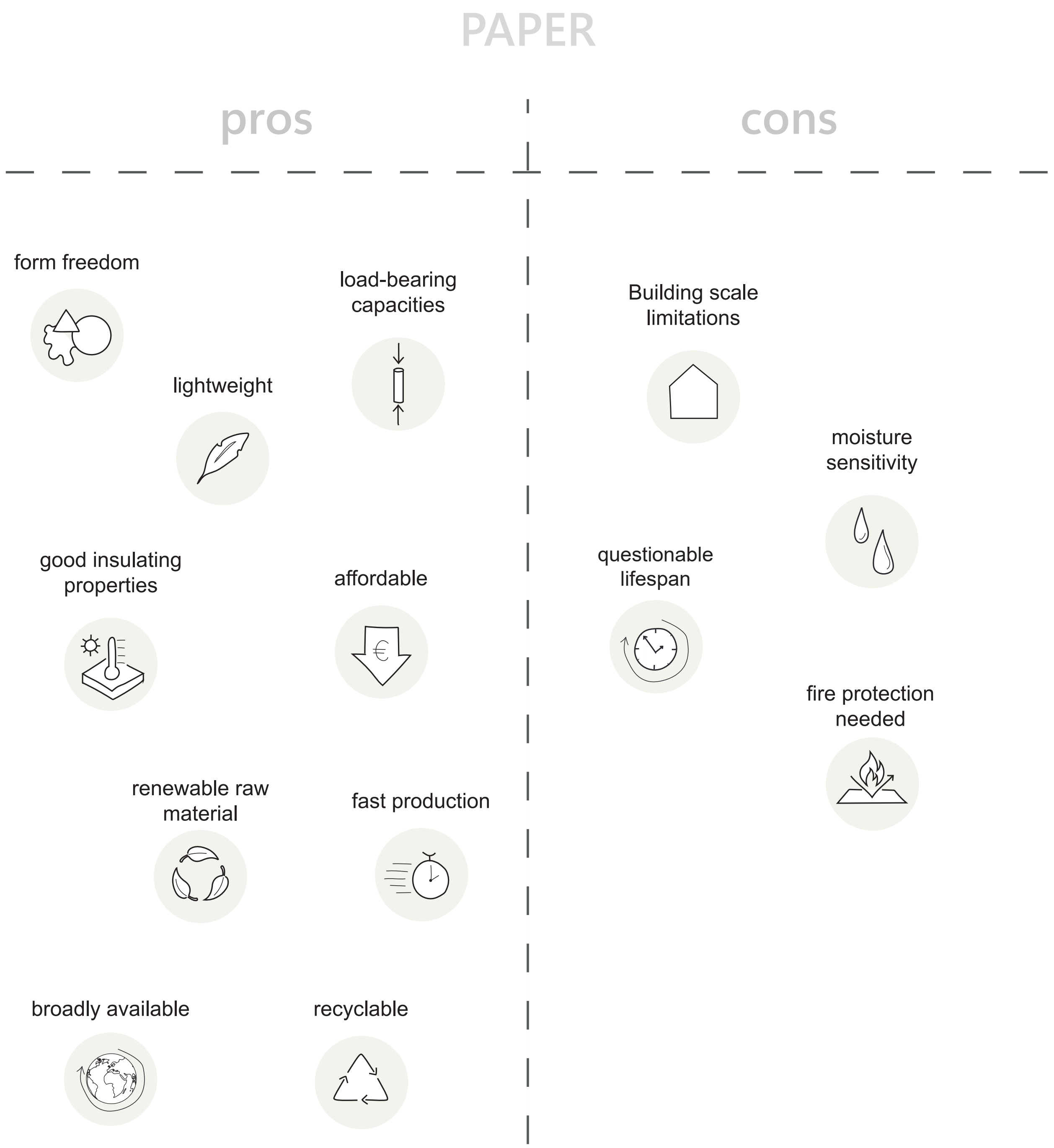
Paper is a planar substance produced by processing plant-based cellulose fibers derived from wood pulp, rags, straw, or other fibrous materials (Latka et al., 2022). A paper sheet is formed by removing the water from previously soaked fibers on a screen. To overcome the adhesive forces and break down the wood into usable fibers, mechanical and chemical wood pulp processes are used. Paper is a robust and flexible material. A more voluminous and resilient paper-based material is cardboard, which comprises several thicker layers of pulp (Knaack et al., 2022). Cardboard is available in different types, like the corrugated fibreboard, sandwich structures and paper tubes.

The lifecycle of paper typically begins with the harvesting of trees, which are then processed into wood pulp. This pulp, which mainly consists of cellulose fibers, is mixed with water and then formed into sheets, pressed, dried, and cut into various sizes (Knaack, et al., 2022). Once manufactured, paper products can be used for a wide range of purposes, including writing, printing, packaging, and technical applications. After using it, paper can be recycled, where it's collected, processed into pulp again, and used to create new paper products. To make new paper, 90% of recycled waste paper can be used. This process is shown in the figure below.



Lifecycle and production process of paper as building material (Own work)

Paper is a robust and flexible material with great potential for the building industry. Moreover, it has a natural composition, which makes it easily recyclable after its lifespan. In this way, this sustainable building material contributes to reducing the environmental impact of construction activities. However, it also has its limitations, for example when it gets in contact with water or fire which reduces its strength. The following diagram gives an overview of the advantages and disadvantages of paper and cardboard as building materials.



Overview of advantages and disadvantages op paper as building material (Own work)

Why would we build with cardboard in our future amphibious buildings in the Dutch landscape?

In the current construction industry concrete and steel are commonly used as building materials (Latka, 2017). However, the production and use of these materials have negative environmental impacts for several reasons. First of all, both materials require a significant amount of energy during their life cycle for mainly production, transport and demolition (De Herde & Evrard, 2005). The production of cement, a key component of gluing the sand and gravel together to form concrete, involves heating limestone and other materials to very high temperatures, which is the biggest contributor to the emission of carbon dioxide (CO_2) into the atmosphere (Brouwers, 2022). Similarly, steel production involves the use of furnaces that require a lot of energy, often sourced from fossil fuels. Moreover, concrete and steel are heavy materials in comparison to natural and renewable materials like cardboard, which means that transportation to the construction sites can result in more emissions from trucks and higher fuel costs (De Herde & Evrard, 2005). Furthermore, demolishing buildings made of concrete or steel generates in the Netherlands the largest amounts of waste, around 25% of the total waste production of all industries, and it is hard to recycle these traditional building materials (CBS, 2019). Currently, only 10% of concrete waste in the Netherlands is reused in new concrete, while the paper industry is able to recycle 89% of its marketed paper (PRN, 2021). So paper as building material could be interesting for multiple reasons when compared to traditional materials.

With a growing emphasis on sustainability and eco-friendly construction practices, multiple researchers and designers have explored the potential of paper and cardboard in architecture and they have found new innovative applications of this building material. Their lightweight and durable properties make them ideal for constructing environmentally-friendly structures, from temporary pavilions and art installations to cost-effective, eco-conscious housing solutions. Some details of these construction techniques are analyzed in the next paragraph.

It is still debatable if paper-based constructions is how we should build in the future in the Netherlands. It raises questions regarding long-term durability, regulatory compliance, and scalability for large-scale projects. The shift towards eco-friendly construction practices demands a careful balance between sustainability, structural integrity, and practicality. Therefore, the discourse around future building methodologies in the Netherlands involves weighing the environmental advantages of this alternative material against the established reliability of traditional ones. After first analyzing the technical details of structural paper applications, a comparison is made with wood and steel in paragraph 4.

4.2 LOAD BEARING PURPOSES

During the last decades paper has emerged as an unexpected versatile material in modern architecture with innovative integrations in constructions. Advancements in paper engineering have led to the development of structural components. Its main characteristics as a sustainable, lightweight and surprisingly sturdy building material is also seen by Japanese architect Shigeru Ban (Ayan, 2009). He has one of the most notable applications of paper in architecture since he uses paper tubes and paper-based elements as load-bearing construction elements in his designs. In his work, he showcases the versatility and strength of the material. Next to the constructional purposes, he also explored the aesthetic potential of paper in architecture, by showcasing the material's adaptability and unique shapes. Ban's use of these materials expanded beyond temporary structures, and he incorporated them into various projects, including exhibition spaces, pavilions, and even permanent buildings like museums and residential buildings. His exploration and use of the material paper also challenges traditional perceptions of unsustainable traditional building materials.

The most common current application in load-bearing paper constructions is the paper tube structure and cardboard wall components. Some of these applications and their possibilities are explained in this paragraph.

Paper tube structures

An example of a suitable load-bearing cardboard construction is the paper tube structure. Despite their lightweight appearance, paper tubes possess remarkable strength owing to their cylinder shape, which provides natural structural integrity (Latka, 2017). When configured and combined correctly, these tubes can effectively bear significant loads, supporting structural frameworks in various architectural applications. A paper tube is industrially manufactured through the lamination of several layers of paper by using adhesive (Knaack, et al., 2022).

In architectural contexts, these tubes find application in diverse load-bearing roles, including columns, beams, trusses, and even entire building frameworks (Latka, 2017). They offer versatility in design and can be customized to suit specific structural requirements, demonstrating their adaptability and reliability. While they might not be the singular solution for every construction need, the load-bearing capacity of paper tubes highlights their potential as a sustainable, cost-effective, and surprisingly durable choice in modern construction practices.

An example of an application of a paper tube structure in a building is the "Paper Atelier" in Japan, by architect Shigeru Ban. The structural framework which is designed for this atelier consists of paper tubes with a diameter of 336 mm and wooden joints positioned 1,2 meters apart. This building does not have a permanent lifespan, but it elegantly showcases the dual functionality of paper tube structures in both load-bearing and aesthetic applications.

Paper atelier Japan - Shigeru Ban (2011)

The span capabilities of paper tube structures can vary based on several factors including the diameter and thickness of the tubes, the way they are assembled, and the overall design. For smaller structures or when used in conjunction with other materials for reinforcement, paper tubes can span several meters without compromising their load-bearing capacity (Latka, 2017). However, for larger spans, it may require additional support or a combination of tubes and other materials to ensure structural integrity. An example of a large span of 14 m with a paper tube structure in combination with additional support of steel tensile bars is the “Disaster Relief Center”, also by Shigeru Ban (see figure). To make this possible, lightweight panels were used as a roof on top of the paper tube structure. The length of the tubes is 1,2 m and 2.2 m.

In the Netherlands, there is also an application of a paper tube roof structure with a span of 8 x 8 meter and a permanent lifespan, designed by the company Octatube (Latka, 2017). There are no screws in the tubes to avoid concentrated forces which could easily damage the cardboard. Instead, the paper tube frame is connected by recycled steel spheres, with pre-stressed steel threads that were placed inside the paper tubes. To prevent the paper tubes against moisture, they are sealed with carbon. Moreover, the cardboard tubes do have a high density, which makes them resistant against fire (Knaack, et al., 2022).

In these two examples, cardboard actually mimics the appearance of another material, namely steel frameworks or spans. Architects working with cardboard as a building material are often in the process of exploring and defining a unique design language specific to the material. An inherent aesthetic value that can be considered more unique is the use of cardboard tubes in load-bearing walls. An example of this application is the MDS Gallery from Japan, built in 1994. All vertical loads are carried here by the paper tubes.

A paper tube has limitations in its maximum dimensions, which depends on the maximum paper formats that can be manufactured. By spiral winded tubes, the circumferential seam joints are the weak points of the tube. It is also possible to use parallel wounded tubes, which are better resistant against breaking. However, from this winding type tube, there is only a limited availability on the market (Knaack, et al., 2022). The paper utilized in paper tube production typically varies in thickness, usually spanning from 0,3 mm to 1,2 mm (Latka, 2017). In the building industry, paper tubes can have diameters ranging from 50 to 1600 mm. In some projects of Shigeru Ban, like the Disaster Relief Center and the MDS Gallery from the images, the thickness of the tubes varies between 25 mm and 40 mm.

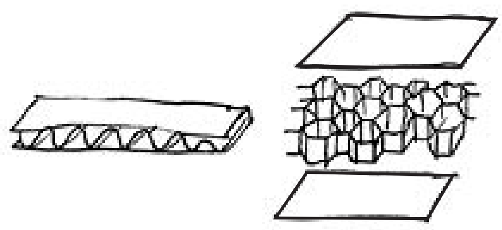
Paper tube roof and wall constructions: 1. Disaster relief center, S. Ban (2013). 2. Ring Pass Delft, Octatube (2010). 3. MDS Gallery, S. Ban (1994)

Cardboard wall components

Another load-bearing application with cardboard can be implemented in the form of a wall component. A company which developed a wall component for load-bearing purposes is Fiction Factory. These components offer remarkable balance between strength and weight. They are designed to withstand and transfer vertical forces, while providing structural stability and a minimized overall weight. Corrugated cardboard is used as the main element. The wall components consist of 24 layers of cardboard with a wooden finishing and a waterproof layer. Cardboard has good insulation values and has strong capabilities in this case. In the middle of the construction a cavity is designed, for the installations and connection of the modules (see image). The RC value of this panel is 3,5, but when producing thicker panels, a better RC value can be reached. Due to limited oxygen reaching the structure, the cardboard is not highly flammable. The lifespan of a Wikkelhouse is around 20 to 25 years. Since every module can be replaced and recycled, it is easily possible to extend the lifespan by replacing some parts of the building.

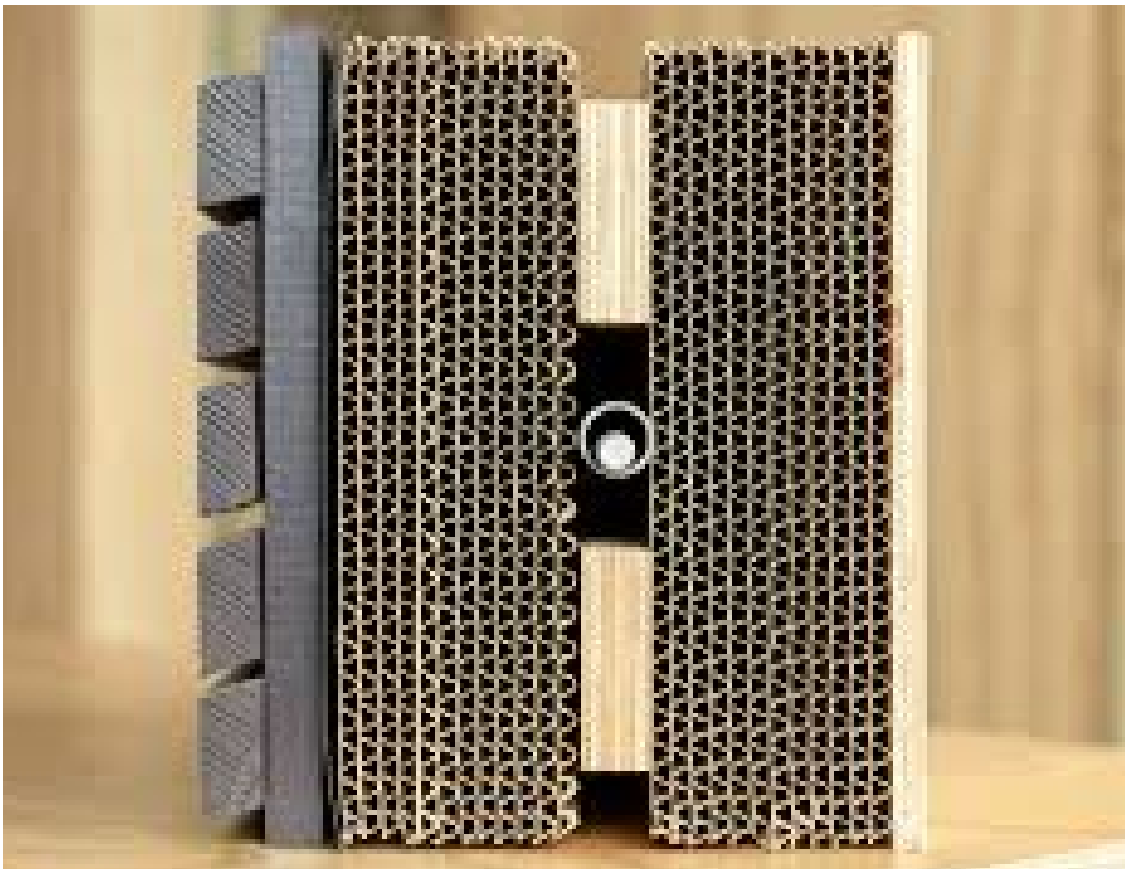
Wall components could also be made with honeycomb panels, which are low-density, cellular sandwich panels (Latka, 2017). These panels have a high compression strength. An experimental test by Ayan (2009) showed that honeycomb sandwich panels can be used as effective wall components in residential buildings. Moreover, it concluded that the insulation and acoustic characteristics of a honeycomb cardboard panel for the construction industry are promising. The biggest confrontation for cardboard wall panels are moisture, fire and local stresses, which results in loss in stability and strength. By the wall component developed for the Wikkelhouse this problem is solved by applying a waterproof layer in the component. Another way of solving this problem is impregnating the material. When compared to traditional wall components, cardboard panels are less expensive to install, it can be done quicker and it doesn't require as much skilled onsite labor.

An industry where honeycomb sandwich panels are already used in a constructional way is the aircraft industry. The weight of the construction plays an important role here, which makes cardboard very useful (Ayan, 2009).



Corrugated cardboard **Honeycomb sandwich panel**

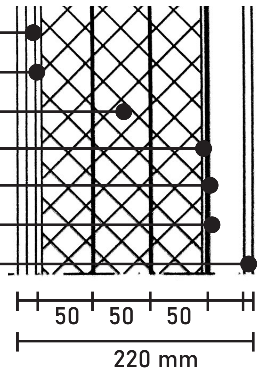
Construction process of the paper-based Wikkelhouse - Fiction Factory (2012)



Wall component of Wikkelhouse - Fiction Factory (2012)

The Cardboard School of West Borough Primary School in the UK is a building from 2001 which is mostly built of paper-based elements. In this building a combination of paper tubes and solid cardboard panels are used. The building was designed to last for at least a period of 20 years and is now considered as the first permanent paper building in Europe. To protect the building materials against fire and moisture, the paper tubes are coated and the panels are equipped with a vapour-proof coating on the inside and waterproof construction paper on the outside (Cottrell & Vermeulen Architecture, 2001). The wall panels are constructed with the following layers (from inside to outside):

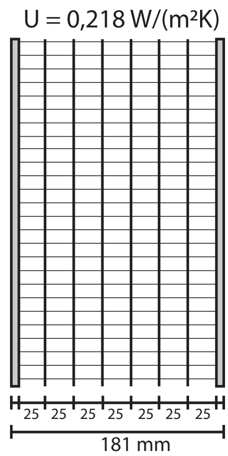
- vapour barrier
- 4 mm solid board
- 3 x 50 mm honeycomb
- 4 mm solid board
- 6 mm solid board
- waterproof paper
- 16 mm fiber cement panel cladding



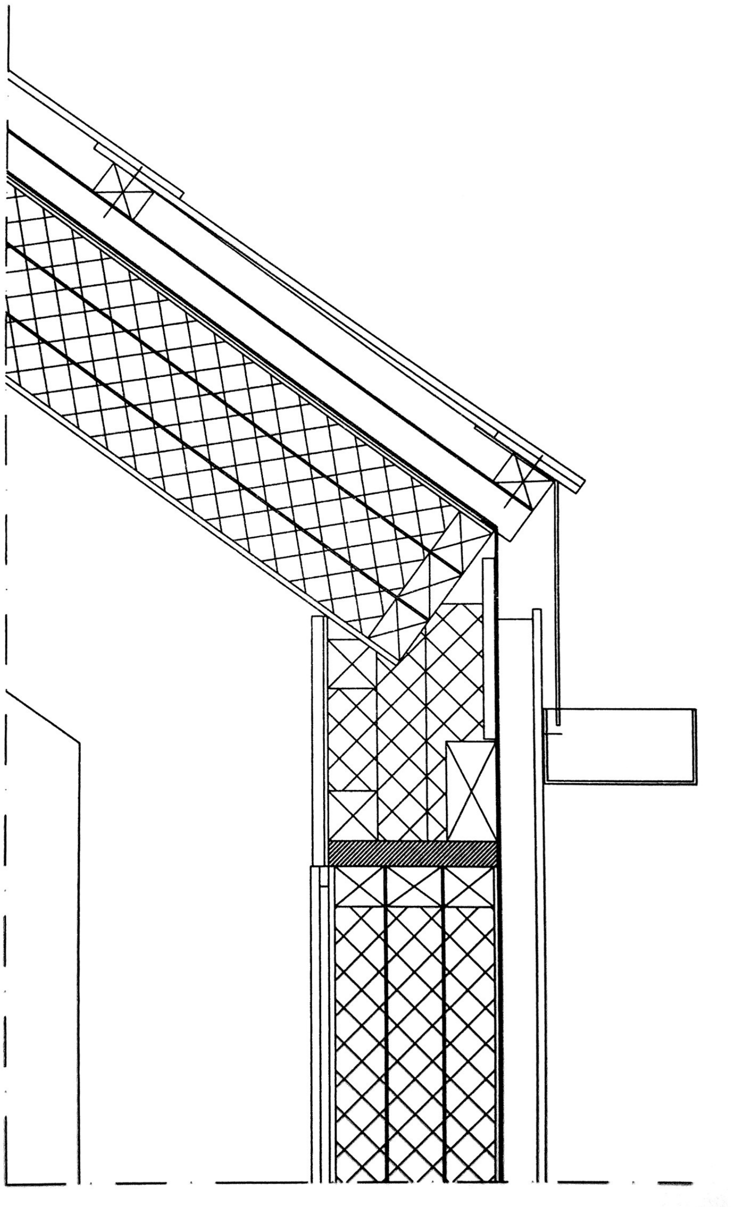
After testing it was concluded that the 4 mm thick solid board is a natural fireproof barrier. When it is exposed to fire, it charres instead of burns (Knaack et al., 2023).

The U-value of this structure is 0,32 W/(m²K). According to Bouwbesluit, the RC-value of new build structures must be 4,7, which equals a U-value of 0,21 W/(m²K). So in the Netherlands this construction must be improved to meet the values. A calculation is done in the publication “Building with Paper” which shows the needed component thicknesses to achieve a U-value of 0,21 W/(m²K). The test concluded that corrugated cardboard meets the desired value by a thickness of 230 mm. Honeycomb boards with a height of 25 mm must have a thickness of 400 mm, and solid boards a thickness of 330 mm (Jasiolek, et al., 2023). So honeycomb boards have to be thicker, but corrugated boards require less material to achieve the same value. Table 3 gives an overview of these data.

The experimental project of TECH analyzed and tested different honeycomb wall compositions and their U-values. A U-value of 0,218 W/(m²K) was achieved by a construction with 7 x 25 mm honeycomb boards and 3 mm cardboard outer layers on both sides (Knaack, et al., 2022). This construction has a total thickness of 181 mm, which is thus considerably smaller than when only one honeycomb board is used. So, it is interesting to create several narrower panels stacked on top of each other.



In conclusion, cardboard wall components have the potential to meet a building’s structural demand. Furthermore, employing cardboard as an alternative construction material not only meets structural requirements but also addresses environmental and social needs, like recyclability and cost efficiency.



Detail of wall and roof panel of Westborough School (Latka, 2017)

4.3 PAPER CONSTRUCTION TECHNIQUES

Cardboard tubes as structural elements

The utilization of cardboard tubes as structural components showcases their remarkable load-bearing capacity. These tubes, constructed from layered and bonded paper, offer robustness while maintaining a lightweight nature. Their cylindrical shape provides inherent strength, ideal for creating frameworks in various architectural applications. Whether used as columns or beams, these tubes demonstrate versatility and strength in supporting vertical loads. The paper tubes can be made in different sizes and thicknesses.

There are many options for connecting the tubes. It is important that the connecting element is carried out carefully, because these points are the weak places of the construction (Latka, 2017). A screw in the paper tube even already influences the strength, which means that it would be better if no screws are required, so that the compressive strength of the material is used. A solution for this problem is developed by the company Octatube, who came up with the idea of joining each tube with a 10 mm threaded steel rod inside the tubes, which was equipped with a steel lid on the ends (Latka, 2017).

The material of the connection element affects the expression of the framework and also determines how durable the construction remains. The first variant of the figure on the next page uses a wood connection for example, while the second design is connected by steel.

Cardboard panels as wall and roof components

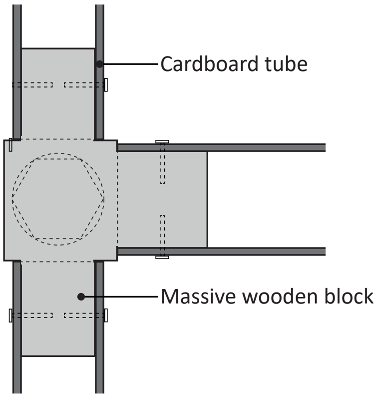
Panels made from cardboard, like multiple layers of corrugated cardboard or honeycomb boards, can provide both structural support and thermal insulation. Their modular nature allows for easy assembly, while their lightweight characteristics facilitate transportation and on site handling. In this type of construction a waterproof layer is needed. In general, the wall structure will be a little thicker than a traditional load-bearing wall to meet the same requirements. A combination of a timber plate and cardboard can be another potential combination to make the structure more stable and protected against point loads. Moreover, it protects the structure against fire. To improve fire safety with corrugated cardboard, it is beneficial to lay the corrugated sheets in two directions. This ensures that the air channels are not all in the same direction and prevents them from acting like a chimney, exacerbating the spread of the fire (Knaack et al., 2022).

Test results of Ayan (2009) indicated that a load-bearing cardboard wall with a honeycomb core for a two-story building must have at least a thickness of 150 to 200 mm. Another study of Latka et al. (2022) showed the result that paper-based samples of wall components presented slightly better insulation results than mineral wool and significantly better than polyurethane insulation, which is due to its stationary air inside the construction. However, it scored worse than EPS, mostly due to its low weight.

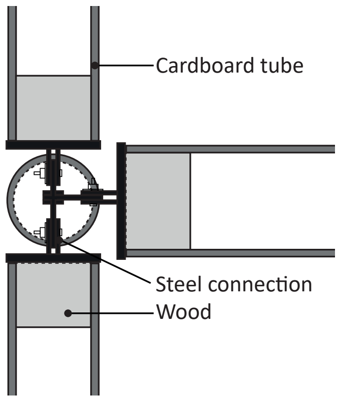
In addition to the paper tube frame variants and the cardboard wall panel options, there are many other paper wall construction possibilities. This overview is made to gain insight into the largest differences and the most obvious potential applications.

Detailled vertical sections

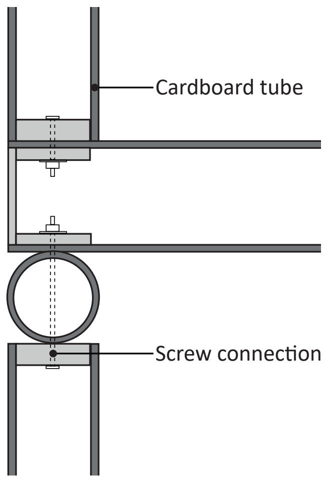
Variation 1



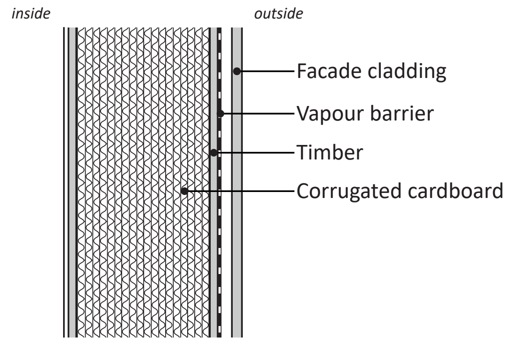
Variation 2

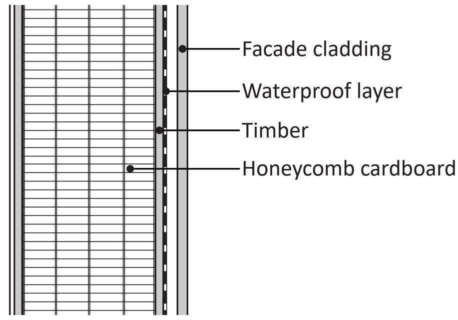


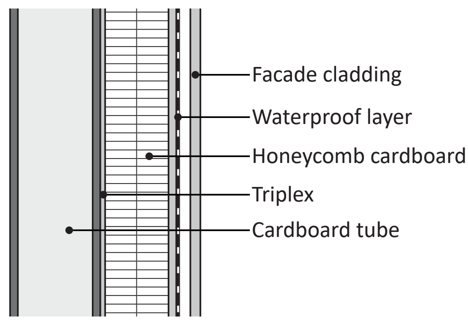
Variation 3



Cardboard tubes as structure







Cardboard panels as walls and roofs

Overview of some possible paper construction techniques (Own work)

	Type	Weight (kg/m³)	Thickness for U-value of 0,21 (mm)	Thermal conductivity (W/mK)	Compression strength (MPa)
Corrugated cardboard	2 x 5 mm A-Flute	80	230 mm	0,047	0,1-0,4
Honeycomb panel	25 mm thick	40	400 mm	0,095	0,03-0,15
Solid cardboard	3,7 mm	273	330 mm	0,14	0,5-3
Paper tube	Ø 100 mm 5 mm thick	200	-	0,05	1-5

Table 3: Analysis of material properties of different types of cardboard

When comparing corrugated cardboard and honeycomb cardboard as main material in a construction, a difference in its thermal conductivity becomes apparent, which is higher for honeycomb panels (Latka et al., 2022). The lower the thermal conductivity coefficient, the better the material insulates. Another difference is that a wall structure will become thicker when honeycomb boards are used. Meanwhile, with corrugated cardboard more material is needed and it results in a little heavier construction.

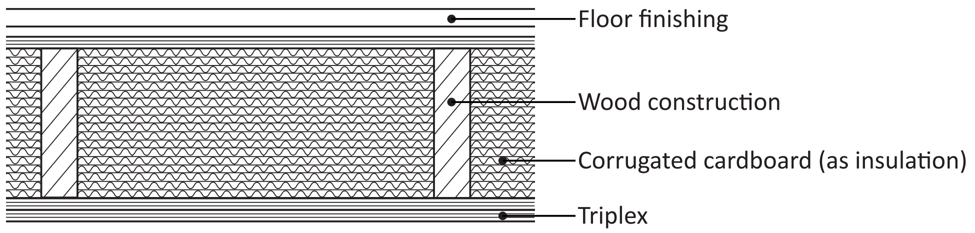
An overview of these material properties are visible in table 3 and can be useful when choosing a specific configuration for a paper-based wall, roof or floor building system.

Cardboard flooring components

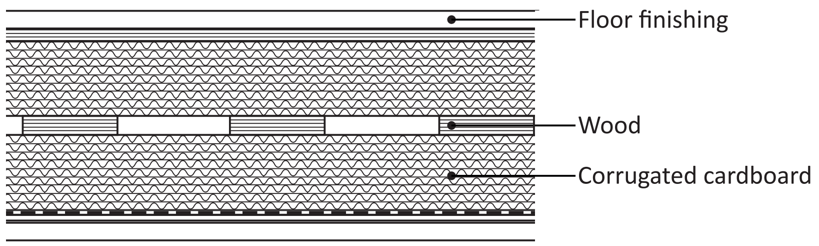
A floor system with cardboard as the main material is not yet widely applied. An additional consideration for structural flooring systems are the point loads which it has to handle. These concentrated forces, applied at specific points rather than uniformly distributed loads, can exert significant pressure on a small area. Structural flooring systems need to account for these point loads to ensure that the material and design can adequately withstand and distribute these forces without compromising the integrity or safety of the structure.

The construction of the building system of Wikkelhouse has a wooden finish for added strength. In theory, it could also be possible to rethink the traditional timber frame construction and replace the insulation by corrugated cardboard. However, both of these alternative floor system designs show no difference from the outside. It is a more sustainable solution, but it does not create a new typology or appearance. Therefore, a third floor system is drawn, where a honeycomb board is combined with cardboard tubes which can remain in sight. However, this system could have a questionable insulation value. During the design phase, various considerations will have to be made when choosing the most suitable choice.

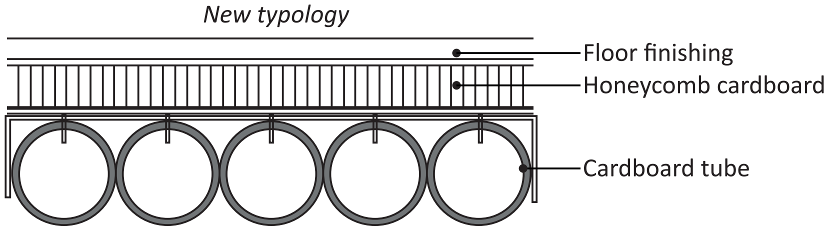
Based on timber frame construction



Based on Wikkelhouse building system



New typology



Cardboard flooring

Overview of paper construction techniques (Own work)

4.4 PAPER, WOOD OR STEEL CONSTRUCTION FOR AMPHIBIOUS ARCHITECTURE

When considering the building material for an amphibious building, the weight of the material plays the most important role. The analyzed case studies of amphibious and floating buildings showed that the mostly used material for the construction of this type of buildings is currently wood. Additionally, steel constructions are sometimes considered. This chapter has delved into an alternative and potentially emerging building material, the paper-based constructions.

Wood provides a harmonious blend of strength and sustainability, making it suitable for various designs in amphibious settings. On the other hand, steel, renowned for its durability and load-bearing capacity, offers robustness and structural integrity, often preferred for more permanent or high-stress architectural projects.

Paper as a building material has both advantages and limitations when compared to wood and steel. Paper is exceptionally lightweight, making it ideal for certain applications, like floating structures. It also offers good insulation properties and has a low environmental impact due to its sustainability. Table 4 gives an overview of the properties of cardboard, timber constructions and steel constructions. Data is collected from: Latka (2017), Ayan (2009), Latka et al. (2022), Morad (2012) and Vaccari (2008).

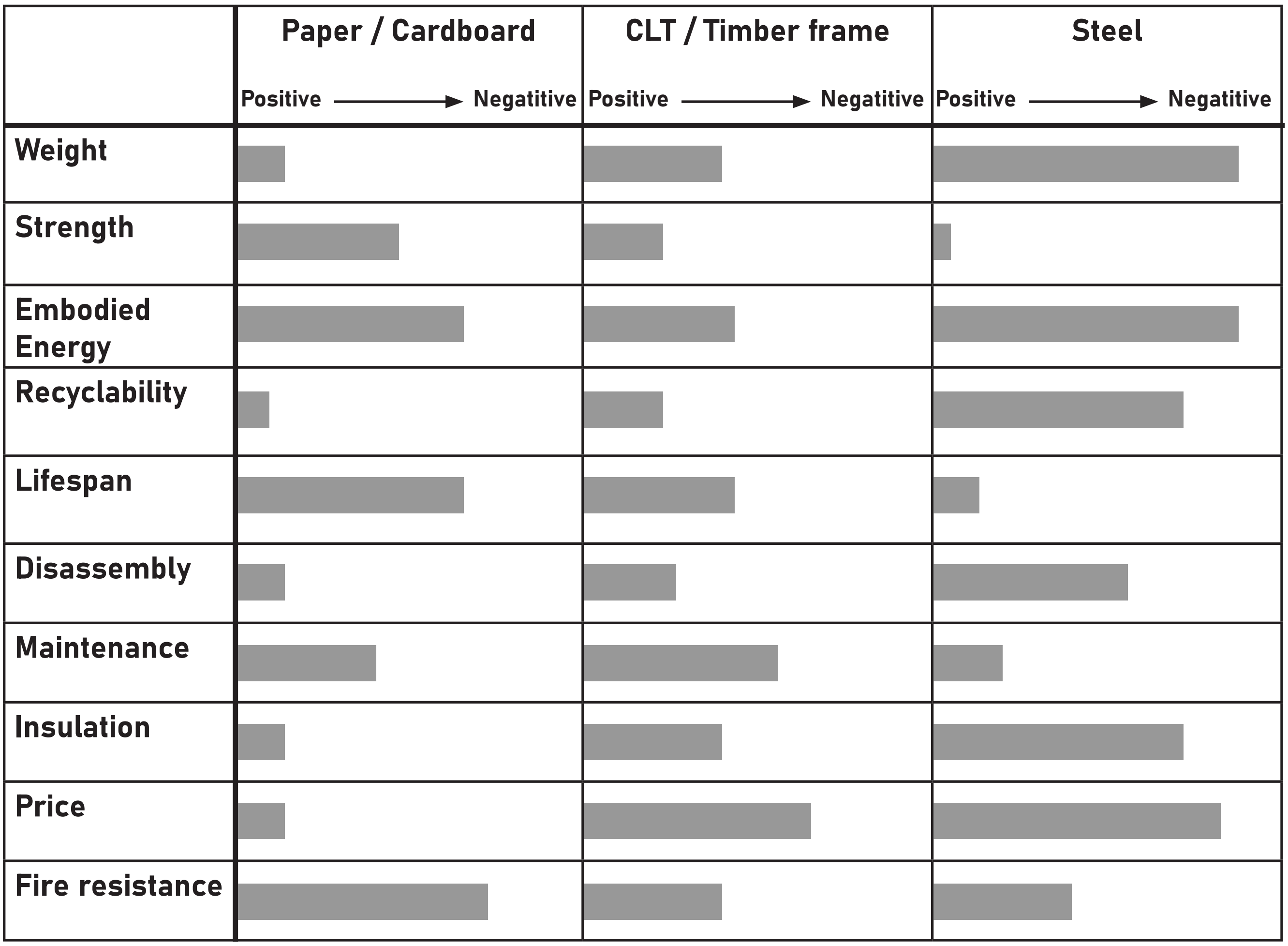


Table 4: Comparison of cardboard, CLT and steel as construction material

The comparison among cardboard and the two traditional building materials illuminates diverse advantages and limitations for architectural applications. The table shows that cardboard emerges as a potential alternative building material due mainly to its lightweight, ease of use and eco-friendly nature. To get more specific, a cardboard panel requires for example half the energy as a brick wall and 14% less energy than a steel frame (Latka, 2017).

CLT or timber frames can offer robustness and combine its strength with environmental consciousness. Yet, wood proves notably pricier and is less easily reused in its original state after the building's lifespan.

Steel performs poorly on several aspects, like its weight, embodied energy, recyclability, insulation and price. On the other hand, for high-rise and long-span structures steel frames can offer perfect qualities. However, in terms of aspects crucial for a future-proof and dynamic building, steel is not the most suitable choice.

Conclusively, paper constructions align with the set of traditional building materials, presenting unique opportunities on several fronts. Building with paper is not suitable for all types of structures. However, for small to medium-scale future-oriented, dynamic, and flexible buildings, paper emerges as a viable solution. Lastly, a SWOT analysis has been conducted to ensure a well-founded assessment, highlighting its strengths and limitations, unveiling both opportunities and threats.

Strengths	**Weaknesses**
▪ Highly recyclable ▪ Easily transportable ▪ Lightweight → promotes buoyancy ▪ Flexible and easibly disassembled ▪ Good insulation properties ▪ Low-costs	▪ Questionable lifespan ▪ Impregnation needed for water proofing ▪ Limited building scale because of strength ▪ Extreme wheater conditions can compromise its structural integrity over time
Opportunities	**Threats**
▪ Growing environmental awareness ▪ Architects have proven its strenghts in precedent paper buildings ▪ Let building floats easily ▪ Promotes stability, because a low center of gravity is created	▪ Legal regulations are not used to paper as building material ▪ Contractors prefer to choose the familiar route, in this case, building with wood (competitor) ▪ More structural certainty with traditional building materials

Table 5: SWOT analysis of paper as building material for amphibious architecture

4.5 SUB-CONCLUSION

In the exploration of paper as viable building material in lightweight constructions, this chapter has substantiated its hypothesis with positive confirmation. The fundamental question centered around the potential of constructions with paper-based materials and was formulated as follows: “Why and how to enhance constructional and load-bearing purposes with the material paper when applied to architectural building structures?”

Through a complete examination of its properties, applications, and comparisons with traditional materials like wood and steel, the potential of paper in construction has been clarified. The analysis has underscored its advantages: lightweight, eco-friendliness and adaptability in load-bearing roles. Moreover, innovative applications showcased by Shigeru Ban and various other architectural projects exhibit the versatility and strength of paper-based constructions. Furthermore, the chapter delved into specific applications, such as paper tube structures and cardboard wall components, unveiling their load-bearing capabilities, insulation values and potential architectural uses.

However, the research has also addressed limitations, such as vulnerability to moisture and fire, which impact its durability and strength. Moreover, considerations around regulatory compliance, long-term durability, and scalability for large-scale projects raise valid concerns. But despite its limitations, paper emerges as a valuable alternative, especially for small to medium-scale dynamic buildings focused on sustainability and flexibility. The adaptability and flexibility makes it a compelling choice in environments where conditions might change. Certainly, an amphibious and future-proof building is suitable considering the properties of this material, but perhaps it will be more interesting at a time when we are more certain of its long-term application.

In conclusion, as answer on the sub-research question, it can be stated that paper offers a lightweight, sustainable and flexible option with notable load-bearing capabilities. It can be applied in the form of a structural frame of paper tubes, as paper wall components, or even as paper floors, where paper is used as the main material. Additionally, it also introduces a unique typology.

The conclusions of this chapter can be further tested in practice under specific design conditions. By conducting practical experiments and pilot projects, the findings of the chapter can be confirmed, refined, or even challenged.

CHAPTER 5

DESIGN PROPOSAL

5.1 DESIGN LOCATION

My vision is that in the future, the Hunze river will carry more water when it is connected to the major rivers from Germany and flows back to the Wadden Sea again. The Hunzevisie 2030 also suggests that it would be a good solution for the future to let the Hunze river follow its old meanders through the Reitdiep area, resulting in restoring nature and improving water safety in Groningen (Het Groninger Landschap, 2015). Allowing more water to flow through the river implies the construction of dikes and the transformation of some adjacent areas into floodplains. These areas which intentionally can be used for flooding during high water can serve a dual purpose by also being made habitable, with amphibious houses being a suitable solution for such regions.

In the past, the Hunze river was used to transport peat from Drenthe through the city of Groningen to the Wadden Sea. The river played a crucial role in the city's development, serving as the gateway to the sea and the hinterland with the peat area. Subsequently, canals were constructed, and the Hunze disappeared (Kijne et al., 2020). Over time, this intervention has led to soil subsidence due to the oxidation of peat and clay, accompanied by natural damage from the drying up of streams, landscape salinization, ecological decline, and erosion of the riverbed (Van Eekelen & Bouw, 2020). However, a significant amount of agricultural land had been reclaimed.

Aerial photo of the current dynamic water landscape of the Reitdiep area
(Kijne et al., 2020 (photo by Schuurman, M.))

So an important advantage of the revival of the Hunze river is that it is beneficial to allow the fresh water from the river to be absorbed by the land to counteract salinization. Salinization is currently a significant problem in the landscape of Groningen, due to its proximity to the sea and rising sea levels (Het Groninger Landschap, 2015). As a result of centuries-long land subsidence, salty groundwater from deeper layers now emerges as seepage into surface water, especially in polder areas. The larger, lower-lying areas in the landscape typology of the polder landscape of Groningen enable extensive water retention zones. Additionally, the water dynamics that have shaped this landscape can enhance the value of the character and identity of the Reitdiep area and create a water-rich landscape which is capable of adapting to rising sea levels. Furthermore, restoring the river corriders and creating space for periodic flooding will support biodiversity and natural processes (Van Eekelen & Bouw, 2020).

Based on this future scenario, a location has been chosen that will be most suitable for the concept of an amphibious neighborhood. It should be noted that this concept has been developed to provide added value in multiple locations across the Netherlands. To test how this concept can be implemented on a larger scale, one location has been selecte in the Hunze River Valley, to demonstrate how it can function in a water-rich area.

The majority of the area bordering the Reitdiep water is agricultural land and is mostly inhabited by farmers. In light of the increasing demand for housing development sites, some of these locations are expected to become more vibrant and inhabitable in the future. The chosen location is situated near the town of Zoutkamp and is indicated on the map below. The reason why this location is considered suitable for new residential development with amphibious buildings is that it is located in an area at risk of salinization from groundwater and this area is prone to flooding. Currently, the areas in this landscape are minimally inhabited because of their minimal facilities and relative large distance from major cities. Moreover, it has frequent water-related issues in the winter. My vision is that future infrastructural connections will significantly expand and improve, making living further away from a city less challenging.

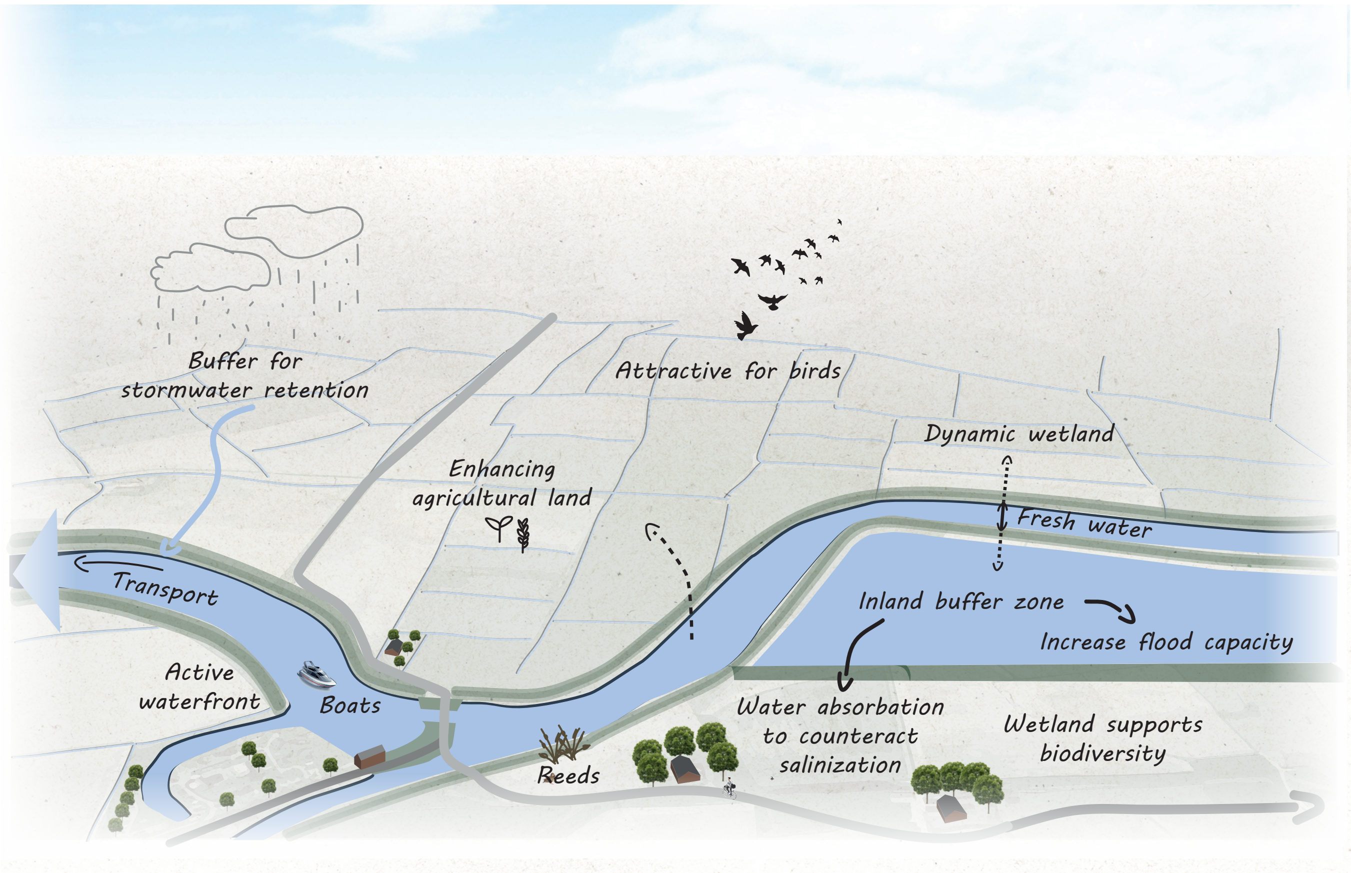
According to the scenario outlined, this location could appear as a vibrant and dynamic area, where nature takes precedence.

The red dot highlights the chosen design location, a flood plain in Oldehove. The dotted red line outlines the area which will be redesigned.

Map of design location (Own work, map data from Milvusmaps, 2023)

A combination of an architecturally creative solution along with environmental awareness is what can reshape this environment for the coming generations. A strategy to make Groningen more resilient to climate change is depicted in the figure below, where more water flows through the Reitdiep, and the environment lives more harmoniously with water. The advantage of this approach is that fresh water is better integrated into the landscape, making it easier to manage extreme rainfall and high water levels. Integration of the natural landscape and a vibrant area is one of the guiding principles, with more areas expected to be inhabited.

One of my future expectations is that the amount of farmland will decrease in the future, with the rise of developments such as vertical farming and technological advancements leading to more efficient agricultural activities. Consequently, less land will be needed for the same level of production. However, I find it important to continue emphasizing the agricultural characteristics of this area. The following figure shows the effects of restoring the river and creating a biodiverse and dynamic wetland area.



Effects of restoring the river and creating space for floodings (Own work)

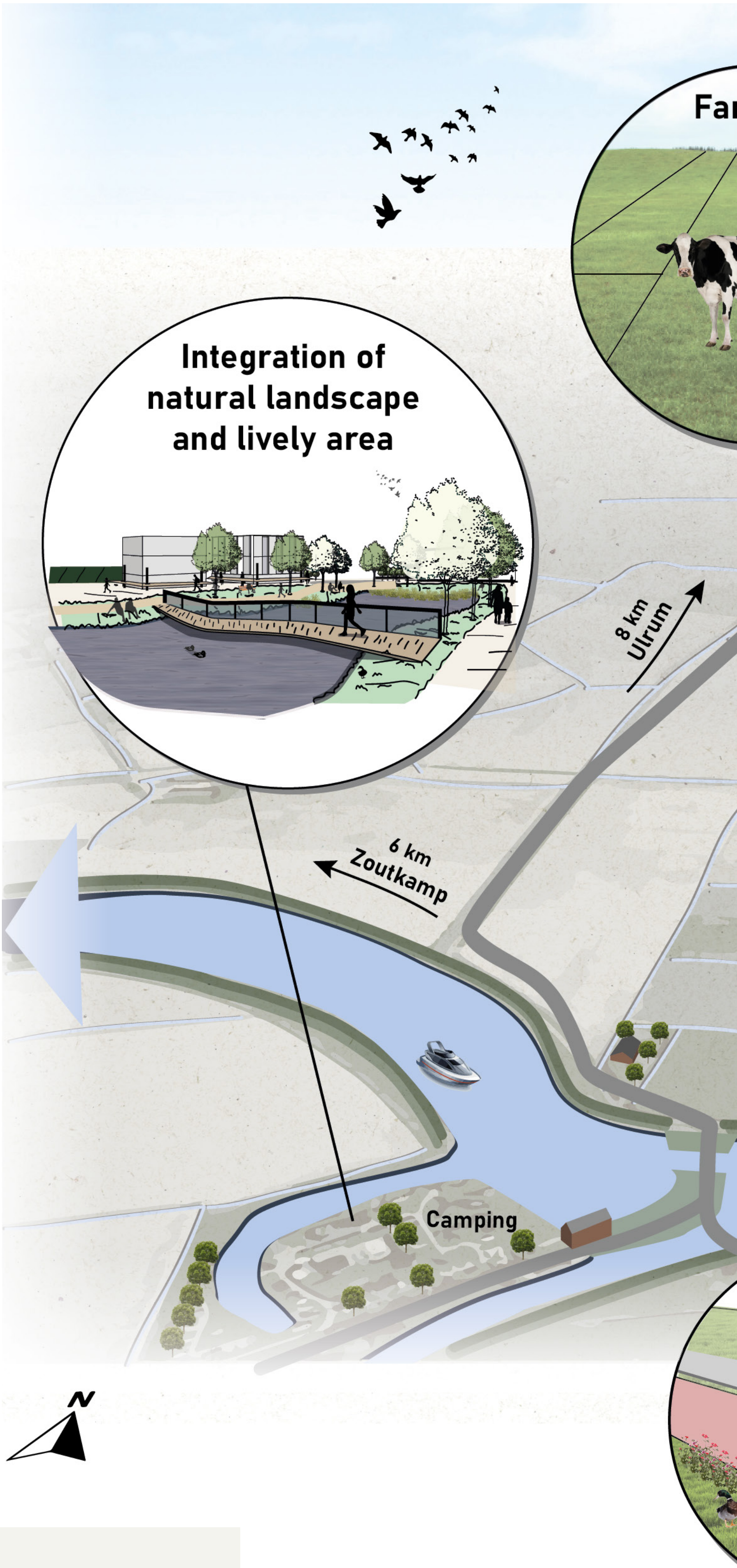
Vision on the design location

This drawing gives an impression of my vision on the design location. The main assumptions are highlighted in circles.

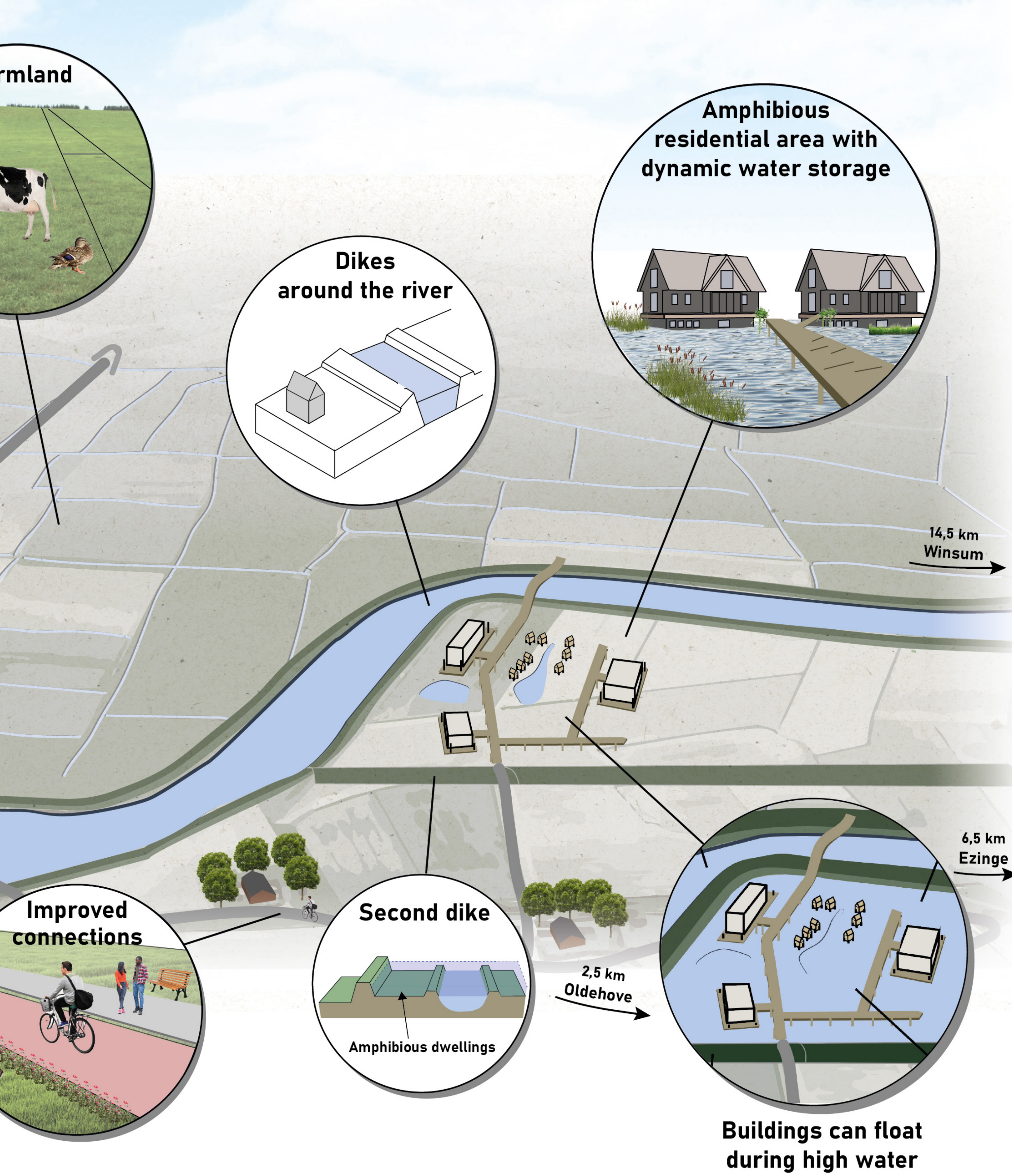
In this scenario it is assumed that the surrounding villages like Zoutkamp, Ulrum and Oldenhove will grow. Therefore, it is crucial to improve infrastructure connections.

Living with the water is the typology of this new residential area. This image provides an impression of how the riverbed along the Reitdiep could be transformed. For the design project, only a small section of the riverbed is further elaborated.

In this new residential area there will come multiple amphibious houses and flexible infrastructure. The challenge lies in investigating whether amphibious living can be applied on such a larger scale. Therefore, it is interesting to look into a housing type that can be repeated throughout the area.



From an amphibious housing concept to an amphibious neighborhood in a floodplain



Future impression of my vision on the design location (Own work)

5.2 TARGET AUDIENCE

When a new residential area is being developed, it is important to carefully consider facilities that are desired to create a vibrant community. The idea behind this neighborhood is to have a small community with residents of different ages who can support each other. This new neighborhood is not located in an urban setting. Therefore it is intended for people who enjoy nature and tranquility. The question that can be asked in this setting is, "What does a neighborhood need to function well?"

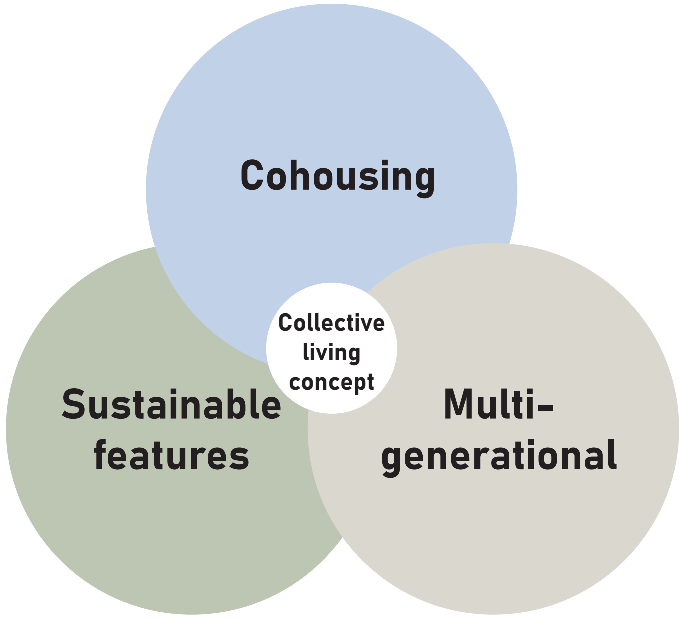
Firstly, this new neighborhood, which is situated along the river, is located within cycling distance of the villages of Zoutkamp and Oldehove. These villages offer essential services as shopping, educational institutions and healthcare facilities. The current residents in this area are mostly agricultural landowners. Additionally, next to the location there is a camping area with recreational (water) facilities, demonstrating how liveliness and the natural landscape can be integrated. To make a residential area function well, it is important to meet the needs of the residents and provide a suitable environment for daily life. It is crucial to establish a good basic infrastructure for accessibility and easy mobility within the neighborhood. Safety is also considered important, as well as social amenities, such as sports facilities or community centers.

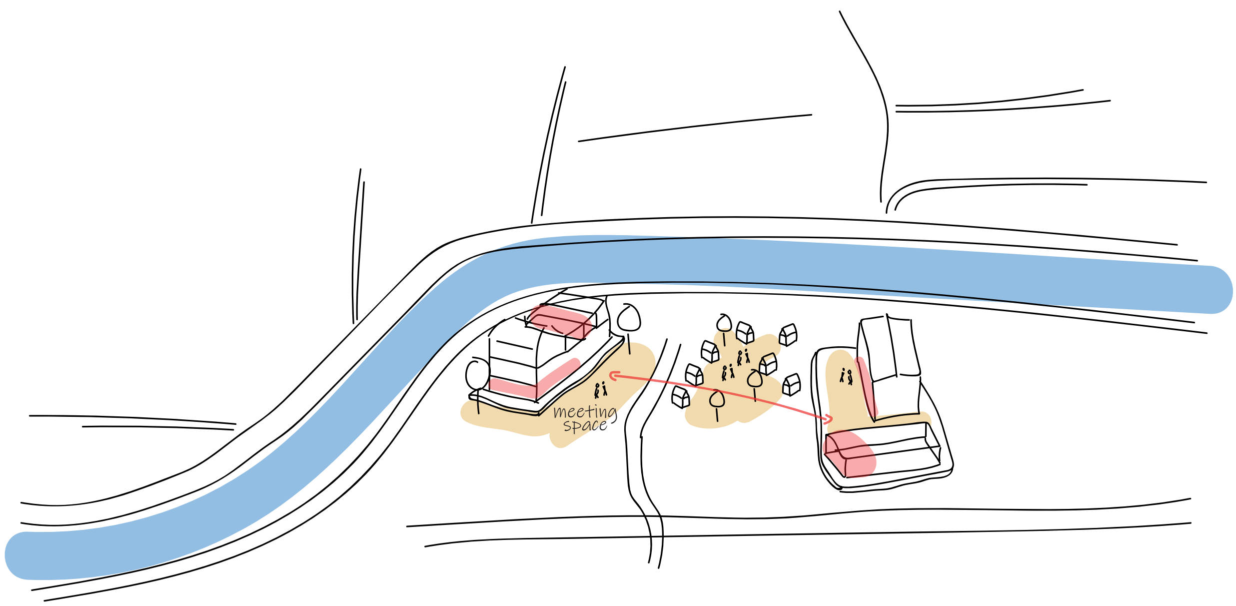
The reason this location is seen as an interesting place is because the river will play an increasingly important role in the future developments. Firstly, restoring the river enhances the historical and cultural value of the landscape. Rivers also offer recreational opportunities that can attract people and enhance the quality of life by fostering a connection with nature. Another factor that can further improve the quality of life in a residential area is sustainability and environmentally conscious initiatives, which can be achieved in this case through sustainable construction methods and making an area habitable that was not previously considered suitable for habitation.

Envisioning the future, collective living could emerge as a new way of living, characterized by shared spaces and facilities. With this communal living, different age groups can be combined, where a sense of community is central. An advantage of multigenerational living is that older individuals can assist in caring for young children, and conversely, younger individuals can help with tasks that older members may find challenging to do on their own (Mullens, 2017). Additionally, it helps prevent loneliness. This collective living concept can also be described as "cohousing", which is a countermovement against anonymous apartments and its individualisation (Mullens, 2017). A cohousing community endeavors to create a sense of neighborhood that can be found in traditional village cores. This has been a significant trend in Dutch cities over the last decades. Small scale initiatives can facilitate the development of a robust social fabric. Moreover, architecture can increase the change of interaction (Mullens, 2017). In recent years, the popularity of collective living has been on a significant rise in the Netherlands, and looking ahead, this housing approach brings numerous advantages for the future.

Together with the application of amphibious houses, it is interesting to connect the homes into clusters with shared inner gardens in the form of a raised terrace. This can be beneficial for enhancing the stability of the homes and provides the opportunity for a terrace where interaction between residents can continue even when the water is high. Therefore, the project will further focus on developing a repeatable housing type that can be linked in various cluster formations, thus creating a vibrant neighborhood.

Collective living in a future-proof amphibious neighborhood in Groningen





Vision on collective living in amphibious neighbourhood (Own work)

5.3 PROGRAM OF REQUIREMENTS

As a result of the research conducted in this thesis, a program of requirements has been developed, incorporating all design conclusions. These criteria will serve as the foundation for further elaborating an amphibious housing neighborhood. By adhering to these criteria, the envisioned project aims to not only address the challenges identified in the research but also to embody the principles of sustainability, functionality, and innovation. This strategic approach ensures that the amphibious housing project not only meets the immediate needs outlined in the program but also aligns with broader goals of environmental consciousness and resilient design.

DESIGN CRITERIA

TYPOLOGY

- Amphibious residential community
- Passively adaptable to changing water level
- Implements climate change

LOCATION

- Natural water storage area (floodplain)
- Near a river
- Correct integration into the existing landscape - max 3 levels high
- Good accessibility by both land and water

TECHNOLOGY

- Maximum depth of pontoon is 1,6 meters
- Flexible cables and pipes, accessible for maintenance
- Water quality must remain healthy and should not accumulate litter
- Meet Dutch building requirements

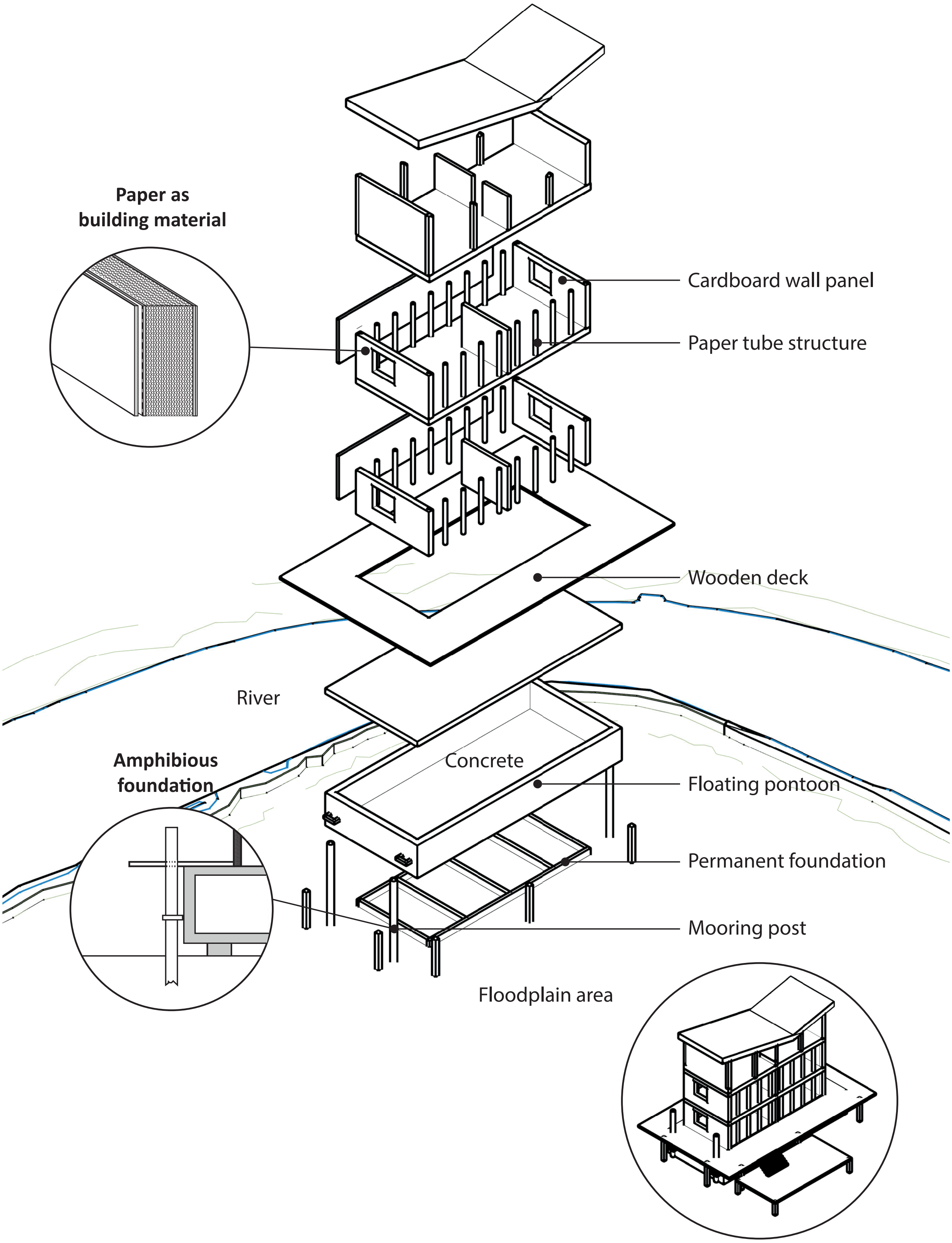
BUILDING CONSTRUCTION

- Lightweight and sustainable building materials
- Modular and prefabricated to repeat on a larger scale
- Meant for permanent lifespan

BUILDING PROGRAM

- 8 to 15 dwellings in a collective housing cluster
- Shared facilities
- Reverse living: bedrooms in the pontoon
- Multigenerational usage

This figure is meant to show an example of how all the research results can be translated in design elements and how this comes together.



Axonometry of conceptual design proposal (Own work)

5.4 ARCHITECTURAL CONCEPT

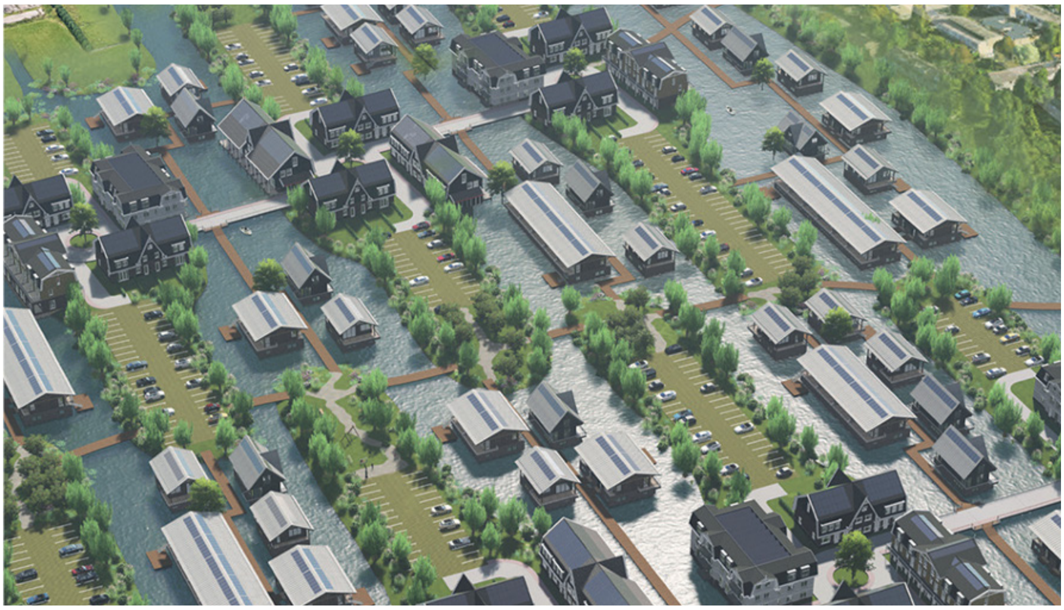
To give a reference of the architectural concept of a “residential water community” three projects are discussed (see photos). In examining these noteworthy floating residential complexes, each project stands out for its innovative approach to aquatic living. The Boston Floating Pier, with its distinctive architectural design, not only provides a novel housing solution but also serves as a captivating addition to the cityscape and a dwelling solution to climate change. All the buildings are built on top of floating pontoons. The lowest floor, which is located half a story below the waterline, has high-level windows that are positioned inside the safe flotation unit’s perimeter, giving the building buoyancy (Baca Architects, n.d.). The shared spaces between the buildings create a sense of community.

In a peat meadow area in Woerden, the Veenetië project showcases an inspiring fusion of traditional architectural elements with modern floating technology. This area is a low-lying area where peat has historically been extracted, which has led to the formation of a meadow and is probably used for agriculture. These grounds are highly susceptible to land subsidence due to peat oxidation and the compaction of peat and clay (Gemeente Woerden, 2019). The pattern of the original agricultural land is still visible in the design. This project interprets a unique and visually appealing community on the water and shows how these type of meadows can be transformed into residential areas. A combination of floating architecture and small islands is applied. However, this project has not been implemented, and what happens during periods of drought may be a matter of debate.

Meanwhile, the Vloat project by Circular Floating District is working on four types of islands where creating communities is the central point. This project is situated in an urban environment and a maritime character is the basis of the plan. One of the interesting aspects of this project is the modularity of the buildings, which results in an efficient and sustainable building process. The design provides a fine example of how various types of floating residential buildings can be implemented on a larger scale.

Together, these projects not only redefine urban living but also underscore the potential for creative and environmentally friendly solutions in the realm of floating or even amphibious housing. They all show an architectural concept which forms an inspiration for the new way of living in amphibious neighborhoods in flood-prone areas, the topic which my design project will carry out.

1. Boston Floating Pier (Baca Architects & Waterstudio, n.d.)



2. Veenetië (Gemeente Woerden, 2019)

3. Vloat (Circular Floating District, 2023)

References of residential water communities

5.5 SUB-CONCLUSION

In summary, the design proposal for the Hunze River Valley envisions a transformative approach rooted in the revival of the Hunze river and amphibious living. The chosen location near Zoutkamp, at risk of salinization and prone to flooding, serves as a canvas for innovative solutions that address current challenges and contribute to climate resilience.

This amphibious housing project embraces collective living in a water-rich environment, catering to a diverse demographic. Leveraging inspiration from successful floating projects, the design incorporates distinctive architecture, biobased materials, and advanced technology. The program of requirements outlines sustainability, functionality, and innovation as guiding principles.

With a focus on adaptability and community, the design envisions reverse living, multigenerational usage, and collective facilities. It integrates seamlessly with the landscape and fosters a strong sense of community. Overall, the project reflects a forward-thinking response to climate change, redefining the relationship between communities and their natural surroundings in the Hunze River Valley.

CHAPTER 6

CONCLUSION & DISCUSSION

6.1 CONCLUSION

In this chapter the research question is being answered and the research limitations are discussed. Thereby, future research topics are suggested and in a personal reflection there is looked back on the research.

The research aimed to investigate how adaptive and biobased architecture can contribute to climate challenges in the Netherlands. A building concept which can integrate with the fluctuating water levels of flood-prone riverside areas is analyzed and further developed. This concept is called an “amphibious building”, with a combination of a fixed and floating foundation. To make this concept even stronger, the research elaborated on lightweight biobased building constructions which can contribute to the stability and flexibility of the building. The hypothesis rested on the belief that a combination of floating and fixed housing construction, with paper as a lightweight building material, could usher in new possibilities for wetland dwellings. Paper as a building material showed its potential. To contextualize the study, the province of Groningen and its future climate conditions are investigated as a case study and design location.

RESEARCH QUESTION

“How can buildings effectively adapt to fluctuating water levels in Dutch polder landscapes by incorporating an adaptable dynamic floating foundation and a lightweight biobased construction?”

To answer the central research question, the research is divided into multiple research subjects and sub questions, which resulted into the following sub conclusions:

The exploration of multiple typologies of living with water demonstrated the urgency of reimagining architectural responses to floods. Insights from Groningen’s historical battle with water, along with a precedent study of innovative residential water projects like the amphibious houses in Maasbommel, laid the foundation for the concept of amphibious living as an optimal solution.

In the realm of construction techniques for amphibious buildings, stability emerged as a key principle, necessitating a thoughtful interplay between the weight distribution of the building and the pontoon. Floating building techniques are used for the underlying technical research. The purpose of this chapter was to gain insight on the technical possibilities of an amphibious building. Scalability considerations, use of catamaran or U-form pontoons, and mooring pole attachments added depth to the technical principles explored. The results that are achieved are translated into a series of design criteria and performance standards, which anticipates a system that could practically and safely adjust to various water levels and meet building standards in high water situations. These criteria form the basis for the design project which followed after this research, where several types of amphibious houses have been further developed, which have the possibility of being connected to each other to form collective housing clusters in an amphibious residential area.

The examination of paper as a building material for lightweight constructions confirmed its potential while acknowledging inherent challenges. The study first focussed on precedent paper constructions and showed that paper tubes and cardboard wall panels already have proven their strength for permanent load-bearing applications. Although, the insulation values that are restricted in the Netherlands were occasionally not achieved in the example projects. This led to a deeper dive into promoting better insulation values with cardboard constructions and the properties associated with different types of cardboard. Also, a comparison was made with wood and steel constructions. From this, it emerged that paper constructions align with the set of traditional building materials, presenting unique opportunities on several fronts. Building with paper is not suitable for all types of structures. However, for small to medium-scale future-oriented, dynamic, and flexible buildings, paper emerges as a viable solution. Impregnation or waterproof layers are essential in the construction. The additional costs associated with the advanced amphibious foundation can be offset by a more cost-effective cardboard construction.

The design proposal for the Hunze River Valley translates these insights into a tangible vision. Rooted in historical context, the proposal embraced amphibious living, collective facilities, and a focus on biobased materials, showing resilience and sustainability. It envisioned a vibrant and adaptable community that harmonizes with the natural landscape.

"Flood-proof living at the riverside" sets a direction toward a future where architecture meets the challenges of climate change with innovation and sustainability. So how can buildings effectively adapt to fluctuating water levels in Dutch polder landscapes by incorporating an adaptable dynamic floating foundation and a lightweight biobased construction? An amphibious construction could be implemented in various ways, depending on the situation and location. When the river's floodplain is submerged, the building will start to float. It should be considered that everything is connected flexibly, and access roads remain accessible. Paper constructions contribute to a stable, more sustainable, and cheaper building, enabling larger-scale buildings to be executed amphibiously. Paper constructions, with the right design, can meet the construction standards of traditional building materials and also score well in terms of recyclability and disassembly.

Practical experiments and pilot projects can further validate the findings, refining and enhancing the proposed concepts. To test the concept a design is made for an amphibious housing cluster, in which the results results have formed a basis. More information about this design project can be found in the vision booklet of this project. The focus in the vision booklet is more on the social value of amphibious living and a specific collective way of living has been elaborated.

6.2 DISCUSSION

Limitations

This research still includes a number of restrictions, because of the defined time frame. In the following areas there are more extensive answers needed to prove effectiveness of the proposed solutions.

First of all, amphibious living will not be suitable for everyone. People who find wind, noise, and light on the water annoying will not feel at home in an amphibious house or complex. Additionally, living on and near the water poses extra risks for safety and water quality. This includes dangers such as the risk of drowning, freezing of water pipes, storms, and pests.

In addition, paper constructions pose additional risks in comparison with the traditional building materials. Also, the practical longevity of such structures remains a matter of debate. For an amphibious building that is specifically aimed at adapting to the future, it is important that the building materials can last a long time. Paper as a building material is still a good alternative, but in the application of amphibious living it could be inadequate due to its lifespan. Besides, the study has not provided an exhaustive analysis of the sourcing of the raw materials for paper-based constructions. Aspects as transportation, cutting down forests and the energy use during the production could question the sustainable and responsible supply chain for the environmental benefits of this material. However, several companies in the Netherlands are already working on producing paper from local and biobased materials, so to complete the sustainability circle, collaboration with them could be considered.

Moreover, the research is specifically focused on the application of amphibious housing in river areas, excluding regions susceptible to seawater flooding. The impact of saltwater and the force of the sea could yield different outcomes, and it remains uncertain whether the developed building concept would be resilient to these conditions.

Future research

After finalizing this research there are still elements which are not completely included in the thesis. First of all, the only example projects of amphibious buildings were carried out on the scale of a single home. Based on the technical feasibility and references of floating complexes, I assume that it should also work on a medium scale with around 8 to 15 dwellings. In the future, it would only be possible to determine whether these conclusions are true on the basis of a truly implemented project. Real scale prototypes could also contribute to this.

Another point is that the research has not considered all possible environmental conditions that could affect the performance of paper-based constructions in amphibious settings. When the newly developed cardboard components which are shown are applied, they will first have to be tested for fire safety, water resistance and strength. These safety requirements are now based solely on research data. Furthermore, the economic feasibility and cost-effectiveness of implementing amphibious foundations may not have been thoroughly addressed. Real-world projects often involve complex financial considerations that could impact the practicality of the proposed solutions. The technology offers advantages, but it also requires additional attention.

6.3 REFLECTION

Reflecting on the process of this research and design project, the design phase seamlessly integrated insights from the research, providing a solid foundation for amphibious living in floodplains. The study emphasized the need for flexible and adaptable housing types in flood-prone areas. The project contributes academically by advancing knowledge in architecture and building sciences. It tackled the global challenge of being able to deal with the rising water level in the built environment. The emphasis on adaptability to the water level can be a vital point of discussion about the Dutch housing future and its limited land available for new construction. Only changing the landscapes, building higher dikes and moving away from high risk areas are all short-term solutions. What makes this project relevant for our society is the fact that the solution is sought in changing construction methods rather than fleeing from or combating the problem. If this concept will be widely implemented in the future, it could prevent a lot of damage to buildings, prevent areas from becoming abandoned, make many more areas suitable for habitation and we could allow nature to take its course. Additionally, the clusters create a collective way of living, which offers numerous benefits both socially and sustainably.

The value of the transferability of the project results lies in their potential to be applied to different contexts and settings beyond the specific case studied. The project's flexibility and scalability gives the possibility to build wherever you want. By developing standardized building modules and construction methods, the concept enables efficient replication and mass production, thereby reducing costs and construction time.

Overall, this project has brought many new insights and creates a future vision for the new way of living in a floodplain. The follow-up tot this research can be see in the vision booklet.

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APPENDIX

INTERVIEW BARTELS AND VEDDER

Company: Bartels and Vedder - interdisciplinary engineering and consultancy firm
Location: Bunschoten, The Netherlands
Date of interview: 12-12-2023

Bartels and Vedder is an engineering firm which is specialized in building on water, from product and concept development of floating pontoon, to the complete engineering of floating homes and islands. To learn about their knowledge of floating constructions this interview is carried out.

Transcription (in Dutch)

AV: “We hebben een aantal vragen opgesteld. De eerste vraag is Hoe begon jullie interesse en betrokkenheid bij het ontwerp van drijvende gebouwen, en wat heeft jullie daarvoor geïnspireerd?”

JV: “Dat is eigenlijk allemaal per ongeluk gebeurd, dus het is niet opzettelijk gedaan. In 2004 ben ik begonnen met het werken vanuit mijn eigen bedrijf, dus direct na de universiteit. Dit was een bedrijf om technologisch georiënteerde bedrijven te helpen naar buiten te kijken, dus eigenlijk dat ze producten gaan ontwikkelen die de consument ook echt wilt. Want op dat moment werden er heel veel producten ontwikkeld, alleen niet met de consument in het oog, maar eigenlijk meer vanuit het innovatief vermogen en het doel om maar nieuwe dingen te ontwikkelen die eigenlijk nog niet klaar waren voor de markt, of dat de markt eigenlijk nog niet klaar was voor die ontwikkelingen. En één van die bedrijven, Aqualife, ontwikkelde aluminium drijvende fundaties. Dit was een dochteronderneming van Voskamp groep. Toen hebben ze mij gevraagd om hun te helpen om dat product op markt te zetten. Dus dat is hoe ik daarin ben gekomen. Dat heb ik een jaartje gedaan vanuit mijn eigen bedrijf, dus als klant. En vervolgens ben ik daar directeur van geworden van het bedrijf, dus ben ik de CEO geworden. We hebben hele mooie aluminium drijvende fundaties ontwikkeld, samen met Sapa aluminium. We hebben nieuwe technologieën toegepast, waaronder het friction stir welding, een nieuw lasten procedé dat nu ook in de TGV wordt gebruikt, de hogesnelheidstrein. Dus we hebben een hele mooie techniek ontwikkeld, alleen je mag nooit vanuit materiaal ontwerpen of ontwikkelen. En dat heb ik toen ook gezegd, met name toen in 2007 de materiaalprijzen enorm omhoog gingen. De economie heeft een golf, nu zitten we ook weer in die in die conjunctuur dat dat we eigenlijk al weer omhoog gaan. Dus materiaalprijzen hoog en dat wordt vaak weer gevolgd door een recessie. Daarom is iedereen nu bang voor een recessie, zoals we dat eigenlijk in 2009 en 2002 ook hebben meegemaakt. Aluminium werd heel duur en vervolgens zijn wij begonnen met nieuwe producten.

Glasvezel Composiet Kelderbak hebben we vervolgens ontwikkeld als alternatief voor beton bakken voor moeilijk bereikbare plaatsen. En we hebben de modulaire betonnen elementen uitgevonden, waarmee we onder andere ook projecten in Maleisië hebben gedaan om grotere drijvende eilanden te kunnen maken op het water en dan modulair. Die hebben we toen ontwikkeld. Toen ging het heel slecht met de economie, het was echt op een dieptepunt. Dat was met name met de ellende met de banken, dus de bankencrisis in die tijd en dus verkeerd beleende hypotheken. Daar ging het eigenlijk fout bij de bij de bij de meeste banken, dus de hele bouwmarkt kwam eigenlijk tot stilstand te staan. Dus alle niche projecten, zoals bouwen op het water werden op dat moment geannuleerd. Dus wij hadden contracten voor 10.000 m² drijvende eilanden per jaar. Die contracten werden verscheurd, want een hele nieuwe business development afdeling ging daar weg. Alles werd gewoon stilgelegd met betrekking tot bouw op het water. En toen heb ik eigenlijk ook gezegd tegen mijn partner, Bartels, van we kunnen ook een eigen bedrijf weer gaan beginnen, met name toen de eigenaar van het bedrijf ook ziek werd. Toen hebben we een bod gedaan op het bedrijf wat niet werd geaccepteerd en toen zijn we eigenlijk het ingenieursbureau Bartels & Vedder begonnen. Ons doel was eigenlijk om alleen te gaan richten op innovaties in de bouw, duurzame ontwikkelingen, nieuwe bouwtechnologieën, noem maar op. Maar binnen een half jaar kwamen al bedrijven als Van Oord, Ballast Nedam, FLEX Bees, dus partijen die met bouwen op het water te maken hadden, naar ons toe om adviezen te vragen voor projecten in Woerden om te gaan rekenen aan die nieuwe systemen, dus de drijvende systemen. En toen is ze eigenlijk in een sneltrein vaart omhoog geschoten met het bouwen op het water. Sindsdien is het echt een steile lijn geweest dat iedereen ons vanuit heel de wereld ging vragen voor bedrijvende projecten en is er ook enorm veel ontwikkeld. De reden dat we het nu nog steeds doen is omdat we eigenlijk de enige met zoveel ervaring zijn met bouwen op het water.”

MR: “Ja het bouwen op het water gebeurt nog niet zoveel, dus waarschijnlijk weten jullie er veel meer van vergeleken met anderen.”

JV: “Precies, het is een groot onderdeel van onze bedrijfsvoering, maar we doen ook traditionele projecten, zoals hallenbouw, de villabouw, kaders, bruggen. Dat zijn allemaal werken die we gewoon met de ingenieursbureaus nog steeds ook daarnaast doen. En alle kennis die we daarop doen, verwerken we ook weer in onze projecten met betrekking tot bouwen op het water en vandaar dat we eigenlijk een heel breed pakket hebben. Andere bureaus, die echt helemaal gefocust zijn op bouwen op het water, hebben dat eigenlijk niet. De kennis van de woningbouw bijvoorbeeld die missen ze, zoals houtskeletbouw en noem maar op. Dus die richten zich alleen maar op die drijvende fundatie. Het is een integraal geheel zoals bij een traditionele woning. Je begint bij de nok en eindigt bij de fundatie. Uiteindelijk bepaalt het gewicht, dus de belastingen vanuit de bovenbouw, onder andere wat je aan fundering onder die woningbouw moet uitvoeren, in de vorm van een ponton.

AV: “ Daar gaat onze volgende vraag toevallig ook over. Dus hoe waarborgen jullie dan bijvoorbeeld de stabiliteit en drijfkracht van een gebouw? En wat voor ontwerp- of engineeringsprincipes passen jullie daarvoor dan toe?”

JV: “De belangrijkste wet is de Wet van Archimedes. Dat is voor je drijfvermogen en als je dat aanhoudt gaat er al veel goed. In het begin had je helemaal geen regelgeving en toen hebben we ook samen met TNO bouw in 2006 eigen regels geschreven. Delen van dat onderzoek zijn onder andere nu toegepast, in de NTA en vervolgens ook in het bouwbesluit. Dus waar je rekening mee houdt is het Bouwbesluit en we gebruiken de Eurocode voor sterkte en vloeistofdichtheidsklasse. En het bouwbesluit zegt ook wat jouw veiligheidsafstanden moeten zijn, de maximale scheefstand en hoe hoog jouw meter centrum mag zijn, dus dat je zwaartepunt goed ligt. Als je die regels aanhoudt krijg je dus een object dat voldoet aan het bouwbesluit. Dit is als een apart hoofdstuk opgenomen in het bouwbesluit voor drijvende bouwwerken en dit is vrij toegankelijk.

MR: “Staan maximale hoogtes daar ook in?”

JV: “Nee, hoogte staat daar niet. Hoogte wordt weer bepaald, net zoals bij traditionele woning, door bepalingen in de omgeving die door de gemeente worden opgelegd. Het is wel zo dat als jij een bepaalt bouwoppervlak hebt en je hebt onbeperkte hoogte, dan zou je gelimiteerd worden door de technische aspecten. Dus de hoogte van jouw zwaartepunt en de maximale scheefstand bij een bepaalde winddruk. Dan komt die technische aspecten naar voren.

MR: “We wilden ook vragen wat voor ingrepen genomen kunnen worden in het ontwerp om wind of golfbewegingen tegen te gaan?”

JV: “Golfbewegingen ga je niet tegen, maar bewegingen ten gevolgen van golven wel. Het meest effectief is het vergroten van de oppervlakte, dus de breedte van het drijflichaam. Tussen zwaartepunt stabiliteit of een geometrische stabiliteit, dus de breedte van je fundatie, zien we ook dat geometrische stabiliteit veel sterker werkt dan het verder verlagen van je zwaartepunt door bijvoorbeeld nog meer gewicht in die fundaties te stoppen. Bij de bewegingen van de golven is met name ook de lengte van de golven belangrijk. Dus de afstanden tussen twee golftoppen, waarbij je wilt dat een object niet over de golf mee gaat bewegen. Je wilt eigenlijk dat er altijd minimaal twee golf toppen onder een object zitten, want dat betekent dat de golf eronderdoor rolt en dat hij altijd op twee golftoppen vastzit. En wordt het object kleiner, dan gaat hij met de golf mee, afhankelijk van de golfhoogte en het gewicht van het gebouw natuurlijk.

Voor de wind is het allereerst afhankelijk van welk bepaald gebied van Nederland je zit. Dus je hebt verschillende wingebieden met verschillende zones. Dat is bebouwd, onbebouwd en kustgebied. De zone bepaalt de stuwdruk. Al krijg je een behoorlijke stuwdruk of je gaat het gebouw nog wat hoger maken, dan betekent het dat je dat het wind moment moet gaan opvangen met het moment wat extra in het water wordt gecreëerd. Dus het water moet het gebouw eigenlijk weer terug gaan drukken. Dat kun je het best bereiken door het ponton bijvoorbeeld gewoon wat breder te maken, zodat je meer tegenmomenten kan creëren tegen het wind moment. En dat is eigenlijk ook bepaald in het bouwbesluit wat die maximale scheefstand daarin mag zijn.”

AV: Maakt het voor de opbouw, dus het gebouw wat op de fundering komt, uit of er een hele lichte constructies wordt toegepast of maakt het in de praktijk eigenlijk niet zo uit wat daarvoor wordt toegepast?”
JV: “Je kan best een betonnen gebouw erop zetten, maar dat zou ook enorm zonde zijn, want het gebouw

weegt heel zwaar. Daar heb je twee nadelen uit. Allereerst wordt het zwaartepunt hoger, dus mijn stabiliteit en mijn comfort level in het gebouw wordt minder en daarnaast is het gebouw vrij zwaar, dus ik moet meer water gaan verplaatsen. Dat betekent dat ik mijn ponton groter moet maken, wat de prijs weer omhoog stuwt. Daarom dat het verstandiger is om een lichte opbouw te gaan maken, zoals HSB, staalbouw, glas. etc. Je kan van alles gaan daarin bedenken wat eigenlijk traditioneel op land ook gebeurt. Alleen het metselwerk en betonbouw raden wij eigenlijk af omdat metselwerk sowieso niet zoveel houdt van scheefstand, en we naar betonbouw gaan kijken dan raak je aan twee zijden het geld kwijt. Dus qua groter en de bouwtechnologie is het wat duurder."

AV: "Wij hadden ons ook verdiept in de toepassing van betonnen drijflichamen, kan dat altijd ook gebruikt worden als gebruiksfunctie of worden hier vaker gewoon de installaties in verwerkt?"

JV: "Wij ontwerpen heel veel drijvende woningen op dit moment en al die betonnen bakken worden gebruikt voor slaapkamers, badkamer, deels onder de waterlijn. Dus ook als functie kan het worden gebruikt. Dat is ook het meest efficiënte, want dat betekent dat je relatief goedkoop extra kubieke meters en vierkante meters woonoppervlakte in jouw woning krijgt. De muren heb je immers al gebouwd."

MR: "Als die bak dieper in het water ligt, heb je dan nog de mogelijkheid om ramen daarin te maken?"

JV: "De drijvende villa 's en woningen die wij realiseren hebben een diepgang van 1,50m tot 1,80m met een betonnen bak. Dat betekent als jij een verdiepingshoogte wil hebben van 2,6m met een wanddikte van 18 cm (minimaal), dat de vloer van een betonbak, waarbij je nog je nog isolatiedikte van 10 tot 15 cm krijgt en een afwerkvloer van ongeveer 7 cm, je op een dikte uitkomt van 26 plus die 15 is ongeveer 41 cm pakket. Met 1,80m diepgang in het slechtste scenario hebben we 1,40m, plus het vrij boord van 50 cm komt op 1,90m. Dat betekent dat je dat je de bovenste 70 cm ook kan invullen als raampartijen. Dat zie je dus eigenlijk ook terug in de meeste drijvende woningen die je die je in Nederland ziet.

AV: "Wordt er ook nog wel eens toegepast dat die beton funderingen met piepschuim, dus EPS worden gevuld?"

JV: "Ja, dat is voor speciale specifieke toepassingen. Wij gebruiken de EPS met beton met name voor steigers, terrassen, voor drijvende weilanden, oftewel voor drijvende drijflichamen, want daar hebben we gewoon de ruimte in de fundering zelf niet nodig. En dat kan soms kostentechnisch wat voordeliger zijn. Maar dan gaan we ook wat minder hoog in die fundering, dus dat we elementen hebben van 1 tot 1,5m bijvoorbeeld. Het nut aan vullen met de EPS is dat we de beton diktes wat kleiner kunnen maken, waardoor je weer kosten gaat besparen. Zo kan het bijvoorbeeld weer €100 of €200 per vierkante meter schelen aan bedrijfsoppervlakte."

AV: "Voor de aansluiting op het elektriciteitsnet, waterleidingen en riolering, hoe werkt dat bij een drijvend gebouw of? Er zijn er al veel projecten zelfvoorzienend uitgevoerd?"

JV: "Nee eigenlijk niet geheel zelfvoorzienend, dat is ook heel lastig, want de meeste woningen die wij engineeren hebben ook een eigen warmtewisselaar in die betonbak, dus de leidingen lopen door de betonbak heen. Dat is om de energie uit het water te halen. En dan heb je nog je warmtepomp wat draait op elektriciteit. Dan krijg je dus de capaciteit die je nodig hebt. We zitten nu In de winter, en ik denk dat je nu maar iets van 10% opwekt van wat je normaliter gebruikt. De opslagcapaciteit kun jij met de accu's niet bereiken. Bijvoorbeeld een 100 kilowattuur batterij van zo'n grote Tesla, die zou ongeveer 7 dagen meegaan in de winter hier in Nederland en dan is ie leeg en dan wordt er niet bijgevuld of nauwelijks bijgevuld. Dus je hebt altijd een vaste lijn naar de kade nodig, tenzij je een aggregaat dat toepassen op de woning, dan zou het daarin zelfvoorzienend kunnen zijn. Alleen dan heb je nog je water. Oppervlaktewater mag je nog niet zomaar gaan gebruiken als drinkwater met de filteringssystemen die op dit moment beschikbaar zijn. Je haalt namelijk nog niet zware metalen en eventuele gifstoffen uit het water die per ongeluk in het water kunnen komen. Je zou het wel via een IBA systeem kunnen doen, dus je individuele behandeling afvalwater, waarbij het zwarte water wat daar in komt er eigenlijk tot 98% gezuiverd uit komt en dat zou je door het filteringssysteem heen kunnen laten leiden en dan drink je dus eigenlijk je eigen urine weer op. Dat is theoretisch mogelijk en is ook een extra veiligheid, want het systeem gaat dood op het moment dat er gifstoffen inkomen. Alleen we vinden mensen het idee nog niet heel erg prettig dat ze dus hun eigen rioolwater opdrinken, al zijn die technologieën wel redelijk ontwikkeld. In ruimtevaart wordt het al gebruikt bijvoorbeeld. En nu bij de vuilwaterinstallaties willen ze daar ook verder naartoe gaan, dus dat ook het rioolwater weer gezuiverd wordt tot drinkwater. Dat zijn technologieën die het mogelijk kunnen maken, alleen blijf je gewoon op dit moment met de huidige stand van zaken bij een aansluiting naar de kade, tenzij je dus echt van die hele radicale oplossingen gaat gebruiken. Het gebruik van elektriciteit voor met name de winter en in de zomer het terug leveren aan het net werkt eigenlijk net als een accumulator. Het grijs watersysteem moet je nog aansluiten, zodat dat het regenwater wordt gebruikt van de spoelen van het toilet bijvoorbeeld. Gas wordt bijna nooit meer gebruikt op drijvende woningen. Verder heb je nog data, dat is ook een aansluiting naar de kade toe.

AV: "Zijn dit soort aansluitingen allemaal flexibele aansluitingen?"

JV: "Ja, rioolwater gaat ook terug naar de kade toe. Het zijn gewoon rubberen slangen met een diameter van bijvoorbeeld 50 tot 80 mm en er wordt met een persriool of druk riool naar de kade toe gepompt. De Floating Office in Rotterdam is daar een heel mooi voorbeeld van, daar hebben we het ook zo gedaan. Daar zijn de kabels en de leidingen wat groter, maar die gaan eigenlijk vanuit het gebouw naar de bodem van de rijnhaven en dan gaat het vervolgens weer omhoog de kade in. Dus daar zitten allemaal flexibele leidingen."

AV: "Ervaren jullie dan ook wel eens nadelen of bepaalde limitaties met drijvende gebouwen ontwerpen, of gaat het eigenlijk altijd wel goed?"

JV: "Ja, je ontwerpt daar naar dat het goed gaat. De enige limitatie die die je kan hebben is gewoon de omgeving. Dus we zijn nu bezig met een drijvend hotel bijvoorbeeld. Had ik het idee om dat in beton te doen, een betonbak, dat is een object van 120-130 meter lang en 13 meter breed. Alleen daar gingen we het gebruiken omdat de waterdiepte bijvoorbeeld onvoldoende was, dus daar gaan we naar een stalen casco toe, een stalen fundatie."
AV: "Want die is minder hoog?"

JV: "Die is minder zwaar, dus die gaat minder diep steken. Je hebt meer diepgang nodig. Dus een lichtere constructie, dan heb je de breedte van 13 meter of bijna 14 meter even uit mijn hoofd. Dat bepaalt dan wel weer een comfort level halen, dus dat die g krachten op die bovenste verdiepingen gereduceerd worden. Dus dat de gasten ook comfortabel daar gaan slapen. Dat betekent dat je ook een die limitatie krijgt in de hoogte om dat te kunnen bereiken, want we kunnen niks veranderen aan natuurkundige wetten, dus dat vormt dan de limitatie. Dat moet je wel met de opdrachtgever bespreken. Dus als jij bepaalde doelstellingen hebt, ambities, dan hebben we ons wel te houden aan de regels, aan de natuurkundige wetten. Daar kunnen we niks aan veranderen."

AV: "Ik kan me voorstellen dat het ook in het onderhoud misschien lastiger kan zijn bij dit soort gebouwen, als er iets vervangen moet worden bijvoorbeeld, of valt dat mee?

JV: "Nee, natuurlijk is wel wat lastiger, dus gevelreiniging moet je vanaf het dak doen of met een drijvend ponton langs de woning heen, tenzij je er rekening mee houdt met een omloop bijvoorbeeld. Daar kun je gewoon ontwerptechnisch rekening mee houden. Beton casco's zijn onderhoudsarm, misschien eens een keer schoonmaken, maar in feite hoeft het niet. Aangroei is vaak net zo zwaar als water, dus het zal niet weer verder weg gaan zakken en het dom punt vermogen hè. Dus boeien wil je bijvoorbeeld wel schoon houden in golfslag, omdat het anders toch een hoge massa kan krijgen en dat die onder kan dompelen. Die massatraagheid die erin kan komen, maar daar heb je met drijvende woningen heb je dat eigenlijk niet, want je probeert eigenlijk in, nagenoeg golf vrije of met kleine golven probeer je zo een woning te bouwen, want je wil dat niet in al te golf rijk gebied realiseren, want dat betekent dat je meteen een consequentie hebt voor je comfortlevel in de woning."

MR: "Worden de drijvende gebouwen weer als prefab modules uitgevoerd of zijn er ook andere mogelijkheden?"

JV: "Alles wat je op het land doet kun je eigenlijk op het water ook toepassen. Kijk, casco dat wordt op het land gebouwd of prefab in een fabriek en dan wordt hij naar de locatie toe gevaren. Opbouw kan uit het ship panels, HSB, steel frame, noem maar op."

MR: "Ja, dat ligt gewoon aan de opdracht eigenlijk."

JV: "De aannemer waar die comfortabel mee is. Noem maar op."

MR: "En hoe wordt dan de waterbestendigheid van de materialen en constructies gegarandeerd?"

JV: "Nou, beton is al waterdicht, dus daar engineeren we op dat die scheurwijdtes gewoon gereduceerd zijn en de bovenbouw is niets anders dan een traditionele woning aan het water. Heb je andere materialen nodig? Nee, want er staan ook woningen aan het water. Gaan we daar dan speciale dingen voor doen? Nee, dan op het water heb je dat in feite ook niet nodig. Natuurlijk moet je gewoon goed met je afdichtingen werken, maar een gewone woning is dat eigenlijk ook zo.”

MR: “Dat vind ik wel bijzonder om te zien. Eigenlijk wordt nog precies hetzelfde gedaan als op het land, maar dan op het water.”

JV: “Precies, alleen de fundatie is dus anders, hè? Dus we hebben ook drijvende fundaties in het land gemaakt, dus met de EPS en beton dat die drijft in het veen. En de woning is gewoon traditioneel die er opgebouwd is, lichtgewicht materialen uiteraard. Dus op het water is dat eigenlijk het hetzelfde. Amfibische woningen die we doen. eigenlijk gewoon hetzelfde. We houden alleen maar rekening ermee dat het ook kan drijven en dat het een grotere scheefstand aankan.”

AV: “Want jullie hebben wel projecten waarbij die amfibische constructie wordt toegepast?”

JV: “Ja, in Roermond wat recreatiewoningen zijn we daar mee bezig. Dus wanneer de Maas overstroomt gaan die woningen langs de palen mee omhoog. Maar het wordt niet heel veel gebruikt hoor. Je hebt nog een project van Dura Vermeer, waarbij er amfibische woningen zijn toegepast. Dus dat zijn projecten die niet heel vaak voorkomen. Het is ook een extra kostenpost vaak. Je hebt een dubbele fundering nodig, dat zijn extra voorzieningen. Dat kan het gewoon wat duurder maken. We hebben ook in Rhenen woningen geëngineerd. Daar hebben we bijvoorbeeld voor een potentiële overstroming, hebben we rekening gehouden met de woningen dat deze mogen overstromen. Dus dat je als je een tweelaagse woning hebt, dan kun je bijvoorbeeld de eerste laag van de woning kun je zodanig in engineeren dat gevolgen van de overstroming minimaal zijn soort.”

AV: “Dus zijn ze dan waterdicht?”

JV: “Nou dat het waterbestendig is, het hoeft niet waterdicht te zijn. Dus wat is het probleem als het overstroomt? Vaak is het probleem dat constructie kan gaan rotten of dat er kortsluiting komt, of dat je rioolwater binnenkrijgt. Maar als je bijvoorbeeld al kleppen in jouw rioolsysteem voorziet. De bouwmethodiek die ik op die begane grondlaag zodanig maakt. Dat in plaats van het stucwerk met gips doe je stukwerk met cement, zoals je dat ook in badkamers doet. Dat de schade van de gevolgen van overstroming minimaal zijn. Dus dat je alleen nog maar hoeft op te ruimen en als je weet dat er een overstroming komt, kun je dure spullen zou je nog boven kunnen neerzetten. Dan ga je overstromingsrobuust bouwen. Dus het hoeft niet altijd amfibisch te zijn. Het hoeft ook niet altijd te drijven te zijn om overstromingsbestendig te kunnen bouwen. Je kan hem ook overstromingsrobuust maken, daar je gewoon rekening houdt met een overstroming. In die keren dat het gebeurt. Ik hoorde jullie aan het begin van het gesprek ook zeggen van nou voor de stijgende zeespiegels. Maar ja, we moeten ook niet vergeten dat alle bestaande infra die nu aanwezig is, laten we dat dan gaan? Of blijven we nog steeds onze we beschermingsmiddelen, de dijken en de sluizen, noem maar op. Blijven we die nog steeds in stand houden en verhogen om de rest van de infra die er al ligt om die ook te beschermen? Dus bouwen op het water, het drijvend bouwen, is niks meer dan één van de middelen die we beschikbaar hebben om eigenlijk klimaatbestendig te kunnen bouwen.”

MR: “Ja, je bent natuurlijk wel veilig als je op het water zit. Dan kun je gewoon meebewegen.”

JV: “Ja, maar tot op zekere hoogte natuurlijk. Kijk bepaalde gebieden in Nederland die liggen echt meters onder de waterspiegel. Als daar een overstroming komt, dan zeggen mensen; ja, dan moet je daar drijvend bouwen. Ja, maar tot die tijd heb jij bijvoorbeeld 14 meter lange palen naast jouw woning staan. Hoe ga je met je aansluitingen om? Om bijvoorbeeld zo’n overstroming te kunnen opvangen. Sommigen plaatsen hebben bijvoorbeeld een water stijging gehad in Amsterdam vanwege een fout met een met een sluis. Maar 25 cm. Nou 25 cm is niet veel. Maar woningen in Amsterdam Noord, drijvende woonarken. We hebben daar twee projecten lopen voor een nieuwbouw en een verbouw. We hebben daar al gehoord dat aansluitingen gebroken waren, dat aanmeervoorzieningen gebroken waren. Dan hebben we het over 25 cm. Dus ja, dat betekent dat je zo veel moet doen om eigenlijk ook gewoon een potentiële overstroming tegen te kunnen gaan of tenminste op te kunnen vangen dat mensen dat nog wel eens willen onderschatten, wat daarbij komt kijken dan nog.”

MR: “Nee klopt. Ik heb daar ook over nagedacht inderdaad van wat nou als er dan grotere drijvende gemeenschappen komen? Ja, eigenlijk moet je dan wel zelfvoorzienend zijn, want hoe wil je aan een stroomnetwerk vastzitten?”

JV: “Ja, daarom hè. En dan heb ik je net uitgelegd dat het tegenwoordig best wel lastig is om al je energie op te wekken. Dat betekent dat je draaiende generatoren moet gaan maken bijvoorbeeld.”

MR: “Ja, dus het is ook zeker een opgave dat denk ik ook.”

AV: “Ik denk ook dat de toegankelijkheid voor grotere schaal projecten misschien wat moeilijker is met de drijvende steigers. Sommige steiger zet je misschien vast ,om wat meer mogelijkheden te bieden, maar dan zit je ook weer met de aansluitingen van de steigers. Hoe werkt dat?”

JV: “Precies, kijk een steiger kan meebewegen, maar je drijvende wegen je voorzieningen, je logistiek die je nog steeds nodig zal hebben in een drijvende stad bijvoorbeeld, dat wordt soms ook wel eens onderschat wat er eigenlijk ook nog bij komt kijken. En natuurlijk, wat doe je met de rest van het land? Dus we kunnen zeggen, daar gaan we een drijvende wijk maken, dat is goed overstromingsbestendig, dus ook heel goed. Maar wat doen we met de rest van het land dan? Dus al die dorpen en steden die eromheen liggen in een bepaald gebied.”

MR: “Ja, dat is goeie vraag.”

JV: “Doen we daar niks mee? Zeggen we gewoon van; nou ja, sorry, we kunnen niks voor jullie doen.”

MR: “Ja, dat denk ik ook weer niet. Dat is ook moeilijk om te zeggen natuurlijk.”

JV: “Bekijk de problematiek, dus er wordt heel veel over klimaatbestendig, maar dan denk ik eigenlijk, drijvend bouwen is maar een middel daarvoor, gewoon bescherming tegen het water. De primaire barrière, die moet je nog steeds in stand houden en verbeteren. Je kan wel zeggen van nou, ik kan overstromingen vanuit de rivieren. Dat is een ruimte voor het water creëren. Zou je wel kunnen zeggen in bepaalde overstromingsgebieden waar ik dus waterberging ga toelaten. Daarin zou je wel kunnen zeggen, daar maakt bijvoorbeeld drijvende wijken om eigenlijk een multifunctioneel ruimtegebruik waar te kunnen maken. Dat zijn eigenlijk de middelen die je kan gaan gebruiken. Maar dat kun je ook dus op verschillende manieren doen. Dat hoeft niet per se drijven te zijn. Ik kan ook alles op palen zetten. Dus als ik weet dat er gewoon met mijn waterberging hou ik rekening met een overstroming van 2 m bijvoorbeeld, in een bepaald gebied. Dat kun je gewoon allemaal exact berekenen, ook voor de toekomst. Wat de overstromingsgevoeligheid is en welke berging ik nodig heb. Je zou ook kunnen zeggen, die woningen zet ik allemaal op palen neer. Zodat ik altijd boven het water blijf. Het hoeft niet per se drijvend te zijn. Het kan wel drijvend, maar er zijn meerdere oplossingsrichtingen die daarin mogelijk zijn. Waaronder amfibisch, waaronder dus drijvend, hè? Maar dan adviseer ik eigenlijk gewoon om het gebied zodanig uit te graven dat het altijd drijvend is. Drijvend in de grond, bijvoorbeeld voor in het Groene Hart. In veel veengronden willen ze de grondwaterspiegel ook iets laten stijgen om dat beter te managen. Ja goed, dan kun je op drijvend in de grond gaan werken, dan kun je weer op palen gaan bouwen. Als palen te lang moeten worden dan kun je gaan zeggen van nou, dan graaf ik het stuk grond uit en dan ga ik drijvend bouwen. Maar op die manier kun je dus heel leuk spelen met dat soort aspecten.”

AV: “Want dat amfibische project dat jullie nu dus doen, moet dat ook nog onder de grond gefundeerd worden, zoals traditionele woningbouw?”

JV: “Nee, dat zijn recreatiewoningen in dit geval. We hebben eigenlijk in gravelbed, dus grondverbetering. Het is ook een goede ondergrond, dus het is zand grind ondergrond. Dus we kunnen daar gewoon een woning op het op het droge laten staan. Ja, kijk, in veengebieden, daar praat je over een hele andere aspecten, maar daar heb je ook het risico op kleef bijvoorbeeld. Dus als ik gewoon in veen of klei gebied een amfibische woning op de grond bouw en ik bouw dat alleen maar op die grond, op die klei of die veengrond, dan zou die iets die grond in willen gaan zakken door het eigen gewicht. Als er dan een overstroming komt, kan er een vacuüm ontstaan, onder die fundatie en dan blijft er keurig aan de grond plakken.”

AV: “Ja, ik denk dat je hem altijd al wel iets moet verhogen op palen. Of een andere optie.”

JV: “Dus betekent dat je in dat soort gevallen moet je dus naar secundaire fundering toe gaan, maar dat betekent dus dat in traditionele gevallen vaak, wanneer je op veengrond zit of in kleigrond, dat die palen het gros van de tijd totale gewicht van een woning dragen, betekent dat ik weer die palen bijvoorbeeld 25 of 30 m diep naar de eerste zandlaag moet gaan brengen om die weer te kunnen dragen. Dus daar heb ik en een paalfundering met of een funderingsring, of een verbindingsplaat. Dan krijg ik nog een woning met de drijvende fundatie, dus moet ik dan ook geld aan uitgeven. Dus er komen best wel wat dingen bij kijken.

En dan heb je ook nog wel wat projecten, die hebben dan een kelderbak gemaakt in de grond, waarbij de woning dan invalt, maar ook die kelderbak moet gewoon weer gefundeerd worden. Moet ook weer gemaakt worden. Heb ik dus twee kelder bakken om mijn woning amfibisch te maken.

AV: "Dus de kostenpost is momenteel een beetje wat het tegenhoudt?"

JV: "Ja, wie gaat dat betalen? Dus zou jij bijvoorbeeld €200.000 meer willen gaan betalen voor een amfibische woning?"

AV: "Nou persoonlijk niet, maar wie weet in de toekomst als het zo veel voordelen heeft."

JV: "Dan denk ik ook van ja, dan zijn we eigenlijk pleisters aan het plakken, hè? Dat is hetgeen wat we doen. Met deze woningen zou ik me nog meer gaan richten op bijvoorbeeld het beperken van de CO_2 uitstoot. Het verbeteren van de dijken, noem maar op. Dus dat ik nog wat meer naar de oorzaak ga kijken om in ieder geval dat scenario te minimaliseren. Daarom zeg ik drijvend bouwen is echt een middel die je kunt gebruiken, maar het moet niet het doel op zich zijn."
AV: "Ja, we hadden nog een vraag staan over vergunningen, daar hebben we het net even kort over gehad. Ik denk dat dat ook een beetje te maken heeft met of je gewoon aan de eisen van het bouwbesluit voldoet en de welstand. Komen er nog andere speciale vergunningen bij kijken?"

JV: "Nee, ja, goed, het ligt eraan waar je gaat bouwen hè. Dus je hebt gebieden dat is het bezit van Rijkswaterstaat, dat is meestal buiten de gemeentegrenzen. Binnen de gemeentegrenzen, dan afhankelijk van het gebied waar je in zit. Havens kunnen dan weer onder Rijkswaterstaat vallen. En waterwegen dat valt onder de gemeente. Je hebt altijd te maken met een bestemmingsplan en bestemmingsplanwijziging, omdat je dus het water anders gaat gebruiken. Dan heb je buiten gemeentegrenzen, krijg je ook te maken nog eens een keer, naast de gemeente, met Rijkswaterstaat die heel lastig zijn wanneer je iets in hun gebied wil gaan doen. En, ben je al die stappen voorbij, dan krijg je gewoon je reguliere bouwvergunning, die je moet gaan aanvragen. En wat moet je dan aanleveren? Je bouwbesluit technische berekeningen, dus voor je warmte weerstanden en dergelijke. Daglichttoetreding, noem maar op, dus alles wat traditioneel ook gebeurt. Je hebt constructieberekeningen, dus constructieve veiligheid. En als extra krijg je hier bij de nautische berekeningen, stabiliteitsberekeningen, conform het bouwbesluit en je aanmeervoorzieningen, dat is extra wat er nog wat er bij drijvende woning komt kijken, dus de aanmeerpalen de meerpaalbeugels of dat je het met een andere voorziening naar de kade toe gaat vastleggen, dus daar heb je dan ook nog je constructieve berekeningen voor nodig."

MR: "Ja over die aan meerpalen vroeg ik mij nog af van welke opties zijn er om een gebouw te fixeren en hoe wordt bepaald wat het meeste geschikt is eigenlijk?"

JV: "Nou, je hebt verschillende methodes, je hebt dat je eigenlijk met triangels aan de kade gaat vastmaken. Dat zijn eigenlijk gewoon stangen die op en neer kunnen bewegen, dus er zit met kogelgewricht zitten die vast aan een woning en de kade en de woning kan gewoon in de vlucht van jouw afstand houder kan die omhoog en omlaag. Je kan hem aanmeren net zoals een boot met aanmeerlijnen. Je hebt de meerpalen, je hebt een soort van … systemen, dus gewoon verankering naar de bodem toe met kabels en rubbers erin. En, dat zijn een beetje de smaken die je daarin hebt. De keuzes die wij over het algemeen voor drijvende woningen doen. Drijvende projecten zoals floating Office, de floating Farm drijvende park, dat hebben we eigenlijk allemaal met meerpalen gedaan omdat die palen werden 30 m, dus het is nog gewoon goed te doen in dat gebied en houdt het object aardig goed op de plek. Het kan dus 10-15 cm kan hij bewegen om die paal omdat die paal is ook enigszins flexibel, maar daar heb je met je aansluitingen geen last dus overal waar een meerpaal toegepast kan worden, gebruiken wij een meerpaal. Is er weinig water variatie, waterniveau verschil, dan willen we nog wel eens met die triangel gaan werken als we een deugdelijke kade hebben, dus dan kan dat wel eens voordelig zijn. Zijn de waterdieptes te groot en de water fluctuaties veel te groot, net zoals projecten in Maleisië. Dan gebruiken we de Sea Flex ankers. Dan gaan we dus echt naar anker blokken op de bodem met de rubbers erin om die waterniveau verschillen op te vangen. Nou het nadeel daarvan is, is dat bijvoorbeeld het project in Maleisië is het meer is daar 50 m diep en dan heb je een waterniveau verschil van 17 m, afhankelijk van de droge of natte seizoen. Wat het object ook in het horizontale vlak 8 m kan verplaatsen in alle richtingen. Dat is betekent dat je veel meer voorzieningen moet gaan treffen om die aansluitingen naar de kade, om die ook zo flexibel te houden, die ruimte te geven die het nodig heeft. Dus dat zijn eigenlijk de smaakjes die we hebben en het ligt echt aan het gebied, waterdiepte, het soort project. Dus drijvende zonnepanelen parken die die doen we vaak met Sea Flex ankers, want dat maakt mij niet uit dat het eens 1 keer 1 paar meter de ene kant op beweegt of die andere kant op beweegt. Aansluitingen, dat is alleen maar een elektriciteitskabel. Dat kan ik goed opvangen ermee. Maar daar een woning heb je toch een bruggetje of een ramp nodig om bij de woning te kunnen komen. Dan is het niet zo handig dat je dan 2 m opzij kan gaan, want daar heb je op gegeven moment 2 m gat zitten waar je overheen moet. Dus dat zijn de keuzes die we eigenlijk hebben. Ja, het ligt echt aan de omgeving, het type object, waar wij de keuze op baseren voor het verankeringssysteem."

MR: "Oké, nou, ik had nog wel wat vragen, want ik ga kijken naar die grotere drijvende gemeenschappen. Dat lijkt mij wel interessant. En wat denk jij dat het hiervoor nodig is om dit te laten werken? We hebben net al wel een paar dingen benoemd, maar wat denk jij?"

JV: "Ja, dat is heel lastig. Je hebt heel veel aspecten heb je nodig. Technisch is het allemaal op te lossen. Dus qua techniek dat is goed te doen. Kosten, dat is heel belangrijk hè, dus het moet goed financiën bij zijn en betaalbaar blijven. Dat is hetgeen wat je nodig hebt, want anders krijg je namelijk geen klanten die woningen gaat kopen. Dat is heel simpel. Als het te duur wordt, dan moet het wel heel bijzonder zijn dat het premium waard is. Een drijvende woning is al snel 15 tot 20% al duurder. Met vergelijkbare woningen op het land. Je moet de gemeentes meekrijgen. Dus dat je in een bepaald gebied mag bouwen naar een grotere drijvende gemeenschap, dus de politiek moet je meekrijgen. De omgeving moet geschikt zijn daarvoor. Er zijn eigenlijk heel veel aspecten die die daarbij komen kijken, dus om dat nu zo eenvoudig te kunnen zeggen van wat heb je allemaal nodig. Het belangrijkste is, het moet betaalbaar blijven en het moet zijn doel kunnen vervullen. Nogmaals, je moet niet drijvend bouwen om het drijven, maar een toegevoegde waarde. Het moet eigenlijk bijna niet op een andere manier op te lossen zijn dan bijvoorbeeld drijvend te bouwen in dat gebied, want dat betekent dat er geen alternatief is. Betekent dat dat de prijs is om daar te kunnen bouwen, om daar te kunnen wonen te werken. Noem maar op."

AV: "Ik denk dat we best wel uitgebreid van alles besproken hebben en dat we gewoon een hoop nieuwe inzichten hebben gekregen. Daar zijn we heel erg blij mee in ieder geval."

MR: "Heel erg bedankt. Er waren toch wel wat vragen die inderdaad de laatste tijd in ons hoofd afspeelde, maar die niemand hier kan beantwoorden, want niemand heeft deze ervaring zeg maar. Dus dat was fijn om te horen."

JV: "Graag gedaan."

INTERVIEW WIKKELHOUSE

Company: Wikkelhouse
Location: Amsterdam, The Netherlands
Date of interview: 24-11-2023

To get more insight into real-life applications of cardboard constructions in the building industry, I visited the company and factory of Wikkelhouse. This company specializes in creating sustainable, modular homes made primarily from cardboard. Their innovative design involves wrapping layers of cardboard around a mold, forming sturdy, customizable sections that can be assembled to create a variety of living spaces. These houses are known for their eco-friendliness, quick assembly, and adaptability to different environments. The modular nature of Wikkelhouse allows for easy transportation and expansion, offering a flexible housing solution with a focus on sustainability. During the visit I had the opportunity to see the factory where these modules are fabricated. Conclusions from this interview and tour are used in this thesis.

Summary of visit and questions

1. What is the main reason you chose cardboard as a structural material?

Cardboard is a sustainable and recyclable material which turned out to be much stronger than we initially thought. The founder of Wikkelhouse has a history in the paper industry and he created a box with rounded corners, made out of three layers of corrugated cardboard. This was the beginning of an idea that this construction could probably also work on a larger scale, resulting in the design of the Wikkelhouse. A machine was made to mold the layers of cardboard in the specific form and after a period of experimenting the modules could be fabricated.

2. The wall has an open facade system, what does this wall construction look like exactly?

The wall components consist of 24 layers of cardboard with a wooden finishing and a waterproof layer. Cardboard has good insulation values and has strong capabilities in this case. In the middle of the construction a cavity is designed, for the installations and construction of the modules. In the picture the specific wall structure is visible.

3. How does the modular connection of the individual building elements work?

The modules are connected by pulling wire steel through the construction. The wall construction consists of two layers of cardboard with an opening in the middle for holes for the connection. There are six points where there's a hole in the construction to allow the passage of the wire steel. The outer module and the bathroom module is not made of cardboard, but of flax insulation and a wooden frame. This is done because a better insulation was needed for this modules and in these parts can be screwed more easily.

4. Does this wall construction have a sufficient insulation value?

The RC-value of the wall construction is 3,5. This insulation value is actually too low for new build constructions within the Dutch regulations, but the BENG (Nearly Energy Neutral Building) is still positive because the building achieves high scores in energy generation, lightweight construction, and sustainability. Currently, we are experimenting with thicker wall elements, so that the Wikkelhouse can also provide comfort in colder countries. In a Dutch climate the comfort within the house is good.

5. Did you have to impregnate the cardboard modules to make it water and fire-resistant?

No. To make it water-resistant a waterproof vapor-open layer is placed on the outside of the construction. This is done to facilitate the escape of moisture produced inside to the exterior. The construction is fire-resistant for approximately 30 minutes. Due to limited oxygen reaching the structure, the cardboard is not highly flammable. Fire tests have demonstrated that the cardboard starts to smolder, which takes a relatively long time before it loses its strength. Additionally, it's a confined space with quick escape options on two sides, so escape routes contribute to the fire safety.

6. What is the lifespan of a Wikkelhouse, and can it be fully recycled after its lifespan?

The lifespan of a Wikkelhouse is around 20 to 25 years. Since every module can be replaced and recycled, it is easily possible to extend the lifespan by replacing some parts of the building. The Wikkelhouse is designed as a modular principle, so that the building can adapt to changing needs of the users, like family expansion or moving to another location. This flexibility contributes to a longer lifespan that traditional housing concepts. After its lifespan, the modules can be reused in the factory.

7. Do you expect it will be possible to use this modular wall component on a larger scale, for instance, in multi-story buildings?

We didn't experience with that for now, because our main goal is a building concept which is easily transportable. This leads to a maximum height and maximum width of the modules which are still allowed to transport on a truck. For this scale our cardboard construction works very well and I expect there will be possibilities with this concept for a larger building.

8. Would a Wikkelhouse be suitable as a floating home?

Yes, there are a few projects in Rotterdam where the Wikkelhouse is build on water. Instead of our regular foundation, the building is in this situation placed on a floating platform. It works comparable to a houseboat principle.

9. What types of foundations are in use to place a Wikkelhouse?

There are two options of foundations that we use. The first option is a concrete foundation, on which the building is constructed with a wooden rails. The second option is a screw-foundation, which we use in situations with soft undergrounds. The building is always placed a little bit above the ground, to create natural ventilation around the building.

10. How is the wooden finish attached to the cardboard?

The façade is connected to the main construction by using a timber frame construction which is screwed into the wooden construction.

11. Is the house fully self-sufficient or is that a possibility?

The Wikkelhouse is not an off grid building, so it is connected to sewerage, water pipes and the electricity grid. We use solar panels to produce electricity, but during winter periods it would not be enough. A heat pump is used for both cooling and heating by using air heating. Outside the building air unit is located and this is connected via the bottom. Our reason to connect to these facilities is because the space in the house is limited, so self-supporting installations take too much space and make it way more expensive. In the current design, one module is needed for the technical installations. For specific requests of our clients we offer the possibility of bio toilets.


Photos from excursion of modules and wall construction (Own photos, 2023)

Research Report

FLOOD-PROOF LIVING AT THE RIVERSIDE

MSc Architecture - TU Delft