REGENERATIVE LIVING ON WATER:

Bio-inspired floating student housing in a harbour in Rotterdam

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Bio Inspired Innovation

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In the process, my supervisor Jaco Appelman suggested to place the quote 'Less is More' by Ludwig Mies van der Rohe above the thesis, which means as much as 'strip it to its essentials'. For long I actually had a motto that closely resembles the critique of Robert Venturi on that very quote, suggesting quite the opposite 'Less is a Bore'. In the process of working on this thesis I once again was confronted with my former motto. For this thesis, I sure could have had more of 'Less is more'. I suggest a nuance, though. For some things, such as writing a thesis, it is desirable to strive towards 'Less is More'.

But for other things, say – a thriving environment – we need to embrace 'Less is a Bore'. In this thesis about thriving, I think that both were necessary in their own way. Let us celebrate the richness of life, and make stimulating works, but remember that not all has to be solved 'all at once'.

Thimo Hillenius

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Acknowledgements

This thesis assignment has been a long journey, but an incredible good fit for me as a person. Merging biology with sustainability (regenerativity!) and architecture lies at the heart of what motivates me every day. Therefore I would like to say thanks to my Master's programme coordinator Jaco Appelman, and the Floating Students team. The extensive help of my supervisors Mireille Langendijk and Jaco Appelman was much appreciated, I remember the meetings as very enjoyable. Pauline Krijgsheld I thank for her caring messages, and good advice at important crossroads. I would also like to express my thanks to the experts Eduard van Vliet, Jennifer de Jonge and Robbert Snep (and others!) for devoting their time in interviews and telephone calls.

Then the story of Floating Students: Two young but headstrong persons Benjamin Cadee and Stan Bastiaansen, dared to start this organisation, that develops regenerative floating houses for students, by transforming discharged inland shipping vessels. Together with Marijn Lintveld, Gijs Neerincx and later Mischa Hillenius we worked together on the project in the garden of a beautifully transformed church in neo-gothic style – the 'Metaal Kathedraal'. This cultural cluster and its staff; Maureen, Abel and Amaya were more than inspiration for us.

Last, but not least, I would like to say thanks to my dear friends Bart and Frederike, and my family members Leny, Eppo, Ruben and Mischa for encouraging and helping me during the whole duration of the project.

Thimo Hillenius

Abstract

Climate change induced sea level rise is endangering urbanised coastlines worldwide. The Netherlands, an example of a country with much ground below sea-level, needs to adapt to the challenges this poses. Simultaneously, the Netherlands has both a large housing shortage and a biodiversity crisis. To come up with an integrated solution to these challenges, this report focuses on the development of a prototype design for housing that moves along with rising seas and nourishes the local environment; floating houses with a regenerative design. This report aims to establish a set of key elements for regenerative design and how these elements interrelate.

For the design, a 67-meter-long inland vessel situated in a river arm in a low-lying urbanised region is used as a case study. Reference projects are analysed to determine common factors for regenerative design. On basis of these common system functions, a literature research is performed, after which a design is made, utilising biomimicry. The design is evaluated by utilising Life's principles and posing questions.

Four system functions that the reference projects share, are regulating water, increasing biodiversity, storing energy & balancing, and circular material usage. Important discoveries are that it is essential to segregate various water streams, to ensure water quality. For nature-inclusive design it is necessary to create favourable conditions from the viewpoint of animals and plants, A focus on aqua thermal energy and included energy storage is preferred, because of the location near water and capacity challenges on the Dutch energy grid. For materials, a circular way of using is necessary, because otherwise problems with reuse in the future occur.

While for some aspects the design does lead to nourishing solutions, this cannot be achieved for all elements. A drawback is that for the design to remain functional and operational, parameters of technological, social, and ecological nature need to be monitored. Emergent effects of the prototype are interrelations between the different sub-systems that lead to synergies and trade-offs. Furthermore, possible emergent effects can be expected by the merging of technological and ecological systems, ecological effects by a dialogue with nature, socio-ecological effects and possibly increased social cohesion. Finally, the immediate impacts of the design on the local environment might be dwarfed by the role of the design as a pilot project for further developments, both in the same neighbourhood and elsewhere in coastal regions around the world.

Layman summary

Climate change is one of the most pressing issues of the 21st century. One of its consequences, sea-level rise, impacts coastlines all over the world leading to mass displacement of people in coastal regions. Around 10 per cent of all people live in coastal areas less than 10m above sea level[1]. In the Netherlands, a housing crisis is ongoing, and space on land is limited. To tackle these problems simultaneously, floating houses might be a good solution.

Moreover, buildings tend to degrade rather than enhance the natural environment, contributing to climate change and biodiversity loss. The goal of this research is to design the most sustainable student homes in the Netherlands, on a boat. This project will act as a prototype of a scalable concept, which can be applied in coastal regions in the Netherlands and internationally.

Sustainability reaches further than minimising harmful environmental effects, therefore the project seeks to go a step further by aiming to deliver a positive contribution to its natural surroundings. This is called 'regenerative design'. The central question is what factors a prototype for floating housing would need to make the local natural environment thrive.

For the design, a 67-meter-long inland vessel is used as a case study. It is situated in a highly urbanised region prone to flooding due to rising sea levels. The focus group is students. As a method, first, examples of other (floating) buildings are studied. Lessons from these projects form the basis for further research, and the design. For the design inspiration is taken by applying biomimicry. This is a discipline that takes inspiration from nature and biology to develop new ideas and innovations.

Four system functions from the reference projects that further guide the research are regulating water, increasing biodiversity, storing energy & balancing temperature, and material usage. Focus is especially on the first and the second of these system functions.

While the level of regenerativity can still be increased, the design poses an example of what is possible with today's technologies. The design does sketch a clear vision of what the system could look like, which is a major contribution to bringing the design into reality. Lastly, the impact of a good example should not be underestimated. It can steer other developments in the neighbourhood or other coastal regions into a more sustainable or regenerative state and therefore have a higher impact than the local environmental impact of the project alone.

1. Introduction

Climate change is one of the most pressing issues of the 21st century impacting lives all over the world. It manifests itself in many ways, of which sea level rise has far-reaching consequences for urban areas in the Netherlands and other coastal regions. In addition, the global decline of biodiversity is just as threatening as the climate crisis. The most important cause for continued biodiversity loss in the Netherlands is habitat loss through agriculture and urbanisation leading to eutrophication, acidification, aridification, and fragmentation of habitats[2]. Therefore, ways to cope with rising sea levels and biodiversity loss are needed. In an attempt to combat both the comprehensive issues of rising sea levels and biodiversity loss, this research explores nature-inclusive human habitation on freshwater ecosystems.

Currently, human habitation on freshwater ecosystems may lead to lower environmental quality than not living on freshwater ecosystems at all. Nature-inclusive building as a practice is a young field, marginally applied to residential floating structures. For example, biological growth underwater is not promoted but instead discouraged by applying toxic paints underneath ships and pontoons.

The research to study the influences of floating structures on water quality and ecology is underdeveloped. Early studies suggest limited negative influences. For example, de Lima et al (2020) found in a test study with a floating structure that dissolved oxygen, nitrate, and ammonium levels were at normal levels or within expectations[3]. Positive influences, such as substantial fish and organisms were found underneath the structure. However, current research does not regard structures as opportunities for building with nature. The effects on a larger scale are not known, but as more and more natural areas are replaced by human-made structures, ecological quality is invariably diminished, both on land and in marine habitats[4,5]. This effect is increased by the fact that the building materials used also contribute to environmental damage. A striking example is the widespread use of the material concrete, which is responsible for 8% of the total global CO_2 emissions[6].

In general building for sustainability has failed to include ecological functioning, focusing on renewable energy technologies and minimising energy usage instead[7]. Although a good start, this is not nearly enough to counter environmental degradation. To diminish the environmental impact of the building industry and housing, the concept 'circular economy' is introduced, defined here as the goal to create a regenerative system by closing technical and biological material and energy cycles while keeping the value of its components as long and high as possible[8]. A movement that includes ecological functioning is called nature inclusive design. When the aforementioned methods are used in synergy, human pressures on ecosystems may decrease while ecological soundness for living on freshwater ecosystems may come into reach. Ultimately, a situation is envisioned where people and nature thrive in harmony, wherein thriving is described as flourishing, gaining health, developing well[9]. This vision is the same as the recent sustainability paradigm 'regenerative design', which can be described as ''enhancing human life and natural ecosystems in a partnered relationship, through comprehensive interventions and coevolution''[10–12].

The main emphasis of this research is merging ecological solutions and integral sustainable design as a basis of regenerative design. This emphasis leads to the following research question:

What factors should a prototype for bio-inspired floating student housing entail, so that it makes the local natural environment thrive?

To answer the research question, a 67-meter-long inland vessel situated in a river arm in Rotterdam is used as a case study. This is an interesting location as this is a highly urbanised region prone to flooding due to rising sea levels[13]. The vessel will be used as a basis for the design combining insights from biomimicry methodology and design methodologies. Theoretically, this research contributes to the existing literature by identifying key elements of regenerative- and nature-inclusive building and how these elements interrelate, adding to the knowledge base of ecological soundness of human habitation on freshwater ecosystems. From a practical point of view, this research provides opportunities to cope with rising sea levels and adds ecological value to its location. It is thought that both technological and ecological components, with a high degree of circularity, are needed to make the local natural environment thrive.

The structure of this report and the sub-questions to answer the research question are as follows: chapter 2 of this research handles the research methodology. In section 3.1, reference projects will describe what research areas are important when considering regenerative design. In section 3.2 these are further researched to describe what bio-inspired, ecological, and technological concepts and solutions can lead to a thriving local environment. The definitive design is presented in section 3.3. Section 4.1 handles whether the design can be described with Life's Principles. Whether the design will lead to nourishing solutions will be answered in section 4.2. However, the emerging system is only functional and operational after certain maintenance and monitoring (section 4.3). Finally, in section 4.4, the emergent effects of the prototype and its upscaling are elucidated, after which in chapter 5 a conclusion and discussion follows.

2. Research Design & Methods

2.1 Research design

For this research, a method and tools derived from architectural education are used. This method is distinctly different from the scientific method, which immediately scopes down to a well-defined research topic. The efforts usually stay close to the research goal, with various experiments (in consequential order, sometimes parallel) advancing knowledge in the direction of the goal. The data from the experiments are analysed and used as support material for a research paper.

In design, a broad overview of information is gathered, after which a phase starts where the information is interpreted. Overarching themes or interesting pieces of information lead to concepts and solutions, that are later implemented into the design. The overarching theme for this research is regenerative design. The design is evaluated using Life's principles (appendix 3&8), and the research questions.

An in-depth analysis and comparison of methodologies used in design, science, and other disciplines is given in appendix 1, just as the used biomimicry methodology (appendix 3).

2.2 Case description

To gain insight into the functioning of a bio-inspired floating student house in relation to its local environment, a 67 m- vessel in Rotterdam (table 1, figure 1) was chosen for the following reasons. First, large parts of Rotterdam are prone to flooding[13]. Situated in the large river deltas and close to the sea, it is particularly vulnerable to the effects of climate change. Second, the city has large water surfaces within its city boundaries, which can be considered an underutilised resource. Third, the city of Rotterdam is welcoming innovative initiatives, of which it has established a reliable base, enhancing possibilities for collaboration[14]. Lastly, the ecological importance of the tidal nature in Rotterdam is vast, being the only site in the Netherlands where rivers have an open connection to the North sea. The underdeveloped relationship between the city and its estuarine character is recognised by the municipality and development plans for nature-based solutions are being carried out[15]. More information on the type of vessel is available in Appendix (2).

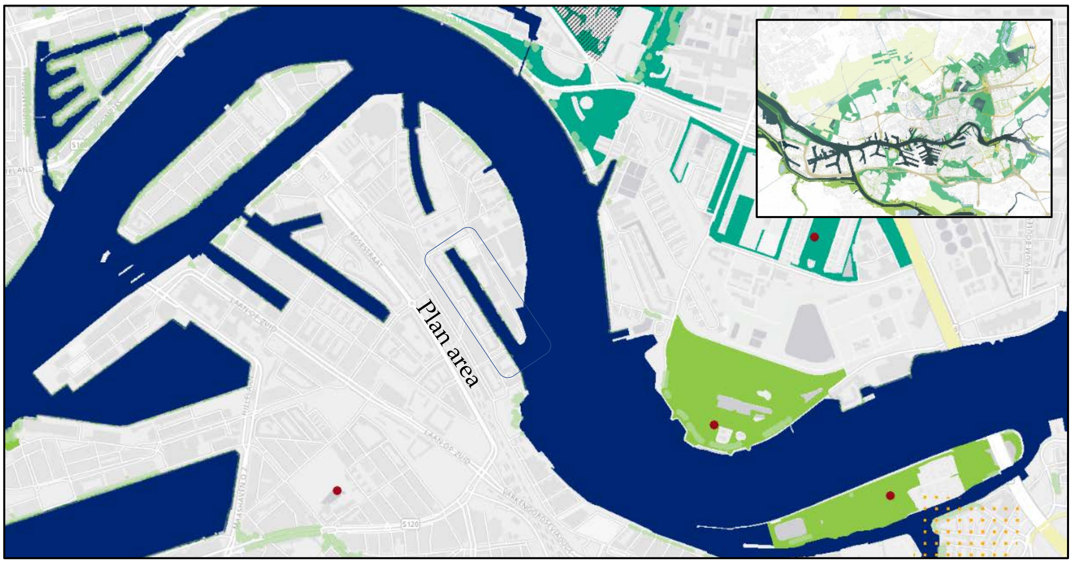


Figure 1. Plan area and landscape overview, Rotterdam. (Natuurkaart Rotterdam, 2014).

Table 1. Characteristics of the Dortmunder ship type. (Binnenvaart Kennis, 2019).

Dortmunder	
	
Ship dimensions	67,00m x 8,20m
Cargo hold	49,00m x 6,60m x 3,40m(height)
Carrying weight	1000 tons
Gross floor area available (max 3 floors):	970,20 m2 (49,00x6,60x3)

2.3 Data collection and analysis

2.3.1 Data collection

Data is collected via various sources. Several reference projects (Vertical, Floating Islands, De Ceuvel and Schoonschip in Amsterdam, The Floating Azolla Farm in Rotterdam, and Urban Rigger in Copenhagen) were selected based on physical and ecological aspects of regenerative design. These are nature-inclusive design, successful integration of technologies with the ecological environment, utilising biomimicry, and progression in the circular and biobased economy[12,16,17]. The reference projects are then studied in detail, to form a basis of state-of-the-art system elements to be included in the design. Biomimicry brainstorms based on biomimicry methodology provide input to the design offering analogous solutions to the question 'How does nature do/solve [..]'. To this end, the database of AskNature is used. Last, the direct physical environment is a major source of data to fit the design into its surroundings. Site visits, news articles, project reports, scientific literature, and websites such as waarneming.nl give insight into the ecological functioning of the area.

2.3.2 Data analysis

Site visits and interviews are used to analyse several reference projects, while others are studied via literature. Special attention is given to system elements and their function within the system. System elements that are thought to fit the design in this research (based on scale, size, context, and availability) are further researched to determine their suitability and to analyse their workings. For the location analysis, both abiotic and biotic factors are studied. The design itself is analysed by comparing it to Life's Principles and answering the research questions.

2.4 Research boundaries

The boundary for this research is one ship in relation to its direct environment. Moreover, emphasis is put on the physical and ecological aspects of regenerative design. Other aspects, such as sociology, psychology and aesthetics are indispensable for regenerative design as well but are less focussed on in favour of narrowing down the scope of the research.

3. Results

The results chapter is based on six reference projects, from which overlapping system functions are distilled that further guide the research. These case studies represent state of the art technological and ecological developments in the field of regenerative design (section 2.3.1).

3.1 Reference Projects

In this section six reference projects are discussed that make progress towards regenerative design. Following the projects *(Vertical, Floating Islands* and *Schoonschip* in Amsterdam, the *Floating Azolla Farm* in Rotterdam, the *Cardboard to Caviar project* in Northern England and *Urban Rigger* in Copenhagen*)* common system functions are distilled, that form the basis for the next section of the research.

Project 1

Floating Azolla farmhouses is a student project from Jean-Christian Whitehouse Posse at the University of Westminster in the field of architecture[18]. It caught attention through its rigorous basis, integration of various disciplines and using biomimicry to envision a regenerative floating farmhouse in Rotterdam.

The departing point for the design was researching Azolla, a small fern with an underutilized potential for producing biomass, food, biofuel, bioplastics and biofertilizer. Doubling in 2 – 3 days, its speed to produce biomass is unparalleled, making it a very versatile crop in the face of climate change.

In his architectural design, Jean-Christian proposed floating residential housing for young entrepreneurs in R&D, integrated with vertical Azolla farming, vegetable farming and a production facility. He argued that the nearby project *the Floating Farm* could be expanded with bamboo growing pods and permaculture rice paddies, providing fast-growing building materials and food. The floating apartments are constructed from the locally sourced bamboo, left-over pallets from adjacent industrial sites and bioplastics produced from Azolla and algae. The building system was inspired by the Azolla fern as well. By researching the plant and its form, he produced many physical and digital artefacts using digital modelling (grasshopper), fabrication techniques (laser cutting, 3D printing), and materials such as bioplastics. The laboratory experiments with bioplastics became the basis for developing an adaptive façade regulating the climate for optimum vegetable growth in the floating apartments. Once more digital modelling came in handy to study the naturally occurring climate conditions at the site and to present compelling renders and animations.

The project by Whitehouse Posse is highly interdisciplinary and shows the potential of lifting with existing successful projects. For example, the proposed Azolla farm can be an extension of *the Floating Farm*, profiting from the growing economy in Azolla and other biobased industries. Furthermore, it shows the potential of biomimicry, as multifaceted solutions can be inspired by a small fern.

Project 2

Few projects illustrate the creation of a meaningful circular business area so well as the ***Cardboard to Caviar project.*** This project was started by Graham Wiles who involved people with disabilities in a recycling initiative. Waste cardboard from shops and restaurants was collected, shredded, and then sold to equestrian centres as horse bedding.

Then the scheme was expanded by recollecting the used horse bedding and composting it using vermiculture. The surplus of worms was collected for a fish farm. When no fish farm in the near environment proved a long-term collaboration, Graham Wiles set up his own fish farm working together with former heroin addicts. Seeing that many youngsters brought junk food to the farm, he involved them in growing vegetables and educate healthier eating. Nearby allotments were made, of which the vegetable waste diminished the need for commercial fish food. As the project grew, more land (from an adjacent neighbour), resources and knowledge became available to optimize the fish farm. While the land was progressively evolving into a productive ecosystem the socio-technological system flourished too.

Selling the caviar from the fish back to the restaurants demonstrated that low-value waste streams could be turned into a high-value product, levering social, environmental, and economic benefits. All this time Graham Wiles bundled the under-utilized human potential from people with great skills and desire to be involved, showing their importance and abilities[16]. See figure 2 for an overview of the food web diagram of the project.

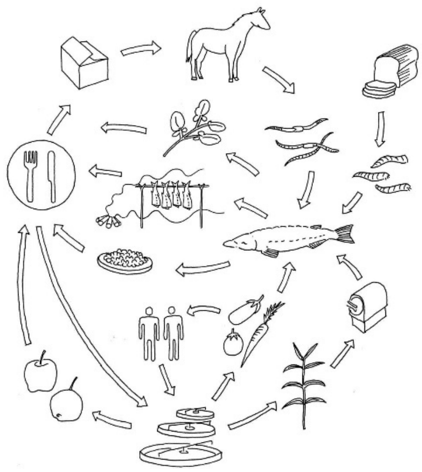


Figure 2. The foodweb of the Cardboard to caviar project. (Exploration architecture, 2016).

The Cardboard to caviar project shows that systems thinking is a valuable tool in creating regenerative social-ecological systems. Building up a biobased economy with marginalised groups of people tackles social and ecological problems in one go. In the book *Biomimicry in Architecture*, Michael Pawlyn further dissects important aspects of Wiles his solution, stating that he transformed weak links, under-utilised resources, and decreased system leaks, in order to make the system work[16]. The more the project grows, the more the possibilities seem to expand. However, the right balance and connectivity between elements is far more important for continuity than endless growth. Moreover, high-tech solutions can lever large benefits, but the possibilities of mostly low-tech solutions such as in the *Cardboard to caviar project* should not be forgotten. Low-tech solutions in combination with a strong community can make a system easier to manage (more resilient) than high-tech solutions, performing under a smaller footprint. Lastly, delivering the benefits of a well-functioning integrated system relies on the realistically scaling of individual processes and elements, both commercially and technically[16].

Project 3

Another project, ***Schoonschip***, is a neighbourhood of floating houses in Amsterdam that combines food production, sanitation, and energy systems[19] (figure 3). The involvement of users in the project was essential because they are the ones investing in the proposed sustainable technologies and adjusting their lifestyles. The costs are kept down by phased execution of the plan, and a strong focus on do-it-yourself and low-tech solutions.

Community-living is important in the project, people with diverse incomes and shared values, especially on the theme of sustainability, can live here together. The building plot is water-based, one of the first to acquire this status in the Netherlands. The plan consists of five piers, with each of the piers surrounded by five to six buildings.

The final targets of the *Schoonschip* project were:

- 100% renewable heat and hot water supply
- 100% renewable electricity
- 100% wastewater and organic waste treatment
- 100% water self-sufficiency
- 60 - 80% nutrient recovery
- 50 - 70% reduction in electricity demand over conventional households
- 60 - 80% vegetable & fruit production using locally recovered nutrients
- sensor network and real-time system performance displays

Figure 3. Render of 'Schoonschip'. (space&matter Architectects, 2012).

The Schoonschip project shows that building a diverse and strong community is important for creating the needed drive and perseverance for making the community and environment thrive. In this project, besides continuous collaboration, it helped that each of the households signed a manifesto on sustainable living. Using sensor networks and real-time system performance displays, externalities can be included in the functioning of a system like *Schoonschip.* Externalities are for example pollution, water filtering, social effects, and nutrient loss. By making these measurable, the success of a project can be judged more holistically.

Project 4

Vertical is a nature-inclusive high-rise building project in Amsterdam Sloterdijk and is being built on a plot in between two city parks that needed an improved natural connection. It was designed by several architects and consists of two towers, on a plinth of four to five stories. In general, backed by a broad theoretical foundation, it shows how architecture can improve biodiversity[20,21]. The plantings are largely a continuation of nearby plantings and birds, bats, and insects were seen as clients of which the nesting possibilities are aesthetically pleasing as well. The project contains one nest for predatory birds while providing 95 nesting possibilities for swifts (swallows), 72 for small birds and 38 spaces for bats. There will be 90 different species of plants and a capacity of 310m^3 for water retention[21].

To design for animals and plants, several nearby applicable biotopes were chosen as models. These were inspired by rocks, hills, a nearby nature area and city gardens (figure 4).

Important is that in this project many practical problems are tackled, giving a substantial contribution to the field of nature-inclusive design in the Netherlands. Some nature-inclusive measures proved to be easier than thought, like storing water on roofs. Other measures were far more difficult to engineer, such as the weight contribution of plantings and water storage on the facades. Continuous collaboration between different stakeholders, and learning each other's language proved to be important success factors to tackle these challenges. The importance of collaboration while pioneering is the most important aspect that *Vertical* teaches.

> Biotope: 'an area of uniform environmental conditions providing a living place for a specific assemblage of plants and animals'.[22]

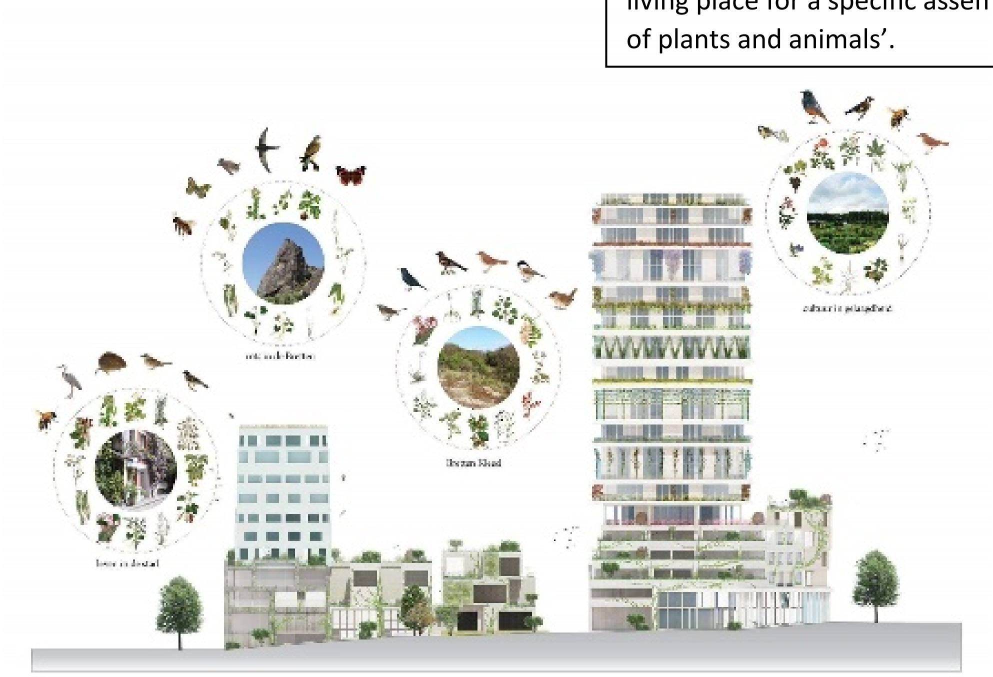


Figure 4. The biotope models of the Vertical building. (DS Landschapsarchitecten, 2019)

Project 5

The ***Floating islands in Amsterdam*** are a continuation of projects by Robert Jasper Grootveld in the 1970s[23]. He imagined and then built floating islands from Expanded Polystyrene (EPS), scaffolding cloth, and fishing nets. Through the years it developed as a craft, and even today new people are learning the skills needed to tie and assemble the islands.

The islands can mean a lot in terms of biodiversity. For this research, two excursions were undertaken to *'t Yland'* which is a floating island of thirty years old with a small house built on it, mooring in Amsterdam (figure 5)[23]. Plants on top of the island are not always able to get their root system to the brackish water of the Amsterdam city canals, nor is the level of salinity right for a lot of the species. For this reason, rainwater is collected, which is used for plants to thrive. The maintenance of the garden is quite some work. Since a few years, the maintenance is done mostly by a foundation, created to ensure the continuation of the project[23]. Whether floating islands are a good solution depends on the consideration if the benefits in terms of durability, biodiversity, climate adaptation and social and cultural benefits outweigh the negative impact of (micro)plastic pollution from the oil-based construction materials[24].

Figure 5. 't Yland, a floating garden and house in Amsterdam. (Taal, Arie.; Kerstin, 1998).

Besides the hard decisions in favour or against these islands, the floating islands show the importance of various water sources for ecology. Some plants need rainwater to thrive, while for others, the brackish canal waters suffice. Furthermore, legislation and political decisions were dealbreakers in both the *Floating Island* projects and *Schoonschip*, imposing requirements that increase the difficulty to make the projects possible.

Project 6

Urban Rigger is an answer to the problem of affordable student housing and climate change, using the waterfront of cities[25]. It is designed by architect Bjarke Ingels from BIG Architects, a large design company in Denmark.

The design consists of nine used sea containers on a hexagonal concrete pontoon (figure 6). In total 12 spacious apartments are created, each including a kitchen and bathroom. Furthermore, a courtyard for bicycles, a communal space, green roofs, and a roof terrace are included.

Using the temperature differences of seawater for heating, solar panels for power generation and high-standard pumps, thermostats and building services, the design focuses on sustainability and durability. Material life cycles were carefully considered and the concrete hull is suited for biological growth. Implementing the newest sustainable technologies, Bjarke Ingels brought a strong expandable concept into reality, that could be successful in many cities along coastlines.

Figure 6. Urban rigger, Copenhagen. (BIG Architects, 2016).

The Urban Rigger project shows the successful integration of state-of-the-art technology in floating apartments. Fitting the project into a larger story can help generate a strong sense of purpose and inspiration. Although now being mainly focused on technical and commercial viability, Bjarke Ingles embeds the Urban Rigger project in a larger and futuristic vision of thriving cities on water. Generating a strong vision is helpful to convince local authorities to develop water fronts as well, although sufficient technical backup to show that the proposed solution is functional, is important too[25,26].

Synthesis reference projects

The reference projects show that a diverse set of system functions is important when considering a regenerative environment. All of them show the importance of systems thinking, integrating social, spatial and ecological aspects. It is not only about the design and construction of single buildings, but also about being able to farm food locally, surrounding infrastructure, energy availability, biodiversity and the well-being and health of the inhabitants. Four functions that are common in these reference projects, and that are elemental to their functioning are **regulating water *(Floating islands, Schoonschip)*, increasing biodiversity *(Vertical, Floating islands, Carboard to caviar project)*, storing energy & balancing temperature (*Azolla farm, Schoonschip, Urban rigger*), and circular material usage *(Azolla farm, Schoonschip)*.** These system functions are essential for the functioning of a bio-inspired floating student house in relation to its local environment and will be the basis to further structure this research (figure 7).

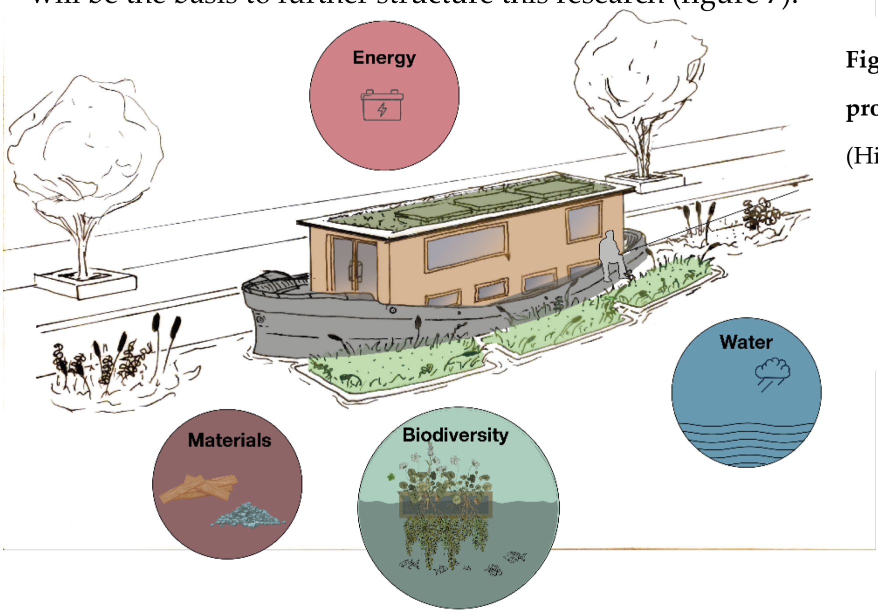


Figure 7. Synthesis reference projects – System functions. (Hillenius, T.; Maas, T.).

3.2 System elements and interconnections

This section focuses on what bio-inspired, ecological, and technological concepts and solutions lead to a thriving environment.

The section continues with the four identified system functions (regulating water, increasing biodiversity, storing energy & balancing temperature, and circular material usage), for which concepts and solutions are worked out: The research focus is on the first and second of these system functions, while the third and fourth are included to incorporate a systems view. The conclusion of this section offers remarks on what developments have the highest chance to implement in the design, as well as potential synergies between them. Figure 8 shows what is thought to be an overview of the system elements that together form the basis for the regenerative design.

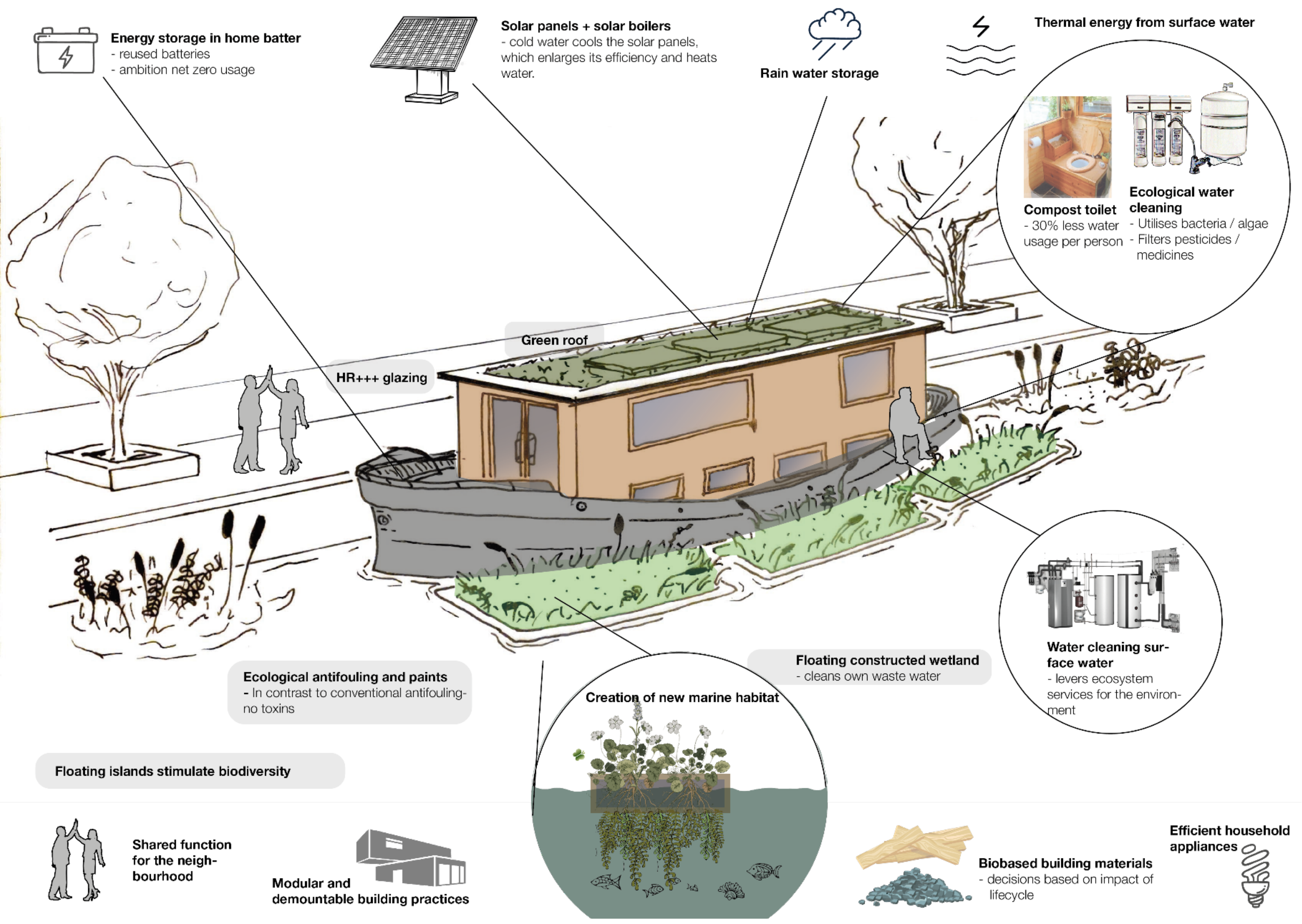


Figure 8. Overview of possible system elements. (Hillenius, T.; Maas, T.).

3.2.1 Regulating water

In this section, the first system function is explored in depth. First environmental water quality is discussed, as this is a basis for healthy functioning ecosystems. Then attention is given to what households can do to minimise their negative impact on environmental water quality. As a third point, various solutions are proposed and described that help filter wastewater streams and deliver a positive impact on the water management in the immediate environment of the ship, thus generating a regenerative water system.

3.2.1.1 Water quality

In a report by the Dutch environmental organization milieu&natuur in 2019, the water quality in the Netherlands was deemed under strong pressure[2]. Two-thirds of the water bodies in the Netherlands are obliged to be monitored by European law. Of these waters of the *Kader Richtlijn Water* (KRW), 99 per cent score insufficient on ecological water quality, while 58 per cent of the water bodies score insufficiently on chemical water quality. With these numbers, the Netherlands is the worst-performing country in Europe[27]. 'Other (smaller) waters', which comprise a third of all water surfaces in the Netherlands, are exempt from European rapportage[2]. These water bodies, ditches, city waters, creeks, and ponds, are therefore hardly monitored. As water is the basis for our society, this has consequences for the health of our environment and ourselves. The most important causes of the meagre water quality are[2]:

- Nitrate and phosphate from manure
- Pesticides
- Sewer overflow
- Medicine residues and other micro-contaminants.

Moreover, the morphology of the waters is important to regulate water quality[2]. By water-morphology is meant: the depth, flow, and meandering of the water and the steepness of the shores.

Apart from these problems, the quantity of water is problematic as well. As climate change enlarges weather extremes, water infrastructure needs to change to stabilise water runoff, ensuring continuous water availability to (vulnerable) nature areas and society[27]. According to natuur&milieu water quality management is not functioning well because of dispersed responsibilities and a lack of enforcing legislation in practice[2]. Another key problem is that a cohesive plan to control the causes of water pollution is lacking in the Netherlands. After being postponed two times, the final deadline to have the Dutch water quality on track is set for the year 2027[2]. Experts warn that the country is not going to meet this deadline, leading to high fines and potentially, situations like the current nitrogen crisis[2,27].

3.2.1.2 Minimising household water impact

Households use water for many purposes, costing resources and energy, after which the water needs to be cleaned.

Various activities in households need water. These include the use of the washing machine, the dishwasher, the shower and bath, but also to drink and preserve food. In figure 9 a distribution of all water usage by households is shown[28].

The next paragraphs describe what households can do to minimise their impact on water pollution, reduce their environmental impact and minimise energy usage by their water usage habits.

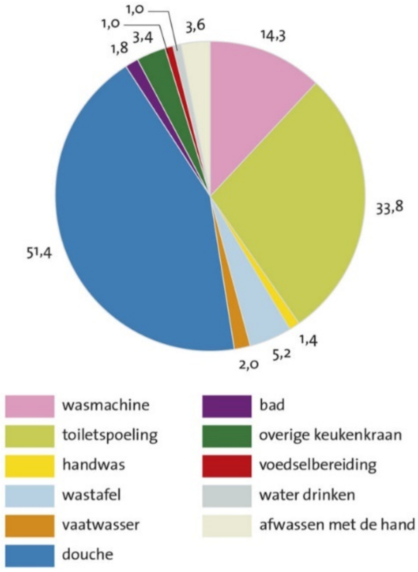


Figure 9. Mean drinking water usage in Litres by Dutch households per day (1995-2013). (Sittrop Grafisch Realisatie Bureau, 2014).

❖ Using environmentally friendly products

First and foremost, water streams must become less polluted, as waste-water treatment facilities are not able to filter all chemicals. This means that households should wherever possible choose to use biodegradable products or products that can be filtered efficiently by waste-water treatment facilities[29]. Furthermore, microplastic pollution is a large problem, as it is omnipresent, and the total damage is not yet known[30]. When synthetic clothes are washed, microfibers are released, which pollute open waters and accumulate in food chains[30,31]. Solutions on the consumer level are using special laundry bags that reduce 99 per cent of microplastics released by washing machines and avoiding the use of synthetic clothing[32,33].

❖ Showering

The highest amount of water is used by households for showering (Figure 7). Taking a shower (m 64L) on average uses less water than taking a bath (m 120L)[34]. Compare this to the washing habits of our grandparents, when it was normal for whole families to wash themselves weekly, in the same tub[35,36]. Apart from showering a shorter time and using water-saving showerheads, getting used to cold showers or implementing a heat-exchanger decreases energy usage[37].

Recirculation showers also drastically decrease the environmental impact[38]. These showers are innovative showers that can real-time clean shower water while showering. During this process, the same water can be used more than once. With these systems, 60 per cent of energy and 80 per cent of water can be saved (Hamwells e-shower)[39]. However, there are several drawbacks of these systems. In table 2 the pros and cons of choosing a recirculation shower are shown, to help decide whether to implement this technology in the design.

Table 2. Pros and cons of choosing a recirculation shower. (Hillenius, T.).

Recirculation shower	
Pros	**Cons**
80% Water saving	Large upfront costs, up to 5,500.
60% Energy saving	Needs additional power supply (and ethernet) infrastructure
Long showers	Water is cheap – long payback period
Save €€ on smaller home energy installation	Might be prone to malfunctions (interview Schoonschip)
	Needs maintenance, and replacement filters
	Repairs are more complex than a normal shower
	In case of malfunctions, health hazards may occur

❖ Washing clothes

Washing clothes impacts water via water pollution by detergents and microplastics (see 'use environmentally friendly products). Furthermore, in an average household, washing machines use 20% of electricity[19]. This is mostly used to heat water. When hot water is supplied to the washing machine by other technologies, such as solar collectors, this leads to an immediate saving of 20% on electricity. Devices that regulate the input water temperature of washing machines are called 'hot fill'. Apart from this, having a high-efficiency washing machine on an eco-programme and washing at lower temperatures with the proper amount of clothes and detergent helps to save water and energy[40].

❖ Kitchen activities

To save water and energy in the kitchen, a lot depends on how you use water. In dishwashing, energy usage has the largest impact[41]. Doing the dishes by hand is often less resource-intensive than using a dishwasher if a tub is used. The best solution is that hot water is supplied by a solar collector[41].

❖ Toileting

More than 30% of drinking water usage in households is used for flushing toilets, after which organic matter, nutrients, medicine residues, hormones and bacteria are diluted in the outflow water[28]. Therefore, it is a key determinant in the generation of household wastewater. Although the flushing toilet is predominant in Western culture, is not the best choice in terms of sustainability. Alternative toilets are compost toilets, vacuum toilets and incineration toilets. The ash from incineration toilets loses valuable nutrients as compared to processing the waste as compost[42], therefore specifically urine-separating compost toilets and vacuum toilets are described in more detail in the following section.

Compost toilets are dry toilets and therefore do not need a connection to the sewer system[43,44].

Collected goods need to be transferred to a composter facility periodically, the timing depending on the size of the collecting bin. Currently there is a lack of commercial composter facilities, which usually results in self-managed compost heaps. When urine is collected separately, odours are significantly reduced by removing ammonia from the faeces, while the effluent may be used as a valuable resource[45]. When urine is diluted in an ejector tank (8 parts water on 1 part water), it can be used as fertiliser for plants due to its high phosphor content[45]. Covering the faeces with humid wood chips to regulate moisture is a useful habit to further reduce odours[45]. This collected human waste needs two years of composting before it can be used as garden-compost[19,45,46]. Whether the composting toilet is a success depends on the user acceptance, and the possibilities to handle and reuse the compost. Urine-separating compost toilets are the most sustainable solution[19].

Vacuum toilets use suction to flush toilets. They use much less water (only 0,5 - 1,5 litres) than conventional toilets[47]. Urine-separating versions are available for flush toilets and vacuum toilets as well. The diverting flows are high in concentration; thus, less volume needs to be transported for further processing. Vacuum toilets resemble the feel of conventional flush toilets. Although being a robust and reliable system[48], initial costs are high and the need for a high-tech system needs to be evaluated. As the flushing by suction produces noise, careful placing is needed to not exceed the noise standards of the building regulations[48]. Vacuum toilets are regarded as more comfortable than compost toilets, while still providing opportunities for sustainability.

The water with diluted substances needs to be cleaned before it can be reused or deposited on the surface water. To account for circularity, the next section will handle the cleaning of household water flows.

3.2.1.3 Cleaning water

The physical, biological, and chemical processes that create clean water in ecosystems are the same for human-made wastewater. When humanity had less impact, ecosystems could handle this impact, but as more people started to live together, the natural ability of ecosystems to clean water was surpassed. Without proper systems, diseases spread easily. At the beginning of the 20th century, several sanitation systems were developed[44,49]. While some were circular, bringing human faeces back to agriculture, it was the flush-toilet together with a sewage system that became dominant[44]. With the broad application of this system, hygiene improved, but the possibility to bring nutrients back to agriculture severely diminished[49].

More than 30 nutrients are needed for plant growth in agriculture, but several of them are getting scarce in the foreseeable future. Zinc in 20 years, phosphate in 300 years, and copper in 50 years[49]. Selenium is already scarce in the European Union[49]. Without these elements, agriculture cannot sustain itself or be regenerative. The current sewage system leaks these vital elements to open waters[49], causing large nutrient problems in aquatic ecosystems as well[50,51]. Cleaning large, diluted wastewater streams is complex due to the plurality of waste sources that cause dangers for safe reuse[49].

Currently, two directions for the treatment of (toileting) waste water are possible for the future according to prof. dr. ir. Cees Buisman[49]. The first is utilising and developing advanced filtering technologies for centralised wastewater streams, in which essential elements are regained from wastewater[49]. The other is segregating waste flows at the source, which makes them easier to handle. The concentrated flow from vacuum toilets is relatively easily used again for agricultural purposes, closing the circle again. Complex in this respect, are logistics and changing the infrastructure of our sewage system[49]. These directions can be developed at the same time, creating synergies between the two strategies[52,53].

In the context of a houseboat, several household water flows can be distinguished, as is shown in table 3. The treatment per water flow to make reuse or safe disposal possible, which is necessary for a regenerative system, is worked out in detail below.

Table 3. Overview of household water flows. (Stichting biowetenschappen, 2018; Saniwijzer, 2018. [49,182]).

Drinking water	official drinking water provided by drinking-water facilities. Reused filtered water can be clean enough to drink. This water is called drinkable water.
Rainwater	clean water, usually with only a small amount of dissolved minerals.
Surface water	ponds, lakes, ditches, and rivers, surrounding the houseboat.
Greywater	household water not from toilets. E.g., from sinks, showers, baths, washing machines. contains soap, microplastics, and other substances.
Yellow water	urine; containing nutrients like nitrogen, phosphorus, hormones, and left-over medicine.
Brown water	faeces; containing organic matter, bacteria, phosphate, zinc, copper, nitrogen, and left-over medicine.
Blackwater	containing urine and faeces as well as toilet paper and left-over medicine.
Small toxic waste / heavy polluted water	residues of paints, chemicals, and aggressive cleaning agents.

3.2.1.3.1 Cleaning black, brown, yellow, and greywater

- Septic tank and grease trap

A septic tank is used to settle solids in blackwater[44]. Floating substances are filtered on top to a certain degree as well. In a septic tank, microorganisms use mainly anaerobic processes to break down organic matter[44]. However, the achieved filtering is incomplete and worsens when blackwater is mixed with greywater or aggressive cleaning agents. Methane is formed in the process as well. Only when the septic tank is only used to filter blackwater and is functioning well, the sludge (if without harmful chemicals) can be reused[44]. The effluent can be handled by the sewage system or a constructed wetland. It is a good solution if it is utilised as a sink prior to a constructed wetland to keep the tubing free from blockages[44].

The grease trap is a kind of septic tank that is specialised in filtering water (usually from kitchens) to remove fats, oils, greases, and solids (FOGS). They function on the premise that these substances float on top of the water, making segregation possible. Depending on the size they need maintenance every other month or each year. Collected FOGS are usually not recycled and go to landfills[54].

- Constructed wetland

A constructed wetland uses plants to clean wastewater. The plants provide soil- and root bacteria with oxygen and favourable growth conditions, while the bacteria clean the water[49]. The plants can be wetland plants, but other (floating) aquatic plants, trees, and decorative or edible plants can be used as well[49]. Constructed wetlands need more space per person than conventional wastewater treatment facilities, but they use less energy, are easy to implement and use, and are versatile in their filtering[49]. Both greywater and blackwater can be filtered and they are usually able to comply with the highest standards[44,49,55]. There is increasing evidence that constructed wetlands are more effective in filtering residues from medicines than conventional wastewater treatment facilities[49]. Vertical-flow constructed wetlands function better for cleaning household wastewater than horizontal-flow constructed wetlands[44]. It functions by an intermittent flow; this creates forced aeration which prohibits anaerobic digestion[44]. Depending on the construction and used materials different filtering results can be achieved.

- Water-purifying wall

Constructed wetlands can be vertical as well. The water-purifying wall in figure 10 filters rainwater, greywater, and urine and was developed by Green Art Solutions[56]. It delivers high water quality, measured against the Dutch norms. The wall of 6m^2 and several large water tanks is more than enough to filter the wastewater for a tiny house with one to two inhabitants. Laws do not permit reused water to be drinking water[57], but the water is clean enough for it after another filtering step with reverse osmosis and

Figure 10. Water purifying wall. (Green Art Solutions).

UV-light and is called drinkable water[58]. When it is problematic to place floating constructed wetlands, this solution might be most practical on board the student ship.

- Photobioreactors

The building of the Netherlands Institute of Ecology (NIOO KNAW) uses a photobioreactor to recover nutrients from blackwater from vacuum toilets[59]. This technique, where microalgae are used to recover macronutrients and trace elements from wastewater is promising. The algae can be harvested and used as fertilizer or to produce bioplastics. For recovering nutrients from wastewater, several technologies are developed, such as struvite precipitation. However, these techniques only filter phosphorus and often are inefficient. Moreover, an unequal recovery of nutrients may cause toxic algal blooms in freshwater ecosystems[60]. These considerations make the choice of technology for the student ship complex, more in-depth knowledge needs to be gathered before the definitive waste-management of human faeces is decided.

3.2.1.3.2 Filtering rainwater and drinking water

Collected rainwater can be used for laundry and toilets. Because it is devoured of minerals it is the best source for plant watering as well. When rainwater is collected on surfaces without harmful chemicals and filtered by a green-roof reed treatment system, drinking-quality water can be created, although it needs continuous monitoring[19,57]. Due to Dutch law, drinking water requires proof of quality, which complicates creating drinking water decentrally. Upcoming contaminants in drinking water cannot be reliably filtered by drinking water companies[61]. To create drinking water decentrally, reverse osmosis filters, UV-light, and constructed wetlands amongst others can help clean water from harmful substances.

- Filtering drinking water with Reverse Osmosis (RO) filters

This is a technique that uses a semi-permeable membrane to filter water with suspended solids and dissolved contaminants[62,63]. When pressure is applied, water is pushed through the membrane, leaving contaminants behind. This process is opposite to natural occurring osmosis, in which water flows from a region of lower solute concentration to a region of higher solute concentration to equalise the concentration[63]. Reverse osmosis can remove dissolved minerals, sediments with a size of 0.0001 microns, nitrates, pesticides, organic compounds, and sodium[64]. Filters, however, need to be replaced periodically and a waste stream of water with a high

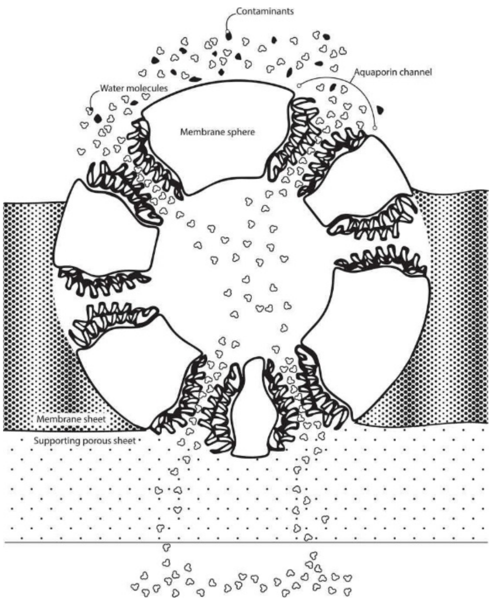


Figure 11. Aquaporin membrane technology. (Aquaporin A/S, 2005).

concentration of contaminants is created. Bacteria and viruses are normally too small to filter.

As osmosis occurs naturally in the human body, it is interesting to know how the semi-permeable membrane of cell membranes works. Scientific research by Peter Agre led to the discovery of the proteins that are responsible for the transport of water through cell membranes (Aquaporins) (figure 11)[65]. Extensive biological research led to a biomimetic device that uses these proteins in a modified membrane to filter water using reverse osmosis. This device, produced by the company Aquaporin A/S, is a faucet-based filtering device that would sit in a small cabinet under the sink[66]. It is said to filter two times faster than standard faucet-filtration systems and can filter viruses and bacteria as well. Filters need to be replaced approximately once every six months[66].

With reverse osmosis, too many minerals can be removed from drinking water[67], leading to a situation of adding beneficial minerals to mimic natural water. Consumption of demineralized water has definite adverse influences according to the World Health Organisation (WHO)[68]. In Malta unfiltered tap water has a meagre quality, despite using Reverse Osmosis and Activated Carbon (AC) filters as the basis for domestic water filtration systems[69]. The majority of people use home filtration systems (RO or AC), to further purify the water[69]. Activated Carbon filters do not remove beneficial minerals[70,71].

❖ Filtering drinking water with UV-filters

UV light with a short wavelength can kill most bacteria, viruses, and algae[64]. Water with contaminants needs an exposure of only 10-20 seconds to be sterilised. This treatment does kill microbes but does not remove the microbes from the water flow. Whether this water is healthy to consume depends on the species and ratio between harmful and beneficial microbes one ingests without UV treatment[72].

❖ Pathogens

Four groups of pathogens that can survive in water can be distinguished: bacteria, viruses, protozoa, and worm eggs[73]. Some are dangerous on low levels (viruses), while for others (e.g. bacteria) higher levels are needed. Pathogens (excluding viruses) can be removed by:

- Temperature increases: Harmful microbes are killed when heated for at least 60 minutes at 70°C.
- Temperature decreases: e.g. Legionella does not grow in water below 20°C.
- High pressure: more than 6 bar is needed to demolish cell walls.
- UV-light, ozone, or chloramines can kill microbes as well.

3.2.1.3.3 Filtering surface water

Surface water differs from place to place. Additional research is necessary to determine the water quality in the neighbourhood of the prototype. Important parameters are the type of substrate, water flow, salinity, oxygen level, light condition, and algae concentration[74]. The association of river water companies is increasingly worried about upcoming contaminants, endangering drinking water, as well as industries that create significant wastewater flows[75].

3.2.1.3.4 Handling heavily polluted water

When chemicals are used, they should not be disposed of in sinks or toilets on the student ship[44,49]. Decentral wastewater cleaning methods cannot filter these substances. This also means users need to use biodegradable soaps, shampoos, cosmetics, and cleaning agents[44,49]. Chemicals can be collected and stored separately before they are discarded at municipal waste sites[76].

3.2.1.4 Software models

Smart systems equipped with sensors may help to measure, regulate, and predict water cleaning and ensure quality levels. Relevant data can be collected at Sanimonitor, which is a medium that provides information and data about new sanitation options, to contribute to the comparability of these technologies[77]. Software models like PCLake and PCDitch that can predict the ecological consequences of adding nutrients to lakes, ponds, and ditches may be helpful to predict the influence of water outflows from floating houses on freshwater ecosystems[78]. These models developed by Dutch research institutions and a consultancy and engineering firm are a large contribution to the understanding of the consequences of proposed interventions in aquatic ecosystems[79]. With sufficient time, these models can be modified for the modelling of city waters with floating houses[80]. This increases the possibility to model the effects of different sanitation options on the surrounding aquatic ecosystem.

3.2.1.5 Sub conclusion on regulating water

Regenerative water systems can be achieved when users use less polluting products, limit their water use, and clean and reuse their water. (Vertical) constructed wetlands offer a multifunctional low-tech solution to cleaning water (section 3.2.1.3.1), while recirculation showers and vacuum toilets offer ways to create smaller water outflows that can be cleaned more efficiently (section 3.2.1.2). Segregated water systems with different qualities further enhance the circularity and functioning of the water system (section 3.2.1.3).

3.2.2 Increasing biodiversity

In the previous section, we have introduced and analysed elements that could be part of a regenerative water system, which maintains sufficient water availability and water quality in and around the floating apartments. Availability of water of sufficient quality is a basis for sustaining biological life[2], which is the topic of the next section. To establish environments where people and nature flourish, well-informed practices in ecosystems are crucial. This subchapter handles key ecological concepts and solutions, such as food web theory and nutrient distribution. Moreover, the ecological analysis of the proposed location in Rotterdam is described. In this way, local ecology can be embedded in the larger ecological, social, and cultural structure of the floating houses.

The relationships among species in ecosystems can be understood by working out food webs[81]. Relationships may vary in their influence on energy flows through ecosystems and their influence on species populations[81]. In previous studies on food webs, three types of food webs were proposed to describe how species influence each other[82]. Connectedness food webs emphasize feeding relations from one species to another, while energy flow webs quantify the flow of energy through the web[81]. The thickness of the arrow can represent the strength of the relationship. Functional food webs show an interaction between- or importance of species to other species. Some species may be crucial for the integrity of communities or the growth rate of other populations, while other species have a less significant role[81]. Functional food webs are the most important, but also the hardest to construct. Connectedness food webs provide the best start to work with nature-inclusive design[83].

Nutrients cycle through food webs in a large process of building and breaking down molecules. All organisms are dependent on these cyclic processes. In biological systems, the most abundant biological elements are carbon (C), hydrogen (H), nitrogen (N), oxygen (O), phosphorus (P), calcium (Ca), and sulphur (S)[84]. Although less abundant, spore elements can be equally important for the functioning of organisms[85].

Food webs often have four different species that can perform the same function[16]. If one species is diminished, another species can take over. This concept is called redundancy. Redundancy helps to create stable systems that are less vulnerable to external shocks[16,86,87].

As life creates conditions conducive to life, ecosystems are at the basis of every organism's existence. Humanity is dependent on the services that ecosystems deliver. The ecosystems framework in table 4 is one way to understand the complexity of ecosystem functions and the interactions that humans have with them[88]. The theoretical foundation for this framework is laid out by Pedersen Zari[17]. Ecosystem services are linked to each other. This means that when improving one ecosystem service, another service could improve (synergy) or degraded (trade-off) (figure 12).

This framework was later developed in an interactive 'strategies for designing urban ecosystem services diagram', which is a useful tool for designing (Appendix 5)[88]. This diagram merges existing designs, concepts, and strategies for generating ecosystems, with their relational synergies and trade-offs in real-life projects.

Table 4. The ecosystem services framework. (Zari, 2018).

Supporting Services	**Habitat provision**	Cultural services	**Aesthetic & artistic inspiration** - Aesthetic value - Artistic inspiration
	Nutrient cycling - Retention of nutrients - Regulation of biogeochemical cycles		**Recreation and psychological wellbeing** - Sport - Outdoor activities - Tourism - Socialization - Relaxation & psychological benefit
	Species Maintenance		**Sense of place and cultural diversity** - Celebration of cultural diversity/history - Sense of place
	Fixation of solar energy		**Spiritual and religious inspiration**
	Soil building - Soil formation - Renewal of soil fertility - Soil quality control - Soil retention		**Education and knowledge** - Educational - Inspiration & innovation - Cognitive development - Knowledge building
Regulation Services	**Disturbance prevention** - Noise - Wave - Erosion - Earthquake - Drought - Flood/Storm events - Wind	Provisioning Services	**Provision of fuel and energy** - Water energy - Wind energy - Active / passive solar energy - Human body heat - Hydrogen energy - Biomass energy - Geothermal energy
	Climate regulation - UV protection - Moderation of temperature - Climate adaptation strategies - GHG mitigation		**Provision of fresh water** - Drinking water - Sanitation - Irrigation - Industrial processes - Recreational
	Purification - Water purification - Soil purification - Air purification		**Provision of food** - Small to large scale urban agriculture
	Decomposition - Biodegradation - Material reuse/recycling - Consumption reduction		**Biochemicals** - Medicine - Natural chemicals
	Biological control - Control of invasive species - Disease/pest regulation		**Raw materials**
	Pollination		**Genetic resources**

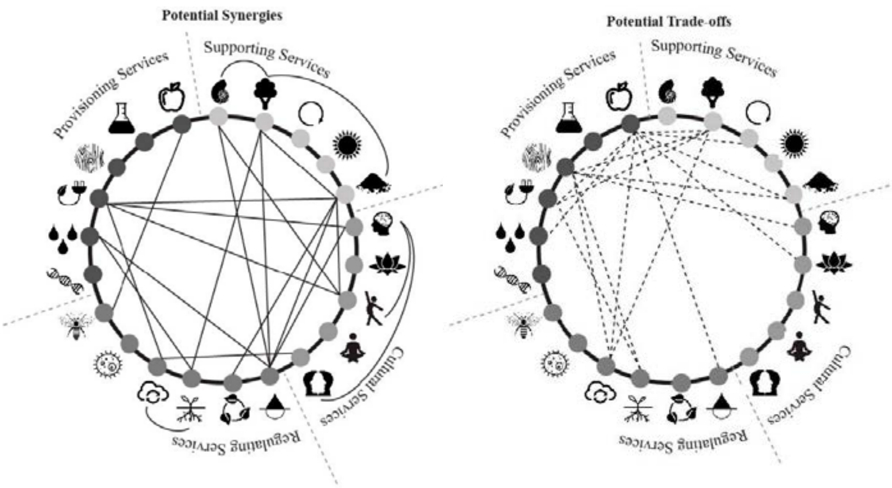


Figure 12. Synergies and trade-offs between ecosystem services. (Zari, 2018).

3.2.2.1 Location analysis

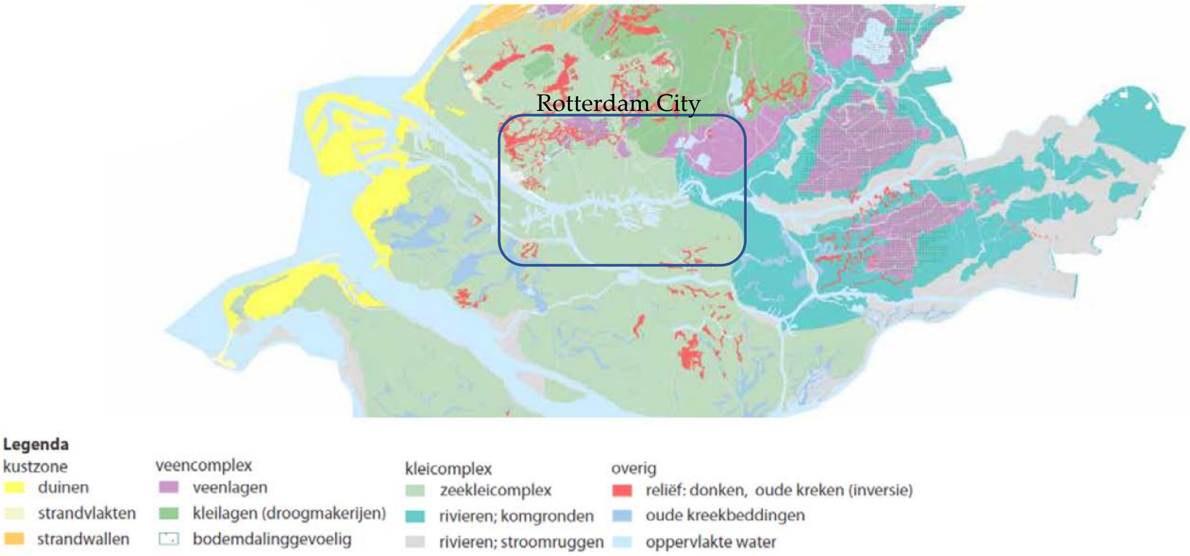


Figure 13. Geographical location of Rotterdam. (Municipality of Rotterdam, 2014)**.**

The city of Rotterdam was built on a river delta where several large rivers flow into the North Sea[89]. Before human occupation, the area was characterized by an extremely diverse and dynamic landscape with large sea arms, islands, meandering rivers, and peatlands. Through human activities, the landscape changed and became a cultural landscape, interspaced with dynamic floodplains, peat meadows, sea clay polders, and dune areas (figure 13)[89]. The subsurface consists of a spatially diverse mosaic of clay, sand, and peat. Together with the water infrastructure (dikes, canals, ditches, and water levels), this is a determinative base layer for the type of nature that can establish itself in these areas. In the last century, the city and the port of Rotterdam experienced explosive growth, with large influences on the landscape. Some nature areas disappeared while others were preserved and evolved in places where recreation and nature coexist. Moreover, within the city characteristic places can be found where nature can flourish, such as parks, old quays and buildings, large trees, and railroad dikes[89].

Figure 14. Nature areas in neighbourhood of plan area. (Municipality of Rotterdam, 2014).

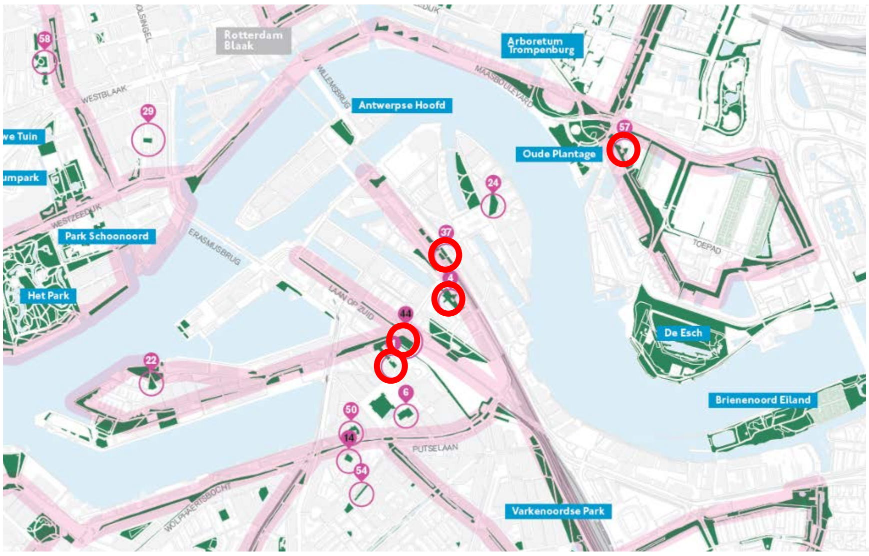


Figure 15. Nature areas. Urban greenery: oranjeboomtuin(37), Binnenhaventuin(4), Stads-kruidentuin(44), Afrikaandertuin(1), Wijktuin de Esch(57). (vereniging Deltametrapool & Lola Landscape Architects, 2016).

At the prototype location, alongside the Nieuwe Maas river, a dynamic play of flooding and erosion created a diverse subsoil, consisting of back swamp soil on a basis of Hollandveen and tidal riparian deposits[90]. Larger ecological zones are shown in figure 14, especially the island 'Van Brienenoord', park 'De Oude Plantage', polder 'De Esch' and the Nieuwe Maas stand out. Smaller ecological elements and community gardens are shown in figure 15. These may function as small hotspots of biodiversity amidst building blocks, where especially birds and insects disperse. Especially the Nieuwe Maas river, 'De Esch' and the 'Van Brienenoord' island form an important ecological corridor and habitats respectively for the wildlife surrounding the plan location[15,89,91].

The water of the Nieuwe Maas is influenced by the tides and shifts 1,7 meters every 6 hours[92]. The neighbourhood is not protected by dikes, and especially the area north of the *Persoonshaven* is prone to flooding in the future[90].

At the coast freshwater and seawater mix and the influence of the tides is apparent several tens of kilometres inland[91]. As saltwater is heavier than freshwater, a salt wedge forms that travels upstream (figure 16)[91]. Organisms that are not capable of handling salinity die and become food for all other organisms in the estuary ecosystem[91]. The force of the tides and the shifting water level in the estuary creates a gradient for plant species along the river[93]. Low on the gradient are strong species such as common club-rush and sea club-rush, while a bit higher fen ragwort and purple loosestrife can be found, and even higher marsh woundwort and bugleweed[93]. The estuary and creeks are important habitats for animals such as birds, fish, worms, crustaceans, and shellfish[94]. Species such as salmon, European river lamprey, European eel, and European sea sturgeon are fish that migrate along the river and through the estuary[95].

As currently 70% of the river banks in the Rotterdam region are hard quays, and this is the only open connection between rivers and the open sea in the Netherlands, there is a large opportunity for improvement of tidal nature[96]. The programme 'River as Tidal Park' is officially adopted by the city of Rotterdam, and the Persoonshaven is suitable for softening the shoreline[15]. The programme 'Building with nature' researches several solutions for enhancing ecological functions in balance with social and economic goals[15]. For example, creating swamps, shoals, floating gardens, vertical structures, and artificial reefs.

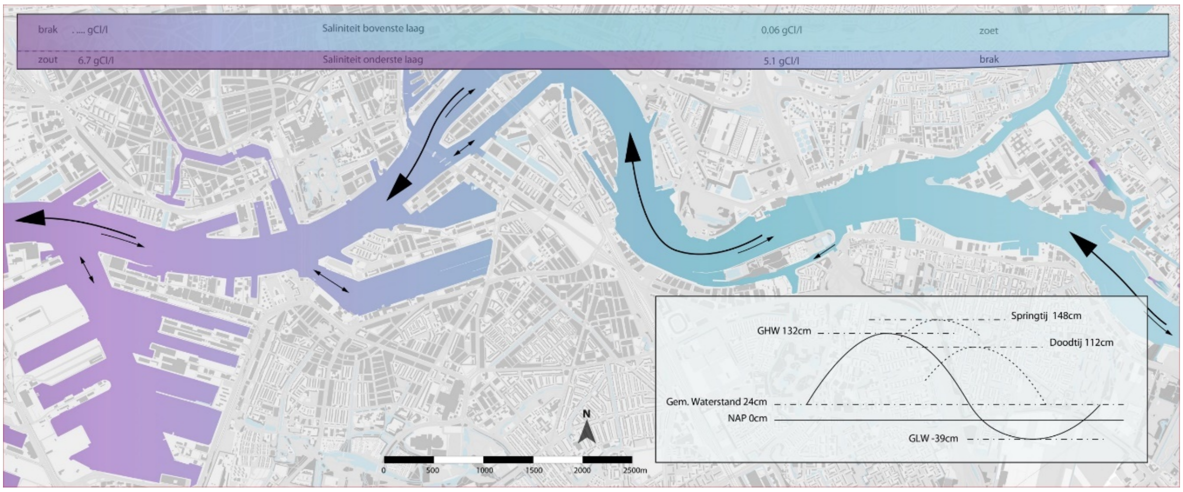


Figure 16. Variety of salinity in the Nieuwe Maas river. (Onderwaternatuur Rotterdam, 2020).

3.2.2.2 Sub conclusion on increasing biodiversity

For helping biodiversity and ecosystem services regenerate, an understanding of the ecological system is indispensable. Through ecological awareness, living more closely with nature, and analysis of the local natural environment, more understanding can be developed. The interactive 'strategies for designing urban ecosystem services diagram' based on the ecosystem services framework in section 3.2.2 may prove an interesting tool to bring this understanding into practice.

3.2.3 Storing energy & balancing temperature

This theme serves the goal of developing a systems view, although the main focus of this research is on water and ecosystems. It is worked out by a colleague (Mischa Hillenius) and the recommendations from his report are included in appendix 7. In summary, energy storage is favourable over energy generation, because of practical, societal, and spatial reasons[97]. Aqua thermal energy is an opportunity to deliver efficient low-temperature heating, in combination with solar boilers[97].

For cooling, new solutions are developed in the last years, some (such as the IceCube system) seem very promising[97]. Apart from this, the building materials, insulation, morphology and design, and lifestyle of the inhabitants impact the energy demand of the floating student homes. Specialists are needed to calculate the operational size of the technological solutions and implement them properly.

3.2.3.1 Sub conclusion on storing energy & balancing temperature

For the energy system, a focus on energy storage is important, while aqua thermal energy and solar boilers are good options for energy generation. Low-temperature floor heating, good insulation, and awareness of energy usage by the inhabitants may limit energy usage.

3.2.4 Circular material usage

Materials offer another angle for regenerative design. Conventionally built structures tend to draw down on their surroundings by extracting resources while not giving back enough for sustainable practices[16]. Thinking in (eco)systems provides a way to give back more than what is taken, leading to regenerative practices instead. When building materials are manufactured more similar to how the natural world uses materials, system compatibility increases[16].

In general, we produce materials with high-energy bonds, while nature uses low-energy bonds. Constructing with natural polymers, which are constructed with low-energy bonds, may provide a better fit as these materials can be included in systems modelled on biology[16]. These materials are under the increased attention of researchers and in material databases[98,99]. Professor of biomimetics Julian Vincent described an important observation by stating: 'In nature, materials are expensive and shape is cheap'[16]. This is opposite to conventional engineering where materials are relatively cheap while creating organic shapes is expensive.

Computational design and fabrication allow us to edge closer to how nature constructs, and therefore are very promising techniques. Self-assembly, self-repair, non-toxicity, and the many other characteristics of biological materials may not all be mimicked to great extent, but they are worthy goals to aim for[16]. Where these characteristics cannot be achieved, concepts from the circular economy offer good alternatives. By working with demountable components and material passports, materials can be kept at high value as long as possible while closing material cycles[16]. Two projects where these techniques are applied are the Liander building and Park 20/20 in the Netherlands[16].

LCA's of materials provide insight into the environmental impact of materials, and possibly data can help to stimulate regenerative practices, although the tools to make data-informed decisions on these matters are still in need of development[10,100]. In general, it can be said that partnering with manufacturing companies that are on the right track towards regenerative practices themselves, helps each other forward.

3.2.4.1 Sub conclusion on circular material usage

Computational design and fabrication and circular economy concepts (such as demount ability) limit material usage, while data-informed decisions and biomaterials limit the environmental impact of the used materials.

3.2.5 Synthesis system functions

This paragraph focuses on the developments that have the highest chance to be implemented in the design, and the potential synergies between them.
The system functions worked out in the previous sections identified concepts and solutions for reoccurring themes in regenerative design. A few of the solutions that stand out for the water system are constructed wetlands, recirculation showers and vacuum toilets. Constructed wetlands offer benefits on both biodiversity and water filtering levels, while recirculation showers and vacuum toilets are state-of-the-art solutions that score high on comfort and provide a good fit with other system elements. Several concepts that can be of help regarding the ecosystem are the ecosystem services framework and the interactive strategies for ecosystem services diagram. Renewable energy technologies such as solar collectors and aqua thermal energy may help provide energy, while large batteries for energy storage are strategical as well. Finally, a strategy for circularity of the used materials is an important development to integrate into the design. Solutions that are less preferable to implement in the design are for example filters that generate drinking water from recycled wastewater, as they have several drawbacks and drinking water quality in the Netherlands is of high quality.

Now that the system functions are worked out, it is possible to start organising them in functional and synergistic ways. First of all, it is necessary to note that there might be trade-offs between the system functions, and between other factors in the design. One of those is a financial matter, usually costs increase when implementing better technologies[101]. Another one is a biological trade off. When there is a lot of disturbance through human activity, this can limit the activity of animals[102,103]. Furthermore, it is unknown what ecological consequences harvesting aqua thermal energy has, although it influences the water temperature[104]. Another possible trade off is that filtering nutrients from wastewater leads to an unfavourable influx of nutrients in the environment[49]. An important social factor is that all functionalities depend on maintenance, which depends on the behaviour of the habitants. Finally, all technologies and design elements depend on the availability of space in and around the student-ship.

On the other hand, by developing these systems together, synergies can be formed. For example; clean energy technologies may help to clean waste water. Sufficient environmental water quality might then help to create more biodiversity. Carefully choosing materials and regular maintenance help to decrease the negative environmental impact of the design, while nature-inclusive measures help to restore the balance between organisms and their surroundings.

Specific synergies that can be stimulated between the system functions are the following:
- Collected rainwater may be used to water plants (they prefer water with low mineral content), which in turn counters the effects of droughts via shade and evaporation.
- Via water filtering, composting and faeces, the nutrient load on the (aquatic) environment might be steered.
- The natural degradation of building materials may offer a growth medium for biological growth, while keeping their functionality.
- Plant growth surrounding the ship (eg willow and typha species) may provide local sources of building or insulation materials.

3.3 Definitive design

In the previous sections, four important system functions for regenerative design are elucidated and possible system elements that help fulfil these system functions are analysed. The four system functions were regulating water, increasing biodiversity, storing energy & balancing temperature, and circular material usage. After giving body to these subjects, and finding state of the art solutions for the system elements, the design was developed. The following section handles the definitive design that was produced for this research. A solution for student housing on water is developed where these technological and ecological subsystems are merged. Subsystems are comprised of elements researched for the four chosen system functions and include the water and energy system and nature-inclusive measures. Furthermore, a maintenance plan is included in the definitive design.

3.3.1 Water system

In figure 17 the envisioned water system is depicted in a flow diagram. Drinking water, rainwater, and surface water are input streams that flow through partly separate water systems (drinking water system, rainwater system, greywater system, urine system). In this way, water is reused at the highest quality, and every drop is used more than once. Throughout the system care is taken to segregate waste flows as much as possible, to create compacted waste flows. This can be seen for example in the use of separate toilets for people who use medicines and people who do not use medicines. Moreover, the toilets are separating vacuum toilets that separate urine from faeces. The outputs are handled in different ways. Urine and excrements from people who do not use medicines are further processed. Excrements, and products from people who use medicines are collected and discharged to a circular waste company. Furthermore, energy and water are spared by implementing recirculation showers and a hot-fill for the washing machine. Heat is recovered from appliances that require hot water using heat exchangers.

Outflows are the vegetation that evaporates water, potential evaporative cooling of the house, animals and humans that drink the water, and outflow towards the surface water. Before water is discharged into the surface water, it is cleaned and reused in the greywater system. Greywater is cleaned in separate steps. A sceptic tank and grease trap gravel filter are used as pre-treatment before the constructed wetlands. After the constructed wetlands the water is analysed for contaminants, after which water is discharged on the surface water or the cleaning is iterated. Part of the water can be cleaned further utilising reverse osmosis filters and UV-light to make safe reuse of the water possible. A struvite reactor is not included in this design as the scale of the ship is too small to make this profitable. A photobioreactor is included, but more research is needed to discover if this is profitable.

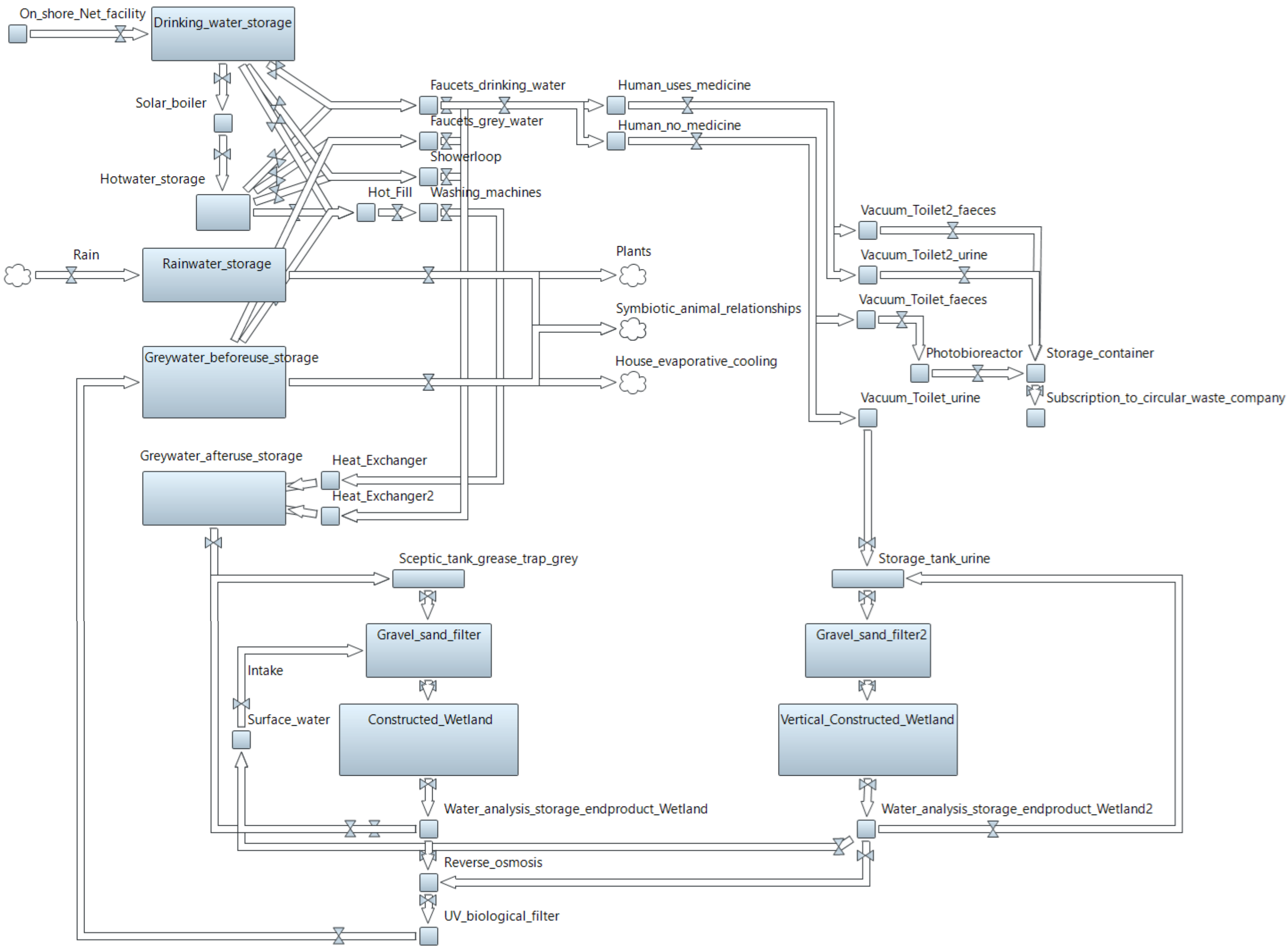


Figure 17. Water system. (Hillenius, T).

3.3.2 Energy system

The main input of the energy system is the heat exchangers that extract thermal energy from the surface water (figure 18). Solar collectors are used in addition. Installing a heat exchanger to extract air from the greenhouse is an interesting option, but more research is needed to discover if this is profitable. Low-temperature floor heating is chosen as an efficient heating option. In this design, the nature-inclusive measures are deemed of higher priority than large surfaces of solar panels to generate electricity, but large batteries and water storage for balancing energy shortages and surpluses are included[97]. When solar panels can be integrated appropriately (for example in the solar shielding), this remains an option.

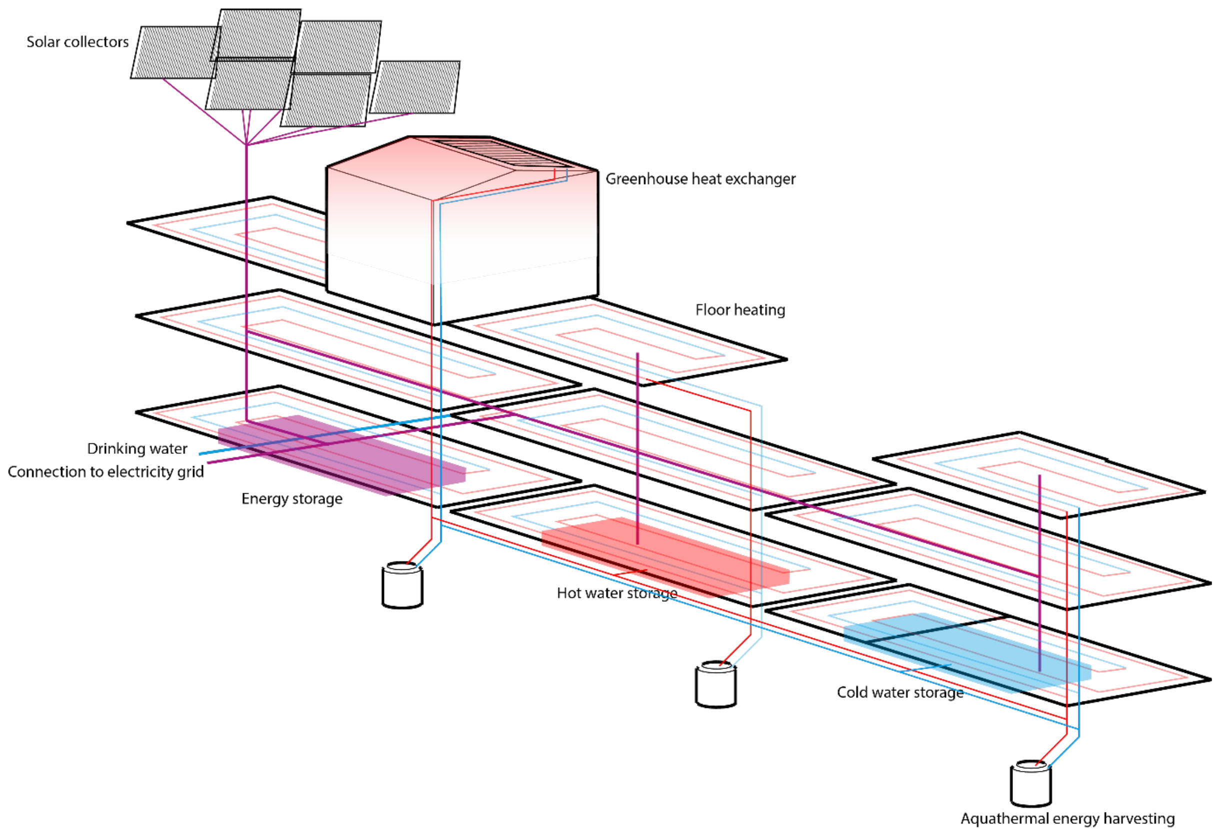


Figure 18. Energy system. (Hillenius, T).

3.3.3 Nature inclusive measures

It is envisioned that the design stimulates the natural environment surrounding the ship. While not everything can be designed beforehand, best practice leads to tailoring various design needs and seeing animals and plants as clients for the design. That is done here for three different species (namely a bird, mammal, and fish) are chosen to represent the nature inclusive measures. These species are chosen on the diverse habitat characteristics near the ship, and by comparing observational data of species in Rotterdam, policy papers and news articles about Rotterdam's ecology[15,105–107]. Especially the chosen fish species (Eel) is an important asset in the neighbourhood of the plan area.

- **Species one – Bird – Swallow**

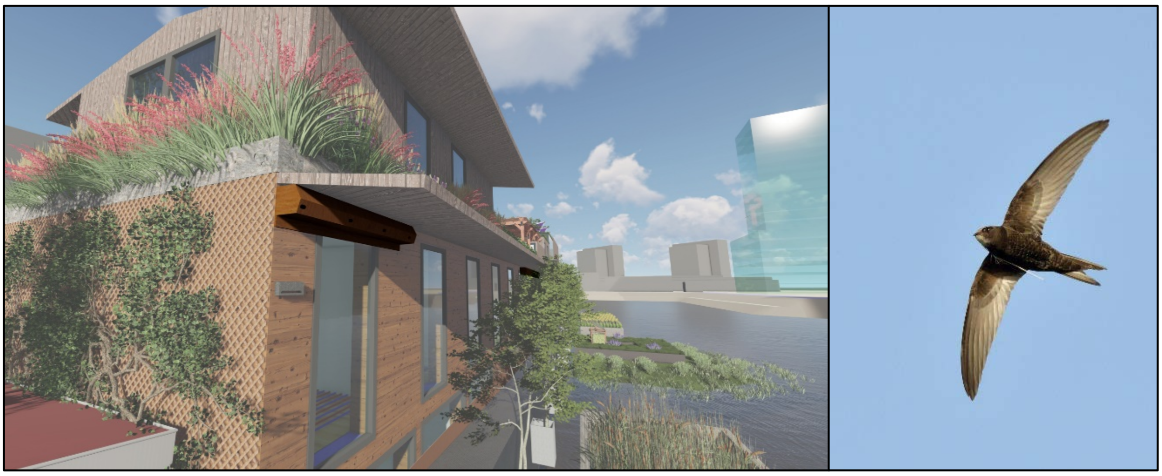


Figure 19. Bird nests for swallows. (Hillenius, T., onze natuur, 2020).

According to a large database of nature observations[105], the common swift is occasionally breeding in the neighbourhood of the plan area, and they are dependent on shelters around buildings in urban areas as they prefer a rocky habitat (figure 19). The common swift is a small to medium-sized bird, known for its agile flight patterns[108]. Travelling long distances from Africa, they visit the Netherlands from April to August to mate and breed. When a suitable nest is found, the birds use it several years in a row. Using houses as rock formations to nest in, the birds expanded their breeding area, however, modern houses are less and less suitable as they are built with minimal openings. When placed with care, artificial nests can be used with great success[109]. The nest and habitat requirements for common swifts are as follows[110]:

- Place the nest on the corner of a north or east façade.
- Make sure the nest is placed 4 meters high or higher. Common swifts need free space in front of the nest, especially vertical, as they use a free fall of several meters before taking off.
- Place the nest in a relatively stable climate. E.g. under the roof edge, not in full sunlight. Place some straw inside the nest.
- Common swifts eat loads of insects. Vegetation in the neighbourhood of water provides a foraging area (figure 20).

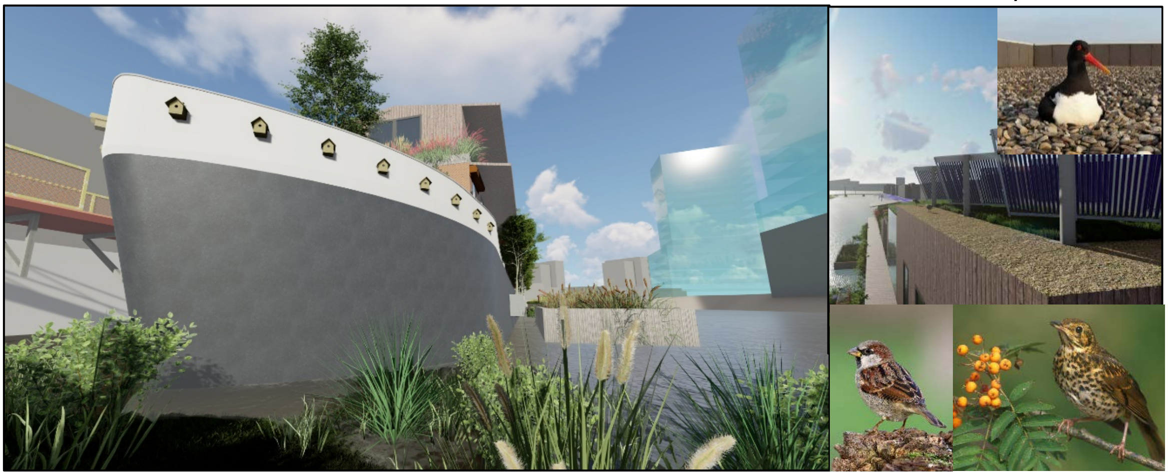


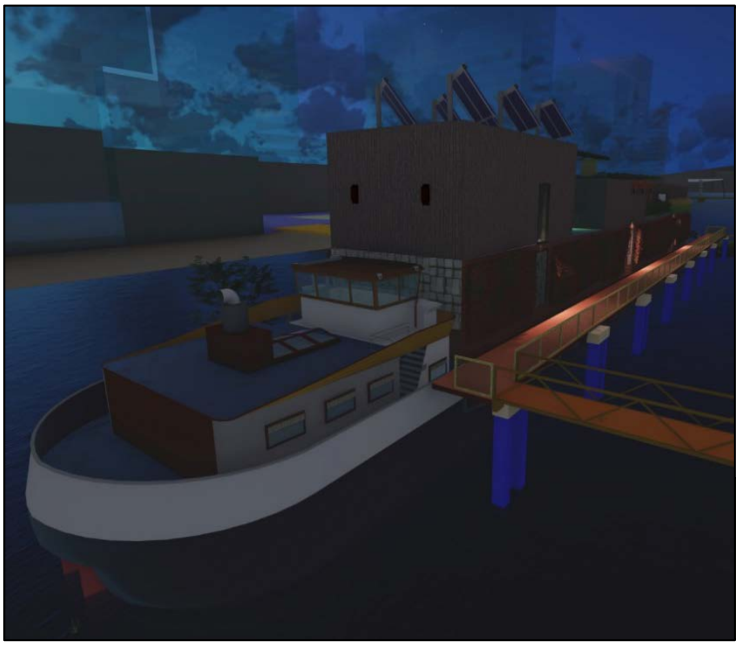
Figure 20. Habitat for bird species. (Hillenius, T., Brenneberry, 2019; Neut, 2014; Willocx).

Other measures for birds include:

- Nesting for house sparrows, at 0 to 3 meters height, on east façades.
- Roof with seashells, offering suitable nesting space for European oystercatchers and common terns.
- Indigenous small trees on the ship and floating islands and shrubs such as berries for the song thrush.

- **Species two – Mammal - Bat**

The common pipistrelle is a bat species that is occasionally observed in the neighbourhood of interest[105]. The serotine bat, although not found in this neighbourhood, is an indicator species that ecologists in Rotterdam like to see thriving (figure 21)[107]. These species can sometimes be found in each other's company, sharing the same roosting spot[111]. Bats choose roosting spots carefully and have separate spots for summer, winter, males, and females[112]. Besides these, temporary and mating roosting spots are used as well for short amounts of time. In the design roosting spots for the common pipistrelle and serotine bat are included. These spots are placed according to the following requirements[113]:



- At least 3 meters above the ground.
- On the short side or front side of a house.
- In a place with little sun and no artificial lighting at night.
- In the neighbourhood of water and trees.
- In the neighbourhood of (natural) corridors and lanes with trees, as the bats use these to navigate.

Figure 21. Wildlife friendly lighting and roosting spots for bats. (Hillenius, T., Overman, 2020).

The lighting of the ship is chosen with care, to minimise the impact on bats and other wildlife. This means lighting is only placed when necessary. Focusing light on places where it is needed, using movement sensors, and choosing yellow, amber, red, and green spectra help to minimise the impact of lighting (figure 26)[114].

- **Species three – Fish – Eel**
  The eel is a migratory fish, that is endangered internationally. Swimming from the open sea into rivers as young fish, Rotterdam is an important entrance for this fish species. Luckily and extraordinary, the species seems to thrive in the neighbourhood of the Persoonshaven[106]. Several organisations wish to stimulate the eel population, and the thought is that creating green shores and shallow waters with vegetation helps[91]. The floating islands that are planned along with the design, fulfil the same function. They can be placed in areas where there is little space for these larger infrastructural developments. Other nature-inclusive marine measures include a set of underwater ropes and structures which mussels and other organisms can use as habitat (figure 22).

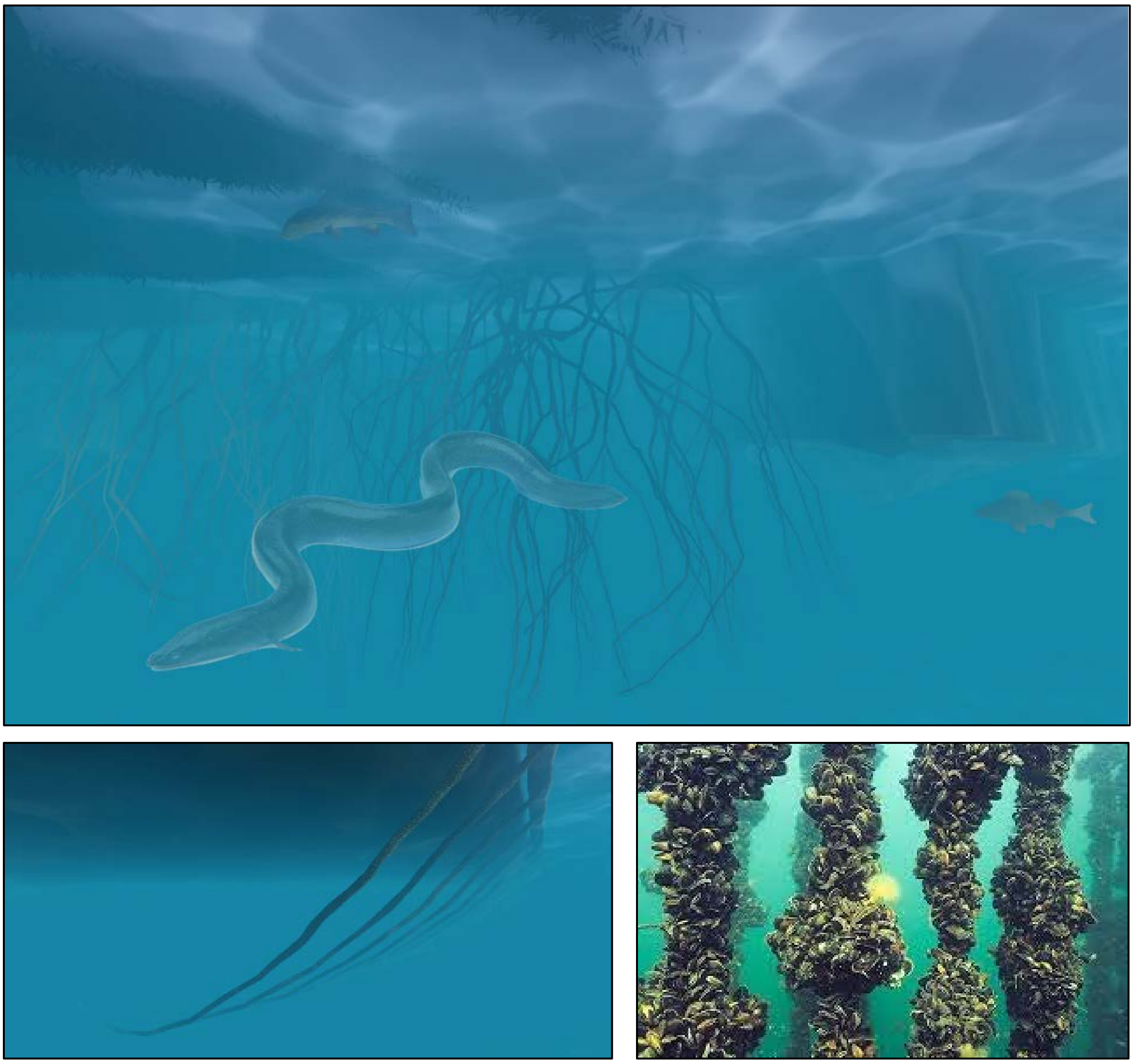


Figure 22. marine nature-inclusive measures. (Hillenius, T,. Murray,. Zeevruchten Gids, 2018).

3.3.4 Planting design

The plants are chosen based on their natural habitats, and care is taken to use local species (figure 23). This can be seen for example in the wet-dry gradient of the floating islands and the species used for the constructed wetlands[93]. Low on the riverside stands Bolboschoenus maritimus, a plant that can withstand the washing forces of the tides. A bit higher Caltha palustris and Lythrum salicaria thrive, while on the higher grounds grassland species, flowers, and small shrubs do well. In the constructed wetlands Iris pseudacorus is a functional plant for water filtering, while leftover spaces can be colonised by Salvinia natans. Lysimachia nummularia might use the concrete walls of the constructed wetland as a habitat. On the ship, trees grow in large planting pots, alongside the ship the trees can root in the surface water. Besides technical and ecological soundness, aesthetics plays a part as well, such as choosing flowering grasses and wisteria for the terraces and pergola.

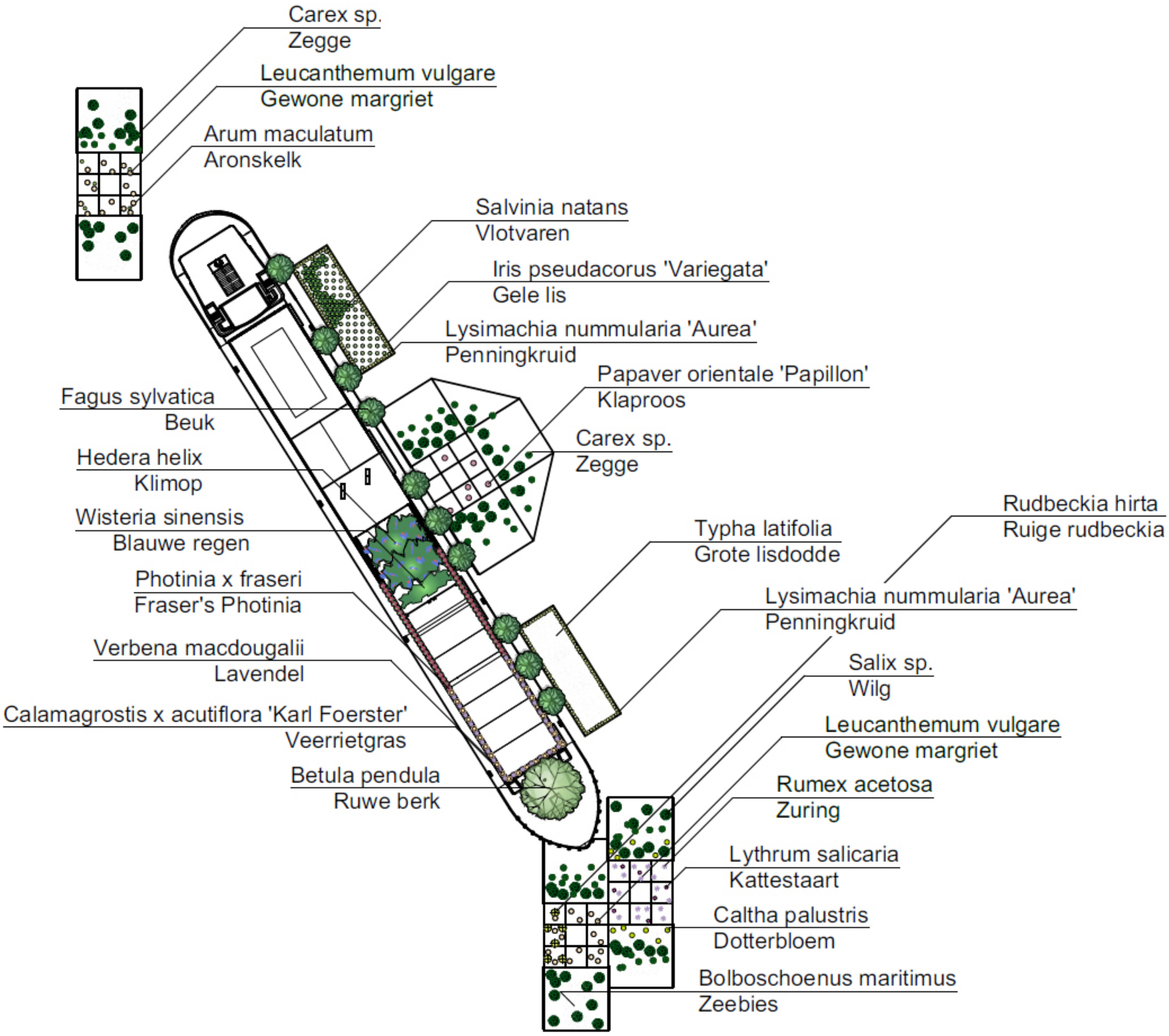


Figure 23. Planting design. (Hillenius, T).

3.3.5 Visuals (collage 1)

Collage 1. Visuals. (Hillenius, T).

3.3.6 Materials

In the materialisation of the design, using wood where possible is a central theme (figure 24). In other applications, appropriate materials are chosen based on LCAs and function. Care is taken that material finishes do not degrade the circularity of the product. If possible, naturel or biobased products are used. Dry construction methods ensure that materials can be reclaimed after usage, which is made easier by making a materials passport and using tags.

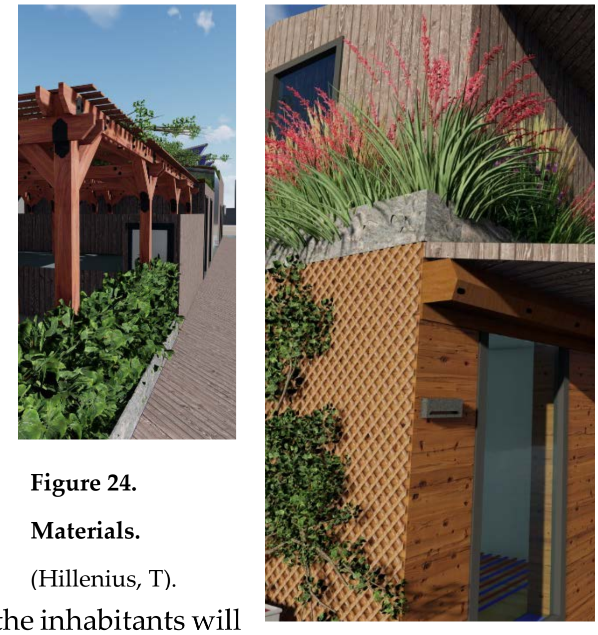


Figure 24.

Materials.

(Hillenius, T).

3.3.7 Maintenance

To cut down on construction and maintenance costs, the inhabitants will be consulted to be responsible for a set of activities onboard and around the ship. Professional oversight in the form of experts, biologists, and engineers ensures the construction quality and maintenance skills on a reoccurring basis. With this assisted do-it-yourself method, large quantities of work can be done while lowering the costs and increasing engagement socially and environmentally. User involvement is essential in the design phase, as it is the inhabitants who adapt their lifestyles to new regenerative practices. The constructed wetland (figure 25), greenhouse, recirculation showers, floating islands, and other installations and vegetation will require a certain level of maintenance and participation (table 5). The students need to clearly define who is responsible for specific tasks and maintain a culture wherein duties are fulfilled to maintain the desired level of maintenance. Furthermore, the students need to follow guidelines on energy efficiency and avoid the use of chemicals. To optimise overall system performance, intelligent systems onboard will monitor precisely how much water and energy is used and where that use is coming from. Finally, the students play a role in registering biological activity on and around the ship to help the decision-making process of developing a thriving ecosystem to live in.

Table 5. Maintenance plan. (Hillenius, T.).

	JANUARY	FEBRUARY	MARCH	APRIL	MAY
CONSTRUCTED WETLAND		Pruning	Weeding[115]	Weeding	Weeding
FLOATING ISLANDS		Pruning	Collecting litter[116]	Weeding	
COMPOST HEAP	Weekly aeration[117]				
PRUNING (BIRCH)					
PRUNING (BEECH)			Shrub pruning[118]		

VEGETABLE GARDEN GREENHOUSE (VOLUNTARY)	Sowing. Protect from frost[119].	Sowing. Ventilate. Watering.	Sowing. Ventilate. Watering.	Ventilate. Watering.	Ventilate. Watering. Harvest.
BIODIVERSITY	Monitoring. Species dependent.				
SHOWER	Weekly cleaning. Monthly inspection of the technical system[120].				
TOILETS	Periodically emptying composting tanks. Annual service.[47]				
PIETER POT	Inventory management. Retour used jars.				

JUNE	**JULY**	**AUGUST**	**SEPTEMBER**	**OCTOBER**	**NOVEMBER**	**DECEMBER**
Weeding	Weeding	Weeding	Pruning	Mowing	Technical maintenance	
	Collecting litter	Construction maintenance		Mowing		
Prevent drying up[121]	Prevent drying up	Weekly aeration				
	Pruning possible[122]					Pruning possible
Tree pruning			Shrub pruning			
Ventilate. Watering. Harvest. Fertilise.	Ventilate. Watering. Harvest.	Ventilate. Watering. Harvest.	Ventilate extra Watering.	Clean greenhouse. Remove plants.		

Figure 25. Constructed wetland. (Hillenius, T).

3.3.8 Synergies

The synergies named in section 3.2.5 are implemented in the design. For example typha plants can be harvested to be used as insulation material, while (rain) water storage can be used as an aid against droughts and be used for watering plants. Furthermore, a less negative and even positive environmental impacts can be reached by choosing biobased materials and using LCA’s. Another synergy is that animal deposits from the animal inhabitants may be reused as fertiliser for growing plants onboard. Finally, the maintenance can be positive for the social cohesion and provide educational benefits for the student community.

3.4 Evaluation

In this chapter, the design is evaluated by answering the research questions.

3.4.1 Can the design be described with Life's principles

The design can indeed be described with Life's principles. An elaborate answer on this can be found in appendix 8. Life's principles that are important are 'be locally attuned and responsive', for the design has numerable aspects that are especially designed for this function. Material handling and water cleaning technologies are done by utilising life-friendly chemistry. Furthermore, dismountable building can be regarded as resource-efficient, while the development of the realised project socially and ecologically is integrated with growth.

3.4.2 Does the design lead to nourishing solutions?

Nourishing solutions are defined as 'solutions that provide the food or other substances necessary for growth, health, and good condition'[123]. The needs and solutions of the clients (humans, animals, plants) are different. For the students, nourishing solutions are characterized by all elements of the pyramid of Maslow[124], while for animals and plants, that model is less applicable. Only the three base layers are included for animals and plants.

The design does lead to nourishing solutions in some aspects, while for other aspects, it remains challenging to make a change. In this respect, it can be argued that nature isn't always nourishing as well. Plant species use toxins in their fruit, and predators inflict trauma and stress among prey[125–127]. However, the environment and lack of nourishment on a dead planet, e.g. Mars, shows that nature, in general, is nourishing. The answers here are an approximation, as extensive research and LCA's are needed to give an accurate overview.

Does the design lead to nourishing solutions?

i. Yes
   1. The used separating vacuum toilets together with composting and the water filtration system can be defined as a nourishing solution. They fulfil students' essential needs for hygiene (health), while it is possible to recycle crucial nutrients and reuse the products as compost[128].
   2. By utilising the Showerloop system and water filtration, significantly less drinking water is used, while all water sources are reused more often. The constructed wetland creates habitat as well. Although the safety of filtered water cannot be guaranteed at all times, with proper care and suitable application, the water is nourishing.
   3. All thriving plants in the design (if biodiverse) provide habitat and food and are therefore nourishing. As specified in the maintenance plan, it is important to

follow specific guidelines to keep the chances for healthy ecosystem development as high as possible.

4. Dismountable building turns out to be essential to keep resources available at later stages, keeping the value of components as high and long as possible.
5. Batteries + energy system are nourishing in the sense that it harvests and stores the solar and environmental energy needed for the metabolism of the building.

ii. Depends on use

1. In the design, a distinction is made between toilets used by people who use medicines and toilets for people who do not use these. Although the difference is made clear, it depends on the actual use if the system will function as intended.
2. Pieter Pot is an online food store that is promoted to use in the design because of its circular nature. LCAs show the burden of reusable glass jars is less high than conventional single-use packaging. How much impact is made depends on the user acceptance and usage of the service.
3. Maintenance is needed for a lot of the building systems and materials to strengthen and keep their nourishing abilities. While a maintenance plan is provided in the design, shared responsibilities in student communities often remain a challenge.
4. The students are also responsible for using appropriate cleaning products and chemicals to keep the quality of water streams and KCA as low as possible. Bleach, for example, is disastrous for nature-based solutions such as constructed wetlands
5. All nature-based solutions and nature-inclusive measures are nourishing, although in some cases, practice will tell if the efforts are successful.
6. Batteries (and some other materials and products) are notorious for having an enormous environmental and social impact in the mining phase[129]. This is a significant setback to begin with. In the design, conscious choices of materials with LCAs in mind are made, and an effort is made to partner with companies that strive for less environmental impact.

iii. No: some respects continue to be complicated:

1. For some products, such as some paintings, chemicals, and manufactured products, environmentally conscious options are not available or remain too expensive.
2. Working with nature means dealing with not having all control over the system. Symbiosis problems such as pests need control measures where purposefully measures are used that are not nourishing to ensure nourishing solutions for other creatures.
3. Pieter Pot is a good starting point for reducing single-use plastics. In a lot of other cases, single-use plastics remain unavoidable.
4. A lot of data remains unknown: the influence of heat pumps extracting energy from surface waters may have either negative or positive effects on ecology.

3.4.3 What factors need to be monitored to ascertain that the emerging system is functional and operational?

Monitoring involves paying close attention to developments[130]. It is a kind of systematic observation used for understanding, as a basis for steering and optimising processes. This is desired for both technological systems and the emerging ecosystem, wherein ecosystems are usually more complex to steer. Evolving over time, the monitoring and steering activities and the development of the ecosystem go hand in hand.

Monitoring is used to track a design's progress toward reaching its objectives. Therefore, the two main objectives of the floating student housing are restated here:

- Housing that copes with rising seas
- Housing that adds ecological value to the surroundings

Ultimately a situation is envisioned where people and nature thrive in harmony. Life's principles guide the way for this thriving state.

The following aspects need to be monitored for the emerging system to stay functional and operational:

a. Water
  - Shower system
  - Fire-installation
  - Pumps – bilge pumps as well
  - Avoiding freezing of ducts and pipes
  - Toilet – vacuum system
  - Water quality, technical systems
  - Water quality, ecological systems
  - Use of cleaning agents

b. Electricity, heating, and cooling
  - Periodical maintenance
  - Energy usage

c. Materials
  - Material state (cleanliness, degradation, functionality)
  - Material specific maintenance
  - Waste production

d. Biodiversity
  - Monitoring (Key species, Insects, water organisms, fish, birds, plant species, abundance, diversity etc)
  - Environmental water quality
  - Invasive species
  - Maintenance influences on animals and plants

e. Social
  - Maintenance level, culture, and accuracy
  - Monitoring level, culture, and accuracy
  - Privacy

f. Overall system
  - Outputs
  - Outcomes
  - Progress
  - Performance
  - Performance validation (sensor accuracy etc)
  - Impact

3.4.4 What might be emergent effects of the prototype, and if scaled up what effects might it have?

Kelly writes that higher-level complexities cannot be deduced from lower-level existences[131]. Emergence requires a multitude of elements, and the emergent effects cannot be calculated without actually playing out the system. There is no way to be certain about all the emergent effects of the designed prototype in this research, but where reference projects and this project share the same characteristics, best guesses can be given. A few of the emergent effects are already given when discussing the functionality of the system functions, in the form of synergies and trade-offs. A broader perspective on emergent effects is worked out below.

Technological effects

Technologies that can work jointly with environmental and technical parameters might create emergent behaviours such as varying water quality, climate regulation, and biological growth. Being able to balance these behaviours is key to the prototype's success. Essential for the emergent effects and well-functioning integrated system is the realistically scaling of individual processes and elements, so that they work well together.

Social effects

As the project has a community focus, the emergent effects might be positive for social cohesion on board as in the neighbourhood. Bringing people with different backgrounds together might play out well for the quality of innovations. Reference projects where this played out well are the 'cardboard to caviar project'[16] and the 'Vertical' project[21].

Socio-ecological effects

As the project contains many elements where nature is brought closer to the inhabitants, and the inhabitants are involved in maintenance practices, more ecological understanding is expected to result from the project. This is also found in other research, which shows that gardening provides experiences that encourage plant conservation behaviour and increase ecological literacy[132,133]. Bringing nature closer to humans increases the risk of ecological conflicts such as nuisance by bird droppings, bird squeaking, and animals such as wasps and mosquitoes. The inhabitants will need to stay in balance with the surrounding nature to increase mutual understanding and find meaningful ways of symbiosis.

Ecological effects

At the basis of any system is the physical flow of materials and energy. Disbalances in these affect ecosystems and species[134]. The design's environmental footprint is likely to be relatively low compared to other housing projects by choosing materials carefully using LCA's, practicing dismountable building and focusing on circularity. Besides these, nature-inclusive measures create habitat for species. Careful design and targeted interventions may lead on a journey towards more swamp- and estuary plant species, macrofauna, fish, insects, birds, and bats. Smart systems can inform these targeted interventions and thus help steer the ecological development towards a healthy ecosystem. However, no full guarantees can be given that the ecological effects will turn out as expected. It is a dialogue with nature.

Effects when scaled up

It may be that the most considerable contribution of the design is not the size of its environmental impact nor its direct nourishing effects, but rather it being the concrete manifestation of a regenerative, positive vision for the future. In several aspects, it is different from societal values of the 20th century and even the last decades, when extractivism remained dominant and the impact of climate change was not felt at large by the general public. This design acts upon the current timeframe by experimenting with resilient and regenerative architecture, technological advancements, and a paradigm where humans are part-of and working together with nature to improve the environment as a whole. Visible both in real-life and by digital means, the prototype can serve as an example and inspiration for further projects, both in the same neighbourhood as elsewhere in coastal regions around the world.

The vision and experimental work of Marcos Cruz are exemplary for this. In an interview[135], he talks about bio-integrated architecture, wherein the inherent growth force of nature is acknowledged and even stimulated. He argues that accepting its volatile changing behaviour in architecture and design, with or without benefits, is necessary for the way forward. Working with the 'bio-receptivity' of materials and design, it is possible to design scaffolds for inhabitation, not only for humans but also for the entire surrounding environment. The combined efforts of all these people (this research project included) on many projects, might create a snowballing effect of environmental impacts.

4. Conclusion and discussion

This study is about merging ecological solutions and integral sustainable design as a basis for regenerative design. This is done to include ecological functioning and diminish environmental impact in the built environment. First, reference projects show what already has been done to integrate these fields. The projects share similar system functions, of which cleaning water, providing biodiversity, generating and storing energy and materialisation are chosen to elucidate in the research. A theoretical basis in these four system functions is laid out for the design produced later in the research. All system functions have different components and techniques to fulfil the given function.

This research aimed to establish a set of key elements for regenerative design and identify how they interrelate. The research question for this research was to find out what factors a prototype for bio-inspired floating student housing should entail so that it makes the local natural environment thrive. Here thriving is described as flourishing, gaining health, and developing well[9].

4.1 Conclusion

First, conclusions to essential components are given, after which conclusions are given on the questions posed in the previous chapter. The design shows that it is possible to implement all of the four system functions in the design of a floating student house. Essential components are constructed wetlands, home batteries, energy generation technologies such as aqua thermal energy and solar energy, wet-dry gradients for plants and habitats and basic food web infrastructure for animals (section 3.2&3.3). The design can be described by Life's principles (section 3.4.1) and does in some respects lead to nourishing solutions, but not in all (section 3.4.2). This is similar to the reference projects, that show that each project is best at different facets, depending on project-specific factors and goals. In the design, both ecological solutions and technological solutions can generate positive and nourishing outcomes for the surrounding natural environment. However, some aspects limit the potential for positive outcomes. For example behaviour change remains a complex issue, (parts of) production chains are degenerating, or data on environmental impact to base decisions upon is lacking. There is a multitude of elements that need to be monitored and maintained, to be able to make decisions on how to progress with the relation between inhabitants, housing and the surrounding natural environment (section 3.4.3). For the system to remain functional and operational, all of the major subsystems within the design need monitoring. Emergent effects of the prototype are interrelations between the different sub-systems that lead to synergies (e.g. water storage for plants can be used during droughts) and trade-offs (e.g. availability of space) (section 3.2.5). Furthermore, possible emergent effects can be expected by the merging of technological and ecological systems, ecological effects by a dialogue with nature, socio-ecological effects and possibly increased social cohesion (section 3.4.4). Moreover, the project can function as an example for further development.

4.2 Discussion

The first sub-question that leads to the conclusion is to create an inventory of elements and subsystems that could stimulate the local environment while simultaneously creating a home for students. For various themes (regulating water, increasing biodiversity, storing energy & balancing temperature, and material usage), this inventory was developed.
If systems are developed integrally with each other, potential synergies can be integrated[7,16,88,136]. Nature-based solutions often have more co-benefits than their technological equivalents – leading to solving diverse challenges in one go[137]. Spatially, various components compete with each other as well, resulting in trade-offs (see the diagrams in section 3.2.2). Researching individual systems (such as the water system) while taking into account the whole picture, shows which elements fit well with other systems (environmental parameters and biodiversity).

One concrete insight is the importance of the circularity of the used materials. No matter their function, a problem is created in the future if the materials cannot be reclaimed, leading to future environmental degeneration. This makes materiality more critical than the best functionality, although minimum functionality is required. It is interesting to research where the cost-benefit ratio lies of utilising materials with (possible) negative impacts for creating regenerative systems. The municipal ordinances on the floating island projects in Amsterdam are a concrete example of acting on these matters[24]. All decisions on materiality and system elements have an impact[138]. For some technologies, materials and parts are shipped from all over the world. For others, one has to choose between recycling materials from other buildings versus demount ability of the project. As all these impacts are scattered, LCA's are helpful to make decisions[138]. However, there are many more important factors, and those can only be valued in relation to each other. Therefore, there is a need for a holistic tool that values the impact of the design in its togetherness. This can be done with a diverse set of KPIs.

The answer to the second sub-question showed that the design does lead to nourishing solutions in some aspects, while for other aspects it remains challenging to make a change. This is similar to other projects, such as the projects described in section 3.1. Complete filtering of medicine residues from wastewater is not possible for example[19,49]. No projects known to the author are fully regenerative, thus it is vital to communicate the extent of how regenerative the different factors of the emerging system are. Here the vision of biomimicry and tools such as Life's principles and data visualisation of key performance indicators might come in handy. Partnering with other pioneering companies adhering to similar philosophies is also a good strategy to work towards the best solution[19,139].

The third research question asks what is needed to keep the system functional and operational. While all sorts of activities are required, this includes monitoring factors within the water and electrical system, materials, biodiversity, social- and overall system functioning. Although already expansive, the list is not exhaustive. Habitants are advised that keeping each other on the same page and working on concrete goals together helps keep motivation high. This is needed for cocreating the evolving system and will ensure that monitoring and maintenance tasks are done, which can be quite labour intensive. Social dynamics play an important role herein[19,140,141].

The fourth research question handles emergent effects of the prototype when it becomes a reality. It is good to think beforehand about whether the intentions and design are as functional in reality as on paper. As the proposal is not yet developed in a fully functioning 'digital twin', the answer still has significant uncertainties, but best guesses can be given. For a functioning system, several factors need to be balanced through time, which leads to improving the local environment. These factors include varying water quality, climate regulation, biological growth, and social cohesion onboard and in the neighbourhood. An understanding of ecology and positive experiences of nature by the people on board and in the neighbourhood may help solve ecological conflicts and develop a healthy ecosystem. Nature-inclusive and ecological living requires a set of cultural practices that involve adapting and moving through time with the changing local environment[12,131,132,142]. The combined efforts and pilot projects such as this research project may steer developments in that way.

Other findings in this project that need discussing are the following. Researching nature-inclusive design poses some challenges. One of them is that ecosystems change non-linear[16,86,131]; thus, the effects of a given measure can turn out positive or negative for the desired outcomes. For example, creating green shores and shallow waters with vegetation may help stimulate eels (the desired effect) but may also boost the pike population, which eats young eels (undesired effect)[106].

Another challenge is keeping the possibility of the prototype to move between various locations. From a nature-inclusive design perspective, this may lead to displaced animals. The prototype is custom designed for the given project location, as animals depend on factors such as building orientation, wind and water conditions, territories, and characteristics of the surrounding natural environment. The basic needs of animals are shelter, food, water and space to survive. By the moving of location, these factors need to be revaluated to ensure the right living conditions. Some examples of what to take into account are the following. Bird nests need to have the same orientation on the building façade[21]. When keeping bees, bees fly back to the original location when nests are displaced in a range of 5km[143]. This effect does not occur when bees are displaced longer distances, and can thus be held on travelling vessels[144]. Plants favour certain environmental conditions such as the right amount of sunshine, proper temperature, rain, nutrients, acidity and salinity.

The design of the technical systems poses some challenges as well. The tides at the project location shift 1.7 meters, which may limit or benefit the impact of the prototype on the aquatic environment and may trouble measuring results. As De Lima et al showed, the water body characteristics are decisive for the extent of the impact that is possible. Monitoring a diverse set of parameters in the prototype may progress this research.

While designing, it became clear that cultural aspects are non-neglectable. Compost toilets were opted for as a sustainable toileting solution in the preliminary design. These are replaced by vacuum toilets in the final design due to cultural reasons. This decision was strengthened by research by Klaversma et al on the social acceptance of compost toilets at 'De Ceuvel'[140]. It is interesting to note that cultural aspects are not included in Life's principles.

4.3 Limitations

There are at least three potential limitations concerning the results of this study. A first limitation concerns the emphasis on water and biodiversity and less on other themes. This was necessary to keep the research project manageable, but no 'complete' overview of elements was researched from a systemic view. Food, mobility, infrastructure, well-being, and health are other themes that need attention before the design can be realised.
A second potential limitation is that the design is compared to positive reference projects and Life's principles, instead of conventional building practices. This leads to an incomplete view of progression toward fully regenerative design and might be done differently in a next research.
A third limitation is that the design did not reach the level of detailed performance calculations. Therefore, spatially the implemented technology and ecology fit the design, but functionally it is not known yet whether the design will deliver the stated operational goals. However, for this project, it was not realistic to integrate a broad set of measures in the design spatially, while ruling out all uncertainties in detailed performance calculations. Therefore the potential exists some claims and integrations done to the best knowledge of the author, will need revision in the next version of the design. The spatial and functional integration of technology and ecology and the visualisation in a design do form a basis for doing these calculations and for further research and design.

4.4 Next steps

Between this research and the realisation of the design are still several large steps to take. More research is needed for each subsystem and on themes not researched in this thesis. For example, research on the social effects and requirements is essential for the design. Calculations and simulations in different configurations and conditions can help benchmark the operation of the design under different circumstances in a process of constant adjusting and improvement. The book 'Thinking in systems' by Donella Meadows provides a thorough basis on systems dynamics[86], which will be a major help for building an extensive system dynamics model of the prototype. This model can be developed further on work already done in this research. The model can then be integrated or work together with a BIM model (digital twin). Ultimately, when the project develops further, and the prototype is realised, it can serve as an example, case study, and inspiration for other projects, both in the same neighbourhood and elsewhere in coastal regions around the world.

4.5 Advice for the advancement of the design

Here per theme is given what the author advises to take from the elaborated design in this research and progress with the design and realisation of the prototype.

Water

When the various water streams are segregated, water can stay at its highest quality and waste water can be minimised. First, compost toilets were thought to be the best solution. In fact, in terms of sustainability and autarky, it is. However, vacuum toilets are a better fit since the technology feels more similar to conventional flush toilets, and the cleaning is less a hassle. Although the system of vacuum toilets is quite complex, and maintenance needs to be done by experts, the aforementioned advantages are thought to be larger. Further integration with constructed wetlands and/or other technologies such as nutrient harvesting and algae production need to be researched further. Constructed wetlands seem to need more maintenance than some promotional texts are suggesting[115], however, as nature-based solutions, they provide benefits in more than one area and this is thought to be an important asset in the design. Storing (rain)water is important for plants, and drinking water and for resilience against droughts and other disturbances. Autarky in drinking water in the near future is not necessary as the quality of drinking water in the Netherlands is very high, but it is good to make installation of additional active charcoal filters easy, as it seems drinking water production gets under pressure in the upcoming decades[145]. Active charcoal filters are less harmful than reverse osmosis filters for the mineral quality of drinking water. Using sensors will be necessary to monitor and steer the water quality in various processes of the water system.

Ecology

In conversations with Mireille Langendijk and Jennifer de Jonge, it became apparent that only conditions for nature inclusivity can be created, but a large part is up to nature how the process of nature inclusive design unfolds. If places for animals are to be implemented, it is necessary to design from the perspective of the animal. This means that animals need to be seen as clients for the design, and places where the animal finds shelter, food, water and habitat need all to be present. Some animals like to live more solitarily while others are used to communal living. When maintenance activities such as mowing are done, do not mow entire areas, but leave patches of vegetation for animals to find shelter and food. Diversity through time is important, develop more than one scenario for the succession of the area. Ecosystems tend to have key species that are important for the structure, biodiversity and resilience of the ecosystem. Finding and working with these species will be an important area of work. Some important elements of the nature-inclusive design are the floating islands and a place for composting. These elements provide habitat for plants and animals and resilience through the cycling of nutrients. Further inspiration for design options can be explored via the 'strategies for designing urban ecosystem services diagram' made by Katherina Hecht.

Materials

Circularity is the most important factor for material selection. However, there are many more important factors (production chain, CO_2 footprint, ease of handling, degradation & maintenance and replacement among other things) to be considered for each material choice. Handling this process with care, exploration and inventiveness will be of great importance to the design. Making the biological material cycle as large as possible and the technological material cycle as small as possible will help the regenerative potential of the design. Proper architectural detailing will help against moisture problems, which can be key to the successful integration of biobased materials. Lastly, but very important, build in a dismountable way and make a materials passport of the building.

Energy

Aquathermal energy seems to be a promising solution for energy generation of housing near water[97,146], and that the water bodies of Rotterdam are influenced by the tides might increase its potential. A focus on energy storage rather than energy generation might be preferable due to the large demand of new connections for energy generation to the Dutch electricity grid. The shipping vessel has lots of opportunities to store weight near the bottom of the ship, which might be needed for stability as well. This space and weight offer interesting possibilities for energy storage, but it is of vital importance that storing energy below the water level is done safely. Besides energy efficient (low temperature) heating, a cooling solution is important (but not handled in this research). Even though the house is nearby the water, it might be that the reflection of the sun on the water surface heats the house quickly.

Design & workflow

Involve expertise from a lot of disciplines early on in the design process, as most influential decisions regarding the innovative potential and environmental footprint are made at the beginning of the design. Build relationships with companies who are also pioneering in the circular and environmentally friendly industry, to increase the resilience of the company and strengthen industries focused on sustainability as a whole. Follow and use exciting research, new tools such as the diagram from Katherina Hecht, the impact monitor for broad welfare and other technologies to work out the best workflow of the company. And finally: Dare to dare, Floating Students knows and shows its drive for futureproof living on water.

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Appendixes

Appendix 1: Elaboration on research methodologies

Design

There are many definitions of the act of designing, and many of them show similarities. Here, one definition is highlighted with broad applicability while still being accurate and straightforward[147].

> *"Design is the thought process comprising the creation of an entity."*
> *William R. Miller*

It means that it is a conscious activity guided by aims and objectives to create an object, process, or even a relationship. Whether a design is successful and 'good', according to Miller, depends not on the definition of design but on its purpose[148]. In designing, one might vary in pace, scale, perspective, medium, abstraction level, empathy, reference, and layer[149]. This is what design makes a complex, hard-to-grasp, heterogenous, personal activity that designers love, drives them crazy and may create admirable and amiable entities.

Scientific method

The scientific method is a procedure of acquiring knowledge, which has defined the progress of science since at least the 17th century[150]. Criticism and careful observation are essential in all parts of the process since one's cognitive presumptions can distort the interpretation of observations. It is based on the principles of induction (formulation, testing, and modification of hypotheses) and deduction drawn from the hypothesis (systematic observation, measurement, and experiment). Apart from the principles, elements (steps) can be distinguished. In every step, information can be revised and refined. A possible pragmatic linearised overview of the steps of the scientific method is outlined below[151].

1. *Define a question.*
2. *Gather information and resources (observe).*
3. *Form an explanatory hypothesis.*
4. *Test the hypothesis by performing an experiment and collecting data in a reproducible manner.*
5. *Analyse the data.*

6. *Interpret the data and draw conclusions that serve as a starting point for a new hypothesis.*
7. *Publish results.*
8. *Retest (frequently done by other scientists).*

It should be noted that the scientific method is more than merely following the above steps; it requires intelligence, creativity, and imagination and is not a single recipe[152]. In this sense, it can be visualized as a cycle (parts 3 to 6 and back), developing ever-increasing quality of models, information and methods[153].

Differences between design, sciences, art, and engineering

To understand the differences in working between design, science, engineering, and art, some key differences are highlighted here, in companion with spot-on quotes (table 6).

Table 6. Key differences between science and design. (Wu, S., 2018).

		Key differences[154]
Phenomenon of study	Science	The natural world
	Design	The artificial world
Appropriate methods	Science	Controlled experiment, classification, analysis
	Design	Modelling, pattern-formation, synthesis
Values	Science	objectivity, rationality, neutrality, and concern for 'truth'
	Design	practicality, ingenuity, empathy, and concern for 'appropriateness'
Essence	Science	finding similarities among things that are different
	Design	creating feasible 'wholes' from infeasible 'parts'
Thinking and doing	Science	verbal-thinking, numerical, literary; pattern recognition, investigate extant forms, analytic
	Design	non-verbal thinking, graphical; pattern synthesis, investigate novel forms, constructive.
Problem solving	Science	problem-focused, analysis
	Design	solution-focused, synthesis

Also S.A. Gregory describes the differences between science and design in a clear way.

> *"The scientific method is a pattern of problem-solving behaviour employed in finding out the nature of what exists, whereas the design method is a pattern of behaviour employed in inventing things of value which do not yet exist. Science is analytic; design is constructive."* Gregory (1966)[155].

In short, it can be said that

> *''The natural sciences are concerned with how things are…Design, on the other hand, is concerned with how things ought to be''*. Simon (1969)[156].

Differences between - arts and design - and - engineering and design – are highlighted in table 7.

Table 7. Key differences between arts and design. (Wu, S., 2018).

	Key differences[154]
Arts	an expression of human emotions and experience, appreciated for beauty or emotional power
Design	an expression of purpose, solving problems in the real world, appreciated for solving human problems
Engineering	Engineering: solve problems between parts and parts in the artificial world
Design	Design: solve problems between human and the artificial world

Historically design stood in between art and engineering, manifested by the contrasting teachings of design at the French schools École des Beaux-Arts and École Polytechnique around the eighteen hundreds[149]. Science played an essential role in the history of design as well. Contemporary interdisciplinary workings are bringing these different approaches together more than ever before, especially due to the rise of digital technologies[154,157]. They complement each other. Key benefits that design can leverage are communication through the creation of imagery and rapid problem-solving, and (co)creation. Below three different schools of thought are summarised.

1. Intermediaries in teaching at the intersection of the above fields

a. Net Positive Design

Janis Birkeland's Positive Development (PD) theory is an approach to improving the built environment that reaches further than sustainability. It elaborates on the difference between doing less harm as opposed to truly regenerative solutions, as is shown in figure 6. The basis of the approach is that the built environment can create a positive relationship between natural and human systems, offering net benefits for both[158]. PD does this by giving four directions:

1. To move away from closed-loop systems that 'cover up' for doing harm to open-loop systems that generate many positive externalities.
2. From negative mindsets (do no harm) to positive mindsets (generating benefits).
3. To go from a reductionist decision-based (negative) approach to a design-based (positive) approach.
4. To not only quantify individual metrics to base the design on but to employ a wide array of metrics (also qualitative data and externalities throughout time) that consider whole systems[159].

In this way, buildings, landscapes and urban areas can be designed to provide for their own ecosystem services (food production, biodiversity, air and water purification etc), circular materials and energy[160].

As Dr Birkeland says: *''Sustainability requires not only disruptive innovations and radical worldviews, but the reformation of design and decision-making frameworks on ethics-based and eco-positive principles. Decision-making systems can make better choices, but only design can create more and better choices.''*[158].

b. ITECH – Engineering Design

In the ITECH master programme at Stuttgart University, students envision, design and build structures and material systems with novel technologies to be fully equipped for the future architecture and construction industy[161]. A combination of design, engineering and scientific approaches is used, offering a rigorous basis for physical prototyping processes. The programme focuses strongly on interdisciplinary skills in architecture, design, engineering, construction, natural sciences and biology. It lies within and puts inspiration from recent ongoing discussions on the future of education to create a personalized, research-driven, experiment-based and transdisciplinary educational framework and learning environment to re-examine current knowledge and techniques and develop new integrative ones.

Bio_ID

The approach of Bio-integrated Design, a master's programme at the Bartlett School of Architecture in London, combines iterative design experimentation and conceptual thinking with laboratory testing protocols and innovative computational methods for the production and simulation of the (behaviour) of architectural artefacts[162]. Marcos Cruz tells in an interview[163] that in the cross-boundaries of disciplines, the great potential of design lies and teaches people to use all sorts of design tools – from laboratory equipment to computational techniques and robots. The education goes a step beyond taking nature as a model by integrating biology into technological and material hybrids. As synthetic biology and technology gain common ground, extraordinary living designs are possible. Cruz argues that nature as an idea apart from humanity is a vision of the past, as our influence on nature is so profound that we created a new nature called 'supra-nature'. Therefore, debate and design on responding to and working with this synthetic world is highly needed. According to Cruz this bio-integration goes beyond the extrapolation of natural principles – by understanding and working with phenomena like growth, evolution, mutation and material. Working with them in entirely different ways, an architecture is created that is an integrated system of inert and biological matter. The volatile dimensions of nature are part of this system, which can lead to problems but is also full of potential. He says: '*we architects need to accept much more the idea that what we are designing and creating are scaffolds for inhabitation, but not only for humans, also for an entire surrounding biota that we depend on in our environment.*'

The above paragraphs show how design and science relate and how they are different. Furthermore, the elucidation of contemporary interdisciplinary workings shows that biomimicry is a method that is similar to other methods. Some of these can be used to further advance the strategies used in biomimicry. The report is written with this broadened view of methodologies in mind.

Appendix 2: Two relevant ship types

The number of smaller inland motor vessels in the Netherlands is decreasing slowly but steadily because of a commercial trend towards bigger ships but through less interest of young people in the industry and extra costs for environmental improvements of vessels as well[164]. Ship types ranging from smallest to largest are spits, kempenaar, dortmunder and Europaschip. Especially the Kempenaar and Dortmunder (figure 26 and table 8) are deemed fit for the prototype, as the size makes them versatile, and both ship types are available on the market. The thickness of the steel hull decreases over time from new ships ranging from six to eight millimetres to used ships having a thickness of four to five millimetres. As for residential purposes, a minimum thickness of 3 millimetres is required; used ships fit the job perfectly[165].

Figure 26. Inland vessels: Kempenaar (left), Dortmunder (right). (Klein & Vereniging "De Binnenvaart," 2009; Wereld van de Binnenvaart)

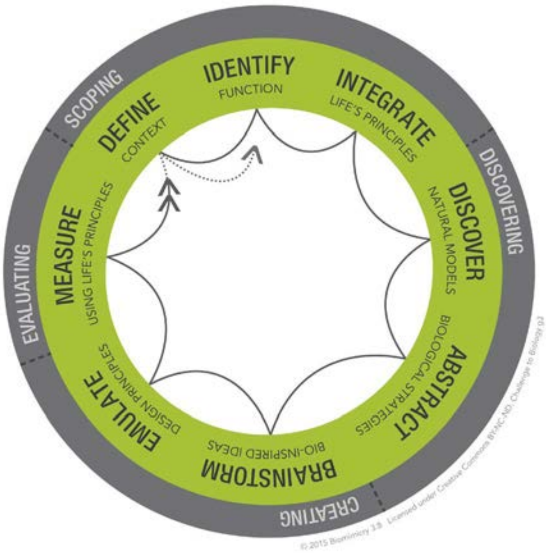
Table 8. Features of two types of inland vessels. (Binnenvaart Kennis, 2019).

Kempenaar	
	
Ship dimensions	55,00m x 6,60m
Cargo hold	44,00m x 5,20m x 3,10m(height)
Carrying weight	655 tons
Gross floor area available (max 2 or 3 floors)	457,60m2 (44,00x5,20x2) or 686,40m2 (44,00x5,20x3)
Dortmunder	
	
Ship dimensions	67,00m x 8,20m
Cargo hold	49,00m x 6,60m x 3,40m(height)
Carrying weight	1000 tons
Gross floor area available (max 3 floors):	970,20 m2 (49,00x6,60x3)

Appendix 3: Biomimicry tools: 1. biomimicry framework 2. Biomimicry taxonomy

Biomimicry methodology

There are two main ways how to approach biomimicry according to biomimicry 3.8[168]; challenge-to-biology, and biology-to-design. The starting point in the former is a concrete design challenge, while in the latter it is the inspiration for a solution. The process of the former is focused on a solution, while the process for the latter is an application (figure 27). An elaboration on the steps involved in the challenge-to-biology cycle is given in figure 28. Two tools that help utilise biomimicry are included hereafter in table 9&10.



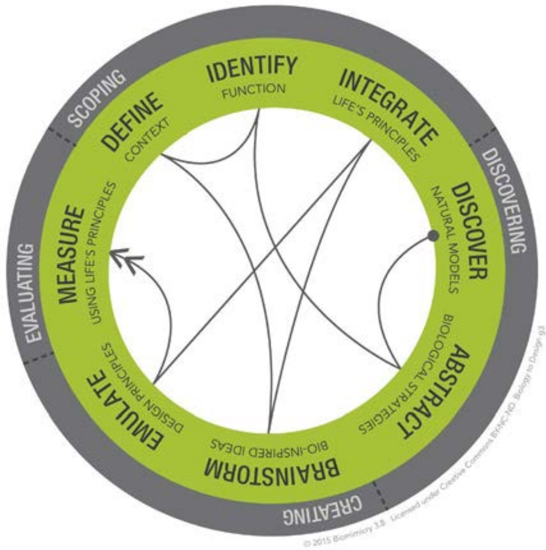


Figure 27. The two different strategies to tackle a problem with biomimicry. Left: challenge-to-biology. Right: biology to design. (Biomimicry 3.8).

1. **Define the challenge**
   What does the design need to do, for whom, and in what context? What criteria and constraints determine success?
2. **Biologize function and context.**
   Reframe the challenge into a biological context, utilising biological terms for the essential function.
3. **Discover biological strategies**
   Use the question 'How does nature … ?', to find natural models that are analogous to the defined function and context.
4. **Abstract design strategies**
   Analyse the strategies that nature uses for its functionality, describing and translating these for other disciplines to generate cross-discipline understanding. Note that designers practise visual thinking. Sketching might be an important communication strategy.
5. **Emulate nature's lessons**
   Design, use the key lessons from nature and human ingenuity to define a solution.
6. **Evaluate fit and function**
   Assess the design in a multitude of ways, refine the design if needed

Figure 28. Schematic Steps within biomimicry thinking. (Biomimicry 3.8).

Life's Principles are fundamental principles that represent nature's strategies for sustainability. They are a major help by offering guidance to refine our choices as we strive to fit in on earth. A more elaborate version of the Life's Principles is given below, which will function as a yardstick to measure the design against (figure 29).

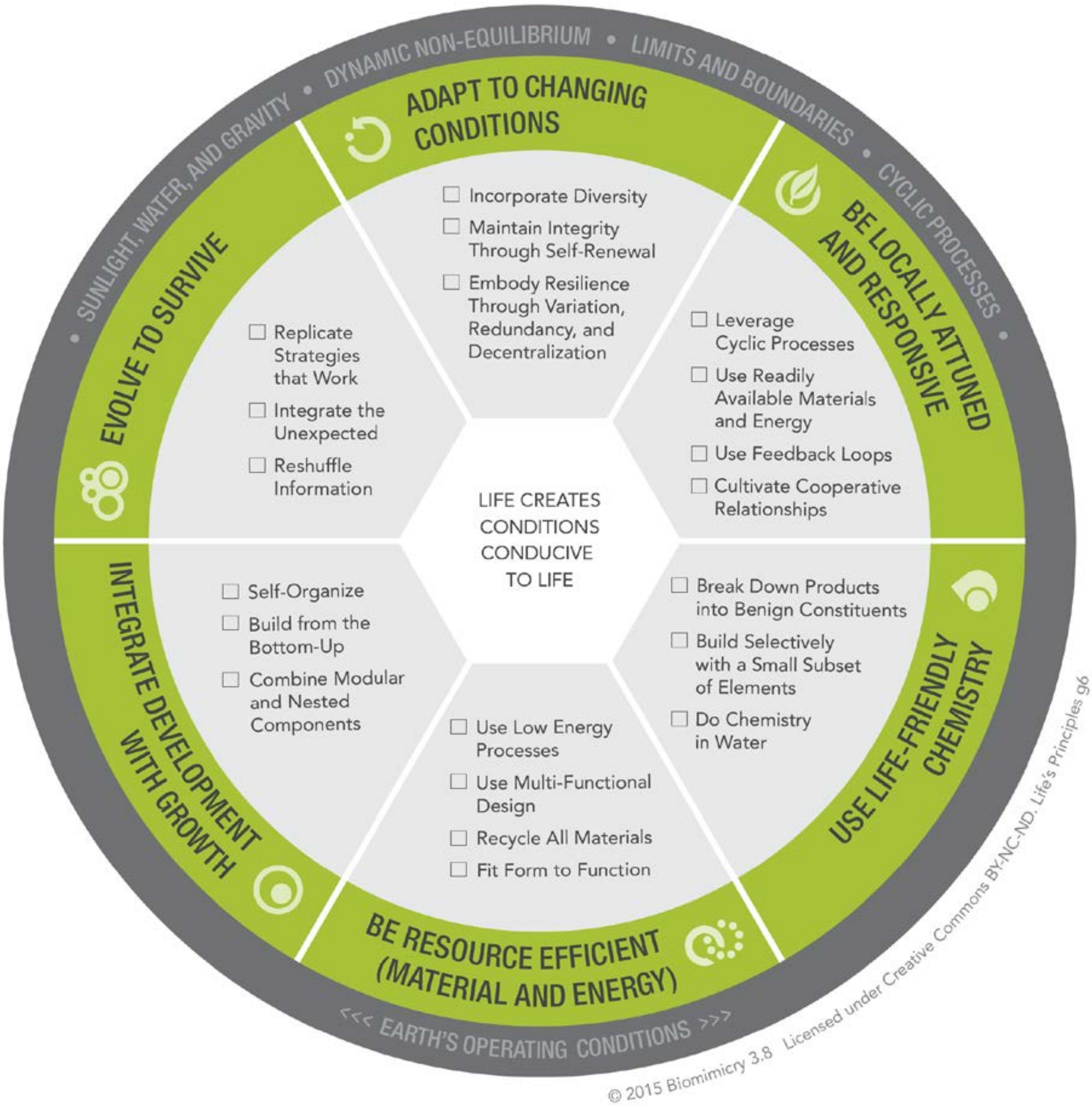
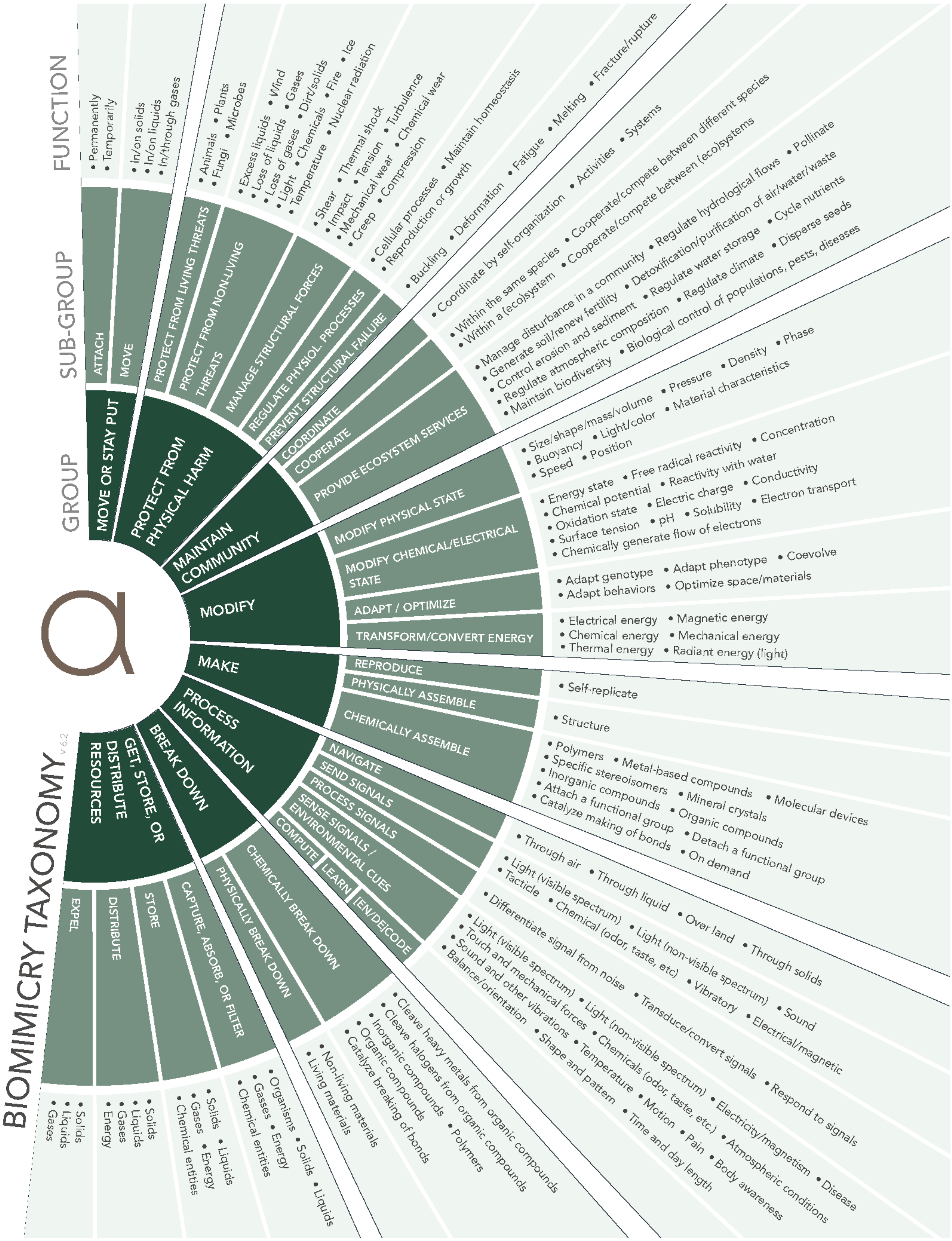


Figure 29. Life's principles. (Biomimicry 3.8).

Table 9. A framework for the application of biomimicry, elucidated based on a building that mimics termites. (Zari, 2018).

Level of Biomimicry		*Example - A building that mimics termites:*
Organism level (Mimicry of a specific organism)	*form*	The building looks like a termite.
	material	The building is made from the same material as a termite; a material that mimics termite exoskeleton / skin for example.
	construction	The building is made in the same way as a termite; it goes through various growth cycles for example.
	process	The building works in the same way as an individual termite; it produces hydrogen efficiently through meta-genomics for example.
	function	The building functions like a termite in a larger context; it recycles cellulose waste and creates soil for example.
Behaviour level (Mimicry of how an organism behaves or relates to its larger context)	*form*	The building looks like it was made by a termite; a replica of a termite mound for example.
	material	The building is made from the same materials that a termite builds with; using digested fine soil as the primary material for example.
	construction	The building is made in the same way that a termite would build in; piling earth in certain places at certain times for example.
	process	The building works in the same way as a termite mound would; by careful orientation, shape, materials selection and natural ventilation for example, or it mimics how termites work together.
	function	The building functions in the same way that it would if made by termites; internal conditions are regulated to be optimal and thermally stable for example (fig. 6). It may also function in the same way that a termite mound does in a larger context.
Ecosystem level (Mimicry of an ecosystem)	*form*	The building looks like an ecosystem (a termite would live in).
	material	The building is made from the same kind of materials that (a termite) ecosystem is made of; it uses naturally occurring common compounds, and water as the primary chemical medium for example.
	construction	The building is assembled in the same way as a (termite) ecosystem; principles of succession and increasing complexity over time are used for example.
	process	The building works in the same way as a (termite) ecosystem; it captures and converts energy from the sun, and stores water for example.
	function	The building is able to function in the same way that a (termite) ecosystem would and forms part of a complex system by utilising the relationships between processes; it is able to participate in the hydrological, carbon, nitrogen cycles etc in a similar way to an ecosystem for example.

Table 10. Biomimicry Taxonomy. (Biomimicry 3.8).



Appendix 4: Biomimicry brainstorm

Four questions are researched for bio-inspired living on water. Namely: how does nature float, how does nature stabilise a floating body, and how does nature balance shortages and surpluses. These questions are chosen as inspiration for out-of-the-box solutions for living on water, and how nature solves these challenges.

❖ How does nature float?

One way is by creating gas-filled floats. Several strategies can be distinguished. Sometimes air is used, while at other times it is a mixture varying in relative proportions (Kelp, figure 30)[169], depending on the condition of the plant or animal and the surrounding medium. The common violet snail sculpts bubbles to keep afloat upside down on the surface of the ocean[170]. Nautiluses, Teleost fishes, and cuttlefish use gas/water-filled spaces, maintained through osmosis or active transport[171–173]. What is interesting is that animals use mechanisms to control the mixture in the gas-filled spaces to keep afloat at various heights in the water column. Another way is using the surface tension of water with nanoscale hairs or scales to trap air and hold weight. Mosquitos combine the hydrophobic abilities of nanoscale structures with optimising the surface tension of water by a contact angle of ~153 ° to optimise the carrying capacity of the water surface[174].

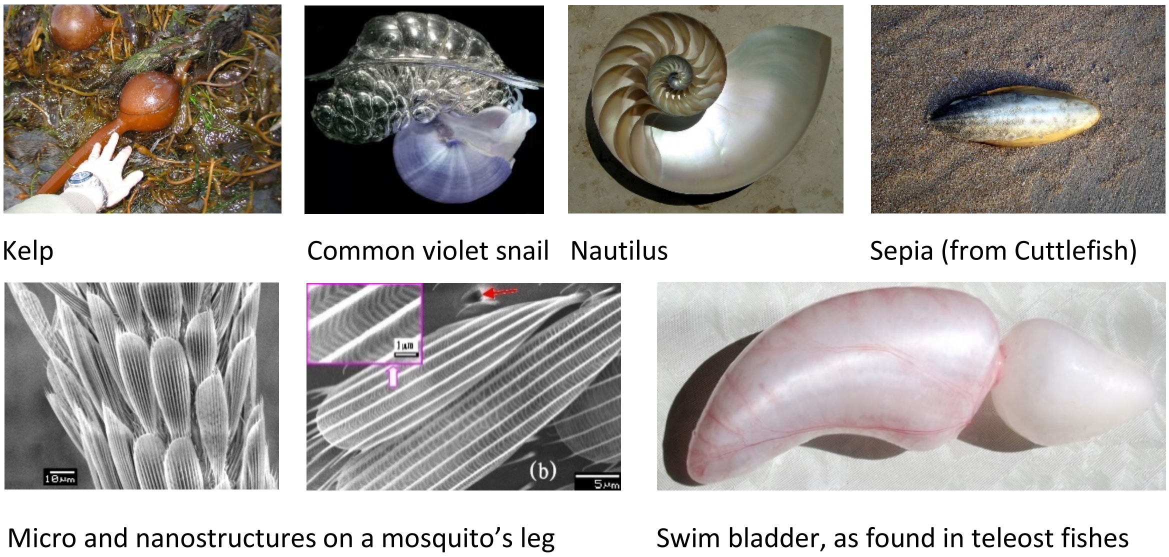


Figure 30. How nature floats. (Ask Nature, 2021).

❖ How does nature stabilise a floating body?

In fish, stability and manoeuvrability often have competing requirements. Surprisingly, this means that most fish species have statically unstable bodies, but high dynamic stability. Within these ranges, the boxfish (figure 31) is highly manoeuvrable. Tiny ridges and edges on the surface of the fish's body destabilise the body but enable a much wider range of movement[175]. Tuna, on the other hand, is a highly efficient cruising fish, that mainly uses a narrow range of movements (whipping its tail) to reach stability[175–177]. Anchoring is another technique to stay put. Mussels use anchoring lines called 'byssal threads' with adhesives that bond chemically to the rock's surface, overruling the rock's chemical preference for water molecules and dissolved salts[178].




Box fish Tuna Mussel bvssal threads

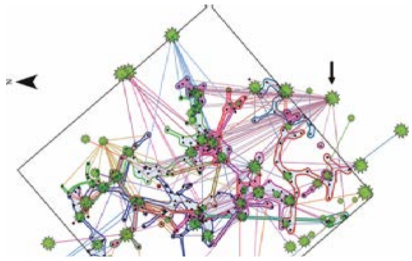
Figure 31. How nature stabilises a floating body. (Ask Nature, 2021).

❖ How does nature balance shortages and surpluses?

Nature distributes resources via various networks[179,180]. In forests trees balance shortages and surpluses via root grafting (figure 32), which helps the overall community of trees in the forest. Another, larger network that distributes resources is the network of mycorrhizal fungi along the tree roots, sometimes called the 'wood wide web'. The trees balance water, nutrients, and can even use the network to send chemical warnings to other trees when it is attacked by for example the bark beetle. Nature balances shortages and surpluses through social networks as well.

Ant-colonies are an example of a decentralised society[181]. Without the inefficiencies of a centralised decision system, the ants are quick responders to both environmental and social cues. Fixing problems through cooperation leads to a community resilient to endure and recover from environmental stresses.





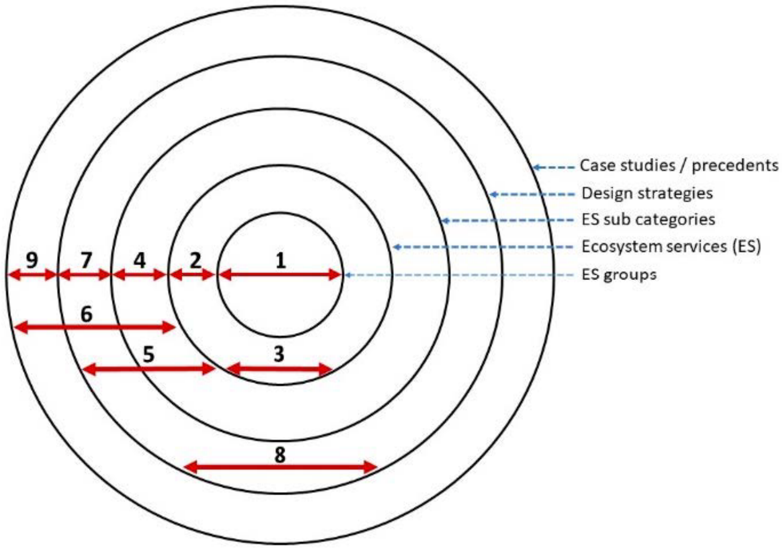
Root graft Ants Tree connections via mycorrhizal network

Figure 32. How nature balances shortages and surpluses. (Ask Nature, 2021).

The above examples spark inspiration for the design process. Gas-filled media, insulation material, or air chambers may be used to help flotation, while chemical bonds may be studied and emulated to develop glues that function well for wet surfaces. Gaining stability through fins and body posture in fish is difficult to emulate in the rigid hull that is envisioned for the design, it might be that sailing boats offer a better inspiration to cope with destabilising wind forces. It would be interesting to use both biomaterials for ducts and pipes, and social networks to distribute resources and balance shortages and surpluses.

Appendix 5: Urban ecosystem services map

Figure 33. Schematic visualization of inner-circle, or inter-circle relationships line connections (1–9) identified between elements (ecosystem services, subcategories, design strategies, and case studies). See map below. (Hecht, Zari 2019).



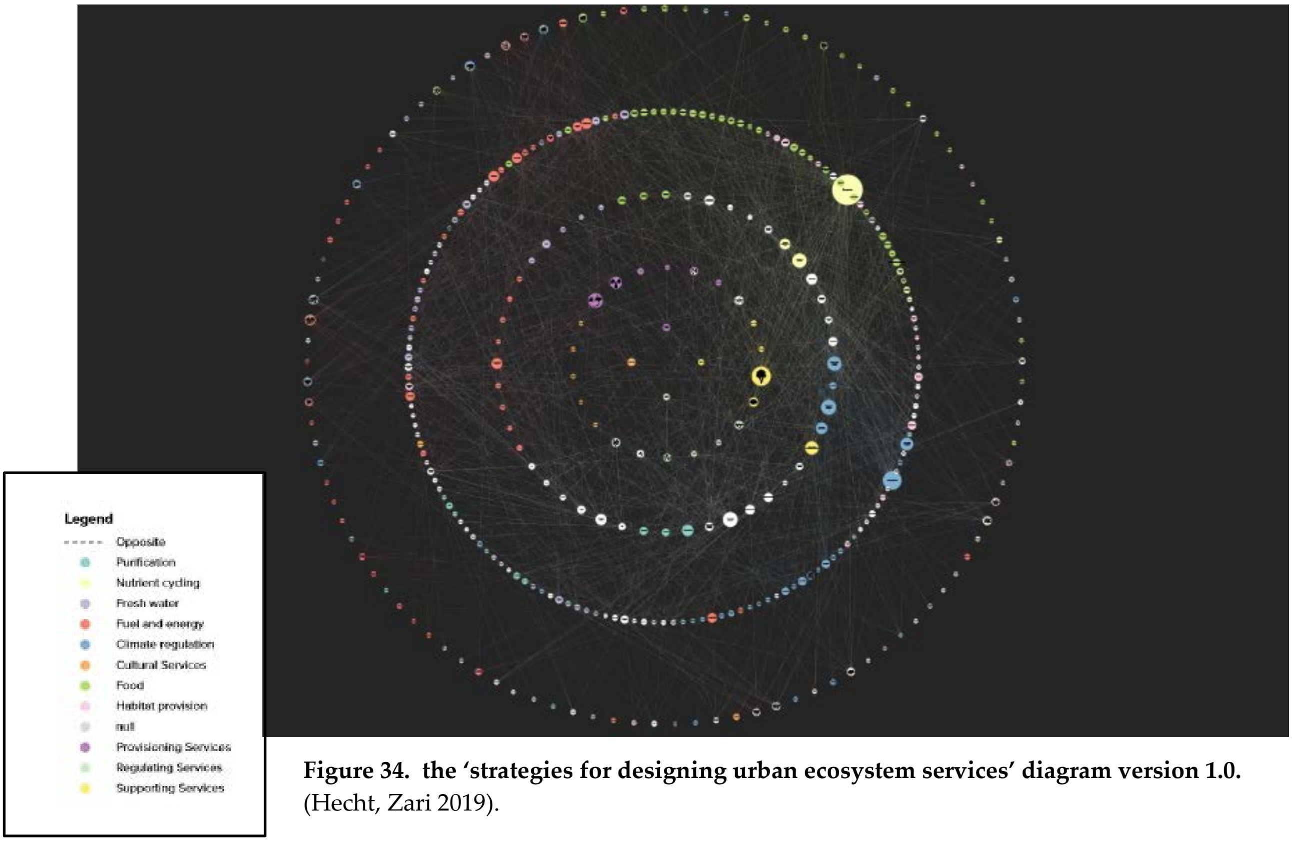


Figure 34. the 'strategies for designing urban ecosystem services' diagram version 1.0. (Hecht, Zari 2019).

Appendix 6: Preliminary design

Preliminary design

In the preliminary design, a first effort is made to make sense of the previous sections, to envision a model that could come into reality. While up-till-now a straightforward and often reductionist way of researching was used, in the next sections, in which the design is worked out, creativity and holism are dominant. Steps forward are made by working out smaller research and design tasks and creating puzzle pieces that are then put together. Here that is done with biomimicry brainstorms, a mood board, and a systems diagram. The goal of the preliminary design is to make a rough sketch, that can be worked out in greater detail in the definitive design.

For the design, the moodboard and systems are shown in figures 19 & 20. There will be two electricity grids on board, to optimise energy usage. Resource-efficient appliances will be placed, and old efficient (but forgotten) practices are supported, such as haybox cooking. Heat pumps and solar boilers will provide energy and heating, while heat exchangers retain heat. Water is segregated in separate systems and stored for extra resiliency. A recirculation shower is installed to vastly lower the quantity of water used. Water is filtered by constructed wetlands that filter nutrients and provide biodiversity. Organic matter from kitchen waste is composted, while a pilot is done with recycling human waste. Various nature-inclusive measures are placed, such as birdhouses and floating islands. Sensors and smart systems keep track of the functioning of the design. Below a drawing shows the placing of various systems (figure 35).

Moodboard

Keywords:

Wood and biobased materials - Sensory rich – Natural - Stimulating interaction and group activities - Growing habitat – Human-animal interaction

Figure 35. Moodboard. (Hillenius, T.).

Evaluation preliminary design

After the preliminary design phase, it became apparent that a lot of the envisioned technologies and nature-inclusive measures need extensive research to integrate them well into the definitive design. How the systems interrelate is not yet visible in the preliminary design, although a first try is given in figure 36. More focus is needed for this integration, although the larger system should not be forgotten. During the design, after the preliminary design phase, a pivot was made to a ship more than double the size of the original ship as the basis for the design. This was done for the profitability of the project.

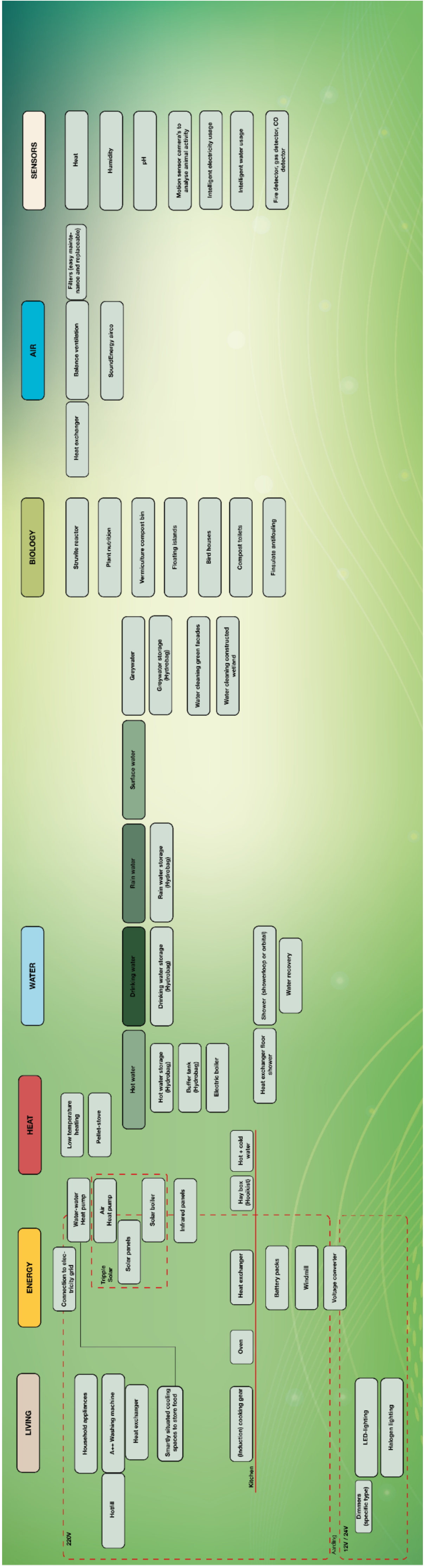


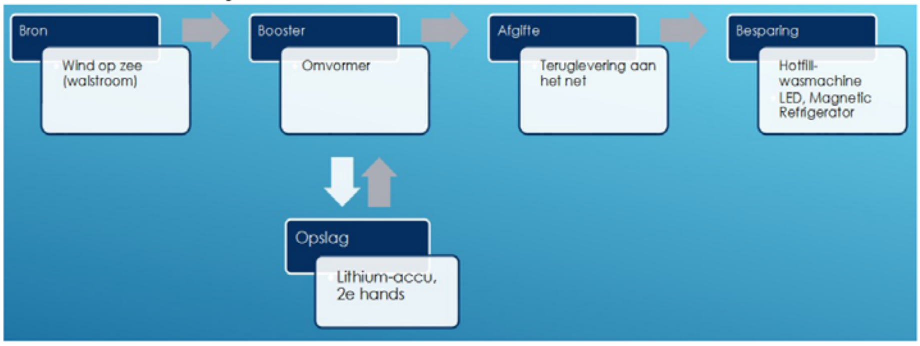
Figure 36. Systems. (Hillenius, T.)

Appendix 7: Executive summary of report on energy, heating and cooling.

EXECUTIVE SUMMARY

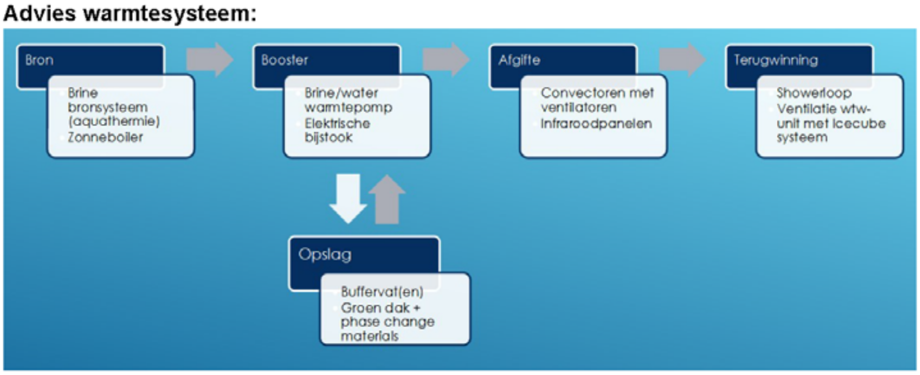
In hoofdstuk 1 van dit rapport worden de eisen voor het energie-systeem op een rij gezet, hoofdstuk 2 beschrijft verschillende opties voor componenten van het systeem. In hoofdstuk 3 worden de opties van hoofdstuk 2 samengevat en advies gegeven. In het kort:

Advies elektriciteitssysteem:



- Wind op zee als bron, geen zonnepanelen, wel accu's:
- Mogelijk is de behoefte aan 'groen' in Rotterdam groter dan een boot die vol ligt met zonnepanelen. Veel planten dragen bij aan de uitstraling van de boot en het project Floating Students.
- Daar komt bij: de maatschappij heeft behoefte aan *energieopslag* om het net te balanceren. Nieuwe zonne- en windparken kunnen momenteel nauwelijks nog aangesloten omdat het net dit niet aankan.
- In de winter is walstroom sowieso nodig om in de energiebehoefte te voorzien, ongeacht zonnepanelen.
- Invulling van specificaties systeemcomponenten in samenwerking met installateur, om alles in het systeem goed op elkaar af te stemmen.

Advies warmtesysteem:



- De boot leent zich uitstekend voor een warmte-systeem op basis van aquathermie, warmtepomp en lage-temperatuur afgiftesysteem door de nabijheid van water.
- Invulling van specificaties systeemcomponenten in samenwerking met installateur, om alles in het systeem goed op elkaar af te stemmen. Een lijst van installateurs is opgenomen in Bijlage B5 – installateurs.
- Zonneboiler op het dak zodat in de zomer de warmtepomp uit kan. Indien de showerloop wordt ingepast, kan gekozen worden voor een kleinere zonneboiler en enkele zonnepanelen.
- Een groen dak is mogelijk voor isolatie en koeling. Maar, een groen dak is niet beloopbaar. Mogelijk kan boven het groene dak een reinforced glas constructie aangelegd zodat er op gelopen kan worden, maar bij elkaar is het gewicht dan zo groot dat aan een metalen exoskelet aan de romp gedacht moet worden om het dak en feestende studenten tezamen te kunnen dragen.
- Passieve koeling en mogelijk het innovatieve IceCube system voor koeling. Indien IceCube te duur is, kan gekozen worden voor koelen met de warmtepomp en afgiftesysteem mits dit ervoor geschikt is.

Volgende stappen:
Zeer wenselijk in de ontwerpfase van Floating Students is meer duidelijkheid over praktische zaken over het energiesysteem waarmee al rekening gehouden moet worden in het ontwerp. Dit zijn oa de boiler niet verder dan 15m leidinglengte van de douches plaatsen, ruimte vrijhouden voor installatieruimtes en de grootte daarvan (minimaal achter 8m2 en vooraan 4m2), duidelijkheid in wat per eenheid is en wat per drie woningen, etcetera.

In referentieprojecten kan verder inspiratie ontleend worden aan hoe energiesystemen werken in de scheepvaart en marine. Een kennis die hierbij zou kunnen helpen is Wessel (via Thimo). In het project is uitvoerig gesproken met Bram Grabijn van Rebra/Ecensy. Dit blijft een waardevol contact voor Floating Students [1] [2].

Een warmtesysteem kan beoordeeld worden door de score op *key performance indicators (KPI's)* te evalueren. Een voorbeeld van hoe dat gedaan is door Metabolic voor Ecodorp Boekel is te zien in Bijlage B2- key performance indicators. In hoofdstuk 1 staat ook veel inspiratie voor KPI's vanuit de bio-mimetica en het plan van eisen. De condities uit het plan van eisen moeten uiteindelijk allemaal gewaarborgd in de definitieve systeemkeuze, overleg deze met de installateur. Kies voor zoveel mogelijk één leverancier/installateur en laat deze de grootte en samenwerking van de systeemcomponenten vaststellen.

Figure 37. Executive summary. (Mischa Hillenius, 2021).

Appendix 8: Can the design be described with Life's Principles?

Yes, it is possible to describe the design with life's principles. The following paragraphs are structured in the six topics of life's principles. First is given how nature solves the challenges at hand, after which the same questions are answered from the perspective of the design.

iv. **Adapt to changing conditions**

Nature adapts to changing conditions by incorporating diversity, maintaining integrity through self-renewal, and embodying resilience through variation, redundancy, and decentralisation.

The design incorporates diversity by accommodating humans, animals, and plants. Plants and animals (such as swallows) are actively engaged by giving them their place in the design and finding ways to assist them in their lifecycles. The design incorporates diversity in energy sources and by housing students from different educations as well.
Inherent self-renewal is hardly possible in today's mechanical systems and conventional materials. Whereas incorporated nature and the community of students change organically over time, mechanical systems and materials are renewed indirectly. This can happen through maintenance by the students themselves or even more indirectly, by utilising financial resources via rent. Biobased materials are opted for as much as possible, which can be regrown.
The design is resilient through utilising various sources of energy (solar and environmental energy) and water (drinking water and filtered water) while storing these locally (in a decentral way). Maintaining a vegetable garden is stimulated by offering suitable locations, such as greenhouse space, integrated planting pots, and ready-to-use irrigation systems.

v. **Be locally attuned and responsive**

Nature is locally attuned and responsive by leveraging cyclic processes, using readily available materials & energy, using feedback loops, and cultivating cooperative relationships.

The design focuses on cyclic processes. They can be found in how the building segregates, cleans, and stores water flows and how energy and water are stored in times of redundancy. A compost heap and maintenance plan make sure organic materials are reused whenever possible. For packaging materials during the usage phase of the ship, PieterPot, offering a cyclic model of food packaging, is promoted to use.
Readily available energy from surface water and the sun is extracted. In this design, no plan for materials is made, although some directions are given in the system elements chapter to use readily available materials that are offered on local materials platforms such as oogstkaart.nl

Feedback loops are used in the smart systems that are used on the boat to regulate water and energy. They are used as well in individual decision-making of the students and the community and in the research that is conducted on the various regenerative measures.
Cooperative relationships can be formed with neighbouring developments pioneering in sustainability and living on water. These are for example, Bluecity, the floating farm, companies concerning floating islands, and the nearby floating houses in the Nassauhaven.

vi. **Use life-friendly chemistry**
Nature uses life-friendly chemistry by breaking down products into benign constituents, building selectively with a small subset of elements, and doing chemistry in water.

A top priority of the design is to avoid toxic substances. Products dissolved in water are cleaned on-site. Efforts are being taken that substances that cannot be broken down on site are segregated and transported to appropriate locations. Organic materials are composted.
A small subset of elements is used by opting for a building system.
Chemistry in water happens by bacteria in the constructed wetlands.

vii. **Be resource-efficient (material and energy)**
Nature is resource-efficient by using low-energy processes, multi-functional design, recycling of all materials, and fitting form to function.

By utilising LCAs, the impact of materials and technologies for the design is weighted and optimised. Choosing energy-efficient and durable devices and technologies is important as well. An example of this is opting for low-temperature floor heating. Ultimately nature itself is harnessed in the constructed wetlands to clean water with low-energy processes.
These wetlands accommodate biodiversity as well and are therefore multifunctional. The greenhouse doubles as a study space, depending on temporal indoor environmental parameters.
Nature is extraordinarily good at recycling materials into reusable components, whereas many manufactured products are usually not easily recycled. The building will be built dismountable, as specified in the system elements chapter, but its elaboration is outside the scope of this thesis.
The casco of the old vessel is a concrete example of fitting form to function, as a casco to place student apartments in. The floating islands are shaped so that slopes accommodate larger biodiversity.

viii. **Integrate development with growth**
Nature integrates development with growth by making an effort to self-organize, building from the bottom-up, and combining modular and nested components.

The nature-inclusive measures in the design are self-organising. Furthermore, some automatic decision-making in the water system is built-in. As the design takes into account relevant constraints set by the inhabitants, it can be described as built from the bottom-up.

The building system from which the building is made consists of combined modular and nested components (like windows and walls), just as the technological installations.

ix. **Evolve to survive**

Nature evolves to survive by replicating strategies that work, integrating the unexpected, and reshuffling information.

The design replicates a multitude of strategies that work. From proven technologies, and developed products from manufacturers to adding elements derived from passive architecture practices. The unexpected is integrated by adding habitats for animals and plants and providing a space where a public function for the neighbourhood can be developed. Furthermore, students are involved in the responsibilities of maintenance.
Information is reshuffled by the student community's continuous development, the research done in and around the ship, and the next floating projects that will be designed.

REGENERATIVE & FLOATING

NATURE INCLUSIVE & STUDENTS