BLUE-GREEN FOR LILA

Designing a Modular Setup for Research Regarding Pitched Roofs

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Abstract

The combination of urbanization and climate change will lead to significant concerns in the foreseeable future, as urbanisation reinforces the effects of climate change. The two major concerns regarding climate change in urban areas are flooding and heat-stress, both of which Blue-Green (BG) infrastructure can offer partial relief to. BG infrastructure refers to a combination of vegetation and temporary water storage.

This thesis covers the process of designing a modular test setup for BG infrastructure for Living Innovations Lab (LILa), that will be used to explore the potential of applying BG infrastructure on pitched roofs in the existing built urban environment. LILa is a field lab currently being developed on campus of the University of Twente, offering a semi-controlled research environment for experimental setups.

For this project, a Human Centered Design (HCD) approach is chosen, while integrating the Double Diamond model of Design Thinking (DT), resulting in a pattern of subsequent diverging and converging phases being used over four steps; discover, define, design and develop. In the first part of this thesis, a deeper understanding regarding the relevance of mitigating the effects of climate change in the built urban environment and how BG contribute to this is gained, the importance of exploring BG infrastructure for pitched roofs specifically is highlighted, and the state of the art regarding both research on BG roofs, whether or not pitched, and available BG roof products is assessed. This section is mostly based on literature research, and additionally a site visit to one of the larger commercial companies specializing in green roofs in the Netherlands. The insights and knowledge gained from this first part form a foundation for the designing and development phases. In the second part, empirical research is used to gain more insight in the target audiences. Firstly, a low-fidelity prototype was developed and tested for usability within an educational context, where students had to place sensors and gather data over a set period. As the prototype is made with limited available resources, no conclusions can be drawn regarding the effectiveness of BG infrastructure on pitched roofs, and evaluation merely focusses on the product-user interaction. Secondly, a co-design session is designed and hosted with homeowners and tenants, gaining insights regarding their ideal product-user interaction, drivers and barriers. The third part of this thesis ties together all the knowledge gained throughout the precursory steps into a final design for LILa, created through a short design cycle, and a guide outlining how this project can be expanded further into the real built urban environment after research at LILa has been (partially) concluded.

The urgency and importance of urban climate resilience are becoming increasingly evident, and BG infrastructure has been already proven to be an effective solution. Moving forward, exploring the possibilities and effectiveness of applying BG infrastructure on pitched roofs has high potential in contributing to a liveable future urban environment in the Netherlands. By implementing a modular test setup at LILa, existing research gaps – particularly regarding the quantification of the effect of pitch angle, orientation and water retention capacity - can be addressed. Following this, the research can be extended to the real-world built environment in small scale, to further evaluate the potential of BG infrastructure on pitched roofs in mitigating flooding and heat stress resulting from climate change. However, before allocating further resources to this project, it is essential to address concerns about structural feasibility. Specifically, the load bearing capacity of both the designated area at LILa for the test setup and that of the typical existing pitched roofs must be evaluated. These assessments are crucial, as they may result in a need for reshaping of the project to ensure its viability.

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List of Abbreviations & Terms

Abbreviations

BG	Blue-Green
BMC	Biomagnetic Centre (building on which setup will be placed)
ET	UT Faculty of Engineering Technology
GHG	Greenhouse Gasses
IPCC	Intergovernmental Panel on Climate Change
LILa	Living Innovations Lab
POA	Plan of Approach
RIVM	Rijks Instituut voor Volksgezondheid en Milieu
RVO	Rijksdienst voor Ondernemend Nederland
UHI	Urban Heat Island

Terms

Sustainability	As formulated in the *Report of the World Commission on Environment and Development*, sustainable developments and designs “seek to meet the needs and aspirations of the present without compromising the ability to meet those of the future” (Brundtland Commission, 1987, p.43).
Climate resilience	Preparedness to deal with increasing extreme weather events caused by climate change
Evapotranspiration	The sum of evaporation from the land surface and transpiration from the soil and plants.
Home	Living unit
Homeowner	Person with the ownership over the concerned home, in which they may or may not reside
House	Building in which one or multiple homes are located
Housing corporation	Company that is homeowner of a larger number of houses, in which they do not reside themselves.
Landlord	Individual that is homeowner of one or more houses, in which they do not reside themselves.
Resident	Person residing in the concerned home
Tenant	Person residing in a home they do not have ownership of
Urbanization	Population shift from rural to urban areas, leading to an expansion of urban areas.

1. Introduction

The combination of urbanization and climate change will lead to significant concerns in the foreseeable future, as urbanisation reinforce the effects of climate change. The two major concerns regarding climate change in urban areas are flooding and heat-stress.

Urban areas, characterized by high concentrations of concrete and asphalt, hinder natural rainwater absorption, causing rainwater to flow directly into drainage systems. As extreme rainfall and droughts are expected to become more frequent in the future, the drainage systems in these areas are likely to be overburdened, raising the risk of floodings (Kourtis & Tsihrintzis, 2021).

Additionally, the high concentration of concrete and asphalt and lack of vegetation additionally cause a phenomenon commonly referred to as *Urban Heat Islands* (UHI), entailing that urban areas often have a modified climate with higher temperatures than its surrounding rural areas (Heinl et al., 2015). Therefore, residents of urban areas will suffer even more from the increasingly frequent expected heatwaves due to global warming, leading to increased emissions and costs for cooling, general discomfort, health issues and even an increased mortality rate.

Over half of the world's population is estimated to currently already reside in urban areas (Ritchie et al., 2024), and within the European Union, this number even surpassed the 70% as it is (*UIA in the European Context*, n.d.). The development of urban areas is extremely fast paced due to social, political and technological developments, replacing nature-rich areas with densely populated developments.

To ensure the liveability of these urban areas in the future, mitigation and adaptation measures must be taken to make cities more climate resilient. Examples of these measures include but are not limited to creating temporary storage spaces for water and increasing green spaces. However, available space in these urban areas is limited and valuable. By implementing measures such as these on otherwise unused spaces, like rooftops, working towards climate resilience can be done at relatively low expense. As the Dutch urban living environment is characterized by a high percentage of pitched roofs, exploring the possibilities of increasing green spaces and temporary water storage using pitched roofs could lead to impactful innovations contributing to climate resilience in the Dutch urban environment.

1.1. LILa

This project is part of the overarching Green Infrastructure research project for Living Innovation Lab (LILa), which is a joint initiative of the faculties of Engineering Technology (ET) and Geo-Information Science an Earth Observation (ITC) of the University of Twente (University of Twente, 2024). The LILa is intended to provide a semi-controlled setting for observation, monitoring and experimentation, support training for vocational schools, university students and practitioners, and education and connect with local communities and industrial partners. Accordingly, a more realistic setting is created to work on larger social challenges, such as urban resilience regarding climate change.

Over fifteen transdisciplinary experimental sections will be hosted at the LILa site, both above and below the ground, within four themes, which all include one or multiple research facilities/projects (Universiteit Twente, 2023). This project is part of the overarching Greening Infrastructure project within the Urban Spaces and Infrastructures theme of LILa, for which multiple temperature loggers will be placed at different sites within LILa, to inspect temperature variations over different lands surfaces, as well as various green roofs and walls, with the goal of quantifying impacts on energy and water from a life cycle perspective.

For this specific project, the roof of the old Biomagnetic Center (BMC) will be used, a small, flat roofed, building on the edge of the UT campus. Inside the building offices will be located.

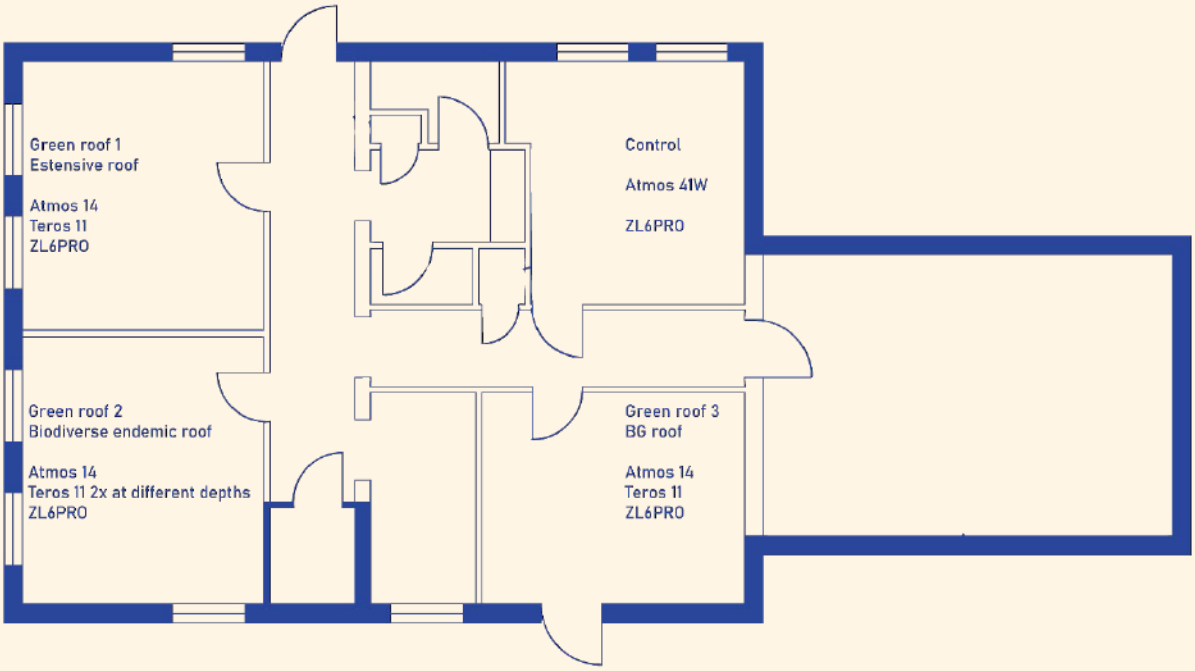
The roof of the lower part of the building will contain a test set up for three different types of flat green roofs (extensive green, biodiverse endemic, BG), a control roof and green walls. Following sensors will be applied to test the performance in all four sections on the roof, all connected to solar powered ZL6 dataloggers (Vrielink, 2025b), see schematic overview in Figure 1:

- Teros 11(*TEROS 11 - METER Group*, n.d.) will measure the soil moisture and temperature of the different green roofs
- ATMOS 14 will measure temperature, humidity and air pressure
- ATMOS 41W will measure solar radiation, precipitation, air temperature, barometric pressure, vapor pressure, relative humidity, wind speed, wind direction, maximum wind gust

The higher part of the building will be available for the test set up for the pitched green roof. The available part of this building is 6,7 by 4,6 meters (Figure 2).

Figure 1

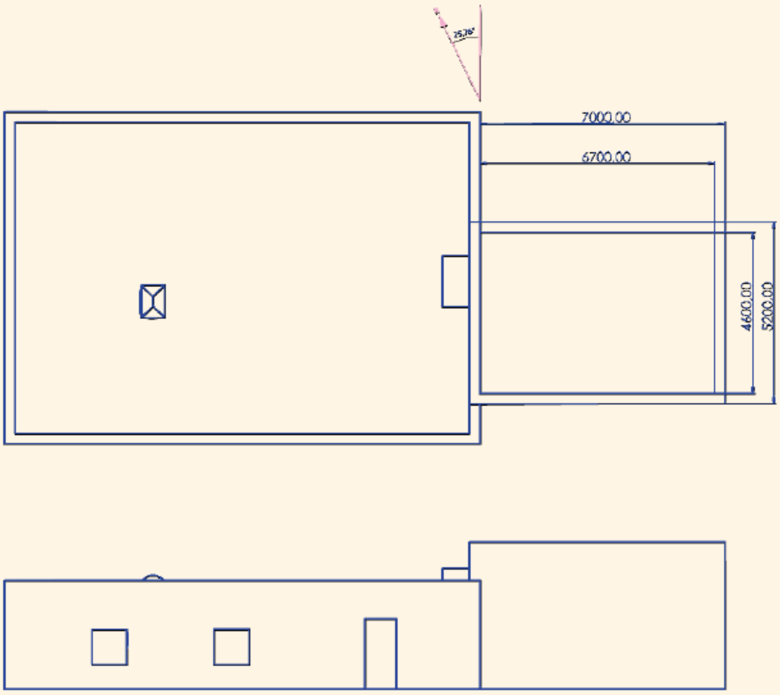
Roof Sensor Placement BMC building at LILa



Note: Created by author based on *LILa green infrastrcture sensor network - roof placement,* by S. Vrielink, 2025

Figure 2

Schematic view BMC building at LILa



1.2. Problem Statement

Mitigating the climate change related challenges in new constructions is possible and already being done, however, retrofitting mitigating solutions into existing buildings is more complex. One of the interventions, although not offering a comprehensive solution, that can contribute to more climate resilient urban areas and can easily be retrofitted on existing buildings, are green and BG roofs.

Green roofs are a nature-based solution that contribute to a more climate-resilient and sustainable environment (Busker et al., 2022). Green roofs refer to a concept of a layer of vegetation, growing on a substrate, on top of a roof. Amongst many other environmental, economic and social benefits, they both help mitigate the UHI effect and decrease risk of flooding by retaining and detaining rainwater, reducing the peak runoff. This intervention is already widely available for consumers to apply to their existing flat or almost flat roofing (pitch angle <20°). For steeper roofs, some more custom solutions are available, but they require larger constructional changes.

BG roofs have an additional layer where water can be captured and held to reduce runoff after precipitation events, reinforcing the water retaining and passive cooling benefits of a green roof. This intervention has only been established for flat roofs and is not as widely available to consumers yet. Easy applicable solutions for BG on pitched roofs can be of large added value when working towards more climate resilient cities, needed to ensure their liveability in the future as climate change will increasingly impact the lives of residents in urban living environments.

The aim of this study is to provide an initial exploration for an open-source solution to apply BG roofs to pitched roofs in the built urban environment. This will be done by developing a modular BG roof concept that offers a platform for applied research at LILa, a semi-controlled research environment on campus of the University of Twente, and an advisory guide for what steps need to be taken to extend this project to the real built urban environment.

1.3. Research Questions

Below, the research questions are formulated. These questions provide structure to the research, especially during the initial phase of this thesis. The information gathered from these questions will later help developing a BG roof setup for research at LILa and write an advisory guide for what steps need to extend this project to the real world.

1. How can we effectively address climate change related challenges that affect the residents of the built urban environment by means of designing a modular roof panel for pitched roofs, that incorporates vegetation and passive water management?
   - 1.1. What does a typical roof-landscape look like in the urban built environment of the Netherlands?
   - 1.2. What challenges do homeowners in the urban built environment face due to climate change? What are known methods to address these challenges?
   - 1.3. What knowledge does the potential end-user of the modular roof in the existing built environment panel have regarding BG roofs? What are their drivers and barriers for implementation?
   - 1.4. What benefits and drawbacks does a BG roof have regarding climate change related challenges? What general benefits and drawbacks does a BG roof have?

2. What can we contribute to research regarding BG roofs on pitched roofs in a semi-controlled environment by means of designing a modular BG roof?
   - 2.1. What products regarding BG roofs are already on the market? What are their benefits and disadvantages?
   - 2.2. What research projects have already been executed, what can be learned from this and what are the research gaps that can be closed with research at LILa?
   - 2.3. What data is relevant for doing research on mitigation of climate change challenges within the built urban environment regarding BG roofs, to close these research gaps?

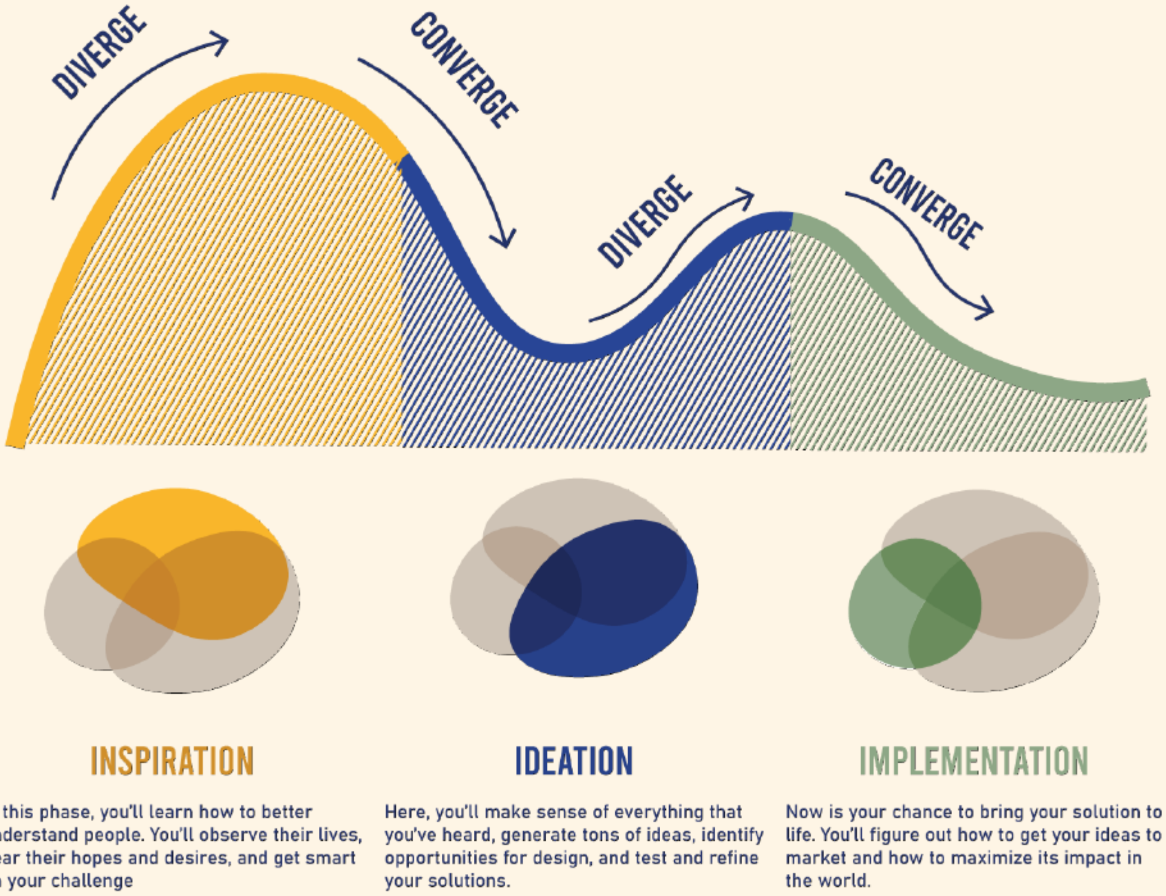
1.4. Methodology

This project adopts Design Thinking (DT) approach, which is grounded in the principles of Human-Centered Design (HCD)(Owen, 2006).

HCD is a user-focused innovation methodology typically leading to better usability, increased adoption and engagement and reduced risk of failure, resulting in saving of time, money and resources. Moreover, HCD promotes innovation, increases system resilience and long-term relevance. There are many different definitions of HCD known, but the consensus is that the main HCD principle is human involvement, which can be in any phase of the process. The HCD process according award winning design firm IDEO should follow three general phases; Inspiration, Ideation and Implementation through which diverging and converging takes place (IDEO, 2015), as visualized in figure 3.

Figure 3

Human-Centered Design Process According to IDEO

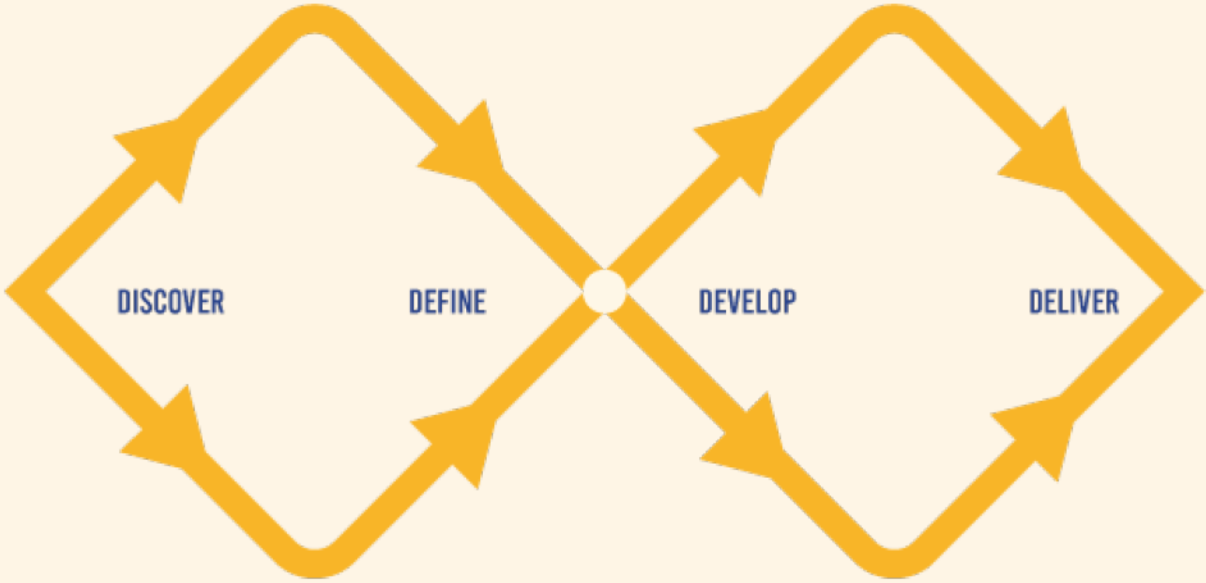


Note: Made by author based on *The field guide to human-centered design: design kit* (p.11,12,13), by IDEO, 2015, Design Kit.

HCD is often confused with DT, as they are closely related and overlapping elements. DT is characterized, aside from its human centred focus and, among others, environment centred concern (Owen, 2006), which suits the objective of this project well. The DT approach that is used is the 4D or double diamond model, diverging and converging over the span of the different stages of the project (Figure 4).

Figure 4

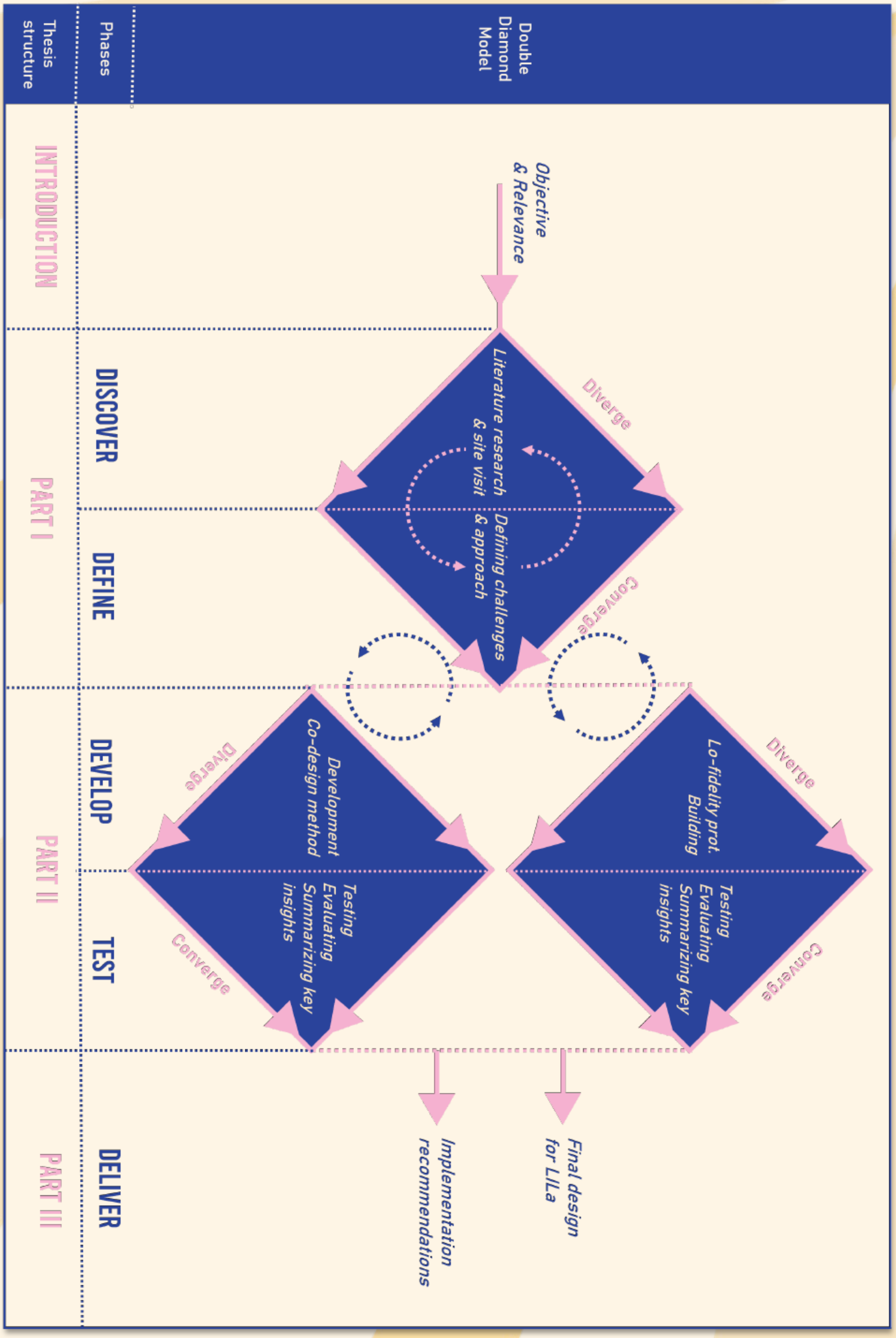
The Double Diamond Model of Design Thinking



For this project, elements of both HCD and DT are combined. A visual representation of how these methodologies are adjusted and applied to this project can be seen in Figure 5. In the diverging phases, information is gathered, and ideas are created, which is structured and summarized in the converging phases. As both HCD and DT are an iterative method, the steps are looped back and forth between as new insights emerge.

Figure 5

Visualization Methodology



1.4.1. Thesis structure

Although the methodology includes iterative cycles between phases, the phases will be presented subsequently in this thesis instead of in chronological order of the process.

I. The first part of this thesis addresses the first two phases of HCD, discover and define, answering the research questions based on literature research and providing a deeper understanding regarding the subject, design context and state of the art.

Discover – This stage, covered in Chapter 2, is dedicated to creating a deeper understanding of the subject, users and their needs, the environment and challenges. During this project, this is done through literature research and contextual inquiry in the form of a site visit.

Define – During the Define phase, which is discussed in Chapter 3, a clear frame of the problem is created based on the insights form the Discover stage. For this project, this means the collected data is structured in the form of key-insights and a defined focus area for the following stages of the project.

II. The second part of this thesis cover the Develop and Test stages, using empirical research to gain more insight in the target audiences. This part consists of two sections, which both separately follow a diverging and converging pattern.

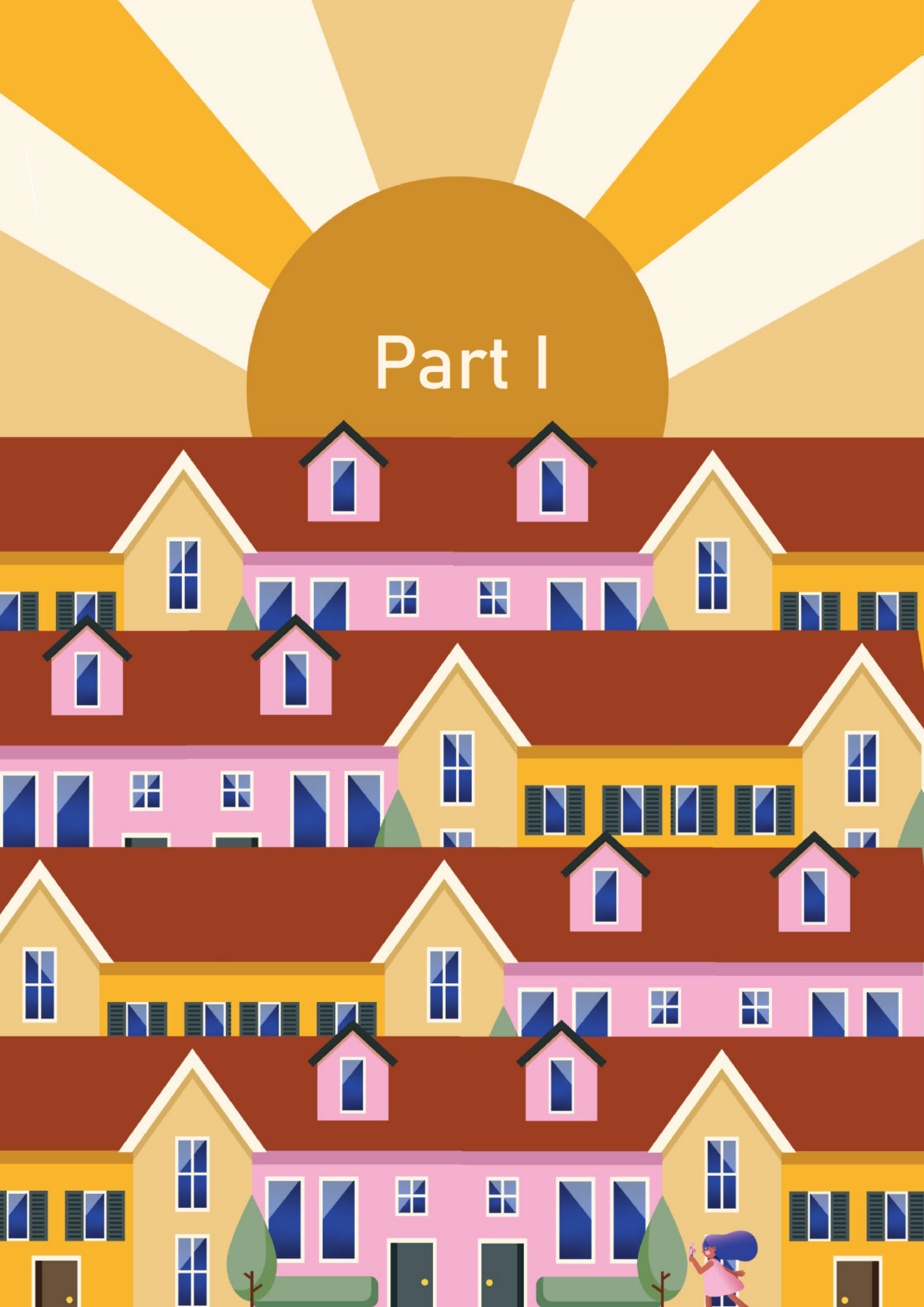
Develop and Test – For this project, two models were developed, one for each target audience that was focussed on: one low-fidelity tangible prototype to test within an educational context and one co-design method to test with potential end-users in the built urban environment. As the develop and test phase are followed separately for both these models, these phases are discussed both in Chapter 4, in separate sections per model. The goal of the development phase is to generate a wide range of creative possible solutions to the earlier defined problem, further developing this into prototypes for testing. In the context of this project, this will be focussed on how to involve the target audiences during and after this project. The goal of the testing phase is to gather feedback from users to further refine the solutions. For this project, the low-fidelity prototype is tested within the scope of educational purposes and a co-design session is hosted according to the developed methodology. The collected information is converged into key-insights and requirements for the final design.

III. The third and final part ties together the insights form part I and II into a final design for LILa of a modular BG roof panel for research, to be placed on the roof of the BMS building, as well as an outline for a guide on how to progress further into the real world form this project.

Deliver – In Chapter 5, all insights are gathered into a final list of requirements and used in a final short classic design cycle to create a final design for LILa, as well as an outline on how this project can be expanded to the real built urban environment after research at LILa has (partially) been concluded.

It is important to note that this project is intended to be completely open source. Open-source models enhance accelerated innovation and knowledge sharing, both crucial for addressing complex sustainability challenges (Maxwell, 2006). As open-source solutions are often more cost efficient, flexible and adaptable, this helps with accessibility of the project and democratizing participation in sustainable initiatives. As will be emphasized later in this thesis, community engagement regarding the topic of urban climate resilience is essential for implementation of small-scale, such as BG roofs solutions on a macro level. Open-source solutions often help empowering communities taking ownership of sustainable development efforts (Maxwell, 2006).

Part I



2. Discover

2.1. Effectively Addressing Climate Change in the Built Urban Environment

In the following chapter, it is discussed what challenges occur in the built urban environment due to climate change in combination with urbanization and how these challenges can be mitigated. First off, an overview is given on the existing Dutch (urban) roof landscape, following up with the current and future challenges the inhabitants of the urban environment face due to climate change and how these challenges can be and are being addressed. In the last part of this chapter, the focus is shifted towards the application of BG infrastructure in the urban environment, and it will be analysed 2what the benefits, drawbacks and implementation drivers and barriers are.

2.1.1. Dutch Urban Roof-Landscape

The Netherlands has close to 1300 km2 roof surface, of which 43% (556 km2) is of buildings with a residential function and from this 556 km2, over 70% (392 km2) is categorized as not flat (RIVM, 2022). In urbanized areas, 40-50% percent of the surface area is estimated to be roof (Dunnett & Kingsbury, 2008), this can even be up to 60% of the surface area (Solcerova et al., 2022).

As the Netherlands has always experienced quite a significant amount of rainfall, the Dutch urban architecture has been defined by steeply pitched roofs. These traditional gable roofs, often covered with ceramic roof-tiles were designed to efficiently drain rainwater (Figure 6). The angle of these tiled roofs generally varies between 15 and 55 degrees, though in some cases pitches of up to 90 degrees are used, requiring the tiles to be anchored. However, such steep roofs are relatively uncommon, especially in older buildings. Pitched roofs still dominate in many residential areas, especially in suburban areas where detached and terraced houses are very common. 42% of the just over 8 million homes in the Netherlands are terraced houses (CBS, 2022b, p. 22).

From the total amount of homes, only 1 million is relatively new (built after 2005) (CBS, 2022b). More modern houses more often have a flat roof and incorporate more sustainable building practices, such as better insulation, energy-efficient materials and integration of renewable energy solutions such as solar panels and heat pumps. The National Institute for Public Health and the Environment of the Netherlands (RIVM) created a map in which an overview of the estimation of the amount flat roofs in an area is visualized. Here it can be seen that residential areas are still dominated by pitched roofs (Figure 7), to which the main exception is larger multi-family houses, which are especially common in larger cities.

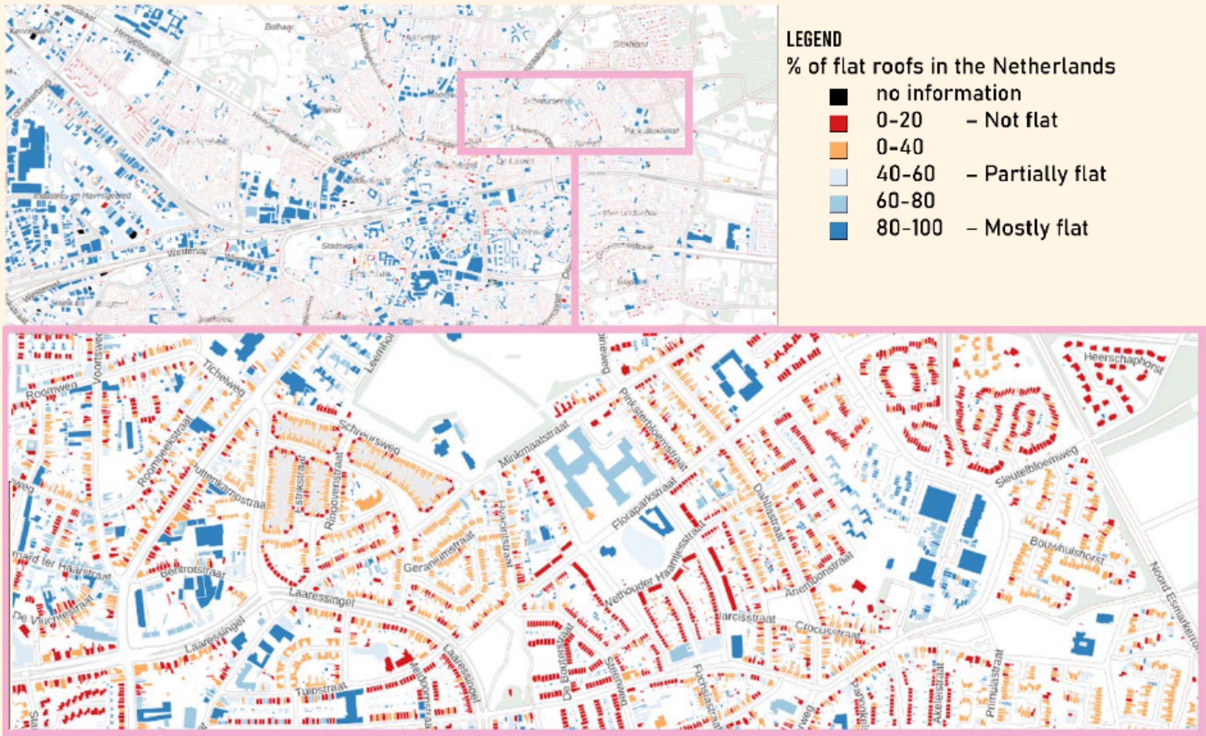
Figure 6

Dutch Urban Roof-Landscape

Note: From *Meest voorkomende type woning in Nederland? Het rijtjeshuis,* by B. van Dam, NOS, 2022. (https://nos.nl/artikel/2439237-meest-voorkomende-type-woning-in-nederland-het-rijtjeshuis)

Figure 7

Overview Map of Estimation Percentage of Flat Roofs in Part of Enschede, the Netherlands



Note: Created by the author based on *Platte daken,* by Atlas Leefomgeving, RIVM, 2022 (https://www.atlasleefomgeving.nl/platte-daken-in-nederland-bag))

During the 20th century, urban expansion and modernization led to an increase in flat roofs, particularly in post-war social housing projects and commercial buildings. These were influenced by the functionalist and modernist movements, favouring efficiency, affordability, and maximization of usable space. Especially in newer developments in high density areas, flat roofs are dominant as they are space efficient allow for additional functionalities. The national roof plan (Nationaal Dakenplan, 2023) focuses on how to give additional purpose to roofs, mainly to flat roofs, in the Netherlands. They provided a comprehensive overview of the four different types of multifunctional roofs, their benefits and additional potential benefits as a result of a combination of different types.

Red roofs enlarge human living space and can be used for social activities and/or sports. An example of this would be a rooftop bar.

Blue roofs function as rainwater buffer, by retaining the water during (short) heavy showers. The water will later evaporate, which also has a cooling effect, and/or be discharged into the infiltration or drainage system at a delayed rate. This reduces the stress on the drainage system during peak loads, helping to prevent waterlogging. By having rainwater available at most times, this can also be used for irrigation of plants and flushing toilets, saving drinking water.

Green roofs enlarge living space for flora and fauna, heighten the biodiversity value of the area, have an aesthetic function, a cooling function, reduce noise and ensure a longer lifetime of the roofing. Although green roofs also retain rainwater to some extent, this is not reliable enough for water management and therefore these are not considered to have a water management function, like blue roofs do.

Yellow roofs generate sustainable energy with solar panels and/or small wind turbines, reducing the co^2 emissions of the building.

Common combinations of functional roof types where the benefits amplify each other are:

Blue-green, where the water of the blue roofs serves the purpose of irrigation the vegetation of the green roof, enhancing evapotranspiration and thus its cooling function

Yellow-green, where the cooling effect of the green roof reduces the rate of overheating of the solar panels during peak hours, resulting in a higher energy production yield.

Yellow-blue, like the yellow-green roofs, the cooling the cooling effect of the blue roof reduces the rate of overheating of the solar panels during peak hours, resulting in a higher energy production yield.

Municipalities, especially in large cities like Rotterdam (Gemeente Rotterdam, n.d.) and Amsterdam (Gemeente Amsterdam, n.d.) encourage these multifunctional roof with, amongst other things, subsidies. See appendix A for an overview of municipalities and corresponding rules for available subsidies. However, although there has been a 10% increase in the number of green roofs over the last 3 years, currently still only around 0,5% of the flat roofs that is deemed suitable has some sort of green applied to it (Readar, 2020).

Most roofs are private property over which municipalities do not have any direct authority. (Benders, 2016). On the first of January 2024, 57 percent of the homes are owner occupied, 28 percent is owned by a housing corporation and the last 14 percent is rented out privately (CBS, 2024). Especially around larger cities, the percentage of owner occupied homes is smaller (CLO, 2024). The number of multiple-family houses is larger here too (CBS, 2022b), which often have a flat roof (apartment buildings, flats, etc.)(RIVM, 2022).

2.1.2. Urban Challenges Related to Climate Change

2.1.2.1. Climate Change

Climate change refers to long-term shifts in weather patterns that define Earths local, regional and global climates (NASA, 2022). This affects the temperature, precipitation patterns and extreme weather events. This can be a natural process, however, due to human activities, particularly the emission of greenhouse gasses (GHG) from burning fossil fuels, deforestation and industrial processes, these changes happen very rapid.

As Schulz summarizes form the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment report, due to this human made climate change, evidence of changes in extremes such as heat waves, heavy precipitation and droughts have already been observed. Over the course of the 21st century, unless GHG emissions are greatly reduces in the coming decades, the global warming of 1.5 and 2°C will be exceeded. On a global scale, it is projected that extreme daily precipitation events will increase about 7% per 1°C of global warming. In the coming 2000 years, the global mean sea level will rise about 2 to 3 meters in the best case scenario, this might be up to 22 meters (Schulz, 2022).

The two main risks for the built urban environment in the Netherlands due to climate change are the risk of flooding and heat stress (Takken et al., 2009).

2.1.2.2. Risk of Flooding

Within the risk of flooding, a distinction can be made between floods due to oceanic storm surges, riverine floods and precipitation events.

As extreme rainfall and droughts are expected to become more frequent in the future, the drainage systems in urban areas are likely to be overburdened, raising the risk of (short-term, local) floodings (Kourtis & Tsihrintzis, 2021), leading to discomfort of inhabitants of the area and water damage to homes. Urban areas are characterized by high levels of impermeable surfaces such as concrete and asphalt, hindering natural absorption of rainwater, causing any rainwater to directly flow into the drainage system (Czemiel Berndtsson, 2010). As, especially in cities built before 1990, a mixed sewage system is used (Rijkswaterstaat, n.d.)., overflowing of the system due to heavy rainfall will, in addition to floods, cause pollution of surface water.

Increased precipitation during winter lead to higher river discharges and thus increased risk of rivers overflowing their dikes. As the frequency of heavy rainfall increases, the risk of flooding due to riverine floods does too. Additionally, older cities are often located along the coast or in low lying areas near the mouths of major rivers, making them particularly prone to risk of (larger scale, longer term) flooding due to sea level rise and oceanic storm surges (Gasper et al., 2011). The flooding on larger areas does not only cause inconvenience and water damage to homes but can impede both industrial and commercial transportation to and from the area as well, affecting the region both economically and socially.

2.1.2.3. Heat Stress

The high concentration of concrete and asphalt, which are materials with a low albedo value, and lack of vegetation additionally causes a phenomenon commonly referred to as *Urban Heat Islands* (UHI), entailing that urban areas often have a modified climate with higher temperatures than its surrounding rural areas (Heinl et al., 2015). The UHI effect is, among other factors, the result of loss of green areas in the urban environment (Wong et al., 2003). Due to the UHI, residents of urban areas will suffer even more from the expected heatwaves due to global warming, leading to increased emissions and costs for cooling, as well as increased heat-stress.

Heat-stress results in heat-related mortality, disease and discomfort (e.g. sleep deprivation resulting in e.g. lower labour productivity). Additionally, air pollution, which is worsened by warm, sunny weather, acts synergistically with heat-stress, increasing the mortality rate even further than each factor individually (Fischer et al., 2004).

2.1.2.4. Magnitude of the Issues

The combination of urbanization and climate change will likely lead to significant concerns in the foreseeable future. 70% of the cities worldwide struggle with the effects of climate change (Benders, 2016). Over half of the world's population is estimated to currently reside in urban areas already (Ritchie et al., 2024), and this percentage is predicted to keep growing (CBS, 2022a).

The above-discussed challenges the urban environment faces can, in extreme scenarios, have far reaching social impacts, and might result in water contamination (Andrade et al., 2018), water and food scarcity (Gasper et al., 2011), heat related illness and mortality (Ho et al., 2023) and an increased spreading rate of infectious diseases (Williams et al., 2021). Especially the lower income classes will be affected by the (lack of preparedness for) climate change-related disasters, as the wealthy and more influential people are able to invest in their own capability set (e.g. a well-built home in a safe area) (De Sherbinin et al., 2007).

2.1.2.5. Addressing Heat Stress and Risk of Flooding

As extreme weather events become more frequent and the urban population continues to grow, these challenges must be navigated to ensure a future-proof living environment in the urban areas. This is already being done in several ways. Solutions are applied to new construction or retrofitted in existing buildings.

A distinction can be made between climate mitigation and climate adaptation strategies. Climate mitigation strategies aim to lessen the impact on the climate, by preventing or reducing the emission of GHG into the atmosphere, whereas climate adaptation strategies anticipate on the effects of climate change in order to minimise or prevent damage, or even take advantage of rising opportunities (EEA, 2024). Some solutions fall into both categories.s

Mitigation Strategies

By improving the energy efficiency of buildings, emissions and energy consumption can be reduced. This is and can be applied to both new construction and retrofitted into existing structures, and includes improved insulation, better insulated windows and more modern heating and cooling systems.

By shifting from fossil fuels to renewable energy sources like solar and wind, the urban carbon footprint is reduced. Implementing decentralized energy systems, like solar panels on the roof, not only decreases GHG emissions but also increases resilience; in case of a malfunctioning grid, the house or area with the decentralized system still has energy to some extent.

The Rijksdienst voor Ondernemend Nederland (RVO) created a framework for energy-neutral neighbourhoods, as part of their toolbox for sustainable area development (Rijksdienst voor Ondernemend Nederland, 2012). One of many examples of the application of mitigation strategies is the new housing estate “Zeuven Heuvels” in Wezep, Overijssel. The neighbourhood is completely disconnected form the gas network and energy is supplied via an energy infrastructure constructer under its own management, where the energy is generated from solar panels at 2 external locations (Rijkdienst voor Ondernemend Nederland, 2018).

Adaptation Strategies Risk of Flooding

By retaining water during and after heavy rain events and slowly releasing this overtime, the stress on the sewage system is decreased, as is the risk of it being overburdened. This temporary storage can be done naturally in open waters like ponds, or storage reservoirs, above or below the surface. An example of this is the water reservoir in the city of Hengelo constructed below their market square. Additionally, water permeable pavements can reduce the amount of water directly flowing into the drainage system, reducing the risk of flooding.

By splitting the drainage system for rainwater from that of the household sewage, the overflow of sewage water into the surface water is reduced, decreasing water pollution.

Larger, permanent, constructional changes can be made to areas as well, such as elevating urban spaces or incorporating dry pumps.

Adaptation Strategies Heat Stress

Heat stress can be reduced by replacing low albedo asphalt with higher albedo pavements, creating more shaded areas and wetting streets and roofs during hot periods.

Combined Adaptation Strategies

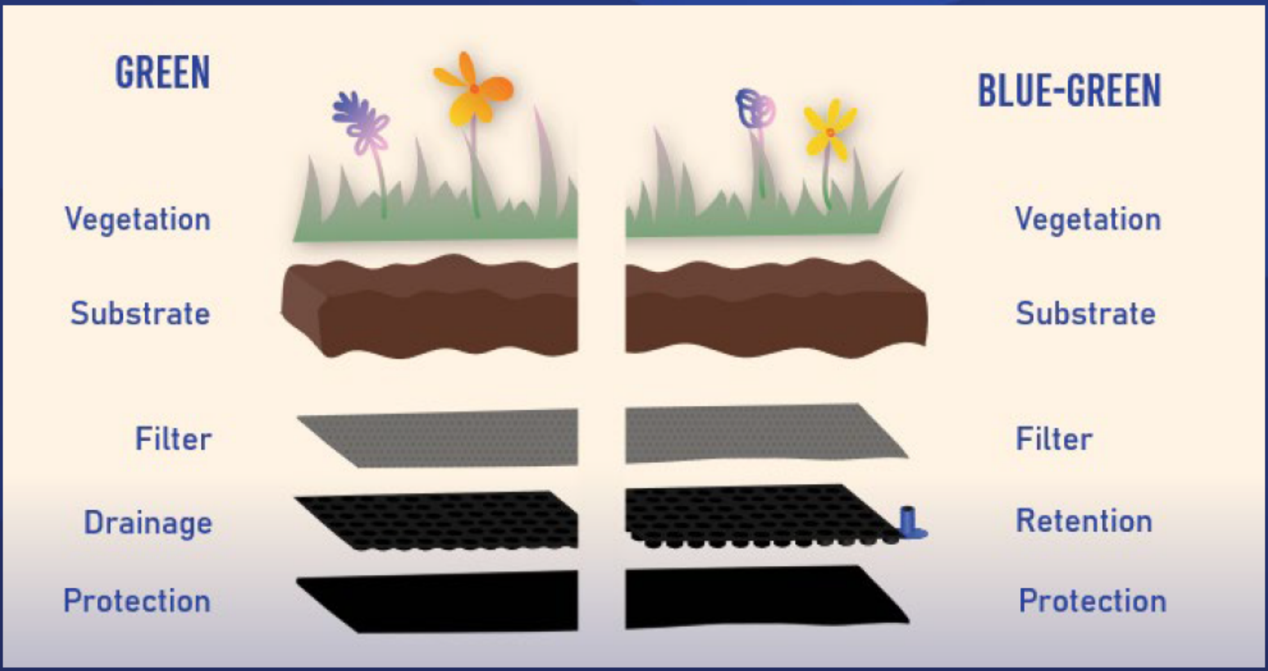
Extra green space mitigates both the heat stress and risk of flooding. Green retains and detains water, decreasing the direct flow of rainwater to the sewage system, as well as mitigating the heat stress by providing shading and evapotranspiration of water.

As space within the urban environment is scarce, BG roofs can be a great solution, as they make use of otherwise unused space. Green roofs are a nature-based solution that contribute to a more climate-resilient and sustainable environment (Busker et al., 2022). Amongst many other (environmental, economic and social) benefits, they both help mitigate the UHI effect and provide a buffer for the drainage of rainwater. This concept is already widely available for consumers. Green roofs are also very suitable to be combined with solar panels. As the vegetation has a cooling effect, the solar panels will be more efficient, resulting in up to a 6% higher yield and a longer lifespan (Branchevereniging VHG, n.d.). There is a large variety in types of vegetation, maximum roof pitch, system thickness, (saturated) weight, type of substrate and, of course, price.

BG roofs have an additional layer where water can be captured and held to reduce runoff after rainfall, increasing the roofs water-buffer capacity, see Figure 8. This separate layer also prevents the roots of the vegetation from rotting. This roof-type has only been established for flat roofs and is not as widely available to consumers yet. An example of existing projects regarding BG roofs that are (being) executed the projects done by Resilio (Resilio, n.d.). The additional water storage brings extra weight and complexity to the design.

Figure 8

Schematic Overview of Layers in Green and BG roofs



Note: Created by the author

2.1.3. Benefits and Drawbacks of BG Roofs

BG roofs are a nature-based solution that contribute to a more climate-resilient and sustainable environment. They have many environmental, economic and social benefits.

2.1.3.1. Environmental Benefits

Passive Temperature Management

Vegetation on rooftops is positively correlated with thermal reduction (Fang, 2008; Kumar et al., 2024; Takebayashi & Moriyama, 2007; Wong et al., 2003) and can help effectively mitigate the UHI effect (Wong et al., 2003). This thermal reduction takes place mainly due to shading provided by the vegetation, evapotranspiration from retained water and reduction of solar reflection. The magnitude of this heat reducing effect is dependent on parameters such as vegetation type, cover ratio, leaf thickness but also to moisture content of the soil.

In the ideal situation, according to a variety of studies review by Resilio, the reduction values can reach up to 1 degree on city scale or 0.3-0.7 degrees when studying the effect on neighbourhood scale. All studies reviewed by Resilio agree that this cooling effect decreases as less water is available to the vegetation, arguing that BG is preferable over just green (Solcerova et al., 2022). As long as there is water to evaporate, there will be no heat-accumulation. This is in line with other reviewed studies (Gößner et al., 2025).

Dependent on the type, amount and maturity of the vegetation and the moisture content, BG roofs have a cooling effect on the inside of the building as well (Takakura et al., 2000). Current research seems to substantiate that the indoor areas underneath a BG roof stay 7- or 8-degrees Celsius cooler than indoor areas with a traditional flat roof (Nationaal Dakenplan, 2023). This temperature difference between inside and outside is the result of a lower surface temperature on the roof, the additional insulation of the soil ensuring less heat transfer from outside to the inside (Wong et al., 2003), as well as reduced heat flow from outside in.

However, in winter, a BG roof offers very minimal isolation. This is due to the high amount of moisture in the roof during winter, as water is a bad thermal insulator. It is therefore preferable to keep the water retention layer empty during winter, and to emphasize that the application of a green roof does not eliminate the need for good roof-insulation. The vegetation on the roof can, however, reduce the heat flow for inside out with 10 to 30% during winter (Stowa & RIONED, 2015).

Water Management

BG roofs, due to their water storing capacity, can significantly reduce the stress on the urban sewage system during heavy precipitation events. The reduction in peak runoff consists in (Mentens et al., 2006):

- Delaying the time of the runoff peak due to absorption of water in the BG roof system.
- Reducing the total runoff by retaining part of the precipitation.
- Distribution of the runoff through relative slow release of excess water from the system.

The peak of stormwater runoff from a green roof is delayed in time and attenuated in intensity compared to that from a hard roof surface (Bengtsson, 2005; Czemiel Berndtsson, 2010), lowering the risk of urban floods during heavy precipitation events. The runoff dynamics and water retention capacity depend on both the roof characteristics (Abdalla et al., 2024) and the weather conditions (Czemiel Berndtsson, 2010; Getter et al., 2007):

Green roof characteristics:

- Number of layers
- Type of materials and material thickness
- Soil thickness
- Soil type
- Vegetation cover
- Type of vegetation,
- Roof geometry (pitch length and angle, roof position)
- Roof age

Weather conditions:

- Length of proceeding dry periods
- Season/climate (air temperature, wind conditions, humidity)
- Characteristics of the rain event (intensity and duration)

Although all reviewed sources conclude a positive relation between green roofs and reduction of stormwater runoff, as the runoff reduction is dependent on many different factors, which are hardly ever the same in different studies, it difficult to quantify this reduction. Based on performed literature review, the yearly rainfall retention capability of an extensive green roof with a median substrate depth of 100 mm is around 45%, where the retention is significantly lower during winter due to lower evapotranspiration and rainfall distribution (Mentens et al., 2006). The addition of a blue layer for water retention to the traditional green roof considerably improves the hydrological performance (Busker et al., 2022).

Increased Biodiversity

Research into the bio-ecological potential of green roofs has shown relevant benefits of green roofs for biodiversity, providing foraging and roosting opportunities for animals such as spiders, insects and birds (Brenneisen, 2003; Wang et al., 2022).

The contribution to biodiversity of a BG roof is larger than that of a green roof, due to the higher humidity. The monoculture of the classic green roofs made mostly out of sedum provide little impulse to local fauna, where the humid environment of the BG roof gives more variety in vegetation, increasing the living area of insects and therefor contributing to more ecological balance.

Improvement of Air Quality

Green roofs are proven to improve the air quality and therefor by extension the public health, shrubs and grasses having the largest effect (Currie & Bass, 2008). Green roofs are shown to significantly reduce the pollutants ozone, nitrogen, particulate matter and sulphur dioxide (Yang et al., 2008).

2.1.3.2. Economic Benefits

Due to a reduction in large temperature differences and reduction in amount of UV-radiation that comes in direct contact with the roofing, reducing the amount of wear, the roofing can last up twice its original lifetime when a BG roof is applied (Stowa & RIONED, 2015). The lifespan of a green roof, although dependent on maintenance, type and weather conditions, varies between 40 and 55 years (Bianchini & Hewage, 2012; Getter et al., 2009). The average lifespan of a bitumen roof, which is the traditional type of flat roof, is 10-15 years. Applying green to an existing flat roof can extend its lifespan (Porsche & Köhler, 2003; Saiz et al., 2006). Additionally, BG roofs provide passive cooling, therefor reducing energy costs for cooling during hot periods.

2.1.3.3. Social Benefits

Noise Reduction

There is a positive correlation between the presence of green roofs and noise reduction (Van Renterghem & Botteldooren, 2009). The noise reduction that a BG roof can provide is dependent on the type of vegetation, the thickness of the system and the amount of moisture content in the substrate, but can reduce sound reflection by up to 3 decibels, however, this is not a constant (Stowa & RIONED, 2015).

Improvement of Well-being

Green roofs improve the air quality and therefor the public health. Beside improving physical health, green roofs are also said to have psychological benefits. Studies have concluded that green roofs reduce stress and improve concentration and mental wellbeing (Lee et al., 2015). Inhabitants of greener neighbourhoods tend to be less scared, suffer less from nuisance and experience lower levels of aggression and violence (Kuo & Sullivan, 2001)

Lastly, green roofs are often experienced to have an aesthetic appeal, have a flame-retardant effect due to the high moisture content (Claus & Rousseau, 2012) and improve property value.

2.1.3.4. Drawbacks BG Roofs

Constructional Considerations

Not all roofs are currently deemed suitable for application of a BG roof, as they come with weight and complexity. For many roofs, larger constructional changes are required in order to apply a BG roof.

High Initial Costs

Currently, only extensive green systems for flat roofs are relatively affordable to the consumer. When the desired system is any more complex, professionals should be hired to do this, resulting in high initial costs.

Maintenance Requirements

Although it was concluded that the maintenance costs of green roofs are lower or comparable to "normal" roofs, regular maintenance and checkups are necessary. If this is not done properly, this can lead to failure and leakages of the system, which can eventually lead to water damage to the building. Knowledge and skills are needed to maintain the roof, and for more complex systems it would be recommended to have it done by professionals, which drastically affects maintenance costs.

Need for Irrigation

Intensive green roofs require irrigation in order to survive longer dry periods, Additionally, irrigation is important to benefit from the cooling effect of the roof, as this effect only takes place as long as water is available to the vegetation. Depending on the water retention capacity and the duration of the dry period, this could also be the case for BG roofs.

Need for High Implementation Rate

Other types of green infrastructure can have a higher impact on reaching climate adaptation goals, such as wetlands and botanical gardens (Kumar et al., 2024). BG roofs have a significant profit when applied on larger areas, >100 m^2 (Nationaal Dakenplan, n.d.).

2.1.4. Knowledge, Drivers and Barriers

Delen (2024) performed an extensive literature research on the implementation drivers and barriers regarding green roofs. This research was used as backbone to review what knowledge the potential end-user (homeowners and tenants) has, and what drivers and barrier exist regarding implementation. Additional literature research was done to complement the initial findings by Delen.

2.1.4.1. Barriers

Lack of Awareness and Knowledge

There are strong indications that the lack of knowledge and awareness of green roofs, associated with benefits and costs, are a major barrier to green roof adaptations (Adriaanse, 2019; Benders, 2016; Joshi & Teller, 2021; Resilio, n.d.; Sarwar & Alsaggaf, 2020). The research conducted by Adriaanse in Groningen highlighted a significant gap in knowledge among homeowners regarding green roofs; over 38% of the participating homeowners could not name any benefits of green roofs, and cumulative over half of the homeowners (52,6%) of homeowners could name one benefit or less. Only 5 of the 78 participants could name more than three benefits. The knowledge gap mainly concerns the costs, benefits and true potential of BG roofs (Benders, 2016). This lack of knowledge seemingly is not completely devoted to disinterest of the stakeholders, as they often are certainly interested in the subject (Benders, 2016), but also to a lack of promotion (Zhang & He, 2021). However, the lack of knowledge on the topic does result in experienced communication difficulty with residents (Benders, 2016).

Financial Concerns

Costs are often concluded to be a substantial barrier (Joshi & Teller, 2021; Sarwar & Alsaggaf, 2020). Subsidies for green roofs are essential to convince private parties, like homeowners and housing corporations, to invest in green roofs, as private costs for construction of an extensive green roof exceed the private benefits for the investor (Benders, 2016; Claus & Rousseau, 2012; Klooster et al., 2008; Prins, 2021). However, as social benefits do exceed the social costs (Klooster et al., 2008), subsidy programmes for green roofs are feasible and the subsidy should at least be as high as the difference between private costs and benefits (Claus & Rousseau, 2012). This is difficult to estimate, since several benefits associated with extensive green roofs could not be expressed in monetary terms (Claus & Rousseau, 2012). Klooster et al. (2008) calculated this yield gap to be around 16 euro per m^2 of green roof in Rotterdam. As many municipalities offer a subsidy between 25 and 50 euro per m2 of green roof, dependent on the specifications like type of vegetation and water retention capacity (Appendix A), this gap should be closed. Information on costs and benefits of green roof construction is often fragmented, and subsidy requirements differ per municipality, making it confusing for potential investors.

The study from Adriaanse concluded 88.5% of the participating homeowners was unaware of the subsidy the municipality has available for vegetational roofs, despite 62.8% of the participants indicating financial considerations regarding the implementation of a green roof were important to them. In addition to the construction costs, perceived maintenance costs are found to be a barrier (Joshi & Teller, 2021), although these are assumably not higher than a traditional roof (Oberndorfer et al., 2007). Altogether, there is a lack of awareness regarding the financial desirability of green roofs.

Perceived Responsibility

Although recent policy guidelines indicated that local water management is in majority the responsibility of the homeowners, there is a low perceived responsibility for local water management among them (Bergsma et al., 2012); there exists a discrepancy in perceived responsibility between homeowners, municipality and urban planners. Although municipalities would like to tackle water retention issues by implementation of private BG roofs, this is insufficient motivation for many homeowners (Benders, 2016).

The government or municipalities should take on a carrying role in encouraging adaptation of BG roofs (Benders, 2016), however there currently still exists a lack of government initiatives (Joshi & Teller, 2021; Prins, 2021).

Technical Challenges

Current solutions for BG roof often require (partial) reconstruction of the existing roofing, if the roof is even deemed suitable at all. This barrier is closely related to the financial barrier, as overcoming these technical challenges can be costly.

2.1.4.2. Opportunities

It is worth considering how communities themselves or through collective organizations can overcome these barriers and reduce their vulnerability to climate change related risks, where governments and municipalities lack sources or initiative (De Sherbinin et al., 2007). This includes neighbourhood initiatives or for example via (social)housing corporations.

Increasing visibility and promotion of BG roofs is beneficial for involvement of residents, overcoming the barrier of lack of knowledge and awareness and thus increasing the implementation rate (Resilio, n.d.).

2.2. Potential Contribution to Research

By reviewing current academic literature and commercially available technologies regarding green and BG roofs, both for flat and pitched roofs, this chapter seeks to identify what has already been achieved and where limitations and gaps exists. Understanding the state of the art is essential for positioning this research within a broader scientific and practical context and establishing academic relevance.

2.2.1. Previous Studies

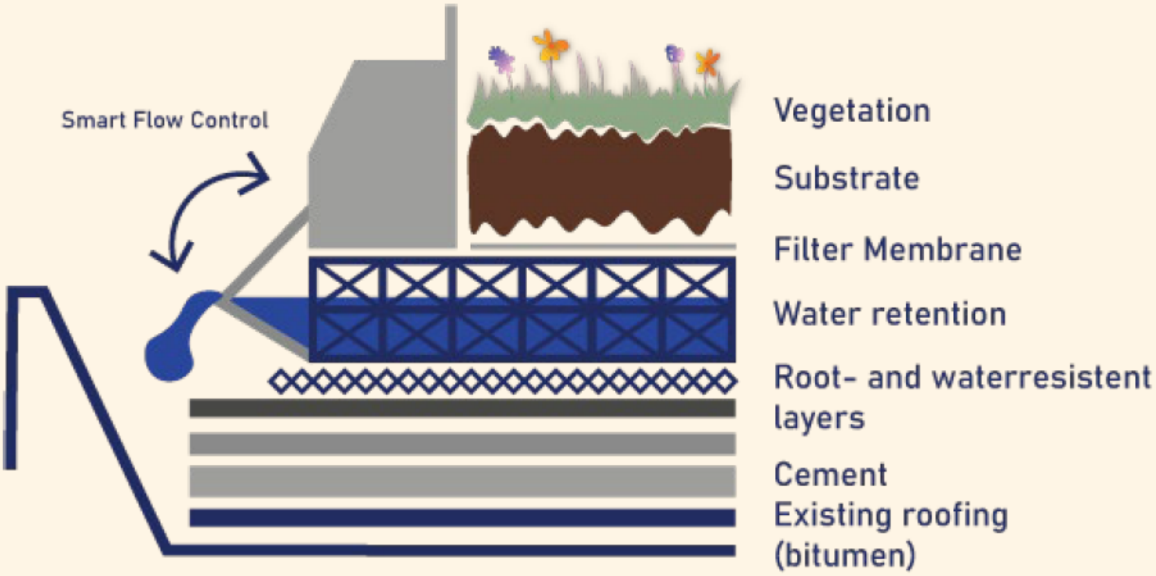
2.2.1.1. Resilio

Between 2018 and 2022 Resilio executed a project focused on a dynamic BG infrastructure (Figure 9) on flat roofs in Amsterdam, eventually construction 10.000 m^3 of smart BG roofs around the city (Holstein et al., 2022). This, as they call it themselves, living lab was spread out over existing social housing and private property. Prior to the Resilio project, the project Smartroof 2.0 installed a research roof on the Maritime terrain in Amsterdam (Figure 10), aiming to demonstrate the function and value of BG roofs, providing a rich scala of information (Gemeente Amsterdam, 2018) which was used as starting point for the Resilio project, as stated by Holstein et al. As this project has much in common with the objective of this current project, in the sense of seeking to extend a research project on BG roofs from a field lab to the real urban living environment, inspiration can be taken from the Resilio project. Therefor, it is especially interesting to look at the structure of the Resilio project and assess the evaluative '*learned lessons*' that were documented by Holstein et al. From this, the following statements are most relevant to this project:

- As the project focused on dynamic BG roofs, the intention was to develop a completely new, comprehensive micro-watermanagementsystem. However, as this system is complex and involves many stakeholders, responsibilities and perspectives, the system is operational but does not integrate all results from all coordinated working teams yet, as this was proved to be too ambitious within the given timeframe.
- One of the key elements in the development of a strategy addressing micro-watermanagement is a new definition regarding governance of water management, especially regarding the intertwined responsibility and authority on the public and private domain when it comes to the drainage of rainwater.
- The decision process regarding investments in BG roofs must be extended with non-monetary and social benefits, and it is an essential prerequisite that important stakeholders are willing to compensate these benefits with funding in order to upscale implementation of BG roofs. Besides that BG roofs will become more effective with a higher implementation rate, upscaling will also lower the financial barrier. It is to be expected that financially it is more beneficial to apply BG roofs to new construction over replacing or renovating the roofing of existing buildings.
- It's important to plan a clear tender strategy ahead of time, including decisions about which products to use, the process to follow, and the types of contracts allowed, before starting the tender for BG roofs. Having a defined list of technical requirements is preferred during this stage of the process is preferred.

Figure 9

Schematic View Cross Section Dynamic BG roof as Implemented by Resilio



Note: Created by author based on *Nieuw land op het dak (p. 10),* by A.N. Holstein, W. Braat and J. Langewen, 2022, RESILIO.

Figure 10

Picture of the Smartroof 2.0 Project at the Maritime Terrain in Amsterdam

Note: From *Nieuw land op het dak (p. 13),* by A.N. Holstein, W. Braat and J. Langewen, 2022, RESILIO.

2.2.1.2. Contradicting Results and Research Gaps

Although all reviewed sources conclude a positive relation between green and/or BG roofs and reduction of stormwater runoff, as the runoff reduction is dependent on many different factors, which are hardly ever the same in different studies, it difficult to put this reduction into numbers.

A considerable amount of research regarding the influence of pitch and length of green roofs on water retention and detention has already been executed, however, often giving contrasting outputs. Some reviewed sources conclude that the pitch influences both retention and detention of rainwater (Abdalla et al., 2024; Förster et al., 2021), some only conclude retention values are affected (Getter et al., 2007) some conclude pitch not to influence the runoff distribution at all (Bengtsson, 2005). Length is said to influence detention performance during low-intensity rain events (Abdalla et al., 2024), and to not have any significant influence on the runoff process (Bengtsson, 2005).

Besides providing contradicting results, the above-mentioned studies have all been performed on relatively gentle pitches, with a maximum pitch angle of 25 degrees. Especially as the pitched roofs in the Dutch built environment are much steeper, further research is needed on this topic.

As the retention and detention of rainwater influence the moisture content and evapotranspiration of the BG roof, this will also influence the thermal performance of the roof. In line with this, from the executed research by Resilio on the functioning of the smart BG roofs during extreme precipitation events, it was concluded smart BG outperform green and static BG roofs when it comes to water retention and arising from this the cooling effect due to evapotranspiration (Holstein et al., 2022).

The contradicting conclusions can be a result of varying study conditions, varying green-roof designs and possibly partly a too short study period (Czemiel Berndtsson, 2010), highlighting the need for more research regarding this topic.

BG roofs are complex systems influenced by physical characteristics of their layers and their reaction to environmental influences, of which there still is a lack of understanding (Gößner et al., 2025). By performing more studies, the effect of the implementation of green on different roof geometries can be quantified, making it possible to make informed decisions about retrofitting green roofs in the existing built environment.

Additional recommendations from previous studies regarding the design of the test set up are to include a control roof and to add a surrounding green roof to minimize potential edge effects (Gößner et al., 2025). It is also advised by Gößner to execute a more in-depth analysis on both direct and indirect influences on variable that potentially include time lags. Lastly, Mentens et al (2006) suggests a need for more research is needed regarding time levels of rain events.

2.2.2. Research regarding the Functionality of BG Roofs

Data gathering

The most important functions of BG roofs regard climate change mitigation in the built urban environment are thermal management, both for the indoor and outdoor environment, and water management. To study the performances of the BG roof regarding those aspects it is important to gather the following information:

- Current weather prediction for the area (temperature and precipitation)
- Environmental temperature in multiple locations (above and below BG roof and control roof)
- Surface temperature of the (control) roof
- Soil temperature
- Soil moisture
- Water runoff BG roof over time
- Water runoff control roof over time over time

Optional: Weight, preferably separately of the different layers.

This way the amount of water retained per layer can be calculated. As the vegetation will grow over time, measuring the weight of the entire system might lead to a skewed conclusion.

Variables

When designing and testing for retrofitting green roofs into the built urban environment, the orientation and pitch of the existing roofs cannot be adjusted. In the ideal situation, both these factors can be adjusted in the test set-up to mimic real-world-environments to optimize the design for specific scenarios.

- Orientation of the roof (wind direction)
- Pitch of the roof
- Drainage layer (yes/no/fast draining/slow draining)
- Substrate thickness
- Substrate compound
- Type and maturity of vegetation

Other potentially interesting data: Air quality, noise insulation, change in biodiversity.

2.2.3. Existing Products

2.2.3.1. Extensive Green for Flat Roofs

A variety of extensive green for flat roofs is widely available to the consumer, varying in price from 39 euro per m^2 for a lightweight system to 90 euro per m^2 for a more elaborate system, see Appendix B for an overview of products available on the market.

The vegetation types offered are considerably mixed sedum plants, in some cases mixed with up to 50% herbaceous vegetation, grass types or wildflowers. The plants can either be delivered in mats (Figure 11), cassettes (Figure 12) or plug plants (Figure 13). There is also a variety in the types of substrates that are available in varying depths, some of which incorporate rockwool, but very little information is given on the exact substance.

The water buffering capacity is dependent on the thickness of the substrate layer and the type of vegetation, and ranges from 21 to 76 L per m^2. Some brands offer the possibility for an additional layer for water buffering (static system).

These systems can, generally, be installed by the homeowner or the selling company can install it professionally.

Figure 11

Picture of Sedum Mat on Pallet

Note: From *Sedum vegetatiematten* by Garmundo, n.d. (https://www.garmundo.nl/products/sedum-vegetatiematten#product-media-2)

Figure 12

Picture of Sedum Cassette

Note: From *Sedumcassette lichtgewicht* by Garmundo, n.d. (https://www.garmundo.nl/products/sedumcassette-lichtgewicht?_pos=1&_sid=6fc0823aa&_ss=r)

Figure 13

Picture of Sedum Plug Plants

Note: From Sedumpluggen by Sempergreen, n.d. *(https://www.sempergreen.com/nl/oplossingen/groene-daken/products/sedumpluggen)*

2.2.3.2. Intensive Green and Dynamic Blue for Flat Roofs

Intensive green, or roof garden, and (dynamic) BG for flat roofs are done mostly on project basis by professionals for larger buildings. These projects are custom, require expertise and planning and therefor are costly and not widely available to the consumer yet (Holstein et al., 2022).

2.2.3.3. Site Visit Groendak

A site visit to Groendak in Scherpenzeel provided the opportunity to assess some products available to consumers on the market in real life, as well as to gain expert insights from company owner Grad van Heck, whose roots lie in architecture and who specializes in, amongst others, sustainable construction. All available products currently available from Groendak focus merely on green roofs, not BG.

Most extensive green roof systems for flat roofs can be placed on a slight pitch, the absolute maximum being 25 degrees. There are several solutions for applying extensive green to pitched roofs with a steeper angle, however, each of them requires constructional changes and/or removal of the original roofing. This means it should be done by professionals, highly driving up the costs. The roof tiles can be done by the homeowner themselves, but require replacement of the existing roofing as well, being both pricey and time-consuming.

Groendakpan

The development of the Groendakpan started by Groendak as an innovative solution to add green to existing pitched roofs, by adding a cover on top of the existing rooftiles. However, it was soon concluded that this is not feasible, as tiled roofs are not constructed to carry significantly more weight than the already applied rooftiles. It was concluded that for a tiled roof to incorporate vegetation, either the weight of the vegetation and water must be compensated in another way (e.g. by removing the tiles) or the construction of the roof must be strengthened to carry this additional weight. The Groendakpan was designed to replace the weight of original roof tiles with vegetation (Figure 14, Figure 15), having a saturated weight of 4,12 kg. The Groendakpan is ventilating and water-resistant, similar and a direct replacement for the "sneldakpan". They can be applied in new construction or renovation on pitch angles between 20° and 55°.

Figure 14

Picture of Sedum Groendakpannen

Note: Created by author during site visit to Groendak in Scherpenzeel

Figure 15

Picture of Sedum Groendakpannen Installed

Note: From Dé dakpan voor een schuin (damp-open) dak, by Groendakpan, n.d. (https://www.groendakpan.nl/)

Sedum pockets

Sam Groofing (Sam Groofing, n.d.) makes pre-fabricated pockets that can be placed on roofs with a pitch angle of up until 45 degrees using industrial Velcro and drain panels (Figure 16, Figure 17). The pockets are filled with 12 to 16 types of sedum plug-plants, which grow in a substrate made from perlite and nutrients. Perlite is a volcanic mineral that is very lightweight and porous, which is often mixed with soil to improve drainage, aeration and water retention.

The company pays a lot of attention to circularity and sustainability; their drainage grids are made from consumer waste by the concept of *Cradle-to-cradle*, their plug-plants are cultivated with a special low footprint, water saving and chemical free process. The pockets are 40 by 100 centimetres. On pitched roofs they must be placed horizontally, due to risk of shearing. The pockets look fairly empty when installed, but will grow into a full green roof over 2 growing seasons, according to Groofing.

Figure 16

Picture of Sedum Pockets by Sam Groofing

Note: Created by author during site visit to Groendak in Scherpenzeel

Figure 17

Picture of Sedum Pockets by Sam Groofing Installed

Note: From Sam Groofing by Sam Groofing, n.d. (https://samgroofing.com/)

2.2.3.4. *Other Extensive Green for Pitched Roofs*

Sedum Mats

Vertical permanent load on the roof is relatively easy to overcome by ensuring enough strength in the construction. The additional oblique load that is created by load on a pitched roof is harder to solve. The loads add up, creating a massive shear force depending on the angle and length of the pitch. There are already several ways to counter this load:

- **Protective layer**: The first layer of a green roof is a protective cloth. By laying the cloth down with ribbing, the substrate pellets that will be placed on top will not roll down as much, creating a "warped" base for the green roof. By creating this layer, the friction with layers above will partially counter the shear force.
- **Substrate raster** (Figure 18): to prevent a thicker substrate layer from sliding down, thick, plastic grids can be used to keep the pallets into place. The grid can also be used for only part of the roof, if desired. The grid also enables drainage of water.
- **Constructive facilities**: there are several constructive alternatives to prevent the slipping of the green roof, such adhering plastic strips to the roof construction or incorporating perforated stainless steel angle profiles into the roof construction (Figure 19). Cavity wall ties can also be used to prevent sliding of the sedum mats.
- **Sedum mats**: Sedum mat type-T is grown on a base of coconut-fibre and has a plastic warping on both the top and bottom side (Figure 20). The warping makes these mats extra strong (tensile strength of the warping net is 10 kN/m) and suitable for pitched roofs with an angle of 25 till 45 degrees.

Figure 18

Picture of Substrate Raster

Note: From *Hellend groen en schuine daken is een vak apart*, by G. van Heck, n.d., Groendak

Figure 19

Stainless Steel Angle Profiles

Note: From Hellend groen en schuine daken is een vak apart, by G. van Heck, n.d., Groendak

Figure 20

Picture of Sedummixmat type-T

Note: From Sedummixmat Type-T by groenbedekking, n.d., (https://groenbedekking.net/product/sedummixmat-type-t/)

3. Define

In this chapter, relevant information gathered from the literature research and site visit discussed in Chapter 2, is translated into key insights valuable later in this project and design implications.

3.1. Key insights Discover

Due to climate change, the built urban environment is, amongst others, increasingly at risk of flooding due to heavy precipitation events (Chapter 2.1.2.2) and its inhabitants suffer increasingly from heat stress, leading to higher mortality rate and diseases, increasing costs and emissions for cooling and overall discomfort (Chapter 2.1.2.3).

BG roofs, although not a comprehensive solution, can help mitigate these effects of climate change in the built urban environment (Chapter 2.1.2.5). Pitched roofs are currently deemed unsuitable BG roofs, and any existing solutions are merely vegetation focussed, custom, costly and require (partial) reconstruction of the existing roof (Chapter 2.2.3). Since these pitched roofs make up a large part of the Dutch built urban roof landscape, especially for the urban areas (Chapter 2.1.1), this makes for an interesting challenge.

One of the main barriers currently when it comes to implementation of existing solutions for BG or green infrastructure by private parties, is costs (Chapter 2.1.4.1). Subsidies are available in some municipalities, which are essential in making BG infrastructure desirable to private parties, as private benefits do not outweigh the private costs without. However, information on subsidies is fragmented and requirements differ between municipalities, resulting in unclarity and therefor heightening the barrier to act for private parties.

Further elaborating on the financial barrier, products currently on the market require larger constructional changes to the existing roof (reinforcement, removal of existing roofing etc.) (Chapter 2.2.3), resulting in high costs. By designing a one-size-fits-all solution the costs and therefor implementation barriers (financial and technical) will be lowered, increasing the implementation rate and therefor the effectiveness of the intervention. However, applying additional weight to existing pitched roofing is challenging due to weight carrying constraints of the original construction of the roofs. This means that it will likely not be realistic to find a universal solution that can be applied without constructional changes or removing the original roofing, which is initially the of this end-goal of the overarching project. For now, load-carrying constraints of the existing roofs of the built urban environment are outside of the scope of this project, however, this is something that should be kept in mind during later stages of the overarching project, when translating the project to the real world.

3.2. Focus Areas Develop and Test Phase

As previous studies regarding the effect of pitch on the hydrological performance of BG and green roofs have resulted in contradicting conclusions (Chapter 2.2.1), there is a need for a long-term test set up in a semi-controlled environment, where single variables can be adjusted. As the performance of BG roofs is dependent on many factors, it is preferable to keep as many factors as possible stable, and preferably only change 1 factor at time. Otherwise, it will be difficult to relate the difference in performance back to a certain aspect. By testing the thermal and hydrological performance of a variety of system set-ups for specific roof geometries, informed decisions can be made regarding retrofitting BG roof panels in the built urban environment.

As some research regarding the effectiveness of BG roof can simply not be done at such a small scale, as implementation rate or area have a large effect on the effectiveness of the BG roofs, this project will have to be translated from semi-controlled research environment to the real world built urban environment at some point. A study similar to this current project has been previously executed by Resilio, during which dynamic BG roofs were installed on flat roofs in parts of Amsterdam, after preliminary research had been performed in a semi-controlled environment under the name of Smartroof 2.0 (Chapter 2.2.1).

This will create a division within this project: the designing of a test-set up for a semi-controlled research environment and the long-term extension of this project into the real world built urban environment.

3.2.1. Research Environment

To make informed decisions regarding whether and where retrofitting BG roofs in the existing built environment is feasible, it is essential to have an understanding of the effect a variety of variables have on the effectiveness of the BG roof. Although the concern regarding load carrying constrains is considered outside the scope of this project, it emphasizes the importance of quantifying the effect of water retention capacity of the BG panels. Knowing the effect of pitch angle and orientation can further help determine what buildings should be prioritized for the most effective climate change adaptation strategy.

3.2.1.1. List of Requirements Final Concept

Based on the insights from the Discover phase, a provisional list of requirements is composed for the final concept, as can be seen in Table 1.

Table 1

Initial List of Requirements Final Concept LILa

Category	Criteria	Requirement
Functional	The influence of a variety of variables can be tested	The pitch of the panel can be adjusted
		The orientation of the panel can be adjusted
		The water retention capacity can be adjusted
		The soil thickness & vegetation can be adjusted
	Allows for A-B testing	A control group for each variable is available
	Relevant data can be measured	The design allows for placement of environmental sensors above and below each panel & on the control roof
		The design allows for placement of sensors within the soil
		The design allows for placement of a flow sensor
	The system survives year-round	The system is irrigated during dry periods to survive
		The vegetation used is suitable to survive outside year-round in the Dutch environment
Technical	The system can be placed at the designated spot at LILa	The system fits within the given dimensions
		The weight of the system does not exceed the maximum carrying load of the building
Financial	The system is financially feasible	The acquirement costs do not exceed the budget available
		The operational costs + maintenance costs fit within the yearly budget of LILa
Sustainability	The production of the system is done sustainably	Production methods suitable for small scale are used
		The production is done locally
	waste of resources during operation is avoided where possible.	No drinking water is used for irrigation
		The panels are re-usable, no one-use product is used

3.2.1.2. *List of Requirements Low-Fidelity Prototype*

As resources available are very limited for this project, the final concept cannot be built into a working prototype. To still build and test a prototype within an educational context, a low-fidelity prototype is developed and tested. For this, a brief, adjusted list of requirements is established, based on available resources:

- The complete prototype fits within the dimensions of 1000x1000 mm
- The prototype allows for multiple iterations of the panel to be tested at once
- The prototype is compatible with the current mounting system, and does not require any adjustments to the mock-roof that is already on the horst of the roof
- The prototype can be mounted on a pitch of 45 degrees
- The prototype is modular: the drainage layer can be removed or exchanged
- The prototype allows for instalment of the following sensors:
    - Soil sensor
    - Environmental sensor
- The design is made from materials available in DesignLab or provided by Farwick and Groendak
- The design allows for collecting the water separately per variant of the panel

This low-fidelity prototype will be further developed, executed and evaluated in Chapter 4.1.

3.2.2. Stakeholders Built Urban Environment

Considering the wishes and requirements of stakeholders regarding extending this project in the real built environment early on in the project can help prevent delay or even failure of the project later, as now these can still be taken into account during research at LILa to make sure these requirements are met. To gain insight into the perspectives of prospective end-users (homeowners, housing corporations and tenants) regarding implementation of BG on their existing roof(s), a co-design session is hosted. The session is a mix between generative research (learning FROM product/service users) and developmental design (learning, testing and creating WITH product/service users).

Insights from this co-design session can be taken into consideration when establishing the revised list of requirements for the set-up at LILa as well as help shape a guide on how to extend this project further into the real built environment after research at LILa has been (partially) completed.

This Co-Design session will be further developed, executed and evaluated in Chapter 4.2.

PART II

4. Develop and Test

4.1. Low-Fidelity Prototype

A low-fidelity prototype for this project was built and used for the course *Smart Solutions for Sustainable Cities*, a minor course of Civil Engineering guided by Dr. Sean Vrielink, according to the brief list of requirements for the low fidelity prototype established in Chapter 3.2.1.

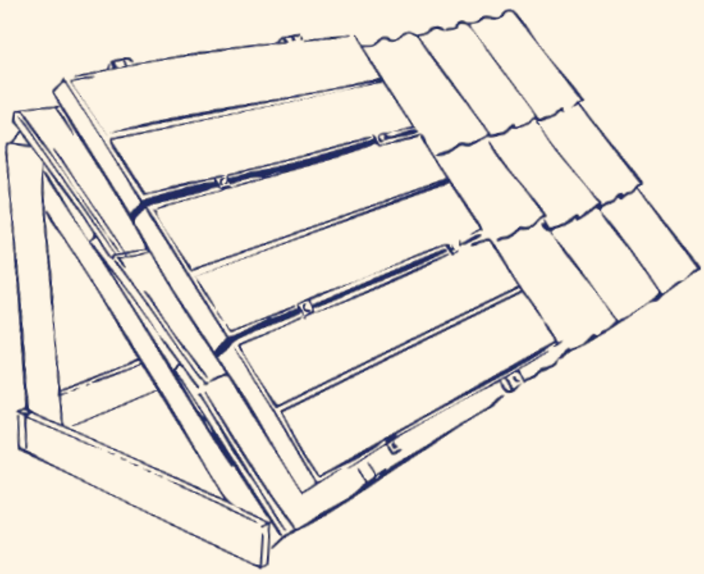
For the *Green Infrastructure* project that was included in the course, the students were required to state hypothesis, place sensors and gather and process data. As part of the objective for this project is to develop a concept for LILa to be used for research, these students would be a potential target group. Therefor, besides potential useful insights from the reports, the students would be delivering useful insights on usability of the design could potentially be gained from this.

A detailed overview of the design and execution of the prototype can be found in Appendix D1. The design of the low-fidelity prototype was largely influenced by the limited budget, resulting in the need to make use of materials already available on site, resources available at University of Twente and materials sponsored by Farwick and Groendak.nl. The materials available to build the casing, plywood being the only material available for a larger construction, are not ideal to be used for products such as this and would therefore not provide data representative of the final solution. The priority when designing the low fidelity protype was to have a representation of a BG roof available in a timely manner, to be used during the green infrastructure course. This combination of limited time, limited available resources and materials and insufficient potential for representative data results in a very rapid, linear design process without many iterations.

From a previous project regarding green on pitched roofs, a mock-roof was already available on site, including a rail system to mount the prototype to the roof. An overview of the inventory already present can be found in Appendix D2. Half of the roof can be used for testing the prototype, the other half would be left empty as control group, resulting in a 1000 x 1000 mm area with a pitch of 45° degrees to place the prototype (Figure 21).

Figure 21

Schematic Drawing of Mock-roof on the Horst



4.1.1. Conceptualisation Low-Fidelity Prototype

It was decided to create three separate panels, in line with the number of clamps already available to mount panels to the rails, since larger panels would result in more weight per clamp, increasing the risk of clamp failure and the panels slipping down.

As, from the resources available in DesignLab, the laser cutter is most efficient for larger construction, the casing design was based on sheets of plywood.

The panels consist of multiple layers, as displayed in Figure 22:

1. Drainage layer, which has small perforations in the bottom strip so that water can drain out of this layer (see images). The water is collected per panel in plastic bottles
2. Filter layer, preventing the soil from entering and clogging the drainage layer. This is a strong permeable cloth.
3. Substrate, a layer of approximately 6 cm was chosen in line with requirements for the type of vegetation.
4. Sedum on a coco-fibre mat

The three panels are similar, except for the drainage layer (1):

- The drainage layer of the first panel is empty: the water that is not absorbed by the vegetation/soil immediately drains out of the system through the holes in the bottom of the panel.
- The drainage layer of the second panel is filled with a plastic hexagonal grid: the water should be retained somewhat evenly divided over the panel (Figure 23).
- The drainage layer of the third panel is filled with a plastic raster typically used for the drainage layer of flat green roofs the water should be retained somewhat evenly divide

Figure 22

Overview of Panel Layers in Low-fidelity Prototype

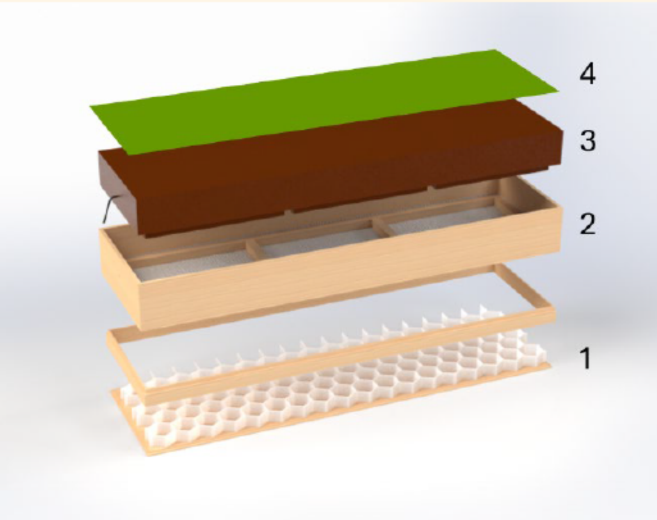
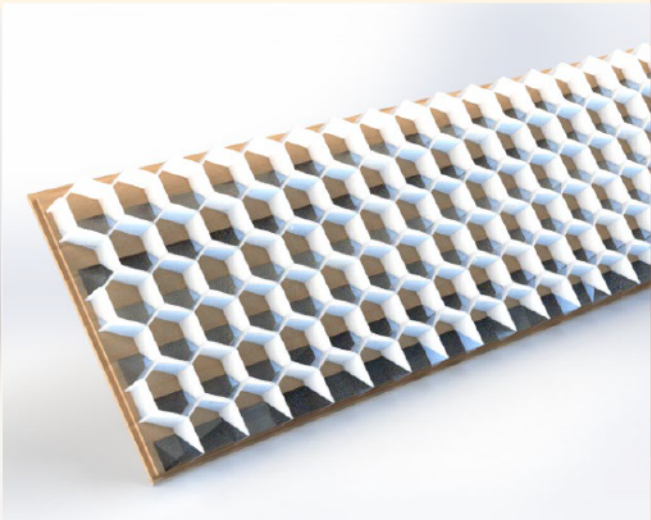


Figure 23

Render of Hexagonal Drainage Grid Low-Fidelity Prototype



4.1.2. Result Low-Fidelity Prototype

The casing was built in DesignLab over the span of a couple of days (Figure 24). The casing was moved to the roof of the Horst in parts, where it was assembled and installed on the mounting rails (Figure 25), and substrate and vegetation were added (Figure 26).

The students from participating in the green infrastructure course placed the following sensors on the set up:

- 3x SMT50, a soil moisture and temperature sensor (Figure 27, Figure 28)
    - One per panel
- 3x BME680, a environment temperature and humidity sensor (Figure 29)
    - One sensor above the BG roof, one sensor above the control roof, one sensor below the roof.

The data collected by the sensors each minute was gathered via SenseBox mini data loggers.

Figure 24

Layers of BG panel Low-Fidelity Prototype

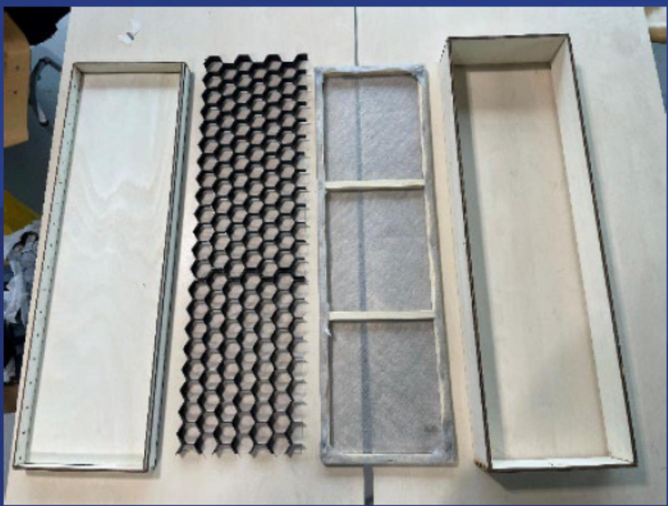


Figure 25

Low-fidelity Prototype Panels with Varying Drainage Layers

Figure 27

Render of Placement SMT50 in Soil

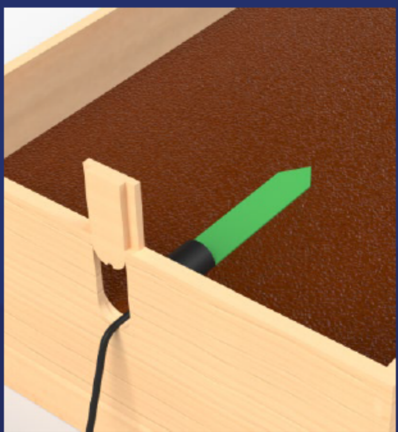


Figure 28

Installed SMT50 Low-fidelity Prototype

Figure 29

Sensebox with BME60

4.1.3. Evaluation Low-Fidelity Prototype

Figure 26

Result Low-fidelity Prototype

Due to a very limited budget, the prototype was built with materials that were on hand. These materials, however, are not representative of the materials that will be used in a final product. The wood is untreated and therefore not water-resistant, thus will rot overtime because of the moisture it absorbs. Additionally, the prototype is not completely watertight thus it cannot be guaranteed that all water that is not absorbed in the soil and the vegetation or returned into the water cycle by evapotranspiration, is caught in the bottles. Therefore, all observations and measured data from the prototype testing is not representative. The evaluation of the prototype therefor merely focusses on the interaction between the prototype and the user during the placement of the sensors by the students of the green infrastructure course as well as invalid data due to the design of the panels in combination with the placement of the sensors and potential research subjects.

The placement of the sensors by the students went relatively smooth, as they had obtained information on the type of sensors as well as the required placement beforehand from both provided material by the course and additional research. However, as there was some confusion on the placement of Sensboxes (plastic encasement around the environment temperature and humidity sensor), as there was no assigned spot for this in the design of the low-fidelity prototype. The Senseboxes were taped in position, which did not hold up; when checking up on the roof after 20 days, the Sensebox on the BG roof had moved out of position. The vegetation matt on panel 1 had also partially blown away due to excessive storm winds, exposing the soil moisture and temperature sensor and thus not providing accurate data measurements.

As mentioned before, no harsh conclusions regarding the functionality of the panels could be derived from the data measured. This was also concluded in the students reports (Lamarti et al., 2025; Madkour et al., 2025). However, during the period in which the data was measured, the BG panels were found to reduce extreme cold temperatures below 0◦C by 0,5-1,33◦C, and extreme warm temperatures by up to 2,06°C, however, in some cases there were noticeable peaks where the BG panels were hotter than the control roof (Vrielink, 2025a). This highlights a need for further research examining temperature increases due to evapotranspiration after precipitation as well as sunlight

The environmental sensors were placed in a plastic encasement during the data collection, shielding the sensor from weather conditions, however, this might have influenced the accuracy of the data measured, aside from the influence of the incorrect position of one of the boxes.

4.2. Co-Design

4.2.1. Objective Co-Design

To be able to make this translation of the concept for LILa to the real world, it is essential that the right aspects can be researched during first implementation at LILa. Therefore, it is important to already consider the wishes and requirements of the end-user (homeowners, housing corporations and tenants) during the design stage of the final concept for LILa. Insight into the ideal product-user relation can be gained through a co-design session with the prospective end-users (homeowners, housing corporations and tenants). The session is a mix between generative research (learning FROM product/service users) and developmental design (learning, testing and creating WITH product/service users).

This co-design session is meant to gain insight into the ideal relation between the product and the user;

- How actively is the user involved with the product in the different stages of the product (design, production, instalment, regular/incidental maintenance)?
- What does the interaction between product and user look like? For example, is there an app or a moderation panel the user can use to see information? Can they also adjust the functionality of the panel?

The complete plan of approach for the co-design can be found in Appendix E1. The plan for the co-design was reviewed and approved by the Natural Sciences & Engineering Sciences ethical committee.

4.2.2. Plan of Approach Co-Design

4.2.2.1. Participants Co-Design

It was expected that from each of the three above mentioned groups (homeowners, housing corporations, tenants), 3-4 individuals will participate, meaning there would be 9-12 participants partaking in the research. A smaller study population allows for personal guidance for the participants through the co-design session, resulting in better results. Additionally, practical limitations such as resource availability and time also influenced the sample size.

4.2.2.2. Methodology Co-Design

No prior knowledge was expected of the participants. They were given a short introduction on the topic in the form of a presentation, including potential drawbacks and benefits of BG roofs, after which they were given two individual assignments as well as a group assignment.

Individual co-design is good for eliciting granular feedback (Arcia et al., 2024), a less filtered insight in the stakes of the participants, as their answers will be less influenced by the perception and feedback of other participants (this limits the need to respond in a "socially acceptable" way). Co-design in groups (≥2) is good for establishing consensus, stimulating discussion and encouraging ideas and brainstorming (Arcia et al., 2024). However, group dynamics might influence the outcome.

For the individual assignment, the participants were asked to note down their most important considerations in favour or against acquiring a (blue-)roof, as well as to map their ideal product-user relation on a day-to-day basis by combining text, the provided icons and drawing. These assignments were done anonymously and without any form of discussion, to limit any social pressure and outside influences. For the group assignments, the participants were divided into two groups: the homeowners and tenants. In these groups, the participants were asked to fill out another product-user relationship map, based on four scenarios. Templates with the assignments (Appendix E2) and visualization tools were provided to help the participants to get started. During and after this second assignment, discussion was encouraged both within and between groups.

4.2.3. Results Co-Design

A complete overview of all filled out templates resulting from the co-design can be found in Appendix E3.

4.2.3.1. Implementation Considerations

For the first assignment, the participants were asked to note both their positive (Table 2) and negative (Table 3) considerations regarding implementing BG infrastructure on their homes.

Table 2

Positive Considerations Co-Design Participants Regarding Implementing BG Infrastructure

Consideration	Times Mentioned
Cooling effect	4
Aesthetic considerations	4
Good for environment/sustainable	3
Decrease of risk of flooding	2
Water retention	2
Increase in urban green space	2
Increase efficiency of solar panels	1
Possible subsidies	1
Total number of considerations mentioned	19

Table 3

Negative Considerations Co-Design Participants Regarding Implementing BG Infrastructure

Negative consideration	Nr. of times mentioned
Uncertainty about maintenance needs	3
Weight concerns	3
Initial costs	2
Housing corporation (not owning their house)	1
Not willing to invest in rented house	1
Maintenance costs	1
Concerns about leakage	1
Water consumption of the roof	1
Requires removal of original roofing	1
Neighbors	1
Total number of considerations mentioned	16

Figure 30

Result Co-design Group Assignment

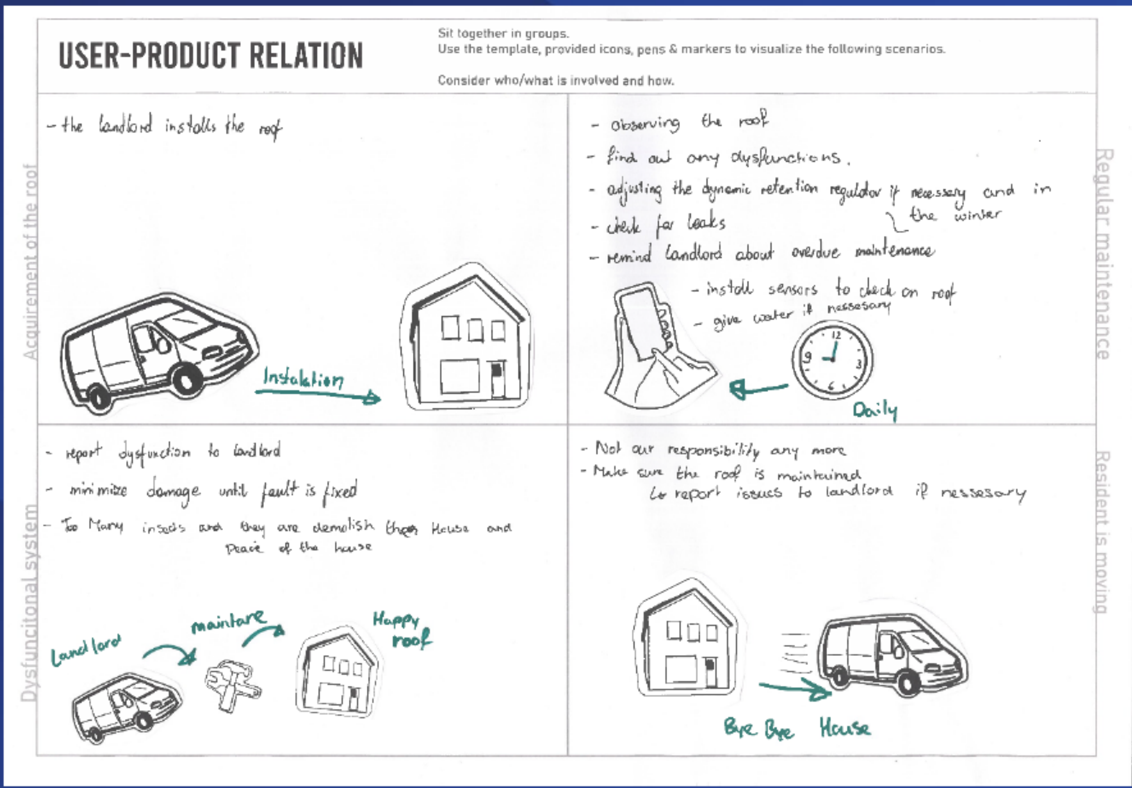
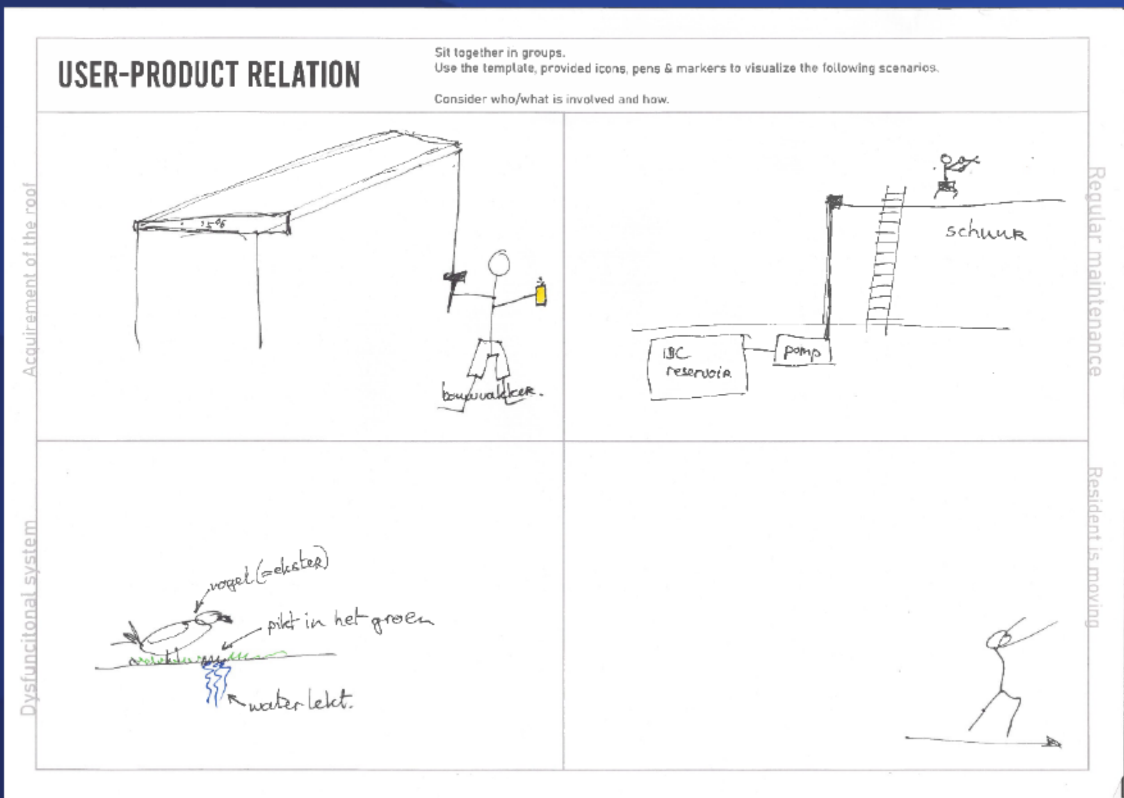


Figure 31

Result Co-design Group Assignment Homeowners



4.2.3.1. Group Assignment

The results of the group assignment are shown in the figures below (Figure 30, Figure 31). The key points they presented in addition to the visual representation are written in the accompanying explanatory text.

The tenants clarified their landlord should be the main carrier of responsibility when it comes to applying BG infrastructure to their houses. They should be responsible for installation and regular maintenance, from which the costs can be (partially) included into the service costs the tenants pay. The tenants are willing to be involved for checkups, needed irrigation and to report any irregularities to the landlord.

The homeowners would outsource the installation, but stated to be willing to do needed regular maintenance themselves. Ideally, they would have an additional water reservoir in their garden with a pump for automated irrigation and reducing the need for large amounts of water retained on the roof, significantly lowering the systems weight. For the scenario of dysfunctional roof, they were mostly concerned about birds causing leakages.

4.2.4. Conclusion Co-Design

The cooling effect of the BG roof as well as aesthetic considerations seemed to be the most significant positive considerations, while weight concerns and uncertainty about maintenance needs show to be the largest negative consideration. Additionally, participants used phrases such as “good/better for the environment” and “sustainable”, which are vague statements that can refer to a variety of things. The tenants showed a low perceived responsibility, although showing a high engagement desire, contradicting as opposed to the homeowners.

4.2.5. Evaluation Co-Design

4.2.5.1. Pilot

Prior to the co-design session, a pilot session was organized. Five Industrial Design Engineering master students were invited to test the co-design approach. From this session, both observatory and verbal information was gathered to improve the methodology. A complete overview of the feedback and made adjustments based on this pilot session can be found in Appendix E4.

Since all participants of the pilot were familiar with both the subject of the study as well as being experienced with co-design sessions and user-product interaction mapping, the feedback was useful but did unfortunately not account for the assignment being unclear to people lacking this pre-knowledge. For future pilot sessions, having a more varied group of participants would be advisable.

The results of the co-design pilot session were merely uses as an evaluation of the clarity of the topic and assignments and are therefore only used to adjust the methodology and are not considered in any further steps regarding the design for LILa.

4.2.5.2. Sample Group

The selection procedure was based on the research objective. This study aimed to gain insight in the ideal user-product relation through a co-design session with the prospective end-users. Individuals could voluntarily sign up to take part in the study if they adhere to one (or more) of the following criteria:

- owns a home
- is a tenant
- is employed by a housing corporation

To find participants, the project was uploaded on the website of university of Twente, where citizens are informed on ongoing research and invited to participate (University of Twente, n.d.).However, due to unclarity regarding the need for an ethical review for the study causing time management issues, this was done only a day before the co-design session took place, resulting in only one sign up via the website. Four other participants were found via personal invitations and word of mouth.

It is important to note that there was a significant difference in demographic (e.g. age and wealth) between the tenants and homeowners, which could be of influence to the outcome of the assignments.

Multiple housing corporations were invited timely, but unfortunately did not show any interest in joining. One housing corporation was contacted personally, where they stated green infrastructure for urban climate resilience is not on their priority list.

4.2.5.3. Co-Design Assignments

A large difference in interpretation and execution of the assignments between the participants of the pilot versus participants of the co-design session was observed. This is assumably due to the difference in familiarity with co-design sessions and user-product relationship mapping. For future pilots it would be advisable to have a group of participants more representative of the eventual participants. For example, the group of homeowners in the second assignment focussed more on the literal aspect of the scenario, for example, for the scenario dysfunctional roof they visualized a cause instead of a possible solution. When asked how they would solve the issue, they stated they simply did not think about that.

Part III

5. Deliver

In this chapter, most relevant information gathered from the empirical research, the low-fidelity prototype and co-design, discussed in Chapter 4, is translated into key insights and design implications.

In the following section, the concept for the final design is discussed. For this thesis, it was chosen to focus on the larger construction of the set up for LILa. The panels would be interchangeable, so several versions of these can be tested in the same set up differing in water retention capacity, soil thickness and type of vegetation. As this design, other than its dimensions and the mounting method, is not dependent of the larger construction and vice versa, the design of these panels is left out of this thesis. This, however, is important for further research before execution of this project, as the weight and costs of these panels will influence the feasibility of this project as well as a possible need for reinforcement of the designed structure of the set up.

In the final section of this chapter, a view on further steps required to continue this project after this thesis is given, highlighting the most important findings from this thesis. As this thesis merely gives exploration into a larger overarching project, there are plenty of future steps to discuss.

5.1. Key Insights Develop & Test

Regarding the low-fidelity prototype, the main concern is that the data measurements of the final set up at LILa should be accurate to be able to perform research on site from which conclusions can be drawn. Therefor, the design should be intuitive in the sense that it allows sturdy placement of sensors in the right spots in such a way that students can do this with a small amount of knowledge gained through provided and/or individual research. The use of the BME680 environmental sensor in the plastic encasement should be reconsidered, as the encasement might influence the data measurements, and lastly it is important to use the correct materials that are representative of materials used in a potential final product for the market for accurate research results.

A co-design session has potential to give valuable insights regarding the motivation, drivers and barriers of homeowners and tenants. A co-design session seems to be a good method to get potential end-users involved and informed. However, it should be considered that the average person participating does not have any knowledge regarding co-designing and BG roofs. Instructions for the assignments should be more concise, and it should be considered how the participants can, if necessary, be steered in the right direction for completing the assignment without influencing the outcome. The relatively small number of participants, under representation of housing corporations as well as private landlords in combination with some of the assignments being unclear made the outcome of executed co-design session did not reach its full potential. It is advisable to repeat a reworked version of the co-design session when translating the concept from semi-controlled research environment to the real world-built environment.

During the currently executed co-design session, homeowners stressed the need for solutions to apply BG roofing without constructional changes and removing the original roofing. They also expressed concerns regarding weight constraints and maintenance of the roof. Tenants seemed to express a higher engagement desire contradicting their low perceived responsibility, however, this difference may be due to variation in demographics between the groups.

Incentives for housing corporations to participate in research activities regarding BG roof seem to be lacking. They are however an important stakeholder and can with certainty in the long term (financially) benefit from keeping the built environment climate resilient. It might be interesting to investigate why this incentive is missing and what tools can be used to involve the corporations in the future.

5.2. Revised List of Requirements

The list of requirements for the final design for LILa established in the Define phase (Chapter 3), is revised and specified according to the new findings from the Development and Test phase (Chapter 4) and additional information gained regarding requirement specifications by LILa. Additionally, it was decided to only focus on the larger construction of the set up, and therefor requirements regarding the design of the BG panels were removed. This revised list can be found in Table 4 below.

Table 4

Revised List of Requirements Setup LILa

Category	Criteria	Requirement	Specification (where necessary)
Functional	The influence of a variety of variables can be tested	The pitch of the panel can be adjusted	Pitch can vary between 15 and 55 degrees in steps of ≤10
		The orientation of the panel can be adjusted	The roof can turn 360 degrees, in steps of ≤5
		BG panels can be mounted on and taken of	There is a universal mounting system incorporated
	Allows for A-B testing	A control group for each variable is available	The set up consists of ≥ 2 panels from which all variables can be adjusted individually
	Relevant data can be measured	The design allows for placement of environmental sensors above and below each panel & on the control roof	
		The design allows for placement of sensors within the soil	
		The design allows for placement of a flow sensor	
	The system survives year round	The system is irrigated during dry periods to survive	
		The vegetation used is suitable to survive outside year round in the Dutch environment	
Technical	The system can be placed at the designated spot at LILa	The system fits within the given dimensions	The system fits within the dimensions of 6,7 by 4,6 .
		The weight of the system does not exceed the maximum carrying load of the building	*
Financial	The system is financially feasible	The acquirement costs do not exceed the budget available	The acquirement costs do not exceed 10.000 euro**
		The operational costs + maintenance costs fit within the yearly budget of LILa	***
Sustainability	The production of the system is done sustainably	Production methods suitable for small scale are used	
		The production is done locally	Production can be done entirely in the region, with the exception of possible ready made parts
	Waste of resources during operation is avoided where possible.	No drinking water is used for irrigation	Water drained from the system is stored and reused for irrigation
		The panels are re-usable, no one-use product is used	

*The maximum carrying load of a flat roof can differ a lot per building, depending on its structure, materials and age. This should be assessed by an expert before execution of this project.

**This is the budget that was lastly communicated to be eventually available for this project. Due to the Universities financial issues, this might not be accurate anymore. This should be confirmed before further execution of this project

***This budget is uncertain. This should be confirmed before further execution of this project.

5.3. Ideation and Conceptualisation Final Design

To create a large variety of ideas on how to integrate the requirements stated in Chapter 5.2 into a working concept, ideation was done. Since working towards a solution to apply BG roofs on top of existing roofing, it makes most sense to work with a similar construction as used for the low fidelity prototype; a mock roof to which BG panels can be added on top. The ideation was split into three variables; adjustment of orientation, pitch angle and layer-adjustment (vegetation, thickness of soil and water retention capacity). A complete overview of the sketches made during the ideation phase is included in Appendix F.

The most promising ideas, based on perceived feasibility, from the ideation phase were combined into three different concepts. During translation of these ideation sketches into concepts, it was focused on the main aspects of adjustable variables, specifically the adjustment of the pitch angle and orientation, as these were deemed most complex and influential to the larger construction.

Due to very limited budget and a relatively small set up, it is not feasible to install an electronic system for the adjustable variables, so the adjustment of the variables should be done manually with a mechanical system. To reduce the margin of human error when it comes to adjusting the variables precisely in a manual manner, it is preferable to make the variable adjusting mechanism so that the adjustments can be done stepwise. The orientation should be adjustable with steps of max 10 degrees at a time (Figure 32), and the pitch with steps of maximum 5 degrees at a time (Figure 33).

As for the placement of the system and the number of separate systems, calculations were made where it was concluded that with two separate systems both divided into 2 sections (half BG half control roof), was most space efficient. These calculations can be found in Appendix G1.

Figure 32

Visualization Stepwise Adjustment of Orientation of the Setup

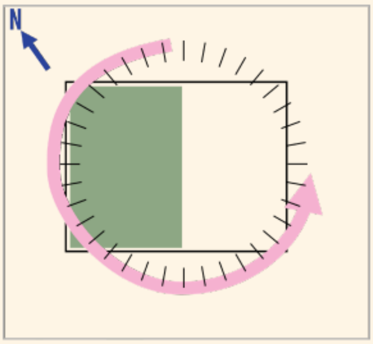
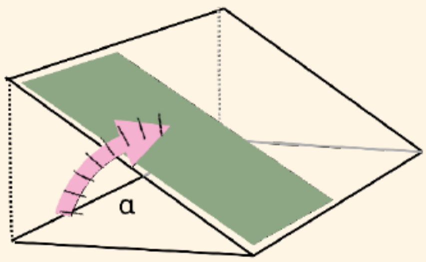


Figure 33

Visualization Stepwise Adjustment of Pitch Angle of the Setup



5.3.1. Concept 1

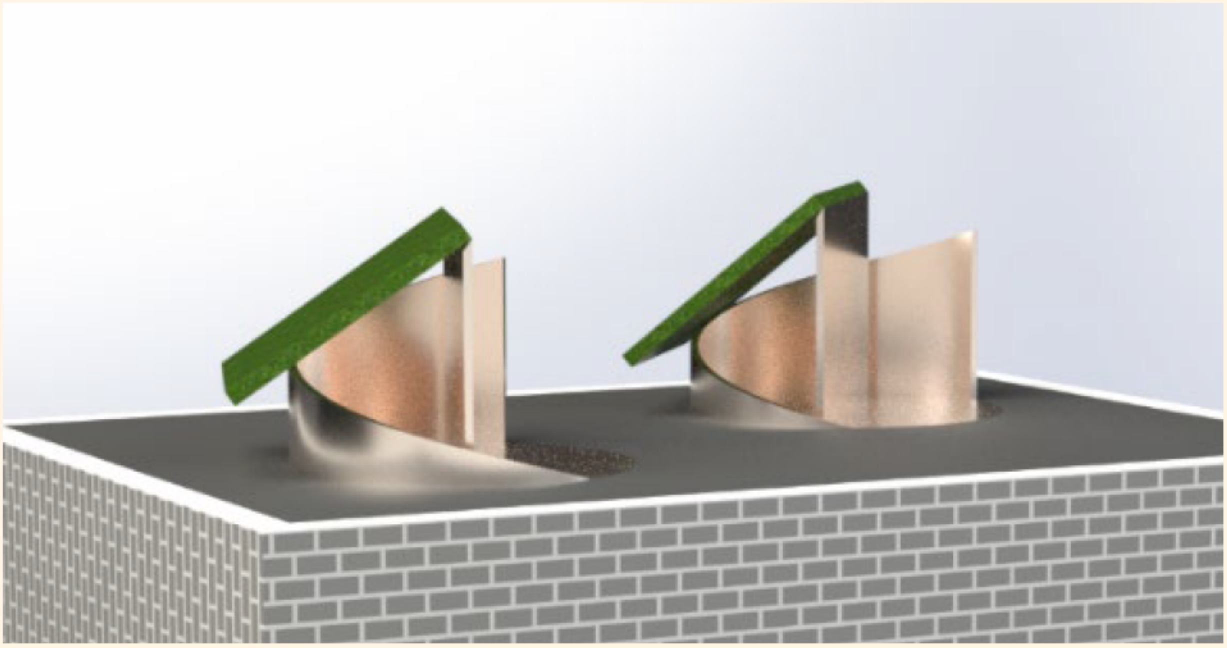
The first concept consists of two circles that can turn separately. On the inner plate, the BG roof panel is mounted on a hinge. By turning this plate, the orientation of the panel can be adjusted. The lower edge of the panel leans of the outer ring, which has a varying height. By turning the outer ring, the height of the lower part of the panel is adjusted and therefor the pitch.

From calculations made regarding this concept (found in Appendix G2), it can be seen that this concept is very space inefficient as the panel has to be mounted in the middle of the circle for the mechanism to work. Additionally, the height-determining outside ring requires specific dimensions and will most certainly have to be custom made, driving up the costs.

Pros	Cons
+ sleek design	- Space inefficient
+ easy adjustment, even by 1 person	- Need for many custom-made parts

Figure 34

Render Concept 1



5.3.2. Concept 2

The second concept has one mounting point with hinge in the middle of the panel, for the adjustment of the pitch. The pillar on which the panel is mounted can be turned, to adjust the orientation of the panel. If needed, which is likely as BG panels are going to be heavy and the size of the panel creates a large momentum, additional supporting legs can be added to the corners.

Pros

+ can for a larger part be made from existing parts

+ Easily allows for larger pitch variation,

+ space efficient

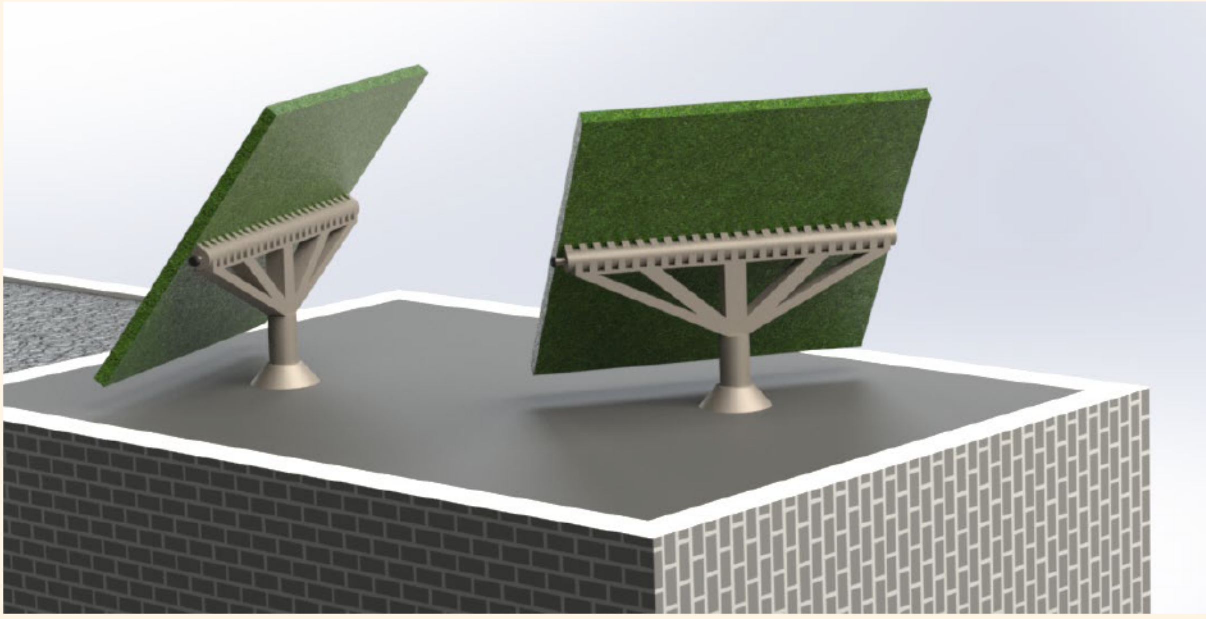
Cons

- Complex adjustment of pitch angle due to additional supports

- Need for custom made parts (mounting of roof to the base)

Figure 35

Render Concept 2



5.3.3. Concept 3

The third concept is a turning plateau with a system for adjustable height of the back of the panel, hence adjusting the pitch angle, as often seen in products like pet ramps or garden chairs. This easy mechanism allows for stepwise adjustment of the pitch, however, only a limited number of steps is possible (see Appendix G3 for calculations). Due to the user having to pull up the top of the roof to change the angle, the adjustment of the slope could be heavier.

Pros

+ easily allows for stepwise pitch adjustments

+ can for larger part be made from existing part, no need for expensive small scale production methods.

+ space efficient

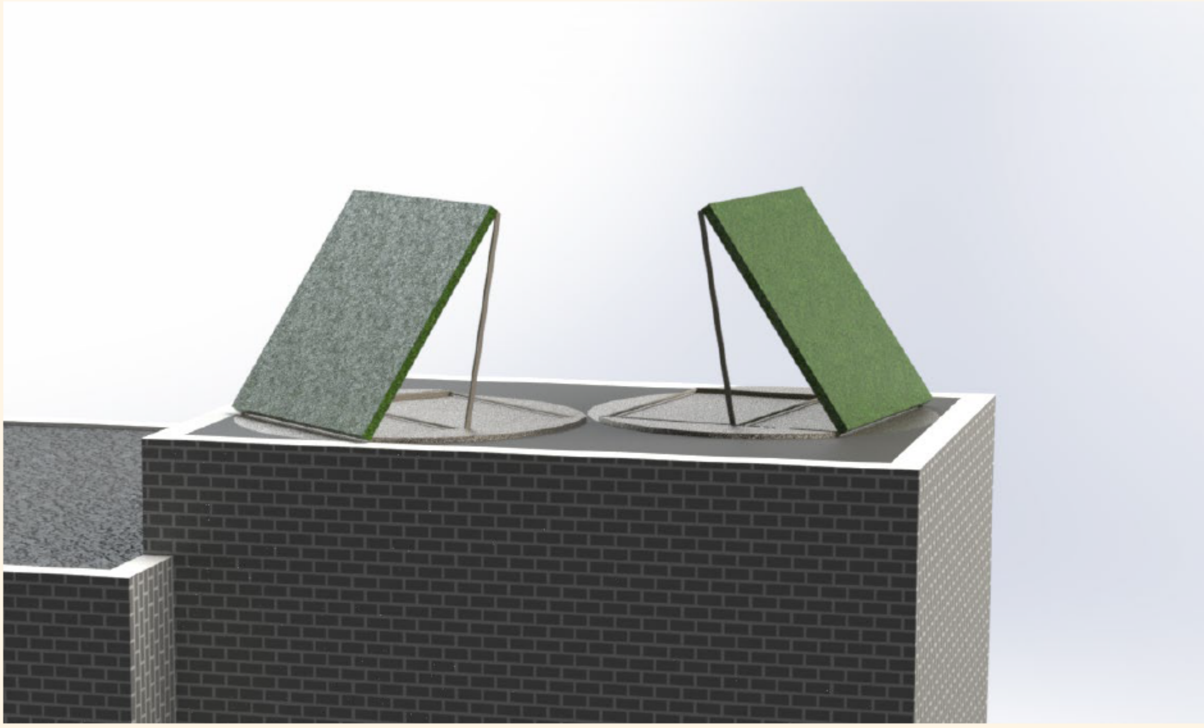
Cons

- Limited number of steps possible for the height.

- Possible heavy in adjustment

Figure 36

Render Concept 3



5.4. Evaluation of Concepts Final Design

To evaluate the concepts, an evaluation matrix was used.

For the evaluation matrix (Table 5), several criteria were established in a variety of categories, based on the requirements as established in Chapter 5.2. Both the criteria and the categories were given a weighting factor in percentage, based on the perceived importance of the matter.

Table 5

Evaluation Matrix Concepts Setup LILa

				Concept 1		Concept 2		Concept 3	
Category	Weighing facotr cat. (%)	Criteria	Weighing factor crit. (%)	Relative compliance	weighted compliance	Relative compliance	weighted compliance	Relative compliance	weighted compliance
Costs	3		10		57		60		90
		Low purchase costs	5	1	5	2	10	4	20
		Low maintenance costs	4	3	12	2	8	2	8
		Installment	1	2	2	2	2	2	2
Usability	2		10		52		56		66
		Easy adjustment of pitch	1	5	5	3	3	2	2
		Easy adjustment of orientation	1	5	5	5	5	5	5
		Low risk of human error in pitch adjustment	3	2	6	2	6	4	12
		Low risk of human error in orientation adjustm	3	2	6	2	6	2	6
		Allows for easy accessible sensor placement	2	2	4	4	8	4	8
Sustainability	2		10		62		70		86
		Can be made from renewable sources	3	4	12	4	12	4	12
		Low passive energy-use	3	5	15	5	15	5	15
		Can be repaired(replacement parts available)	4	1	4	2	8	4	16
Efficiency	3		10		30		132		102
		Space efficient	4	1	4	5	20	4	16
		allows for later adjustments	6	1	6	4	24	3	18
Total%	10				201		318		344
Ranking					3		2		1

All three concepts were then graded on each criterion on a scale of 1 to 5, 5 being best and 1 being worst. It should be noted that the perceived importance of the criteria, which is reflected in the weighing factors, is subjective to some extent.

From the evaluation matrix, it became clear that concept 3 held the most potential, scoring by far the highest in each category except for efficiency. As concept 1 scores lowest on all criteria except for ease of adjustment for both the pitch and orientation, this concept was first eliminated.

Both concept 2 and 3 needed some adjustments when translating them into a final design, both mainly regarding sturdiness of the design. The weight of the panel with just one support in the middle of concept 2 would likely lead to failure. Adding extra support on the bottom and/or side of the panel would have been possible, but this would complicate the design, significantly decrease the ease of adjustment of both variables while increasing the production/purchase costs.

For concept 3, the ease of adjustment of the pitch was mainly lowered by the need to slightly lift the top of the panel before being able to adjust the pitch. Implementation of a gas spring could resolve this problem, or implementation of rails with stopping mechanism.

Concluding from the evaluation matrix and reviewing the necessary adjustments to both concepts, concept 3 seems most promising and will therefore be chosen as a basis for the final design.

5.5. Final Concept

For the final concept, concept 3 was chosen as a starting point as this showed to be most promising from the evaluation matrix. However, some adjustments were made to counter the most significant downsides from this concept. These adjustments will be discussed in the following sections.

Figure 37

Render Final Concept with Pitch Angle of 15 Degrees

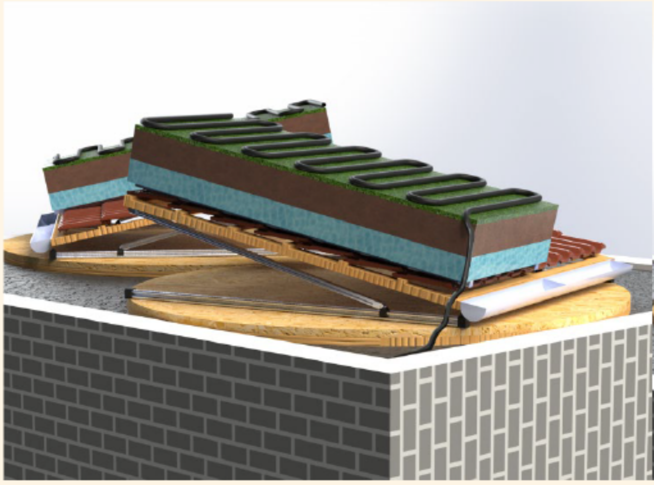


Figure 38

Render Final Concept with Pitch Angle of 55 Degrees

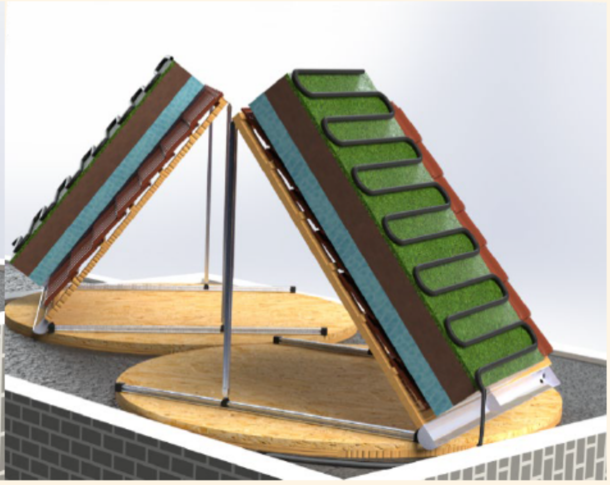


Figure 39

Render Final Concept Backside

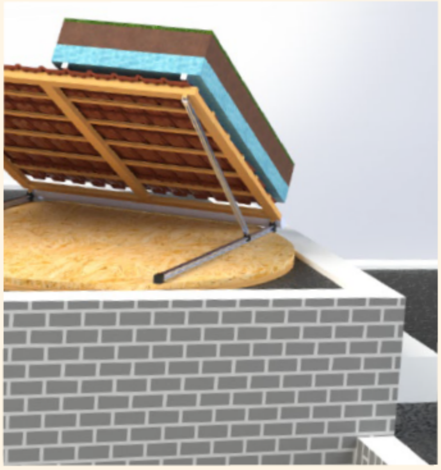


Figure 40

Render Final Concept Top View

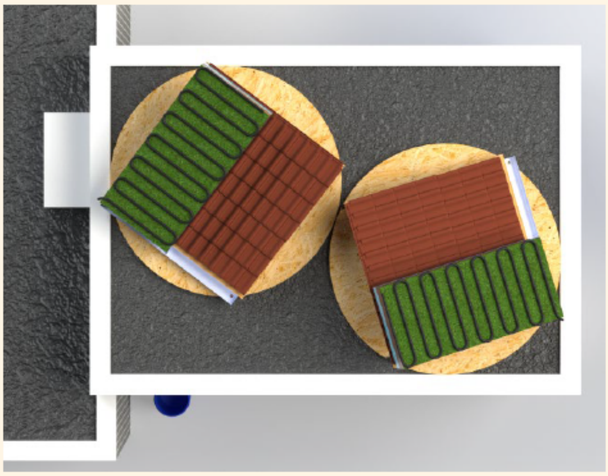
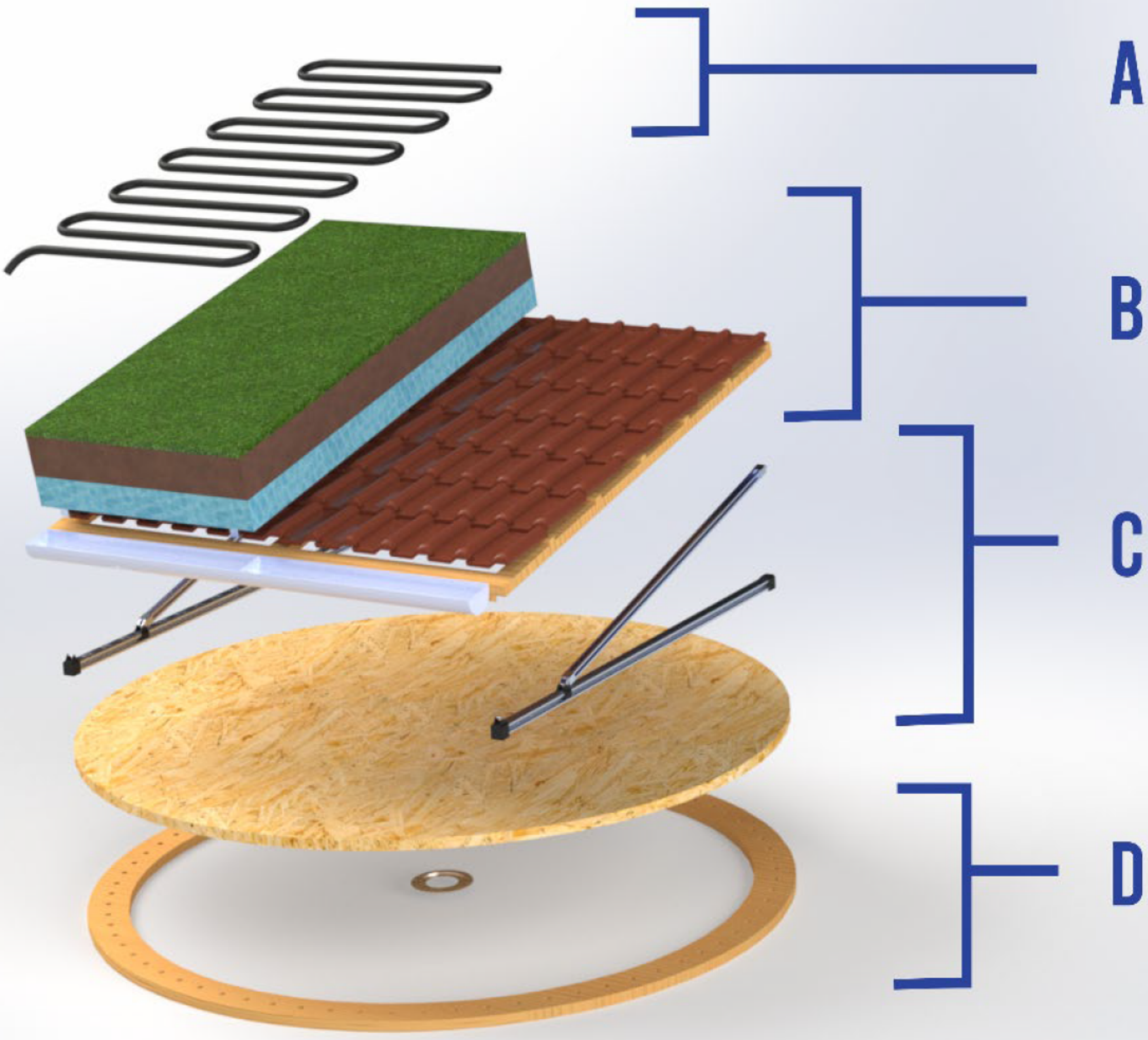


Figure 41

Annotated Exploded View Final Concept



Note: A. Irrigation system, B. Roofing, panel and mounting, C. Pitch Adjustment, D. Orientation adjustment

A. Irrigation System

BG infrastructures, especially when “younger”, require irrigation during persistent dry periods. Two irrigation methods can be considered. Manual irrigation is energy efficient and low-cost, if labor costs are omitted. However, this tends to be an inefficient method when it comes to accuracy and timing. As the BG roofs need for irrigation does not consider weekends and holidays and irrigation is most effective during evening hours, as the vegetation has time to absorb more of the water before it evaporates, this is not a practical long-term solution. An automated irrigation system can be controlled by a timer or soil moisture sensor, which is already going to be incorporated in the system. The irrigation will automatically start when deemed necessary and can be dosed more accurately.

An automated irrigation system is considerably more desirable within this setting. To this automated system, either a drip or misting hose can be connected. A drip hose allows for more precise irrigation per roof panel, although water tends to quickly sink to the bottom. A misting hose delivers more natural and gentle irrigation to the plants by mimicking rain. However, due to a lesser ability to target very specific areas, imbalanced irrigation between the panels and water loss are larger compared to the drip hose. As the BG panels will retain (part of the) excess water in the retention layer, keeping it available to the vegetation, the drip hose seems most suitable.

To ensure sustainable water use, excess rainwater will be collected in a buffer tank via a flexible drainage pipe. This tank can be replenished with rainwater collected elsewhere at LILa when needed, depending on what can be facilitated, to avoid using clean drinking water. As the irrigation system is not connected to a tap with pressure, a pump is needed to create pressure and transport the water from the buffer tank to the drip hose. If this small, submersible pump, that is places in the buffer tank, can be connected to a smart or remote-controlled switch, a simple automated drip irrigation system can be created. Although the drip hose is to be placed on top the BG panels that is considered outside of the scope of this thesis, the irrigation system is part of the permanent infrastructure and therefor considered.

B. Roofing, Panel and Mounting

As the roof can vary in pitch from 15 to 55 degrees, it is important to choose a suitable rooftile. Most rooftiles are not designed for such flat slope angles, and therefor water accumulation might be caused leading to inaccurate data measurements. Rooftiles can easily be acquired second hand, which is preferable due to financial and sustainable concerns of this project, however, they should be the same over the entire set-up for most accurate research results.

As the BG panel should be changeable, it should come off easily. To achieve this, mounting rails typically used for solar panels can be used. This should be kept in mind during the design of the BG panels.

C. Pitch Adjustment

The initial design for Concept 3 includes a base with slots at certain distances from the connecting point of the panel to the base to secure the panel on certain pitches. This base with slots needs to be custom produced, and limited the variety of pitch angles the panel could be set on due to the distance between the slots needed, which could not be smaller than the radius of the bar that falls into the slots.

By replacing the slotted base with linear rails with index positions, the pitch adjustment can easily be adjusted stepwise. How this stepwise locking mechanism will work is dependent on the rails that are being used, but rails like these can acquired ready-made in many variations. Depending on the mechanical locking mechanism chosen, index positions can be added if necessary. As for the weight concern, based on the calculated estimated weight of the roof, the force needed to adjust the angle can be calculated. If needed, gas springs can be added to decrease the required force.

D. Orientation Adjustment

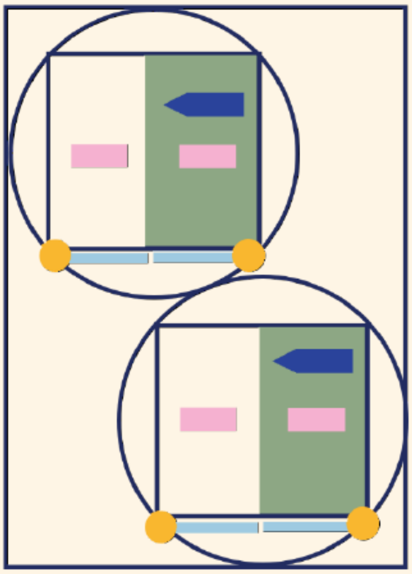
Each set up will be placed on a turning plateau individually, so the orientation of the set-ups can be adjusted separately. These turning plateaus can be ready-made and can be chosen dependent on the calculated estimated weight of the set-ups. A baseplate can be made from scrap wood or other available materials deemed suitable. Swivel wheels between the baseplate and the roof help lower the load on the turning plateau and ease the turning of the plateau.

A fixed ring with perforations around the edge under the baseplate allows for fixing the turning baseplate stepwise in different orientations with one or multiple quick release ballock pins. Markings are made on the edge of the ring, indicating the different wind-directions.

5.5.1. Sensors

Figure 42

Visualization Sensor Placement



Per roof section of each set up, the following sensors are installed (Figure 42):

Environmental sensor (temperature & humidity) - The use of current environmental sensor, which is located in a plastic box, should be reassessed, as discussed in Chapter 4.1.3. If the same sensor set up is to be used, roof hooks can be used to secure the plastic sensor encasement.

Soil sensor (moisture & temperature)- Aside from collecting data overtime, this sensor can be used to automate the irrigation process

Flow sensor - This sensor will collect data on the amount of water entering the drainage system over time per panel. This sensor must be placed at the end of the gutter. The gutter must be split per section for accurate measurement. Additional sensors can be placed, based on the data needed for the research that is being executed.

5.5.2. Dimensions

The dimensions of the set up are based on the dimension of the designated area the set up will be placed, which is on top of the flat roof on the higher part of the BMC building. This area is 670 cm by 460 cm. Ideally, the green roof area is as large as possible. The set up will be placed on a round plateau in order to change the orientation. The calculations in Figure 43 show the largest possible radius for the two plateaus to be placed on the roof.

Figure 43

Calculation Dimensions Orientation Plateau

$$L = 670\ cm \qquad B = 460\ cm$$

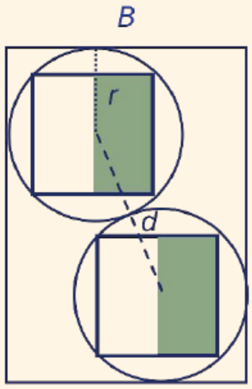
$$d = \sqrt{(670 - 2r)^2 + (460 - 2r)^2}$$

$$\sqrt{(670 - 2r)^2 + (460 - 2r)^2} \geq 2r$$

(for circles not to overlap)

$$r = 172\ cm$$

$$A^{panel} = (172\sqrt{2})^2 = 59168\ cm^2$$

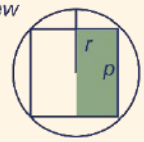


On each plateau, a modular mock-roof is placed, form which the pitch angle can be adjusted between 15 and 55 degrees. In the calculations below in Figure 44, the largest possible dimensions of the roofing are determined. Value p gives the dimension of the larges possible flat square to be placed within the plateau with radius r=172cm, as calculated in Figure 43. Value α is the pitch angle and x represents the projected distance from the top of the roofing (b) to the plateau. Value b is a constant. The value of b can be determined at $\alpha_1 = 15°$, where x_1 is equal to p, as the smallest pitch angle α will have the largest horizontal projection. Roof length b is determined to be 251 cm. Based on constant b and $\alpha_2 = 55°$, y_2 can be calculated, which gives the maximum vertical projection of the roof, which is determined to be 205 cm.

Figure 44

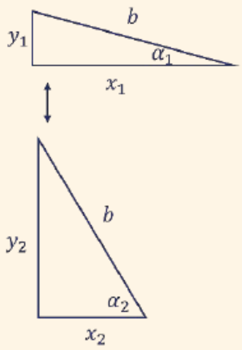
Calculation Dimensions Roofing

top view



$$r = 172\ cm$$
$$p = 172\sqrt{2} \approx 243\ cm$$
$$15 \leq \alpha \leq 55$$

side view



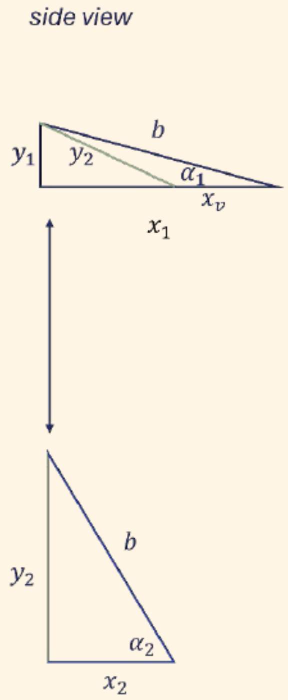
$$\alpha_1 = 15$$
$$x_1 = p = 243\ cm$$
$$y_1 = \tan 15 * 243 \approx 65\ cm$$
$$b = \frac{243}{\cos 15} \approx 251\ cm$$

$$\alpha_2 = 55$$
$$x_2 = \cos 55 * 251 \approx 143\ cm$$
$$y_2 = \sin 55 * 251 \approx 205\ cm$$

As y_2 is equal to the length of the support from the top of the roof to the plateau or rails. As the length of the supports is a constant, x_v can be calculated for each α, providing the distances from mounting point of the rails to the roof, to the brake points of the supports on the rails to attain the various pitch angles of the roof (Figure 45).

Figure 45

Calculation Dimensions Stopper Points Roofing on Rails



$$\alpha_1 = 15$$

$$x_1 = p = 243\ cm$$

$$y_1 = \tan 15 * 243 \approx 65\ cm$$

$$b = \frac{243}{\cos 15} \approx 251\ cm$$

$$\alpha_2 = 55$$

$$x_2 = \cos 55 * 251 \approx 143\ cm$$

$$y_2 = \sin 55 * 251 \approx 205\ cm$$

$$x_v = x_1 - \cos\left(\sin^{-1}\frac{x_1 \tan\alpha}{y_2}\right) = 243 - \cos\left(\sin^{-1}\frac{243\tan\alpha}{205}\right)$$

5.6. Future Steps

5.6.1. Carrying Load Capacity

It should be emphasized that it would be advisable that this more in-depth analysis regarding weight constraints of existing buildings with pitched roofs in the urban Dutch environment should be performed BEFORE continuing this project. Conclusions regarding weight constraints might bring very strict or even unachievable requirements to the table that can now still be considered for the research at LILa as well, such as looking at light weight substrate alternatives and looking at alternatives for the water buffer. It should be noted that there is a risk in this that the projects aim of retrofitting a one-size-fits-all solution of BG on existing buildings without constructional changes, is an unachievable goal.

As mentioned in Chapter 9, the roof designated for placement of the system should be assessed by an expert on the maximum load carrying capacity, and a calculation should be made on the estimated weight of the construction of the system. Furthermore, a design for the panels to be tested at LILa should be made. Based on the heaviest possible formation of panels and the weight of systems the permanent infrastructure, calculations can be made regarding the feasibility of this system at LILa.

5.6.2. Expanding Research to the Real World

Once the research at LILa has advanced so that there is a better understanding regarding the effect of orientation, slope and water buffer capacity on the effectiveness of the BG roof, as well as how these aspects interact, the research project should be extended into the real built environment on a small scale. As the social benefits of implementation of BG in the built environment cannot be quantified with the small-scale set-up at LILa, as this is not representative of the real-world context.

It should be assessed what neighbourhood is most suitable for rolling out the pilot. Here should be looked at:

- ***The roof geometry*** - Based on the results from the research at LILa, conclusions are drawn regarding, among others, the relationship between orientation, pitch and effectiveness of the panels. Once expanding this research into the real worlds, ideally a neighbourhood with a high percentage of roofs with a more effective geometry is chosen.
- ***The roof owners*** - Preferably a neighbourhood with high percentage of (social) housing owned by one (or more) larger corporations. This will ease the process of coming to an agreement and thus increase the implementation of rate. A higher implementation rate will result in a more accurate quantification of the effect of the BG roofs.
- ***Vulnerability*** - Preferably this neighbourhood is in a high-risk area is chosen, where they are vulnerable to flooding during heavy precipitation events both now and in the future. If an area does not flood easily, it is harder to observe a significant difference.

Before installing the BG roofs, data must be available in this area regarding, (heavy) precipitation events (drought beforehand (number of days without precipitation), precipitation amount (in mm/h), duration). If the precipitation event resulted in a (local) flooding, the level of flooding (amount of water in the streets at pre-determined spots, duration of the flood). Additionally, data must be collected on environmental temperature at pre-determined spots.

This data should be gathered preferably over an entire year, in order to be able to compare this to the new data that will be gathered over time after the instalment of the BG roofs. However, this will result in that this project will be a longer-term project, as conclusions on the quantification of the social benefits can only be drawn after 2 years beyond the research at LILa. Alternatively, only half of a neighbourhood would have the BG panels installed. Data measurements would then be done in both halves of the neighbourhood to compare, but as there are always going to be slight differences between sections of a neighbourhood that might be of influence on the outcome, the outcomes might not be as reliable, As during this pilot in the real built urban environment, the effects of BG on a larger, social scale are tested, not all BG roofs need to be equipped with sensors, but only a small percentage to validate the results from the research at LILa. It is difficult to say how much area of BG infrastructure is needed in order to achieve measurable results, as this is partially dependent on assumed effectiveness of the BG infrastructure. To determine this more accurately, the outcomes of the research at LILa regarding the effect of pitch and orientation on the effectiveness are needed, as well as an analysis regarding the water retention capacity that is feasible to install due to load carrying constraints of the existing buildings

.

5.6.3. From Research to Product

If future research proves favourable, an open-source design can eventually be developed for larger scale implementation in the existing built urban environment. However, this remains a long-term goal, and this is currently still too far ahead to discuss specific details beyond outlining this as an aspiration.

As this project continues and eventually extends into the real world, new opportunities and gaps regarding retrofitting BG infrastructure in both the market and academic field are likely to emerge. LILa should continue to provide a platform for research to enhance sustainable innovations within the field of urban climate resilience, to utilize those opportunities and fill these gaps.

6. Conclusion

From previous studies, it was concluded that BG infrastructure effectively helps mitigate the impacts of climate change in urban areas (Chapter 2.3). Its benefits—including improved stormwater management and the reduction of urban heat stress —are increasingly acknowledged in cities around the world. As urban areas are densely populated and space is very limited, implementing BG is a, although not comprehensive, meaningful solution that can help increasing the areas climate resilience without compromising on living space, as these rooftops otherwise remain unused.

Despite the high potential benefits, the current application of nature-based solutions on pitched roofs remains largely limited to green roofs alone (Chapter 2.2.3). The integration of a blue layer, which has already shown to enhance the performance of green roofs on flat surfaces (Chapter 2.2.1), is not yet widely explored for pitched roofs. As the Dutch urban landscape is characterised by its high percentage of (tiled) pitched roofs (Chapter 2.1.1), the exploration of BG for pitched roofs could potentially be valuable when looking at urban climate resilience. However, research is needed regarding e.g. efficiency and strategic placement (Chapter 3). A modular BG roof test setup was designed (Chapter 5.5) to be placed at the field lab at LILa, where it will provide a platform for the required research. As small-scale research in a semi-controlled research environment can only merely provide insights into the small-scale effectiveness of BG roofs, this research project should later be extended into the real built urban environment to quantify the larger social benefits, such as flood reduction and reduction of the UHI effect.

When considering the retrofitting BG solutions in the existing built environment, structural feasibility—particularly in terms of weight load—must be addressed in. Although a detailed structural analysis was beyond the scope of this project, the topic emerged in discussions with both homeowners (Chapter 4.2) and experts (Chapter 2.2.3.3). An affordable solution that avoids major structural changes, such as reinforcing the existing construction or removing the original roofing, is highly desirable, as this lowers the barriers to implementation and increases the likelihood of widespread adoption (Chapter 2.1.4) and thus effectiveness of the solution (Chapter 2.1.3.4).

7. Geographical Limitations

This thesis focusses on the Netherlands, as this is a unique country in the sense of population density and particular roof landscape in the urban areas, this thesis only applies to the Netherlands. To some extent, future results from research executed at LILa can be applied to counties with a similar climate now and in the future, thus the north-west of Europe; Belgium, the north and west of France, the north and northwest of Germany, parts of Denmark, the United Kingdom, Ireland (Beck et al., 2018).

8. Reflection

In this final chapter of my thesis, I would like to reflect on the process I went through over the last year, writing this thesis, on a more personal note. I would like to briefly address parts of the process that, in retrospect, I would have gone about differently, things I learned and aspects that were out of my control but might have influenced the process and outcome of this thesis.

Initially it was communicated that there was quite a large budget available for this project, which is why, amongst other reasons, the methodology Research through Design was initially deemed most suitable. With this approach, various (partial) prototypes are created, tested and evaluated through which knowledge is gained that is then incorporated into the subsequent design cycles. However, when transitioning from the initial literature research into the first prototyping phase, it was announced that the university was going to make some significant budget cuts, and it was likely but uncertain that this project would be affected by that. This had a major impact on the speed and course of this project; as the details and actual impact of the situation only became clear after the summer break, this led to an uncertain period and a need for completely changing my approach to this project after it became clear that the budget for this project changed to practically zero.

When changing methodologies, a combination of HCD and DT was chosen as foundation, initially intending to follow the double diamond model, diverging and converging over the different stages of the project. In practice, however, it was found that the diverging stages tended to follow a linear path, possibly caused by the large scope of this project. Trying to address both the real-world urban climate challenge and develop a research-oriented concept for LILa simultaneously resulted in two parallel but somewhat incomplete tracks. While exploring the broader context of the overarching projects end-goal provided valuable insights, focussing on developing a system for LILa would have resulted in a more satisfactory outcome.

An additional struggle that resulted from not initially narrowing the scope of the project, is that it quickly became clear the overarching goal of implementing BG on existing pitched roofs without any structural changes might not be realistic. Although it was discussed and decided to leave this for future research, it felt like avoiding a fundamental obstacle – the "elephant in the room". While I recognize the insights that can be gained from the research at LILa's field lab regarding the effectiveness and efficiency of BG on pitched roofs, it at times felt demotivating to pursue a vision that, in its current form, may not be realistically attainable.

During this thesis, I have learned a lot regarding both the topic and myself. As during my entire study of Industrial Design Engineering most projects were done in groups, I only realized during this thesis how much I thrive working in teams in terms of inspiring and motivating each other, building forward on each other's ideas and having a broader set of expertise on hand. I also found that it is much easier to make informed and well-argued decisions after having had the chance to discuss with people with a similar knowledge and understanding.

In retrospect I would have done many parts differently, such as narrowing the scope, the choice of methodology and asking for support from my peers and supervisors, but that only emphasizes that this project has been a valuable learning experience for me.

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Appendices

Appendix A: Available Subsidies BG roofs per municipality

1	2	3	4	5	6	7	8	9	10	11
Tilburg	E.B.	€ 25,00	50%	€ 2.500,00	6				10	
	E.B.	€ 40,00	50%	€ 2.500,00	6		30			10
Utrecht	E.S.	€ 25,00	50%	€ 20.000,00	10	Yes	15	Sedum and moss	5	
	E.B.	€ 35,00	50%	€ 20.000,00	10	Yes	50	sedum with at least 30% herbs and flowers	5	
	I.	€ 50,00	50%	€ 20.000,00	10	Yes	70	maximum 50 % sedum and moss and minimal 50% shrubs/trees and grasses	5	minimum saturated weight of 200 kg/m2

1. Municipality
2. Vegetation type (Extensive (E)/Intensive (I), Sedum (S)/Biodiverse(B), not specified (n.s.))
3. Maximum subsidy per m^2
4. Maximum amount subsidized
5. Maximum amount of subsidy per application
6. Minimal area for valid application in m^2
7. Combined subsidy with neighbours possible (yes/no/not specified (n.s.))
8. Minimum water buffering capacity in Liters per m^2
9. Vegetation requirements
10. Minimum time the system stays on the roof in years
11. Additional requirements

Table A1: *Overview Available Subsidies for (Blue-)Green Roofs per Municipality* Including Requirements

1	2	3	4	5	6	7	8	9	10	11
Provincie Flevoland	E.S.	€ 25,00	50%	€ 2.500,00	25	n.s.				
	E.B.	€ 35,00	50%	€ 2.500,00	25	n.s.				
Amsterdam	n.s.	€ 30,00	50%	€ 50.000,00	30	Yes	30	maximum 50% sedum and moss	5	
	n.s.	€ 50,00	50%	€ 50.000,00	30	Yes	50	maximum 50% sedum and moss	5	
Den Haag	n.s.	*	50%				1000 for entire system			500 per 1000 L rain-water retained
Enschede	E.S.	€ 20,00	50%	€ 3.000,00	1	No	20		10	
	E.B.	€ 30,00	50%	€ 3.000,00	1	No	20	minimum 50% native grasses, herbs and/or shrubs	10	
	E.	€ 30,00	50%	€ 3.000,00	1	No	40		10	
Haarlem	n.s.	€ 25,00	50%	€ 1.000,00	20	yes	30		5	
	n.s.	€ 35,00	50%	€ 1.000,00	20	yes	30	maximum 50% sedum and moss	5	
	n.s.	€ 35,00	50%	€ 1.000,00	20	yes	50		5	
	n.s.	€ 35,00	50%	€ 1.000,00	20	yes	30		5	Includes solar pannels
Rotterdam	n.s.	10+		€ 40.000,00	20		(500 at least in total to get additional subsidy)			Additional subsidy for waterbuffering + diverse vegetation
Schieland/krimpenerwaard	n.s.	€ 10,00	100%	€ 25.000,00	15	yes				Additional subsidy for waterbuffering (0,30 per L, minimum of 500 L)
Tilburg	E.B.	€ 25,00	50%	€ 2.500,00	6				10	
	E.B.	€ 40,00	50%	€ 2.500,00	6		30		10	

Appendix B: Available Extensive Green for Flat Roofs

1	2	3	4	5	6	7	8	9
rotsplantenshop	traditional	25	30	Sedum	loose substrate	9	80	45
	lightweight budget	15	30	Sedum	rockwool fiber	6	55	39
	lightweight		37	Sedum	rockwool fiber	9	55	45
	sedum tray light	10	21	Sedum	integrated in casette	7,5	58	54
	sedum tray		31	Sedum, 8-12	integrated in casette	8,5	80	54
	Sedum mix		30	Sedum, 8-12	loose substrate	9	80	45
	Sedum-herb		31	sedum 4-6, herbs 14-20	loose substrate	17	90	53
	Bees & butterflies		61	sedum 4, grass types 5-7, >40 other plants and herbs	loose substrate	22	45	82
SedumSpecialist	traditional	5	35	sedum	loose substrate	9	85	55
	lightweight	25	30	sedum	rockwool fiber	7	45	50
	sedum tray	15	30	sedum	integrated in casette	8,5	80	64
	sedum tray light	20	21	sedum	integrated in casette	7,5	55	57
	Herbs	10	45	sedum 4-6, herbs 20-25	loose substrate	12	105	66

Table B1: *Overview Extensive Green for Flat Roofs Available to the Consumer*

1	2	3	4	5	6	7	8	9
NatureGreen	Lightweightsedum roof	20	31	Sedum 95%, 10-12	rockwool fiber	6	45	52
	Lightweightsedum roof	20	42	Sedum 95%, 10-12	rockwool fiber	8	60	55
	Standard	15	35	Sedum 95%, 12	loose substrate	10	80	56
	Sedum casettes	15	30	Sedum 95%, 12	integrated in casette	8	80	59
	Carbon greenroof	15	35	Sedum 95%, 12	loose substrate with dunite	6	80	55
	Carbon sedum casettes	15	30	Sedum 95%, 12	substrate with dunite integrated in casette	8	60	69
Green Roof Shop	Ms. Slim fit	15	41	Sedum	rockwool fiber	10	61	55
	Mr. quick and easy	15	25	Sedum	integrated in casette	7	66	55
	The big slurper	15	47	Sedum	rockwool fiber + loose substrate	12	89	63
	Queen B(iodiverse)	5	75	Sedum + wildflowers	loose substrate	18	193	90
	Plain Jane	15	23	Sedum	loose substrate	9	83	53
	Plain Jane - the slow starter	5	24	Sedum propogations	loose substrate	9	91	45
	Queen B(iodiverse)	5	76	sedum plug plants	loose substrate	18	204	76
	Plain Jane - the developer	5	31	sedum plug plants	loose substrate	11	120	60
Sedumworld	Lightweight			sedum, 6-8	substrate mat	8	45	42
	Sedum casettes							55
rotsplantenshop	traditional	25	30	Sedum	loose substrate	9	80	45
	lightweight budget	15	30	Sedum	rockwool fiber	6	55	39
	lightweight		37	Sedum	rockwool fiber	9	55	45

Appendix C: Low-fidelity prototype

C1. Detailed design & production plan prototype

Table C1.1

Bill Of Materials

Item nr.	Quantity	Material	Dimensions	Supplier
1.	6	4 mm Plywood	600 x 1200 mm	DesignLab
2.	4	Pine wood slat	20 x 20 x 2700 mm	Hornbach
3.	3	Filter cloth	400 x 1100 mm	Farwick
4.	1	PP Gravel grid (hexagonal grid)	300 x 1000 mm	Hornbach
5.		HDPE drainage grid	300 x 1000 mm	Farwick
6.	2	pvc pipe	∅ 13 mm, 1050 mm	DesignLab
7.	3	Plastic bottles	500 ml	Store
8.	3	Balloons		Store
9.	3	Sedum mat	300 x 1000 mm	GroenDak
10.	4	Substrate	20 L	GroenDak/Farwick
11.		D3 Woodglue		DesignLab
12.	±20	Nails 25 mm		DesignLab
13.	± 50	Staples type A 4 mm		DesignLab
14.		Ductape		DesignLab
15.	6	Tie-wraps		Action

Tools

- ☐ Glue clamps
- ☐ Hammer
- ☐ Staple gun
- ☐ Scrap cardboard/wood
- ☐ Stanley knife
- ☐ Laser cutter
- ☐ Band saw
- ☐ Scissors

Item specifications

Item 1

The 6 4 mm plywood plates (**1**) will be cut with the laser cutter according to the laser cut file as shown in the figures below (Figure C.1.1, C1.2), resulting in the following parts:

Table C1.2

Item Specification Item nr. 1

Item nr.	Quantity	Item code*	Specification
1.1.1	3	B1	
1.1.2	3	B2	
1.2.1	6	MSO	
1.2.2	6	MSI	
1.2.3a	3	MLO	
1.2.3b	3	MLO	With perforations
1.2.4a	3	MLI	
1.2.4b	3	MLI	With perforations
1.3.1	6	TSO	
1.3.2	6	TSI	
1.3.3	6	TLO	
1.3.4	6	TLI	
1.3.5	3	TIO	
1.3.6	3	TII	

*Item codes imply to what part of the prototype the Item belongs. The first letter implies the layer (**B**ottom, **M**iddle, **T**op, **F**ilter), the second the side (**S**hort side, **L**ong side, **M**iddle) and the last whether it is the **I**nside or **O**utside of the part.

The items configured on the plates as below result in a need for 2 1200 x 600 mm plywood plates per panel. The individual items are labelled with their item code to make assembly easier.

Figure C1.1

Configuration Item nr. 1 on plywood for laser cutting 1/2

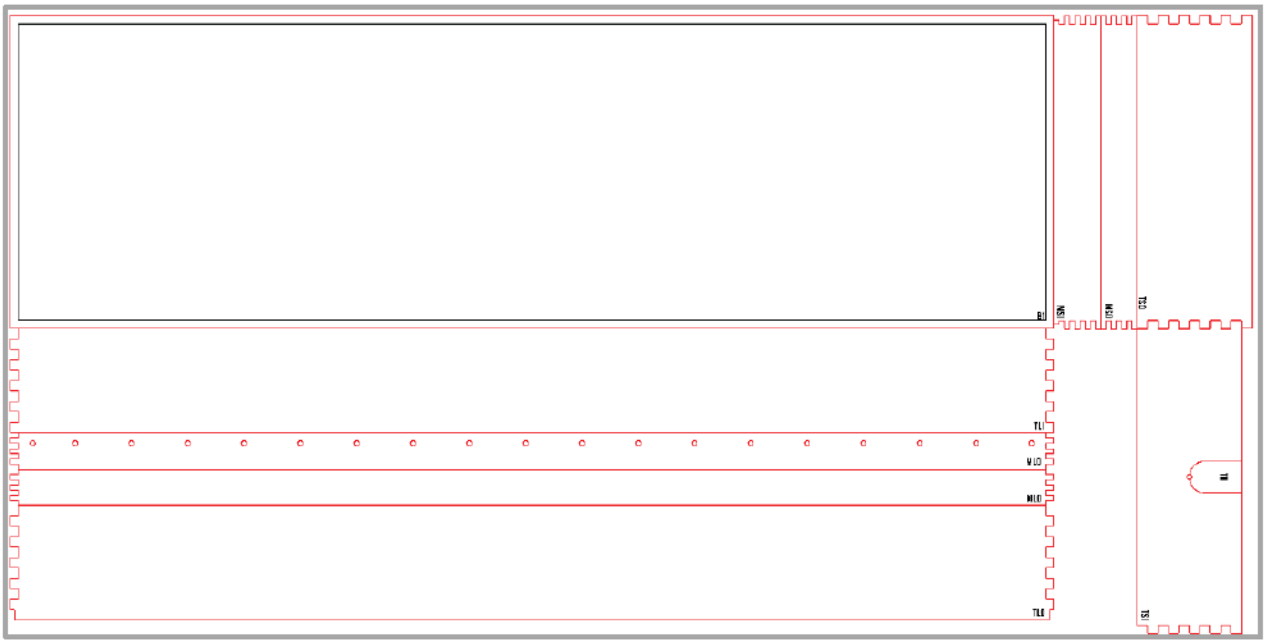
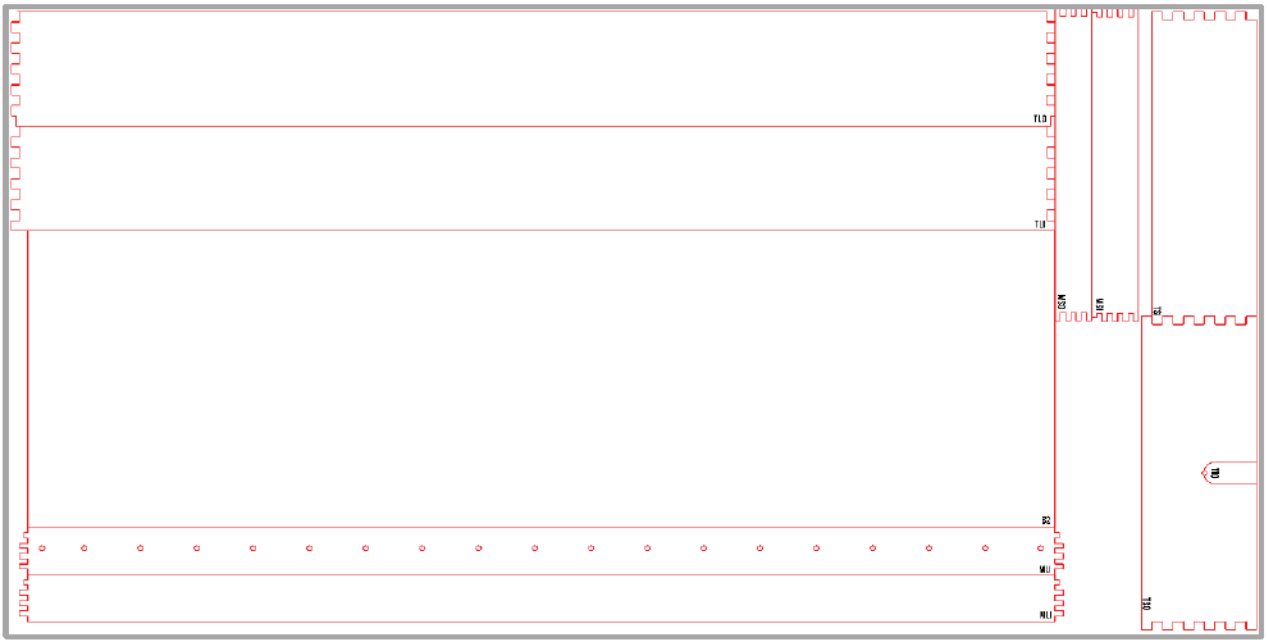


Figure C1.2

Configuration Item nr. 1 on plywood for laser cutting 2/2



Item 2

The wooden slats are cut into the correct length and shape (Figure C1.3) using the band saw.

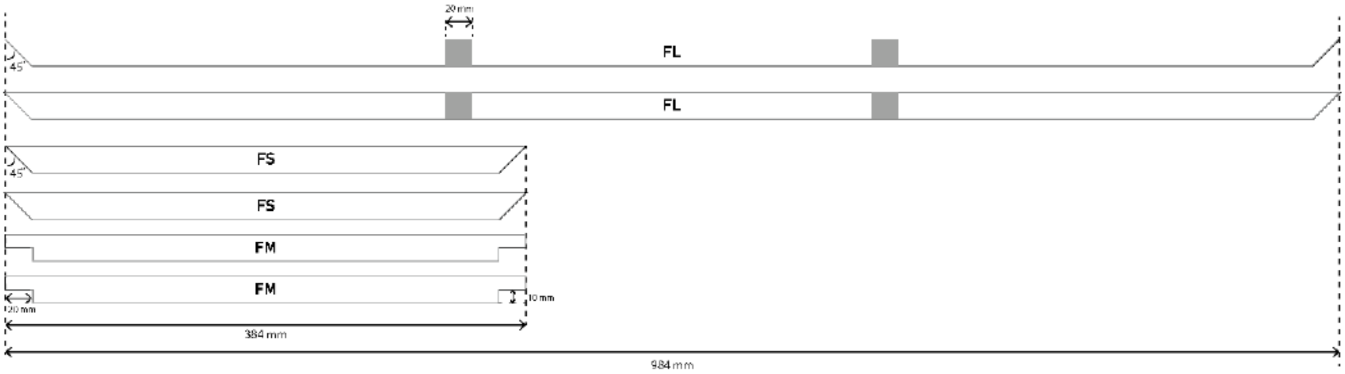
Table C1.3

Item Specification Item nr. 2

Item nr.	Quantity	Item code*	Specification
2.1	6	FL	2 slots of 20 x 10 mm
2.2	6	FS	
2.3	6	FM	

Figure C1.3

Configuration Item nr. 2



Item 10

Nutrient base for green roofs, extremely suitable for sedum. The mixture consists of mineral parts, pure organic materials, 100% natural fertilizers and some additives. The substrate complies with the guideline 'BRL 9341', an assessment guideline regarding the environmental hygiene requirements for stony substrates.

Product specifications

- Grain size 0 – 12 mm
- delivery weight approximately 950 kg / m^3
- saturated weight approximately 1350 kg / m^3
- shrinkage 19 %.

Assembly tree

The prototype was then assembled in the order as seen in the assembly tree below (Figure C1.4, Figure C1.5).

Figure C1.4

Assembly Tree Order Of Assembly

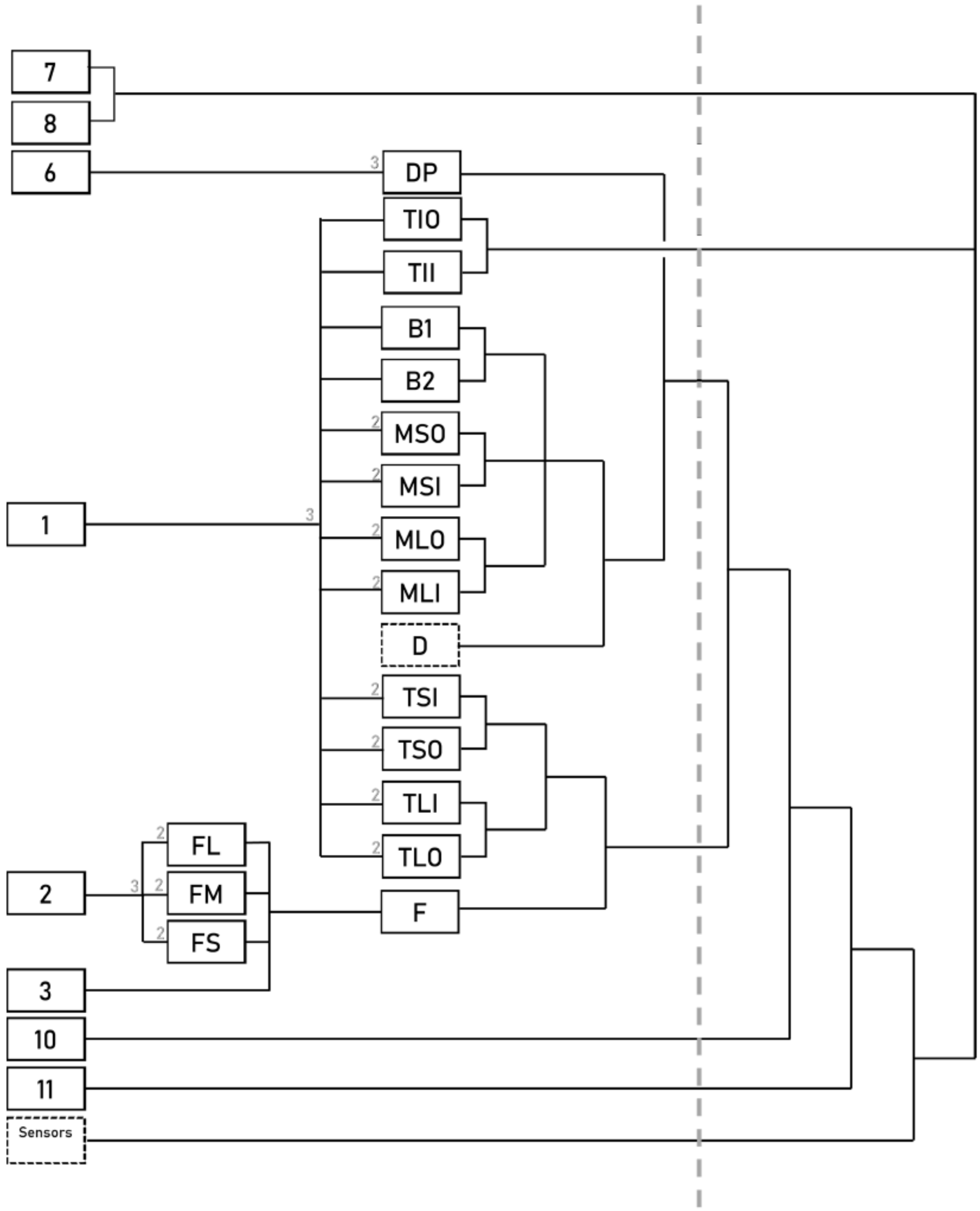
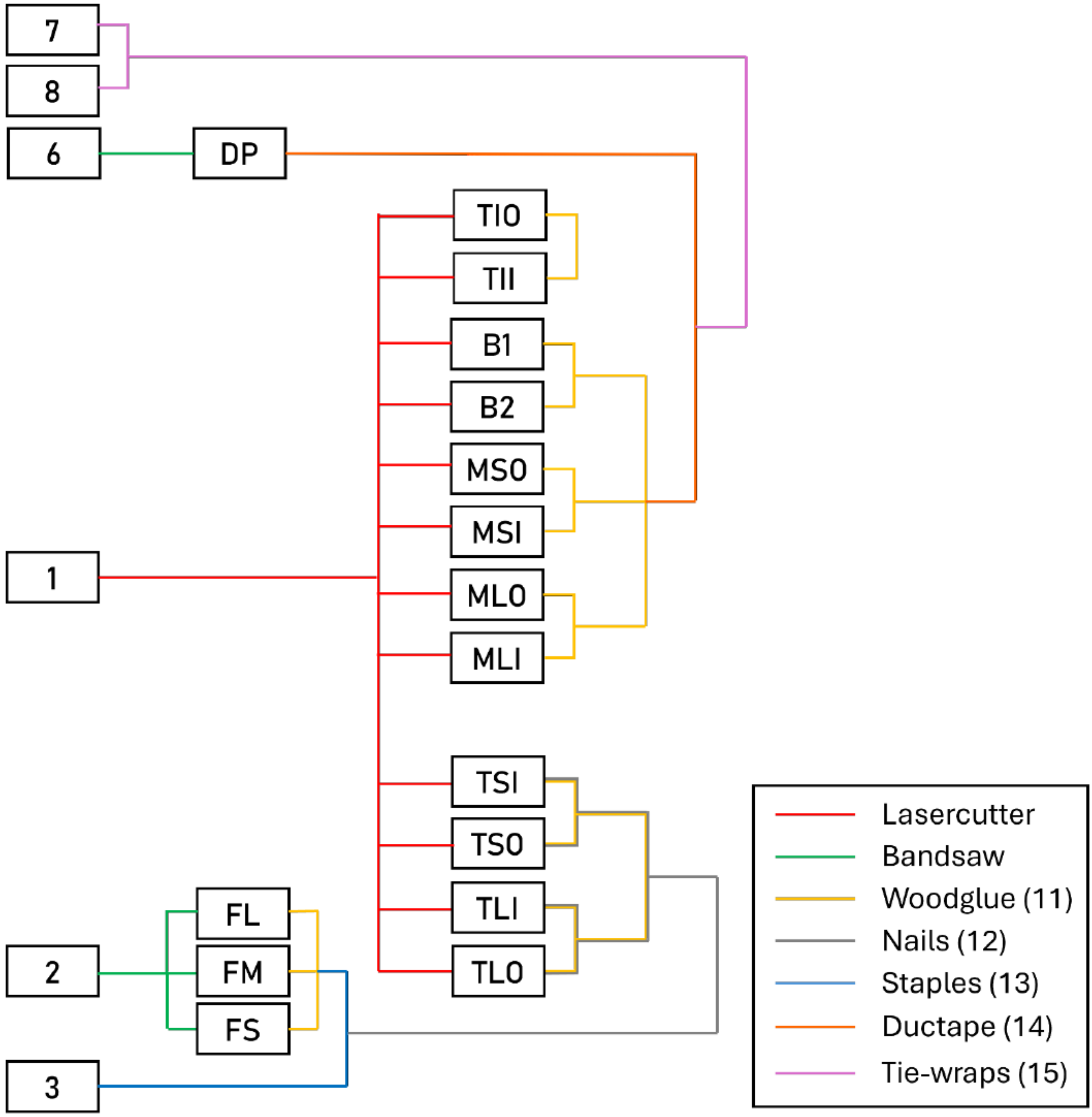


Figure C1.5

Assembly Tree Method of Assembly

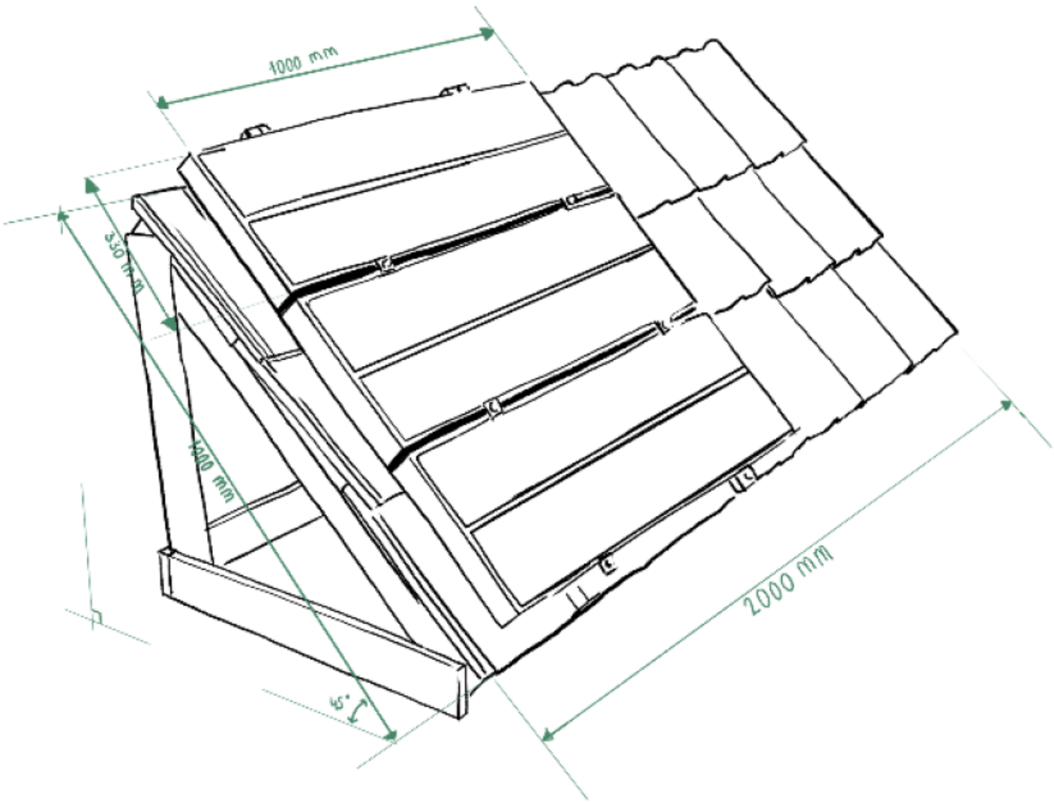


C2. Inventory Materials Present

A previous research project, conducted by Youssef El Sadek, was done on the performance of green roof panels on a sloped roof (roof angle of 45 degrees). This project was done on request of Green Panels B.V. During the project, the main objective was to analyze the performance of different substrates in regard to moisture content and compare temperature differences between the roof with the green roof panels and the control group, to see if green roof panels are effective in heat reduction.
A test-set up was built and placed on top of the Horst, a building on the campus of University of Twente. The test-site itself was a flat roof, but for the tests a section of sloped roof was build, on which the tests were performed (Figure C2.1).

Figure C2.1

Schematic Drawing of Mock-roof on the Horst with Dimensions



The project by Youssef and associated installation can be used as starting point and inspiration for this project.

Inventory of the test-installation

- A wooden roof structure with the following dimensions: 100 x 200 cm, slope angle of 45 degrees
- Sloped section covered with *Neroma* roof tiles
- 2 vertically placed rails
- 4 hooks/ that attach the rails to the roof tiles (2 per rails)
- 6 clamps with wingnut that attach the green panels to the rails
- 3 green panels filled with different kinds of substrate and sedum plants, made from recycled HDPE (1000 × 330 × 60mm)

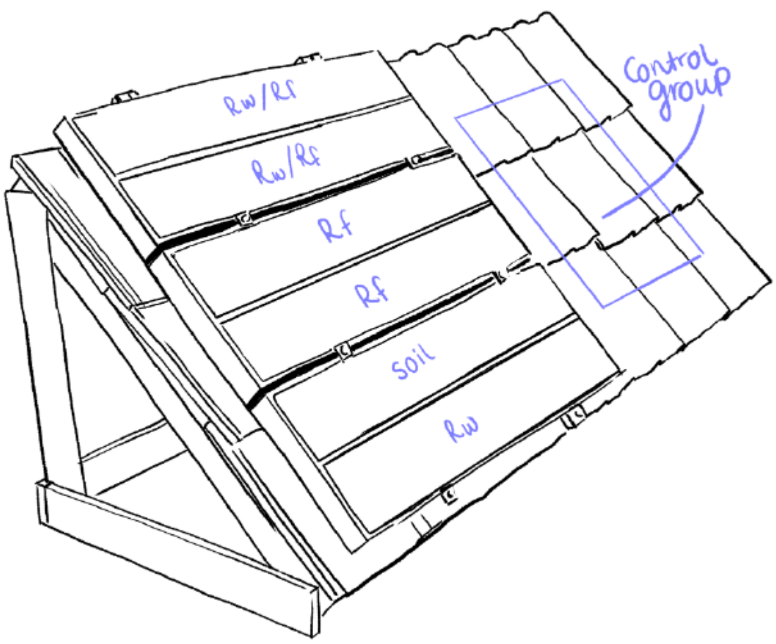
Used sensors

- 6x sensbox mini
- 6 Environmental sensor (BME680)
- 6 Soil moisture & temperature sensor (Treubner SMT50)

From this research, it was concluded that the Rockwool (Rw) and Recycled Fabric (Rf) substrates, although they seemingly had a lot of potential, did not outperform the standard soil.

Figure C2.2

Schematic Drawing of Test Setup Youssef



Appendix D: Co-Design

D1. Plan of Approach

Objective

A co-design session with the target groups involved by the implementation of blue-green for sloped roofs in the existing built environment. The session will be a mix between generative research (learning FROM product/service users) and developmental design (learning, testing and creating WITH product/service users).

This co-design session is meant to gain insight into the ideal relation between the product and the user;

- How actively is the user involved with the product in the different stages of the product (design, production, installment, regular/incidental maintenance)?
- What does the interaction between product and user look like? For example, is there an app or a moderation panel the user can use to see information? Can they also adjust the functionality of the panel?

Before a product will be designed for implementation in the built urban environment, a functional prototype for research at LILa will be implemented. By having this co-design session before developing the final concept for LILa, the need for certain research regarding translation of the concept to the built urban environment can be considered in the design.

Participants

The co-design session will be done with the target users of the future product. They can be split into three categories:

- Home owners
- Home renters
- Housing cooperations

Individual co-design is good for eliciting granular feedback (Arcia et al., 2024), a less filtered insight in the stakes of the participants, as their answers will be less influenced by the perception and feedback of other participants (limits the need to respond in a "socially acceptable" way).

Co-design in groups (≥2) is good for establishing consensus, stimulating discussion and encouraging ideas and brainstorming (Arcia et al., 2024). However, group dynamics might influence the outcome.

Methodology

As the three groups might have different points of view/stakes for this product, it is important to have them split into these groups at least for the first part of the session, or let them do this as individuals, to not lose potential insights on this difference in stakes.

There might be a large difference in motivation/involvement between as well as in the different target groups. Therefore, it might be interesting to have a discussion between the participants within and from the different groups to see if a middle ground or a solution can be found here.

A short introduction on blue-green roofs and their potential benefits and drawbacks will be given, after which the participants are asked to all individually design their relationship in the ideal situation. An example of human-product relation mapping will be given regarding a completely other product (e.g. a Fitbit, or IKEA bookshelf). The designing of scenarios/interaction/relations will be done on paper.

Each individual / group will be given markers/pens, paper and a set of "icons", representing a person, tool or service. This might already nudge them to think in a certain direction, which is why the icons will not be detailed. They are mainly meant for participants to spark their creativity and speed up the process, as most of them are probably not used to these kinds of activities and starting form a blank canvas.

The participants can combine writing, drawing and the icons to clarify what they have in mind.

This first part will mainly comprehend the interaction between the user and the product in the day to day live. This part will not be discussed, but anonymously handed in.

In the second part, the users will be split into groups, for which 4 varieties are possible:

- Homeowners
- Home renters
- Housing cooperations
- ~~Home renters + housing cooperations (→especially interesting what the consensus will be on who is responsible and to what extent)~~

Again, the participants are asked to design their relation and interactions to the product, but now in 4 different stages/scenarios:

- Consideration of why to buy or not
- Purchase/installation (who designs, produces and installs it?)
- Regular maintenance (who does this? During hot months the panel might need irrigation, and the panel has to be completely drained during the wintertime. How will this be done?)
- Incidental maintenance (something is broken, who will fix it?)

All groups will briefly pitch the relationship/interaction between them and their blue-green roof panel.

00:00	00:15	00:30	00:45	01:00	01:15	01:30	01:45	02:00
Walk-in	Introduction Explain part 1	Part 1		Make groups + explain part 2	Part 2		Groups present + Evaluation	Clean up

D2. Co-Design Materials

Figure D2.1

Icons Co-Design

Figure D2.2

Implementation Considerations

WHY WOULD I DECIDE TO INSTALL A GREEN ROOF:	WHY WOULD I DECIDE TO NOT INSTALL A GREEN ROOF:

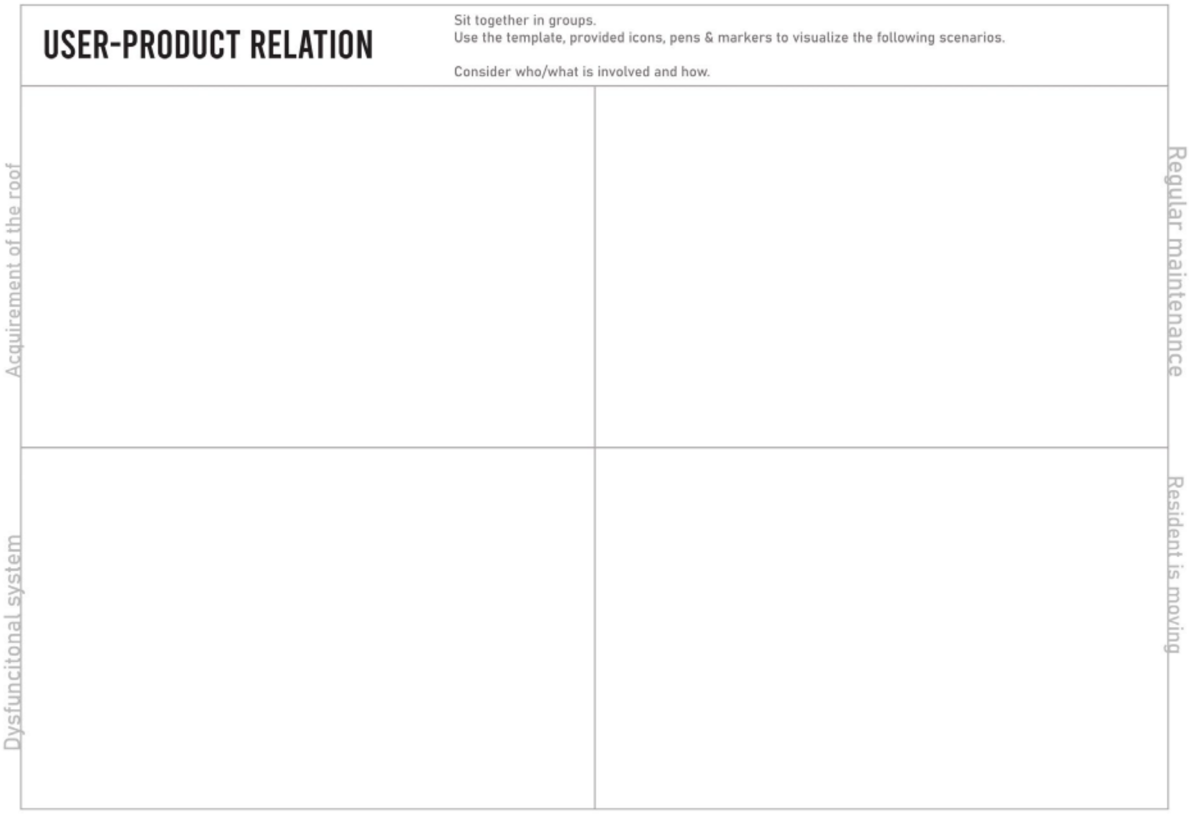
Figure D2.3

Individual Assignment Product-User Relation

USER-PRODUCT RELATION	Use this template, provided icons, pens & markers to visualize your PRODUCT-USER RELATION with the roof. Do you interact with it? If yes, how? With what purpose? How often? If you don't, how are you sure the roof is functional? How do you feel about the roof?

Figure D2.4

Group Assignment Product-User Relation



D3. Co-Design Results

Figure D3.1

Implementation Considerations P1

WHY WOULD I DECIDE TO INSTALL A GREEN ROOF:	WHY WOULD I DECIDE TO NOT INSTALL A GREEN ROOF:
primarily because I like green vegetation	possible problems with periodic maintenance of the roof?
support of nature & environment	I expect my neighbours will dislike it, but that won't stop me. :)
balancing heavy rainfall on the house & garden	
just feels good. ♡	

Figure D3.2

Implementation Considerations P2

WHY WOULD I DECIDE TO INSTALL A GREEN ROOF:	WHY WOULD I DECIDE TO NOT INSTALL A GREEN ROOF:
Better insulation/cooling	High load on roof might incur maintenance costs over many years
I think they look nice	expensive
It is more sustainable	maintenance might be difficult depending on the vegetation
Works well with solar ~~pol~~ panels	hard to maintain over extreme weather
Water retention (ties into sustainability again)	

Figure D3.3

Implementation Considerations P3

WHY WOULD I DECIDE TO INSTALL A GREEN ROOF:	WHY WOULD I DECIDE TO NOT INSTALL A GREEN ROOF:
* mooi uiterlijk -	* net nieuw dak op boerderij en zonnepanelen
* groen in de stad +	* wij wonen in buitengebied, dus al veel groen
* koeling (tuinhuis) + isolatie	← maar- zie links
* subsidie mogelijkheden	* aanleg? ingewikkeld - te zwaar? golfplaten op constructie

Figure D3.4

Implementation Considerations P4

WHY WOULD I DECIDE TO INSTALL A GREEN ROOF:	WHY WOULD I DECIDE TO NOT INSTALL A GREEN ROOF:
looks nice/more green!	Concerns about leakage
less heat in the summer?	Weight: requires construction
	water consumption (in summer)

Figure D3.5

Implementation Considerations P5

WHY WOULD I DECIDE TO INSTALL A GREEN ROOF:	WHY WOULD I DECIDE TO NOT INSTALL A GREEN ROOF:
cooling effect with in the appartments on top floor and the whole complex	My "Woningbouw" does not want to spend money on it, ~~as it need~~
~~less~~ less water 'overlast' (we have that often)	It needs often maintainance, which i dont know how that ~~would~~ would look like.
Better for the environment.	I am happy to pay for maintance, but not for installation as i cannot life there as long as I would like.

Figure D3.6

Individual Assignment Product-User Relation P3

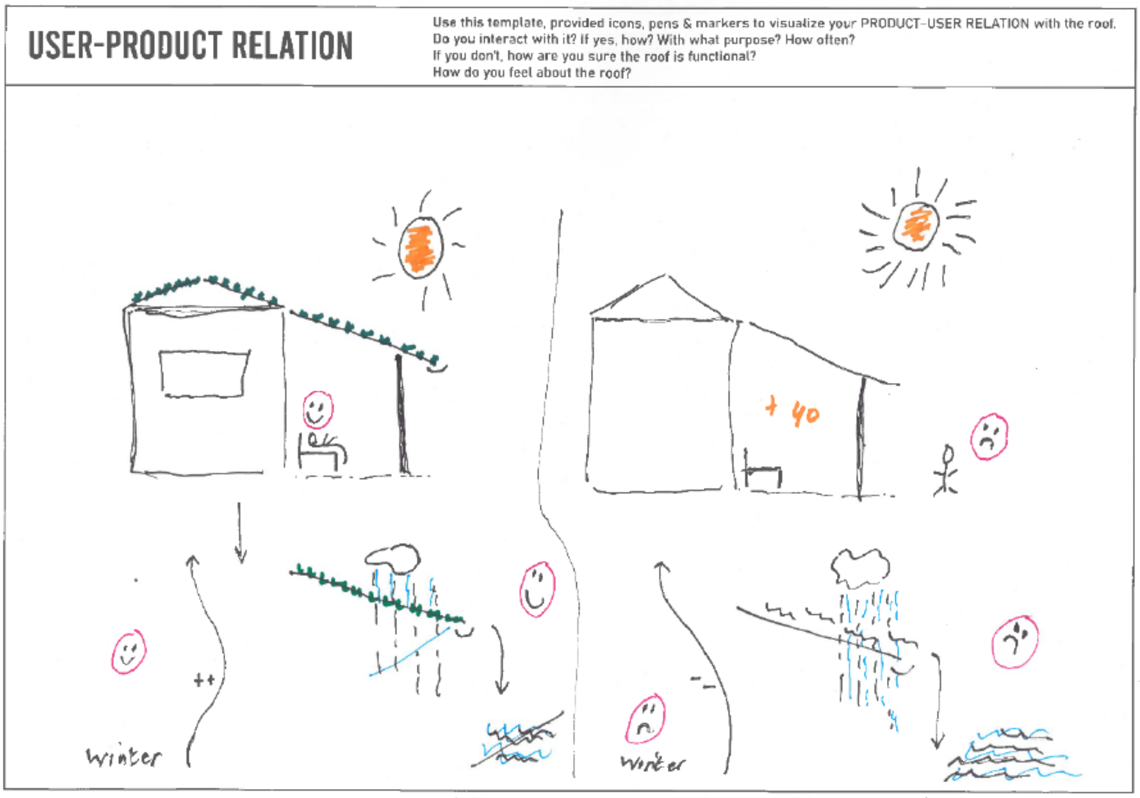


Figure D3.7

Individual Assignment Product-User Relation P4

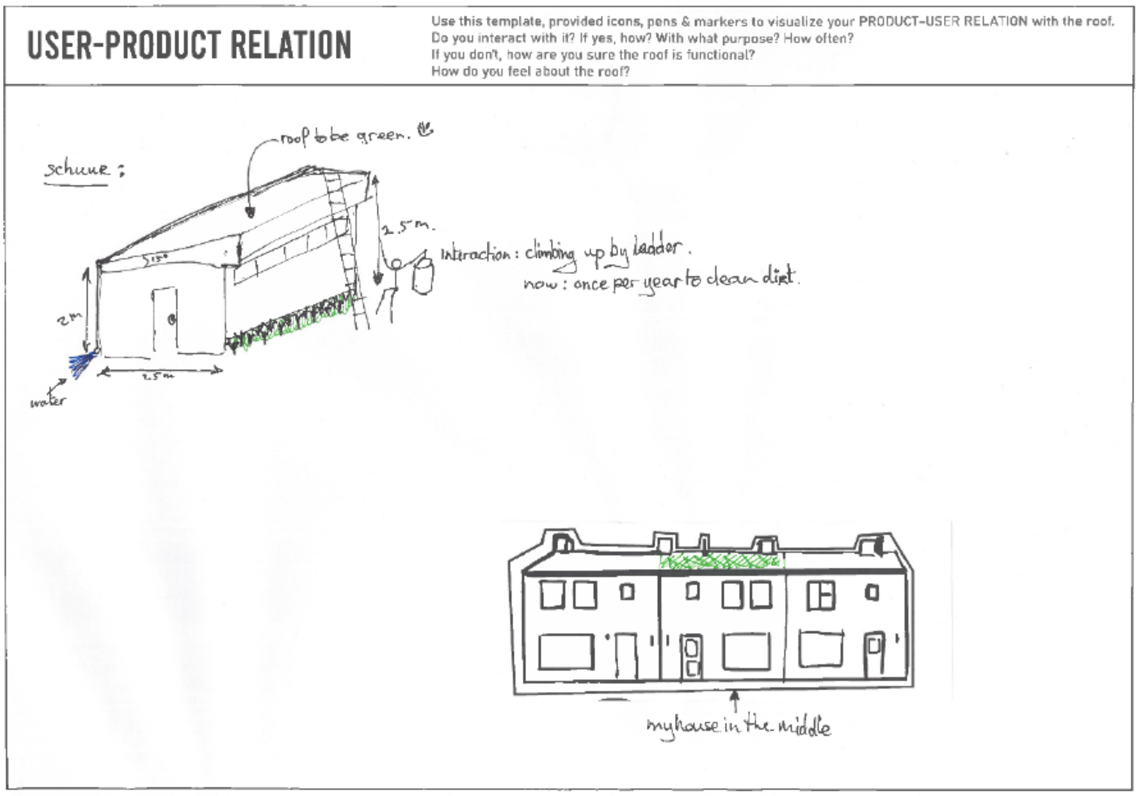


Figure D3.8

Individual Assignment Product-User Relation P1

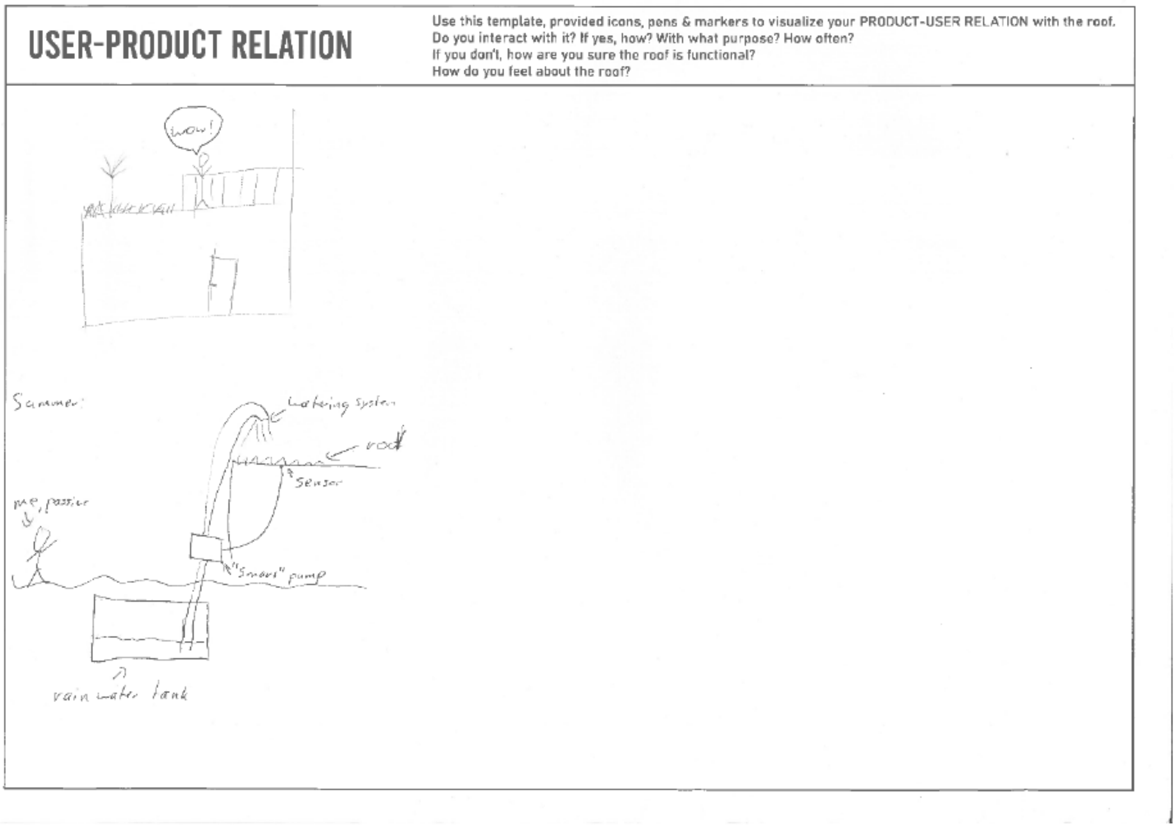


Figure D3.9

Individual Assignment Product-User Relation P2

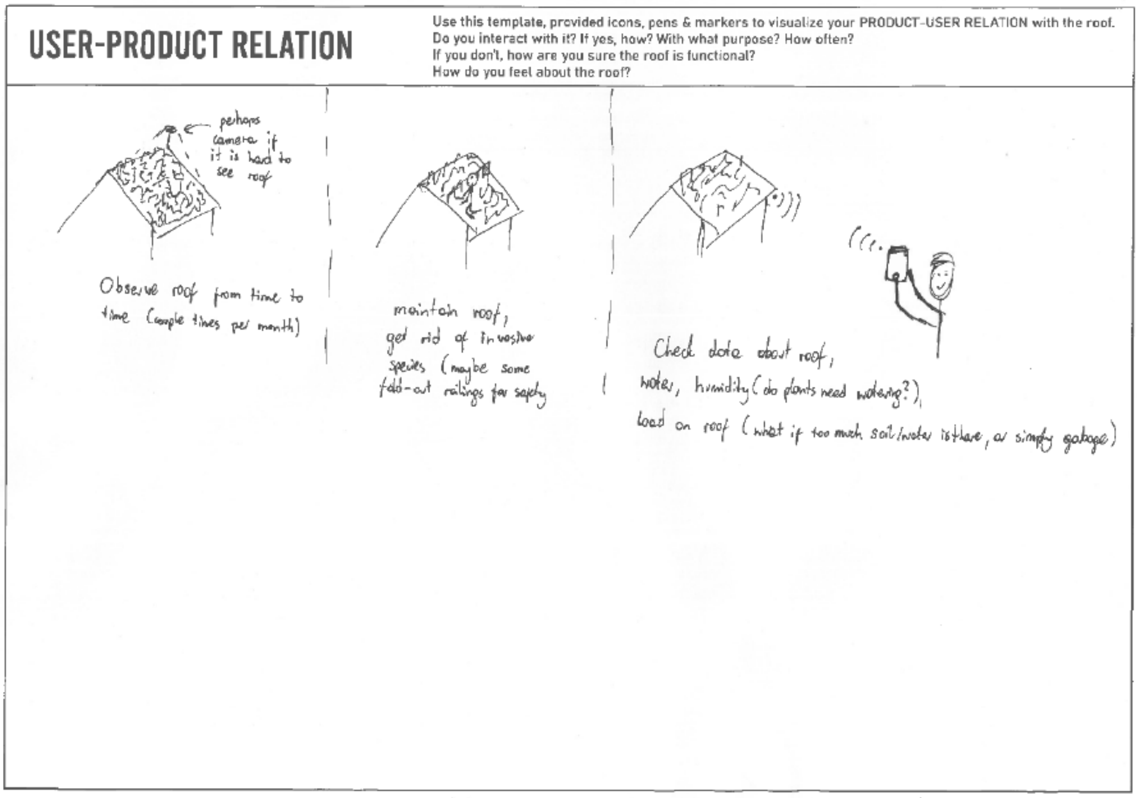


Figure D3.10

Individual Assignment Product-User Relation P5

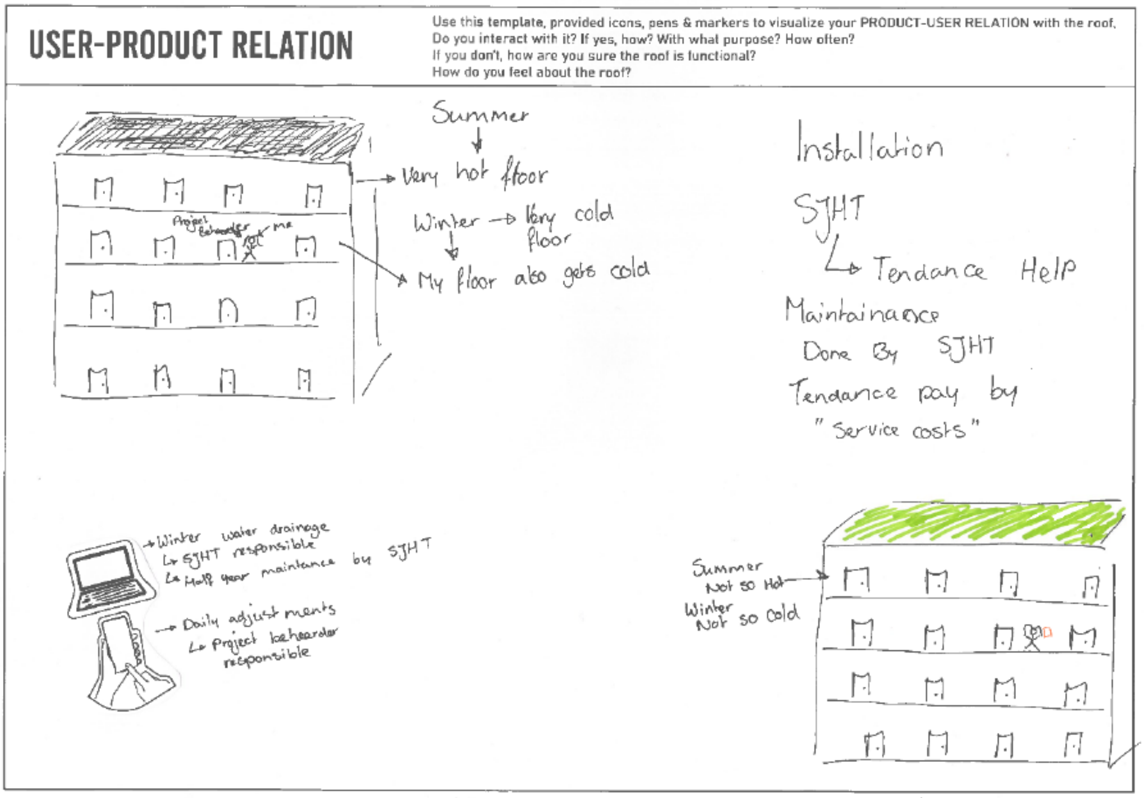


Figure D3.11

Group Assignment Product-User Relation - Tenants

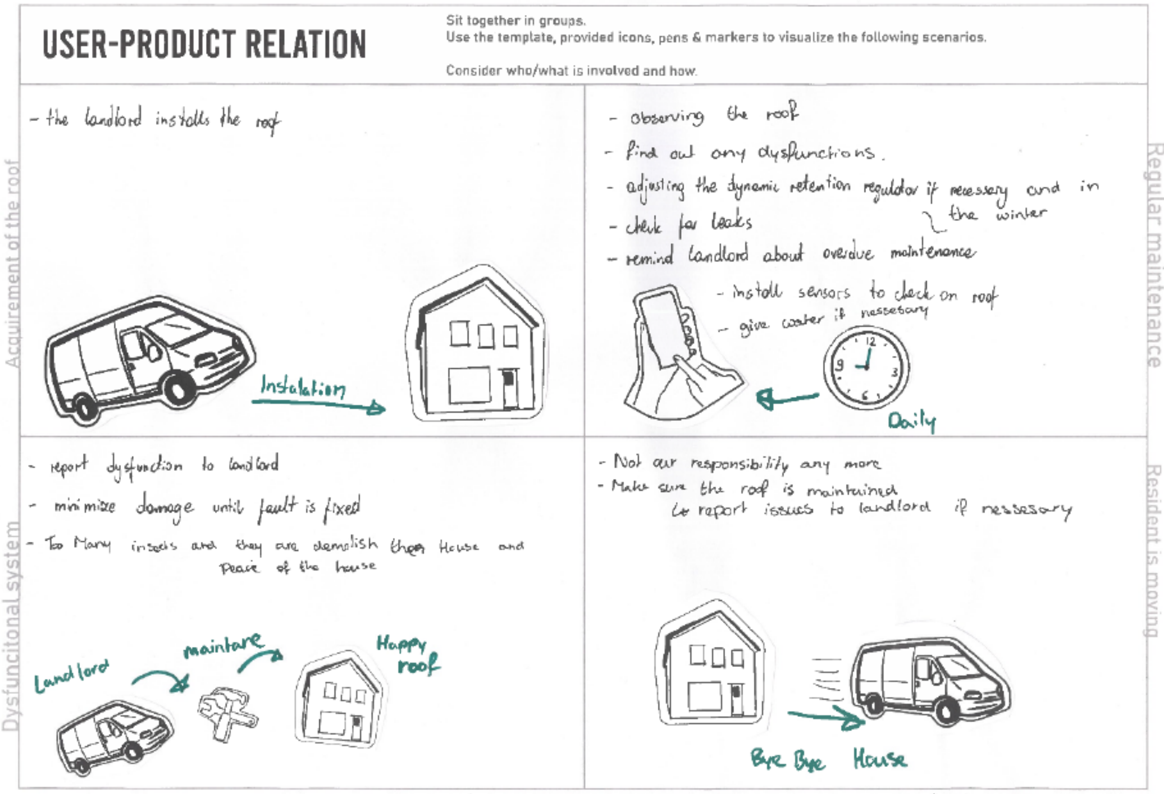
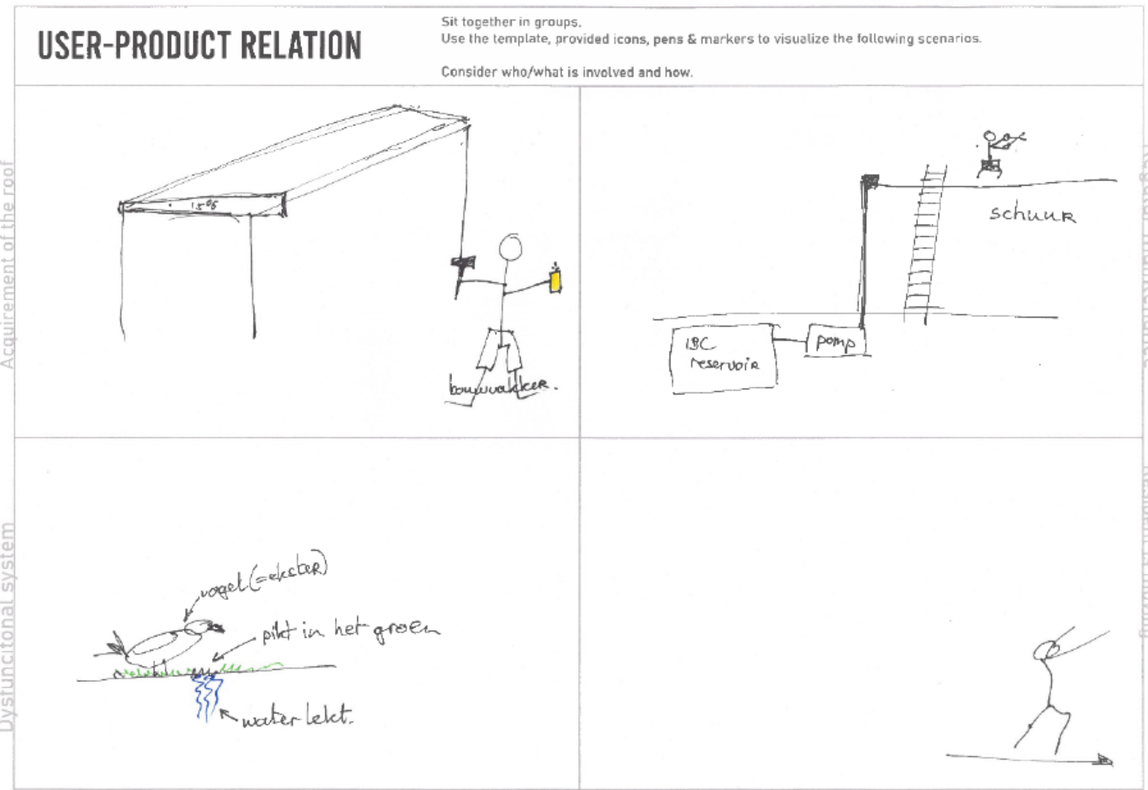


Figure D3.12

Group Assignment Product-User Relation - Homeowners



D4. Evaluation Pilot Co-Design

For the co-design pilot, 6 individuals with a background in Industrial Design Engineering were invited to participate in the session. The session would be performed as described in the plan of approach, apart from the individuals getting assigned 'persona's'. These personas were either homeowners, tenants or employed by a housing corporation. A short paragraph gave the participants some insights into the core values and beliefs of these persona's, and they were asked to perform the assignments from the point of view of the personas.

After the session, a short evaluation took place on how the participants experienced the session, and if they had any remarks on what could be improved. As they were all familiar with the concept of co-design sessions as industrial design engineers, their feedback would be very valuable to improve the plan of approach for the actual co-design session.

Start: 10:05

5 participants (1 person did not show): 2 home owners, 2 housing corporations, 1 tenant.

During the 2nd assignment, the housing corporations grouped up with the tenant, resulting in interesting but long discussions. For the first frame of the 2nd assignment, there was also some discussion on whether people wanted the roof.

Finish: 11:45

Feedback points from evaluation with participants

Timeline

- Have a longer introduction, as participants of this session were already familiar with the topic but participants of the next session will not be.
- Introduce more specific details, like what it costs and how much it will make a difference, include information on subsidies.

Assignment

- Adjust example for the first assignment, as it now had the clear division of the 2nd assignment already (cross thingy)
- Maybe don't mix tenants with housing corporation during the assignment, as this will result in long discussions. Have this discussion after the pitches in a dedicated discussion time.
- Include dedicated part for discussion whether or not people actually would want this on their roof and why (not)

Tools/Icons/overall set up

- Have more scissors available if people are cutting their own icons
- It was nice to have icons, maybe have some more different houses so people can find something that resonates with the more.

Other

- Have a dedicated part for discussion on whether people want the roof, pros & cons and their considerations.
- Emphasize need for irrigation during dry periods

- Overall, everyone understood the assignments and the outcome of what people did was as I expected. (not the specific results: they are not important, its more about how people understood the assignment and how the went about it).

Changes to the plan of approach after pilot

Introduction

- Elongate
- Add in more details on costs and results (numbers)

Assignment 1

- Adjust example to be more like the assignment (remove division in template)
- Add in list for people to state why they would consider getting/not getting the roof

Assignment 2

- Just split into the different stakeholders, don't combine tenants and housing corporations in a group

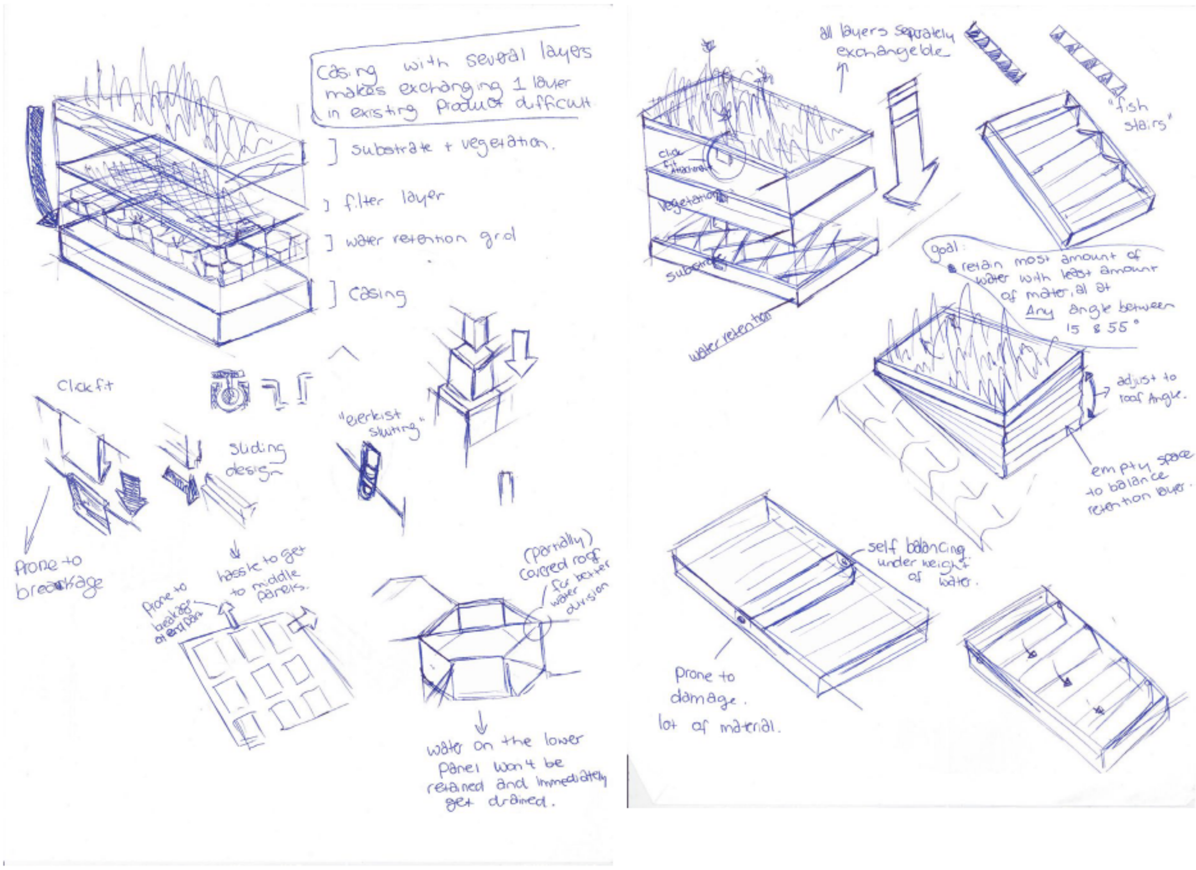
Tools

- Have more scissors + glue available
- Precut some icons

Appendix E: Ideation Sketches

Figure E1

Ideation Sketches BG panel



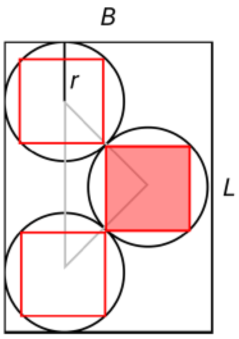
Appendix F: Calculations

F1. Calculations 2 or 3 systems

To decide on whether to place two or 3 systems on the roof, the largest possible BG roof area is calculated for both possibilities, see calculations in Figure F1.1 and F1.2. Basic geometrical formulas were used for these calculations, from which it was determined that the placement of 2 setups would be most space efficient.

Figure F1.1

Calculation Roof Area 3 Systems



$$2r = \frac{L}{(\sqrt{2}+1)} \quad or \quad r = \frac{B}{2(\frac{1}{\sqrt{2}}+1)}$$

$$L = 670\ cm \qquad B = 460\ cm$$

$$r = \frac{670}{2(\sqrt{2}+1)} \qquad r = \frac{460}{2(\frac{1}{\sqrt{2}}+1)}$$

$$\boxed{r \approx 139\ cm}$$

$$A^{panel} \approx (139\sqrt{2})^2 \approx 38642\ cm^2$$

$$A^{green\,roof} = 2 * 38642 = 77284\ cm^2$$

Figure F1.2

Calculation Roof Area 2 Systems

$$B = 460\ cm$$

$$d = \sqrt{(670-2r)^2 + (460-2r)^2}$$

$$\sqrt{(670-2r)^2 + (460-2r)^2} \geq 2r$$

(for circles not to overlap)

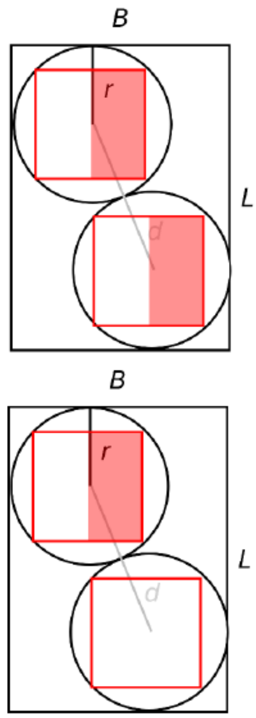
$$r = 172\ cm$$

$$A^{panel} = (172\sqrt{2})^2 = 59168\ cm^2$$

$$A^{green\,roof} = 2 * \frac{1}{2} * 59168 = 59168 cm^2$$

$$or$$

$$A^{green\,roof} = 1\frac{1}{2} * 59168 = 88752\ cm^2$$



F2. Calculations concept 1

For Concept 1, the panel would be mounted on a plateau and be supported on a ring with varying heights that rotates relative to the plateau, to adjust the pitch. In order for this to work, the mounting point of the panel to the plateau must be the middle of the plateau. In Figure F2.1, it is calculated how large the radius of the rotating ring should be to achieve the desired change in heights.

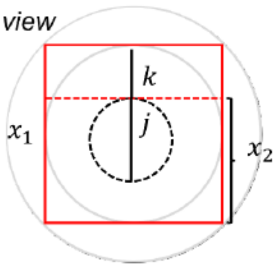
- X_1 is the projection of b (length of panel) when α= 15°
- X_2 is the projection of b when α= 55°
- J indicates the maximum radius of the rotating ring if the panel is mounted in the middle, as the panel should always be supported by this ring.

As j_i is the distance needed from the bottom of the panel to the other side of the ring in order for the ring to fit completely unde the panel. As this distance is significantly larger than j, this concept is deemed not possible.

Figure F2.1

Calculation Concept 1 Middle Mounting Point

top view

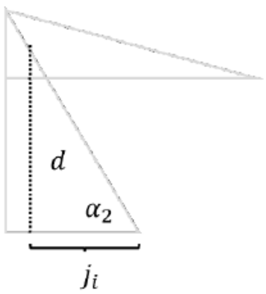


$$j = x_2 - k$$

$$k = x_1 - x_2 = 257 - 153 = 104\ cm$$

$$j = 153 - 104 = 49$$

side view



$$j \geq j_i$$

$$j_i = \frac{d}{\tan a_2} = \frac{159{,}5}{\tan 55} \approx 111{,}7$$

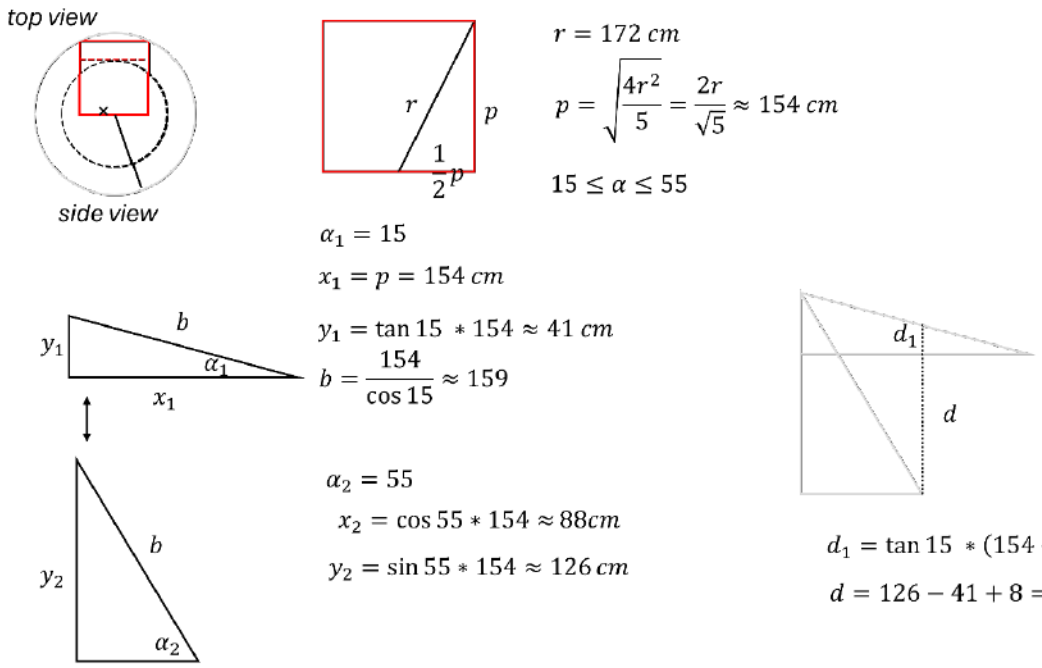
$$\nvDash j \geq j_i$$

This concept is not possible.

An alternative would be to mount the top of the panel to the middle of the plateau, significantly lowering the space efficiency of this concept.

Figure F2.2

Calculation Concept 1 For Principle to Work



$$r = 172\ cm$$

$$p = \sqrt{\frac{4r^2}{5}} = \frac{2r}{\sqrt{5}} \approx 154\ cm$$

$$15 \leq \alpha \leq 55$$

$$\alpha_1 = 15$$

$$x_1 = p = 154\ cm$$

$$y_1 = \tan 15 * 154 \approx 41\ cm$$

$$b = \frac{154}{\cos 15} \approx 159$$

$$\alpha_2 = 55$$

$$x_2 = \cos 55 * 154 \approx 88 cm$$

$$y_2 = \sin 55 * 154 \approx 126\ cm$$

$$d_1 = \tan 15 * (154 - 126) \approx 8\ cm$$

$$d = 126 - 41 + 8 = 93\ cm$$

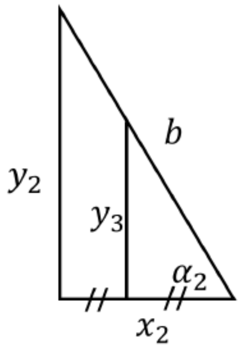
F3. Calculations Concept 2

For concept 2, calculations were made regarding the minimal height of the mounting pole, y_3 in cm.

- b represents the length of the panel
- x_2 is the horizontal projection of b when α= 55°
- y_2 is the vertical projection of b when α= 55°

Figure F3.1

Calculation Concept 2 Height Mounting Pole



$$\alpha_2 = 55$$

$$x_2 = \cos 55 * 251 \approx 143\ cm$$

$$y_2 = \sin 55 * 251 \approx 205\ cm$$

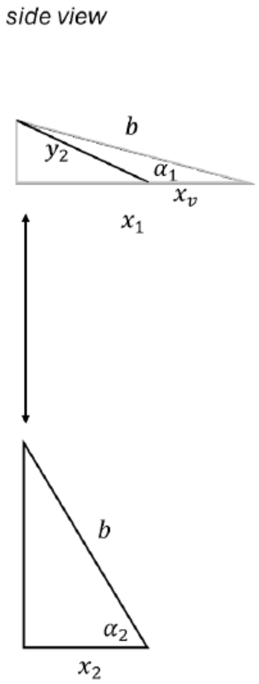
$$y_3 = \tan 55 * 71{,}5 \approx 102$$

F4. Calculations Concept 3

For concept 3, the supporting legs will be moved forward in order to change the pitch angle. Here, the supporting legs will be the length of y_2, and the stopper points of the legs can be calculated accordingly, see Figure F4.1. This was already done for the desired pitch angles, however, especially at a lower angle these distances lay very close together. With the current design, it would not be feasible to have both 15 and 20 degrees included.

Figure F4.1

Calculation Concept 3 Stopper Points



$$\alpha_1 = 15$$

$$x_1 = p = 243\ cm$$

$$y_1 = \tan 15 * 243 \approx 65\ cm$$

$$b = \frac{243}{\cos 15} \approx 251\ cm$$

$$\alpha_2 = 55$$

$$x_2 = \cos 55 * 251 \approx 143\ cm$$

$$y_2 = \sin 55 * 251 \approx 205\ cm$$

$$x_v = x_1 - \cos(\sin^{-1}\frac{x_1 \tan\alpha}{y_2}) = 243 - \cos(\sin^{-1}\frac{243\tan\alpha}{205})$$

Table F4.1

Distance x_v per pitch angle

A (°)	x_v (mm)
15	480
20	SKIP
25	520
30	553
35	597
40	658
45	749
50	902
55	1043