GREEN ROOF TILE

IMPROVING LOCAL BIODIVERSITY

COLOPHON

TITLE •
Green Roof Tile - Improving local biodiversity

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“When you talk, you are only repeating what you already know. But if you listen, you may learn something new.”

— Dalai Lama XIV

LIST OF DEFINITIONS

Biodiversity
Number of species and population size of native flora and fauna

Compriband
A foam tape, coiled under pressure to reduce its size. After applying, it will swell up to its original size within an hour.

Gradients
A gradually change between two different ecosystems. A transition between a shrub and a grass field on small scale or from a city center to agricultural area on bigger scale.

Green roof system
System that has positive influence on nature, making this arise or improve. System itself has minimum impact on material and energy use.

Green roof tile
A green roof system consisting of lightweight roof tiles. These roof tiles form a waterproof layer on a slanted roof on which planters, breeding boxes, and insect hotels can be placed.

Green roof tile planter
A container connected to a green roof tile in which plants can grow.

Green roof tile sideplate
A Green roof tile adjacent to a conventional roof tile

Pitched roof
A roof with an angle of 20 degrees or more

Stakeholders
1. People aware of global threats, such as climate change and decreasing biodiversity, willing to pay something extra to reduce their impact
2. Project developers, housing corporations, and contractors choosing green solutions consciously or obligated by municipalities

SUMMARY

World's population of human species is increasing every year. Also, Dutch population is growing. More and more people are moving into urban areas. All these people are part of ecosystems of a city. These ecosystems are under stress because of global problems such as diseases, pests, and climate change. To make future cities a liveable place, ecosystems need to be healthy and resilient. Biodiversity of an ecosystem is a serious indicator of health and resilience. Therefore, nature needs to be included into building environment and form a natural symbiosis with people living in it. To do so, the right location needs to be divined, a place nature can grow without intervention of people. This location is above our heads, roofs, in particular pitched roofs.

Municipalities are aware of the necessity to include nature into buildings. Therefore, more and more cities require green solutions in, on or at buildings. This makes a green roof system, designed for slanted roofs, a realistic solution.

A green roof system implemented on pitched roofs can improve biodiversity by increasing habitat of living creatures and creating opportunities for population growth. Next to biodiversity, a green roof system reduces heat island effect, filters air, collects water, and extends lifespan of a roof.

A design methodology was used to identify design problems, determine criteria and guide designer to a suitable solution of a green roof system. Obtained solution consists of an herbs roof, combined with a roof tile. These will be overlapping and hanging from purlins, secured by screws and tile hooks.

This solution is developed into a concept using research by design. Prototypes are made to analyze functionalities, FMEA and SWOT analyses are implemented to find points of improvement and an injection molding guideline is composed to optimize design for production.

Final design consists of four products:

- Green roof tile
- Green roof tile sideplate
- Green roof tile planter
- Green roof tile baseplate - breeding box
- Green roof tile baseplate - insect hotel

Green roof tile and Green roof tile sideplate form a waterproof layer, connecting the whole system to conventional roof tiles and roof structure. These two products are designed to be integrated into roofs, independently from conventional roof tile type. One, ten or two hundred conventional roof tiles can be replaced by Green roof tiles, making it possible to anticipate on people’s budget.

On a green roof tile or sideplate, a planter, breeding box, and insect hotel can be connected. Through this, plants can grow, birds can breed, and insects can live on slanted roofs of the Netherlands. All products have identical hanging system, making it possible to interchange them during assembling, but in a later stage too.

A 1:1 test is performed to find out the best planter volume/surface ratio and orientation. During a test period of seven weeks, March to May 2021, a ratio of 1:1.6 performs best, orientated south. This test concludes that planters, located on slanted roofs, function. This makes the Green roof tile system a real and possible solution for Dutch cities.

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INTRODUCTION

This introduction will give an overview of biodiversity within the Netherlands, and urban areas specifically. It puts it in context of urban development and growing cities. These growing cities and municipalities recognize problems of decreasing biodiversity and require green solutions from architects and project developers. One of those solutions can be a green roof system for slanted roofs, the objective of this research.

1.1 GROWING CITIES

World's population of human species is increasing every year (Worldometer, 2020). Also, Dutch population is growing to 17.4 million in 2020 (CBS, 2020). Besides that, more and more people are moving into urban areas. In 2018, 55 percent of world's population lived in urban areas, a proportion that is expected to increase up to 68 percent by 2050. In the Netherlands this proportion is expected to increase to 97 percent (UN, 2018).

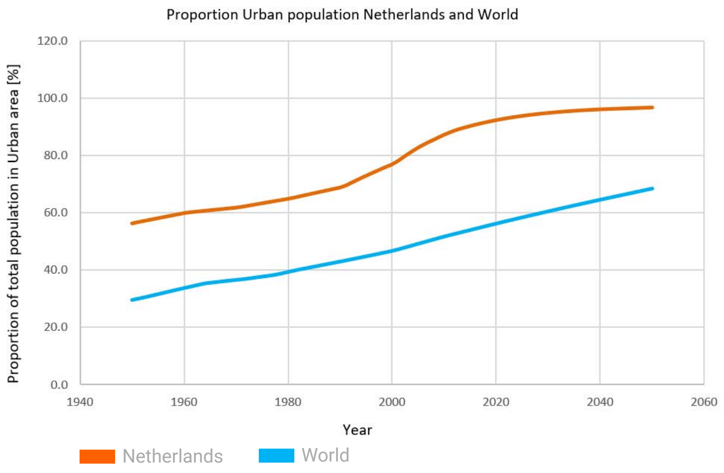


Figure 1.1 | Urban population (2018 United Nations, DESA, Population Division)

To house all these people, the cities of the Netherlands are growing with 1 million houses by 2030 (NU.nl, 2018). These houses are mostly developed within the municipality boundary, removing possible location for nature.

In this way, the connection between people and nature is decreasing, while studies are showing that nature has positive effects on people. Two studies in the Netherlands (Vries et all, 2004; Maas et all, 2006) support the widely held belief that contact with nature is beneficial for one's health (De Jong, Dekker and Posthoorn, 2007). Nature within 3 kilometers from people's home was, on average, positively related to self-perceived health. Possible mechanisms underlying relationship between nature and health can be the stress-reducing ability of nature, sound absorbing effects of plants (SBR, 2009), physical activity people tend to do in nature, and better air quality of greener environments (De Jong, Dekker and Posthoorn, 2007).

Municipalities are taking action to stop decrease of biodiversity and develop more nature within city boundaries. Rotterdam has made a Uitvoeringsagenda to guide inhabitants and partners to a city with more biodiversity (gemeente Rotterdam, 2020). The Hague developed a system of points for nature inclusive building and design. This system obligates project developers to improve quality of nature on, at, or around buildings. (gemeente Den Haag, n.d.). Policy plans of Amsterdam are combined in Groenvisie 2050 in which green areas need to be improved and connected, using a variation of green: ecological green and residential green. Nature inclusive design is getting the norm by building, renovating, and transforming of urban areas. (Municipality of Amsterdam, 2020). Next to Netherland's three largest cities, more municipalities are developing similar policy plans and tools to improve nature and biodiversity within their cities.

1.2 BENEFITS OF NATURE

Besides direct positive effects on people, nature has indirect effects as well. Plants and trees reduce heat island effect. Vegetations lower surface and air temperature by providing shade and through transpiration (EPA, n.d.). Trees and plants absorb water, reducing the maximum amount of rainwater in sewage systems (Denters, 2020). These side effects have positive effect on people too, for instance lower temperature during summer nights or no overloaded sewage systems.

Plants and trees produce oxygen we breath and store carbon dioxide, they filter and clean air making a city a livable place. Animals are depending on plants and trees while we are depending on animals for food production (for instance bees). Plants cannot only be eaten; they can provide us building material (Cross Laminated Timber) or energy (biofuels). So, it is important to be careful with nature we have.

Green facades are made to humidify air and improve acoustic performance of offices and buildings. These positive effects of nature on people have economic impact as well. Less absenteeism and higher productivity can be beneficial for companies (SBR, 2009).

Nature in a city consists of many ecosystems and biodiversity is an important indicator of health and resilience of an ecosystem (Vink, Vollaard and De Zwarte, 2017). An ecosystem with a high biodiversity is more flexible and can adjust itself to global changes. If one species becomes extinct because of a disease, pest, or climate change the system can adjust itself to a new equilibrium. Within a monoculture, such an event can be fatal for the whole system including health of humans.

So, biodiversity is important because of mutual relationships among all species (Vink, Vollaard and De Zwarte, 2017). A more diverse ecosystem will be healthier and more resilient such that humans can live a healthier and more resilient life.

1.3 DUTCH BIODIVERSITY

Dutch planning office for living environment (planbureau voor leefomgeving) published a report about balance of living environment 2014. One of the outcomes is that biodiversity decreased from 40 percent in 1900 to 15 percent in 2010. Biodiversity is measured in MSA (Mean Species Abundance). An MSA of 15 percent means that size of a population is 15 percent compared to a natural situation. Dutch biodiversity is lower than average of Europe (40 percent) or the world (70 percent) (Planbureau voor de Leefomgeving, n.d.).

In the Netherlands, factors of biodiversity decrease are use of land for agriculture, urbanization, environmental stress, and fragmentation (Planbureau voor de Leefomgeving, 2014).

This report is published in 2014, same trends are published on the website of the Dutch government by 2019 and 2020. Last thirty years, eight butterfly species and twenty bird species are monitored. The population trends are compared to reference year 1990. Different species show a variation of trends, but overall, population of butterflies (-38%) and birds (-57%) has decreased, see figure 1.2, 1.3 and 1.4 (NEM: Sovon, Vlinderstichting, CBS, 2020). This decline is caused by eutrophication, acidification, desiccation, poor water quality, and fragmentation (Rijksoverheid, 2018). Last decade, deterioration of eutrophication and acidification is getting less, however it is still not getting better (Planbureau voor de leefomgeving, n.d.).

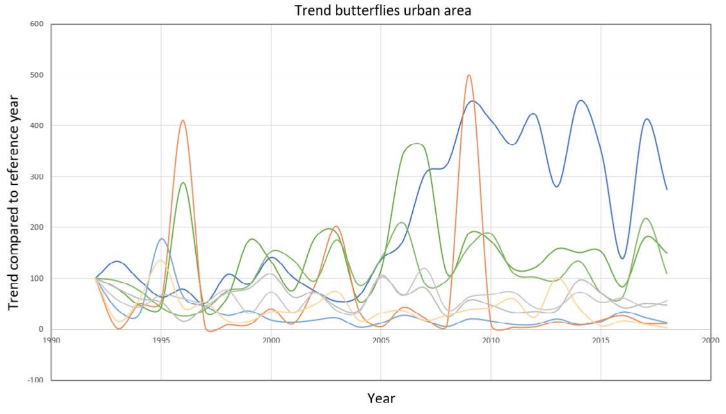


Figure 1.2 | Butterfly population urban area Netherlands (2020 NEM; Vlinderstichting, CBS)

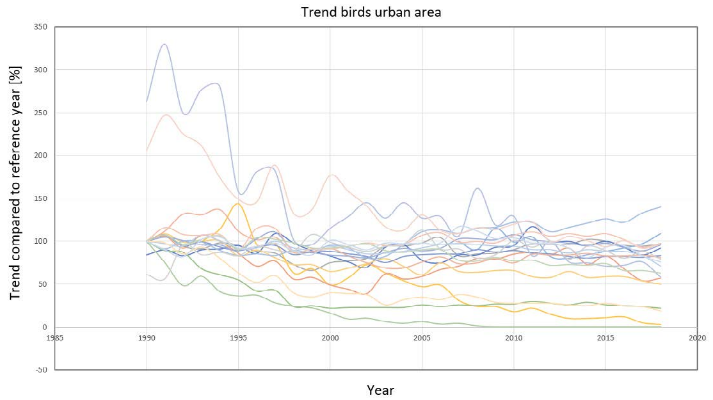


Figure 1.3 | Bird population urban area Netherlands (2020 NEM; Sovon, CBS)

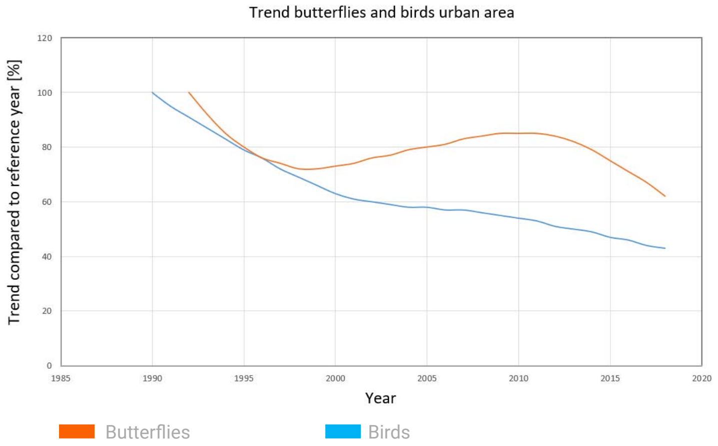


Figure 1.4 | Butterfly and bird population urban area Netherlands (2020 NEM; Sovon, Vlinderstichting, CBS)

Fauna population decline can not only be seen in urban areas, other parts show it too, except forests, see figure 1.5 (NEM: soortenorganisatie, CBS, 2019).

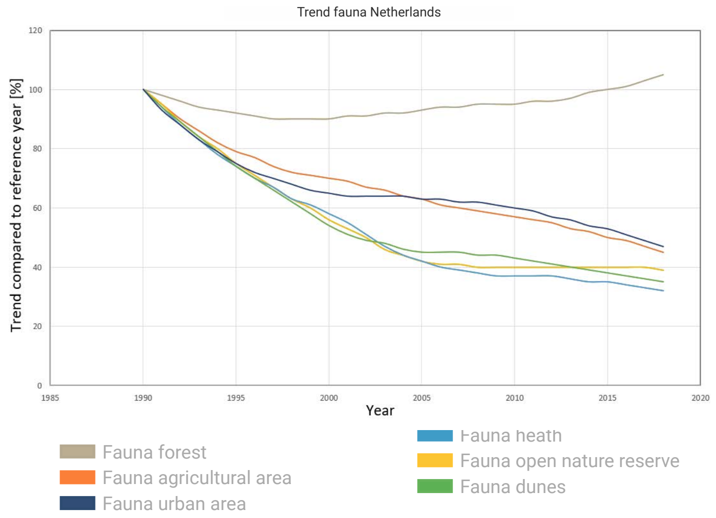


Figure 1.5 | Fauna population Netherlands (2019 NEM; Soortenorganisatie, CBS)

1.4 TOWARDS A NATURE INCLUSIVE CITY

As stated before, municipalities are recognizing problems with nature and are developing systems to enhance nature inclusive design and maintenance. Next to requirements regarding energy use, insulation, strength, and stiffness of buildings, municipalities require nature to be included into building envelope too. Municipality of Amsterdam developed a list of twenty nature inclusive ideas, from breeding boxes to water roofs (A. Blokker, G. Timmermans, 2018). This overview gives detailed information about location, size, impact, species, and implementation of all ideas. With this, the municipality of Amsterdam wants to inspire, stimulate, or impose project developers and citizen to create nature in, on or at buildings.

Similar to Amsterdam, other cities require nature inclusivity too, such as The Hague, Ede, Tilburg, and Arnhem (Gemeente Den Haag 2020, Eco consultancy Ede n.d., Gemeente Tilburg 2010, gemeente Arnhem n.d.)

1.5 GREEN ROOFS

One of the interventions, to include nature in building envelop, is a green roof. Especially flat roofs can be changed into green roofs. Companies like Groendak, Rooftop revolution, and De Dakdokters are developing systems for that. Variations of green roofs are brown roofs with stony surfaces, water roofs with open or closed water reservoirs, and Polder roofs, a combination of water and green roofs (gemeente Amsterdam, 2018).

Total roof area of the Netherlands is 1281 km2 (Atlas leefomgeving, 2019), which is more than Nature reserve De Veluwe (884 km2) (Natura 2000, n.d.). So, if all roofs are green, it creates one of the biggest nature areas of the Netherlands. However, more than half of Dutch roofs are pitched (50.3 %, 645 km2, see appendix A) (Atlas leefomgeving, 2019) and green solutions for pitched roofs contain sedum plants. Sedum plants are often seen as green solutions, but biodiversity on these roofs is low (De Levende Natuur, 2019). To increase biodiversity by making a green roof means the use of herbs, flowers, and grasses. However, weight of such a roof can become critical. Sedum is used because it's low substrate thickness and low weight (Dak&Gevel groen, n.d.).

Nature is important for people, from food production to self-perceived health, from farmers to city people. Therefore, connection between people and nature needs to be improved, biodiversity decline needs to be stopped, and roofs need to be greened. This research is about product development of a green roof system, improving biodiversity of Dutch cities.

RESEARCH METHODOLOGY

Research methodology consists of a problem statement, sub-problems, general objective, sub-objectives, and boundary conditions. An overview is given of used research methods and final products.

2.1 PROBLEM STATEMENT

World's population is increasing, people are moving to urban areas. Green is replaced by houses and connection between nature and people is fading. Biodiversity of Dutch cities is reducing at a troublesome rate. Next to damage to nature, this has negative impact on our food production, well-being, energy use, air pollution, and water management too. Cities need to include nature again to restore biodiversity. Focus should not only be on green streets, parks, and quays but also into building envelops. Facades and roofs need to become an integrated part of urban nature.

Companies like Groendak, Rooftop revolution, and De Dakdokters are developing systems for green roofs. However, their focus is on flat roofs, while flat roofs cover only half of the Netherlands. Green roof systems for pitched roofs exist but contain sedum because of low weight, low maintenance, and resistant to draught. Contribution to biodiversity of sedum plants is low, so these roofs have little impact.

To conclude, nature needs to be implemented into building envelops. Existing solutions focus on flat roofs while half of the Dutch roofs are slanted. Solutions for pitched roofs are insufficient to improve biodiversity.

2.2 SUB-PROBLEM

A green roof system with herbs, flowers, and grasses (an intensive green roof) asks for a minimum substrate thickness of 10 cm due to depth of roots and water management. Enough rainwater needs to be collected by a system to keep plants alive during hot and dry periods. Total weight of plants, substrate, and water is more than conventional pitched roof structures can hold.

So, conventional pitched roof structures are not strong enough for the loads of an intensive green roof.

2.3 GENERAL OBJECTIVE

General objective is directly related to problem statement: "To develop a green roof system for pitched roofs which has sufficient positive impact on urban biodiversity".

2.4 SUB-OBJECTIVES

Sub-objectives are related to sub problem. Since weight of a regular green roof is too much, a goal is to find an optimum surface/volume ratio of a green roof system. Smaller surface/volume ratio means more substrate and water per plant.

To increase impact, green roof system will be developed for conventional pitched roofs of the Netherlands. Therefore, a system needs to be developed which connects to multiple conventional roof tiles.

2.5 FINAL PRODUCTS

Final product is a design of a green roof system developed to be integrated into conventional Dutch pitched roofs. Used methodology will provide a way of testing and comparing different solutions. To test the proposal a 1:1 prototype is built. This prototype gathers information about orientation, surface/volume ratio, water management, and plant growth. 1:4 prototypes are made to test connections with standard roof tiles and integration of the whole system.

2.6 BOUNDARY CONDITIONS

Existing systems

Existing houses are 99 percent of current house stock, per year only 1 percent is new (CBS, 2021). Therefore, development of this green roof system is focused on integration with conventional roof systems. If more houses can have a green roof, biodiversity impact is bigger.

Location
The system will be universal and can be implemented into roof systems worldwide. However, to reduce parameters this system will be developed for Dutch market.

Sustainability
This research is focused on designing a sustainable solution. Therefore, embodied energy and environmental impact of components need to be considered too. This can be done by material choice, expending lifetime and end of life treatment.

2.7 METHODOLOGY

Knowledge from nature, ecology, and biodiversity is the backbone for nature inclusive design. Research is carried out on discipline of ecology and on architecture. Goal is to fill in the gap between these two disciplines.

Theoretical framework is based on several theories related to nature, ecology, and biodiversity. This knowledge is obtained by literature review of scientific papers, expert journals, books, and relevant case studies. During prototyping and testing (1:1), hands-on information about ecology is applied. Findings will be used as guidelines, evidence, and inspiration for development of architectural concepts.

For architecture and building technology focus will be on practical information of building components derived from various companies, contractor offices, and case studies. 1:4 prototypes will be made of conventional roof systems to test connections with Green roof systems.

All information will be combined into a concept using research by design. This consists of the following research methods: desk analysis, case studies, design studies, and prototyping. All is done with conventional design tools and software. Concepts and prototypes will be used to optimize product to its final design.

So, research methods are:

- Literature review
- Expert books and journals
- Expert consults
- Reviewing case studies
- Research by design
- Prototyping and testing

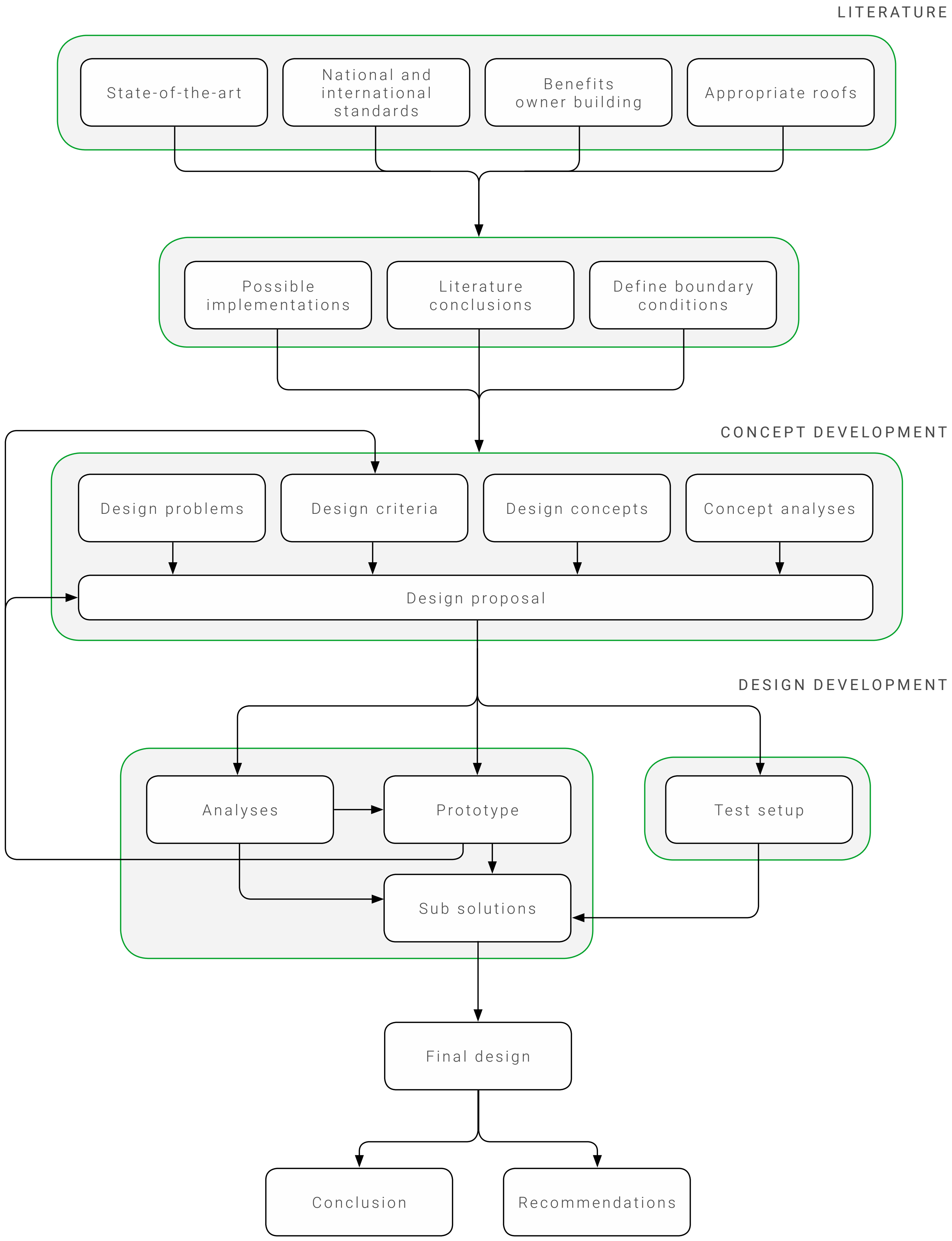


Figure 2.1 | Methodology (own)

RESEARCH

In this chapter, the research question will be substantiated by sub-research questions. The product, green roof system, is placed in context of other, existing, green solutions. Forces and loads working on a green roof system are explained based on national and international standards, together with requirements such as fire safety. And lastly, benefits for user and owner of a green roof system are clarified.

Aim of this research is to find answer to the following question:

HOW CAN A GREEN ROOF SYSTEM IMPROVE BIODIVERSITY OF PITCHED ROOFS IN DUTCH CITIES?

To substantiate the research question, research is done on following sub-questions:

- How will a green roof system improve biodiversity of Dutch cities?
- What is state of the art of biodiversity improvement in cities?
- What type of roofs are most appropriate for a green roof system?
- What are national and international standards for roof systems?
- What are benefits of a green roof system for owners of a building?

3.1 IMPROVE BIODIVERSITY

Two factors play a role in biodiversity measurements: richness of species and population size. Measuring biodiversity is difficult, especially focusing on small creatures, mosses, and plants. So, target species are selected, ones which are at the top of the food pyramid and easy to count (birds, wolfs, beers). But how do you measure biodiversity improvements?

On long term, increasing population of target species, or presents of new species, can be counted. This process can take decades, because first the basis of food pyramid needs to increase. In total, this research takes nine months and two months of testing. In this period, measuring improvement in biodiversity is not possible. Therefore, another definition is used:

"if plants grow on a slanted roof and they can survive a hot and dry summer and a cold and wet winter, they provide food and shelter for other living creatures. Therefore, they increase the living habitat of these species, creating opportunities for population growth or new inhabitants. In that case, the local biodiversity has improved."

This is the reason why a 1:1 prototype is built, to test if plants can grow and survive within this research period. If that is the case, a green roof system can improve biodiversity of cities.

3.2 STATE-OF-THE-ART

Based on point systems made by municipalities, a list of interventions is made. These interventions improve biodiversity of urban areas in different ways. A breeding box is small and made for birds only, while a city park has a bigger impact on more species. The list of interventions contains small adjustments/ additions for buildings up to modifications on the scale of landscape architecture.

All interventions are scored on area (what is size of intervention) and what is impact on different species (mammals, bats, birds, insects, and plants). This is done to give an overview on state-of-the-art on the topic of biodiversity improvements, and as inspiration. On the other hand, this list is made to find a possible niche for a green roof system and how it can contribute to existing solutions.

As can be seen in the overview, multiple adjustments can be done for flat roofs (Intensive green roof, green roof, sedum roof, PV panels in combination with green roofs, brown roof, blue roof, and polder roof). For slanted roofs only two solutions exist: sedum roof and sedum roof tile. As said before, sedum's contribution to biodiversity is low. Therefore, a green roof system with herbs, flowers, and grasses on slanted roofs can have a significant impact on the urban biodiversity. This is the niche this research is about.

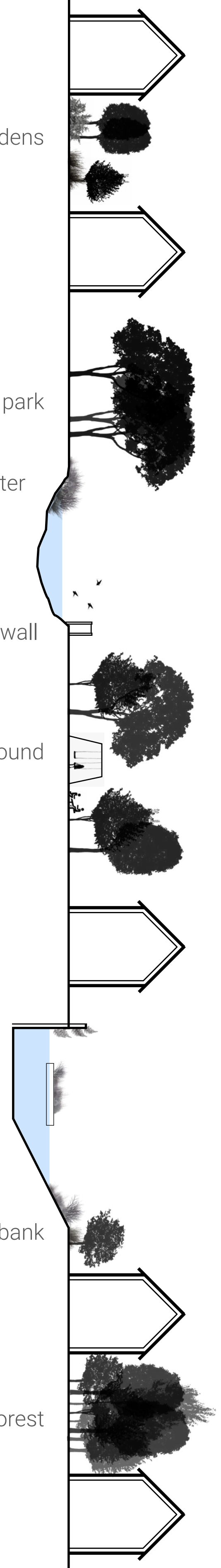
Flat roofs 617 km^2

- Intensive green roof
- Green roof
- Sedum roof
- PV panels and green roofs
- Brown roof
- Blue roof
- Polder roof

Slanted roofs 645 km2

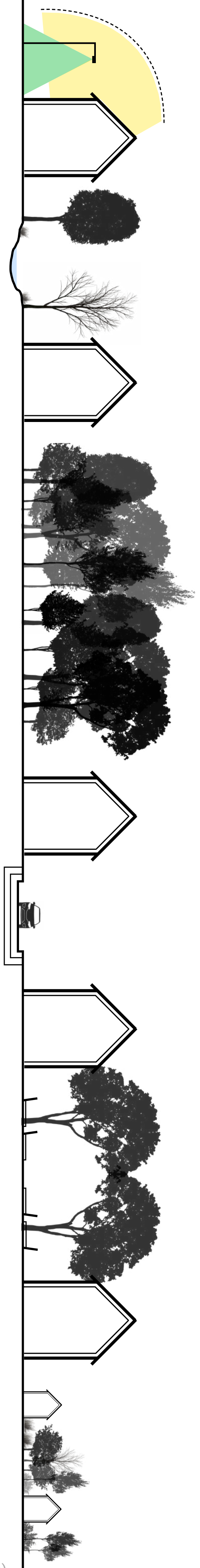
- Sedum roof
- Sedum roof tile
- [Green roof system]

Figure 2.4 | Interventions (own)



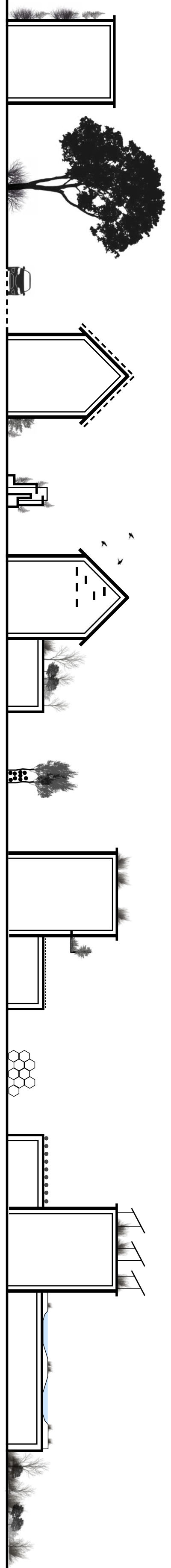
	Area	Mammals	Bats	Birds	Insects	Plants
Green private gardens	●●●	●●●	●	●●●	●●●	●●●
City park	●●●	●●●	●●	●●●	●●●	●●●
Helophyte filter	●●		●	●●	●●	●●
Pond	●●	●	●	●●	●●	●●
Sand martin wall	●			●●●		
Nature playground	●●●	●●	●	●●	●●	●●
Green quays	●●			●●	●●	
Floating banks	●●			●●	●●	●●
Ecological bank	●●	●	●●	●●	●●	●●●
Tiny forest	●●	●●●	●●	●●●	●●●	●●●

Figure 3.1 | State-of-the-art (own)



	Area	Mammals	Bats	Birds	Insects	Plants
Light color	●●	●●	●●	●	●	●
No light emission	●●	●●	●●	●	●	●
Street trees	●●	●	●	●●	●●	●●
Wadi	●●	●	●	●●	●●	●●
Dead tree	●	●		●	●●	●
City forest	●●●	●●●	●●	●●●	●●●	●●●
Food forest	●●●	●●●	●●	●●●	●●●	●●●
Fauna passage	●	●●●				
Cemetery	●●●	●●●	●●●	●●●	●●●	●●●
Allotments	●●●	●●●	●	●●●	●●●	●●●

Figure 3.2 | State-of-the-art (own)



	Area	Mammals	Bats	Birds	Insects	Plants
Green facade	●●			●●	●●	●●
Flowery tree ground	●	●		●●	●●	●●
Open pavement	●●				●	●
Sedum roof tile	●●			●	●	●
Facade garden	●	●		●●	●●	●●
Wilderness wall	●	●●		●	●●	●●
Breeding box bird	●			●●●		
Breeding box bat	●		●●●			
Intensive green roof	●●		●	●●	●●	●●
Branchesril	●	●●		●●	●●	●
Green roof	●●		●	●	●●	●●
Balcony garden	●			●	●	●
Sedum roof	●●			●	●	●
Bee and insect hotel	●		●	●	●●	
Brown roof	●●		●	●●	●●	●●
PV panels and green roofs	●			●	●	●
Blue roof Polder roof	●●		●	●●	●●	●●
Shrubbery	●●	●●		●●	●●	●●
Butterfly and bee garden	●●	●		●●	●●	●●
Open sand	●	●		●	●●	●

Figure 3.3 | State-of-the-art (own)

3.3 APPROPRIATE ROOFS

If a system, like this green roof system, can be implemented into all roofs of the Netherlands it has maximum impact. More roofs mean more opportunities for plants to grow, insects to hide and birds to eat. Therefore, as many roofs are appropriate as possible. However, boundaries are needed to focus this research.

First, inclination. 5, 10, 20, 50, 90 degrees, all kinds of roofs exist. However, this system is only designed for 20 to 60 degrees. Below 20 degrees a different roof system is required, whereby roof systems need to be totally waterproof. Roof tiles only work from 20 degrees onward. The other limit, 60 degrees is chosen to set a boundary and limit design options.

Second, roof structure. Because a green roof system is using same systems as conventional roof tiles, it can only be implemented on roofs with purlins, strong enough and close enough to each other.

Third, orientation. Different plant species grow different orientations. To make a green roof system suitable for all orientations, a mixture of plant species is used. This mixture contains plants growing on south, north, west, and east side. Nature selects which plants grow best in which circumstances. So, one system is appropriate for all roofs independently from orientation.

3.4 NATIONAL AND INTERNATIONAL STANDARDS

Roof systems need to meet national and international standards for structural strength, structural stability, fire safety, and waterproofness. This research focusses on slanted roofs of the Netherlands. In general, buildings of 5 floors and higher do not have a slanted roof with roof tiles. Therefore, maximum height will be 12 meters (4 floors, 3 meters per floor). User load, wind load, snow load, fire safety, rain load (waterproofness) and own weight will be considered within this research.

3.4.1 USER LOAD

Slanted roofs are classified as class H: non-accessible roofs, except for routine maintenance and renovations (NEN-EN 1991-1-1+C1, 2019). With an inclination angle more than 20 degrees, even distributed user load (q_k) is zero and concentrated user load (Q_k) is 1.5 kN/m^2 (NEN-EN 1991, table NB.4). These values are most important for main roof structures. However, it would be possible that someone is walking on top of a green roof system during renovation or maintenance. Therefore, it needs to withstand this concentrated load.

3.4.2 WIND LOAD

Wind loads on the outside of building envelope (W_e) can be calculated by next formula (all values and formulas used in this paragraph are obtained from NEN-EN 1991-1-4+C2, 2011):

$$W_e = q_p(Z_e)*C_{pe}$$

- q_p is extreme wind load
- Z_e is reference height for wind loads
- C_{pe} is wind load coefficient

As explained in introduction, maximum height of most slanted roofs is 12 meters (Z_e). Extreme wind conditions can be found in coastal areas, wind load area 1. 12 meters at this location corresponds with 1.63 kN/m^2. So, q_p is 1.63 kN/m2 (NEN-EN 1991, table NB.5).

Wind load coefficient (C_{pe}) has two values, $C_{pe,1}$ and $C_{pe,10}$. $C_{pe,1}$ can be used for local coefficients (used for small building elements, less than 1m^2) and $C_{pe,10}$ for general coefficients (used for main building construction). Because a green roof system is less than 1 m^2 per unit, local coefficients can be used.

With an inclination angle α, see figure 3.4, of 20 to 60 degrees, positive and negative wind load coefficient limits are -1.83 and +0.7 (NEN-EN 1991, table 7.4a).

So maximum wind loads on the green roof systems are:

$W_e = 1.63*-1.83 = -2.98$ kN/m^2
$W_e = 1.63*0.7 = 1.14$ kN/m^2

In this construction, pull forces generated by wind are leading. Extra security is needed to hold the green roof system on a building.

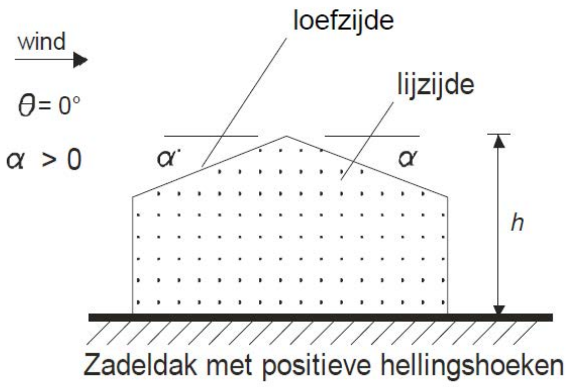


Figure 3.4 | Wind load (NEN-EN 1991-1-4+C2, 2011)

3.4.3 SNOW LOAD

Snow loads (s) on building envelope can be calculated using next formula (all values and formulas used in this paragraph are obtained from NEN-EN 1991-1-3+C1+A1, 2019):

$$s = \mu_2 * C_e * C_t * S_k$$

- μ_2 is snow load coefficient of a gable roof
- C_e is exposure coefficient
- C_t is heat coefficient
- S_k is characteristic value of snow load on the ground

Snow load coefficient at an inclination of 20 to 30 degrees is 0.8. At an inclination of 30 to 60 degrees, snow load coefficient can be calculated by: $\mu_2 = 0.8*(60°-\alpha)/30°$. However, a green roof system implements obstacles, preventing snow from sliding off a roof. Therefore, snow load coefficient may not be reduced lower than 0.8. This means that μ_2 = 0.8 too (NEN-EN 1991, table 5.2).

Exposure coefficient is depending on surrounding of a building. Because green roof systems can be used on any roof, the highest value is used: 1.2. This value corresponds with a sheltered surrounding (NEN-EN 1991, table 5.1).

Green roof systems will be placed on roofs with normal to good insolation values (< 1 W/m^{2}K) therefore C_t = 1.

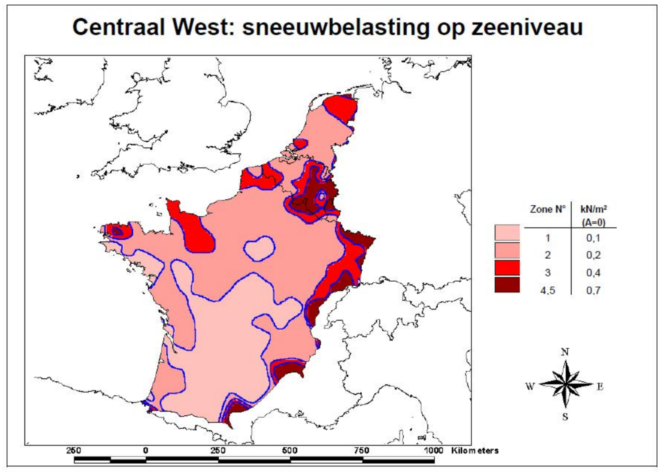
The characteristic value of snow load in central west (Europe) can be calculated by the next formula:

$$S_k = 0.164*Z - 0.082 + A/966$$

- Z is zone number, see figure 2.5. A value of three is chosen to calculate maximum snow load in the Netherlands.
- A is the altitude compared to sea level. A value of 10 is used to take an average. This gives a characteristic snow load value of 0.42

To conclude, snow load (s) is calculated as

$s = 0.8*1.2*1*0.42 = 0.40$ kN/m^2



Figuur C.7 — Centraal West: sneeuwbelasting op zeeniveau

Figure 3.5 | Snow load (NEN-EN 1991-1-3+C1+A1, 2019)

3.4.4 FIRE SAFETY

All products need to meet fire safety standards. New products with new materials need to be tested before it gets a certificate. If a roofing system meets class B-roof$_{t1}$ of NEN-EN 13501-5, 2016 it is considered fire safe. If classification B-roof$_{t1}$ is envisaged, only test 1 (assesses the performance of a roof under attack with burning brands) is carried out following criteria of EN 13501-5, 2016. So, if this green roof system wants to meet these requirements, tests need to be done.

Performing a B-roof$_{t1}$ test 1 is not within the scope of this research, so, rules of thumb are used such as use of non-flammable material and mechanical connections.

3.4.5 RAIN LOAD

Rain load (Q_h) on building roofs can be calculated using next formula (all values and formula used in this paragraph are obtained from NEN 3215+C1+A1, 2018):

$Q_h = \alpha*i*\beta*A_d$

α is the reduction factor for rain intensity. For slanted green roofs (>5° and < 45°) this reduction factor is 0.75. No reduction factor is given for slanted green roofs > 45°.

I = rain intensity, 0.03 l/s/m2

B and A_d are reduction factor of roof width and roof surface. In this case 1 m2 is used because the green roof system can be used on any roof in any configuration. Therefore, both values are 1. So:

$Q_h = 0.75*0.03*1*1 = 0.023\ l/s/m^2$

3.4.6 WATER IMPERMEABILITY

Green roof system developed in this research is similar to roof tiles. The system hangs on purlins and creates a waterproof layer by overlapping and interlocking. To test water impermeability of roof tiles, the procedure as described in EN 491, 2011 needs to be followed. This test is suitable for green roof systems as well.
Green roof system needs to be hold within 10° of the horizontal. Water is poured on the system from a level of 10 – 15 mm above the highest point. The whole test setup is stored at 15 to 30 Celsius degrees and at least 30 percent relative humidity for 20 hours +/- 5 minutes. Record if drops of water fall form underside of the system during this period of 20 hours.
A system passes this test if no drops have fallen during the test.

An objective of this research is to perform a water impermeability test, on scale. However, due to time limits, this is not possible.

3.4.7 OWN WEIGHT

Maximum weight of a green roof system is limited to strength of roof structures. An important requirement is the ability to add this system to conventional roofs without any adjustments to its structure. Experts are consulted by mail regarding strength of conventional roof structures (Constructie adviesbureau Booms, January 22, 2021) (DEJA bouwadviseur, January 22, 2021) (Bouwkundig adviesburo Baas, January 23, 2021). Roof structures build last century are designed for an even distributed load of 65 kg/m^2. A roof system with higher mass may require adjustments. Therefore, green roof systems will have a mass of 65 kg/m^2 max.

User load, wind load, and snow load will be input for a strength analysis. Own weight of a roof tile roof is one of the key parameters for Green roof tile and planter design. A water impermeability test is not performed due to time limits and a fire safety test is out of the scope of this research.

3.5 BENEFITS

As explained in introduction, nature on roofs has many benefits. It improves biodiversity of a city, it reduces heat island effects, it filters air, and stores carbon. However, what are benefits for owners of a building, users, and stakeholders of a green roof system?

During an interview with one of the developers of green roof tile (groendakpan), this question was asked. Their experience is that most people buy a green roof tile for its cooling effect. Especially for buildings build halfway twentieth century. These buildings have a top floor with sleeping rooms which can become hot during summer days and nights. This discomfort is the reason for people to buy a green roof. Additionally, sustainability and aesthetics are reasons too.

Another benefit is lifespan of a roof. Because sunlight (UV radiation) does not pass plants and substrate, the layer beneath it is protected. Therefore, a green roof extends lifespan of a roof, reducing maintenance costs.

3.6 RESEARCH CONCLUSION

Improving urban biodiversity by a green roof tile is hard to measure. Number of species or total population of urban flora and fauna will not significantly improve by one green roof tile. So, another definition is used to conclude whether a green roof tile improves urban biodiversity or not. This definition focusses on survival of plants. If plants can survive a hot, dry summer and cold, wet winter, it creates food and shelter for other living creatures and therefore improve biodiversity.

This solution is placed next to other existing solutions and compared based on area and species. This overview of state-of-the-art shows that slanted roofs need more green solution. This substantiates the necessity of this research.

To have maximum impact, this product can be placed on any roof with roof tiles of an angle of 20 to 60 degrees independent from orientation. Different loads act on roof systems and based on national and international standards, these loads are calculated. Because of high negative wind load (pulling), extra security is needed to hold a green roof system to a building. Another critical outcome is own weight of the system, with a maximum of 65 kg/m^2.

Lastly, people buy a green roof tile (Groendakpan) mainly for its cooling effect. Sustainability and aesthetics are reasons to buy it too.

CONCEPT DEVELOPMENT

Based on the methodology of Jeroen van Veen, a concept of a green roof system is developed. First, it is split into four different topics. For each topic, concepts are made and compared. The comparison is done related to program of requirements, with scores and weights. At the end, the best concept of each topic will be merged into a design.

4.1 APPROACH

Concept development of this research is based on methodology introduced in research report PD_LAB, a file-to-factory envelope by Jeroen van Veen (2016). While that research is focused on digitalization of production processes, its methodology can still be used for product development, such as a green roof system.

4.1.1 DESIGN OBJECTIVES

Methodology starts with a specific design goal. In this case, goal is to develop a system which improves biodiversity in cities. From this, several design objectives can be derived, namely: connection to conventional roof tiles, connection to conventional roof structure, water management, and how to improve biodiversity. For all aspects, alternatives can be developed. To analyze and compared these alternative solutions, criteria need to be generated.

4.1.2 CRITERIA

In product design, needs of end users are important. For instance: weight is limited by strength of a roofer and aesthetics by an owner of a building. Both criteria can make or break a product. Next to this, thirty-two criteria are listed divided into hard and soft requirements. These requirements are based on boundary conditions, design goals, technical findings from prototyping, and literature research (national and international standards, positive effects of biodiversity, production processes, and user requirements).

4.1.3 CONCEPT SOLUTIONS

Design question is split up into four aspects: biodiversity, construction, connection roof and connection modules. For all four, concept alternatives are developed independent from each other. Design criteria are used to analyze and compare solutions. Best four solutions will be integrated into a first design.

4.1.4 DESIGN DEVELOPMENT

Based on concept solutions, designs are developed. These designs are analyzed using rapid prototyping (3d-printing), analyses (FMEA, SWOT) and consultation with experts. Making designs on a scale of 1:4 gives information in a fast way. Design development is an iterative process of developing, printing, and analyzing designs, optimizing design tasks and combine sub-solutions into one product.

4.1.5 TEST SETUP

As mentioned before, weight is a critical requirement for green roof solutions. Maximum amount of substrate is less than normally used. Therefore, a 1:1 test setup is developed to test multiple solutions and circumstances. This information is used to substantiate design development.

4.1.6 FINAL DESIGN

Solutions of sub-questions are combined into a final design. This design is optimized for its production process, injection molding. A strength calculation is performed to validate the product in relation to national and international standards.

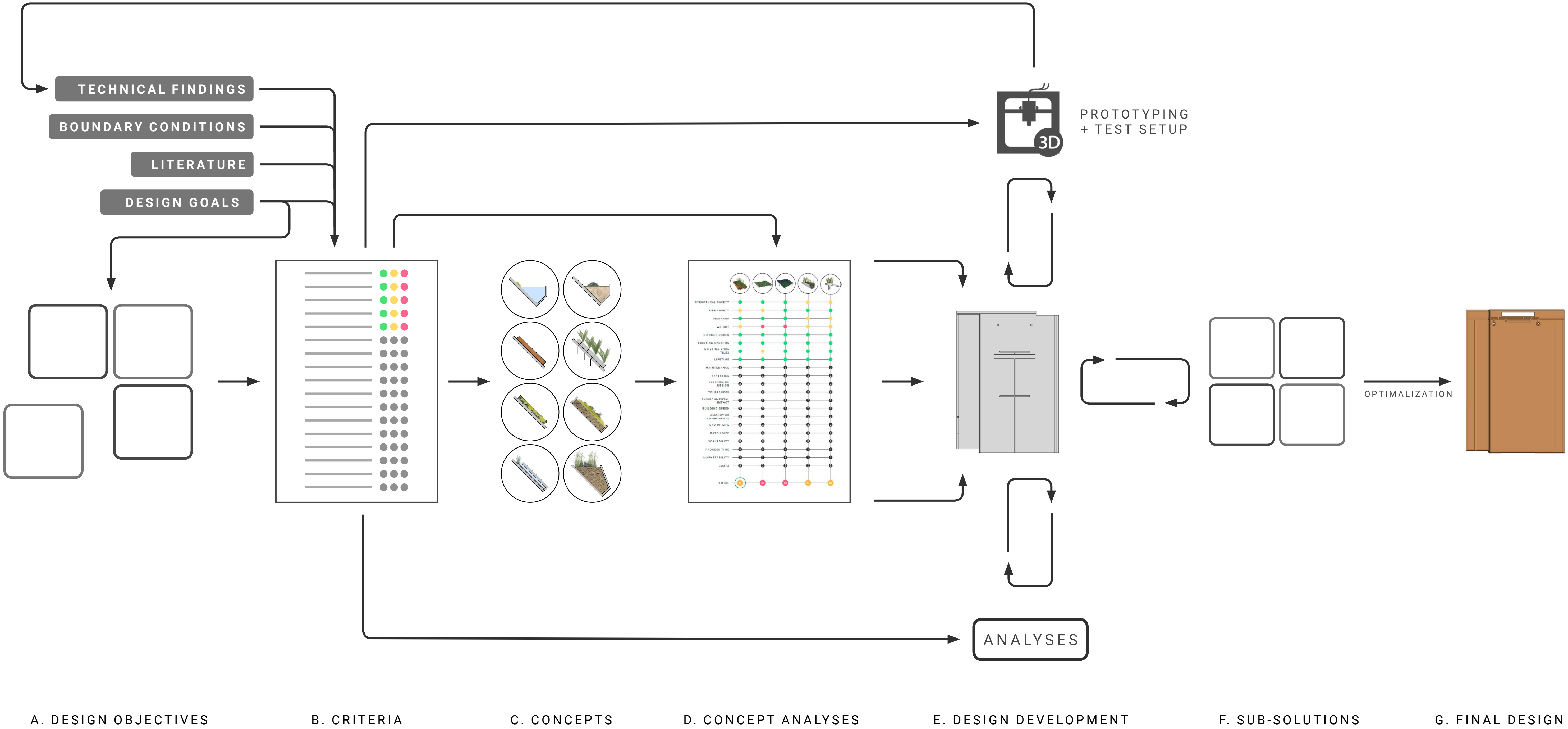


Figure 4.1 | Concept development (own)

4.2 PROGRAM OF REQUIREMENTS

All requirements are split up into hard and soft requirements. Hard requirements (boundary conditions) can be tested, such as weight or drainage. Soft requirements are less convenient to test and no number can be added to it, such as aesthetics or impact. Some requirements listed can be tested/calculated however they are placed as soft requirements (maintenance, tolerance, cooling effect, water storage, acoustics, air filtration, environmental impact, building speed, number of components, process time, and costs). On one hand, this is to optimize alternatives to these requirements. Instead of using costs as a hard requirement (product costs no more than 10 euro) it can become a soft requirement (aim for an economical feasible product). On the other hand, this stage is too early to calculate most requirements (cooling effect for instance).

4.2.1 SCORES

Hard requirements need to be passed, otherwise the product does not function. Therefore, scores are divided into green, yellow and red. With green, a solution does fulfill, red it does not, and yellow indicates that alternatives could pass with some changes/adjustments.
Soft requirements have scores from one to three. A solution scores a one if it does not fulfill the requirement, a two if it does and a three if it does good. These scores are added up, giving solutions a final score. The one with the highest score meets all requirements best.

4.2.2 WEIGHT

Not all requirements are similar important. Biodiversity requirements define the core of this product, while number of components is less important. Therefore, criteria get a weight of one to three. Weights are based on influence of a criteria on other criteria, see appendix C. Scores will be multiplied by a weight before added up to a total number. So, if a solution scores a three on diversity it becomes a nine and if it scores a one, it becomes a three. In this way, solutions with high scores, score best on important aspects.

- A weight of 1 means: not necessary for the product but can be a nice extra improvement or feature.
- A weight of 2 means: side function of the product, it needs to be considered. Can improve overall product or become a unique selling point.
- A weight of 3 means: core function of product, needs to be good.

4.2.3 DESIGN PROBLEMS

Not all requirements are relevant for all design problems. Technical criteria influence construction and not biodiversity solutions. Therefore, all design problems have their own list of requirements. Alternative solutions will be analyzed and compared using these criteria. In total, the product is split up into four design problems:

- Biodiversity. This is the core function of product, a solution to improve biodiversity in cities.
- Construction. Plants, insect hotels and breeding boxes cannot float in the air, they need a construction to hold it in place.
- Connection roof. A construction needs to be connected to conventional roof systems in a structurally safe way.
- Connection modules. Not only a connection with conventional roof systems is important, but also a rain proof connection between modules.

BOUNDARY CONDITIONS	Structural safety	🟢🟡🔴	Needs to fulfill all national and international standards
	Fire safety	🟢🟡🔴	Needs to fulfill all national and international standards
	Drainage	🟢🟡🔴	Needs to fulfill all national and international standards
	Weight	🟢🟡🔴	Maximum weight is 10 kg
	Dimensions	🟢🟡🔴	Needs to fit on conventional roof structures
	Pitched roof	🟢🟡🔴	Needs to function on a pitched roof (20-60 degrees)
	Existing systems	🟢🟡🔴	Needs to work together with conventional roof structures
	Existing roof tiles	🟢🟡🔴	Needs to work together with conventional roof tiles
	Lifetime	🟢🟡🔴	Needs to function for at least 10 years
BIODIVERSITY	Gradient	●●●	Create gradients
	Diversity	●●●	Create diverse opportunities
	Opportunities	●●●	Create opportunities and let nature do most of the work
	Native Flora and Fauna	●●●	Focus on native Flora and Fauna
	Impact	●●●	Create maximum impact
USE	Adaptability	●●	Can product adapt in case of changes
	Maintenance	●●	Minimize necessity of maintenance
DESIGN QUALITY	Aesthetics	●●●	The look and feel of product
	Freedom of design	●	Can design adapt for future needs?
	Tolerance	●	Minimize strict tolerances
	Cooling effect	●●	Optimize cooling effect of product
	Water storage	●●	Optimize water storage of product
	Acoustics	●	Optimize damping effect of product
	Air filtration	●	Optimize air filtration of product
MATERIAL	Environmental impact	●●	Minimize environmental impact
ASSEMBLY	Building speed	●	Minimize building time
	Number of components	●	Minimize number of components
	Replacing module	●●	Is it possible to repace a individual module?
	End of life	●●	What happens at end of product life?
PRODUCTION	Batch size	●	Is a big batch size possible?
	Scalability	●●	Is it possible to scale up production?
	Process time	●●	Minimize production time
COSTS	Overall costs	●●	Aim for economical feasible product
	Marketability	●●	Aim for saleable product

Table 4.1 | Program of Requirements (own)

BIODIVERSITY

- **Weight**
- **Pitched roofs**
- **Dimensions**
- **Lifetime**
- Gradients
- Diversity
- Opportunities
- Native flora and fauna
- Impact
- Environmental impact
- End of life
- Batch size
- Scalability
- Process time
- Adaptability
- Maintenance
- Aestetics
- Freedom of design
- Cooling effect
- Water storage
- Acoustics
- Air filtering
- Marketability
- Costs

CONSTRUCTION

- **Structural safety**
- **Fire safety**
- **Drainage**
- **Weight**
- **Pitched roof**
- **Existing systems**
- **Existing roof tiles**
- **Lifetime**
- Maintenance
- Aesthetics
- Freedom of design
- Tolerance
- Environmental impact
- Building speed
- Number of components
- End of life
- Batch size
- Scalability
- Process time
- Overall costs
- Marketability

CONNECTION MODULES

- **Drainage**
- **Pitched roofs**
- **Existing roof tiles**
- **Structural safety**
- **Lifetime**
- Tolerance
- Building speed
- Number of components
- End of life
- Batch size
- Scalability
- Process time
- Overall costs

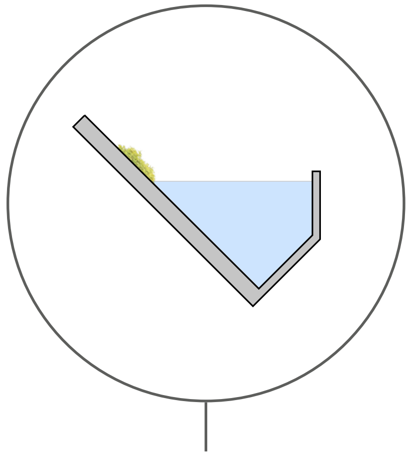
CONNECTION ROOF

- **Structural safety**
- **Dimensions**
- **Pitched roof**
- **Existing systems**
- **Lifetime**
- Tolerance
- Building speed
- Number of components
- Replacing module
- End of life
- Batch size
- Scalability
- Process time
- Overall costs

Table 4.2 | Program of Requirements (own)

4.3 BIODIVERSITY

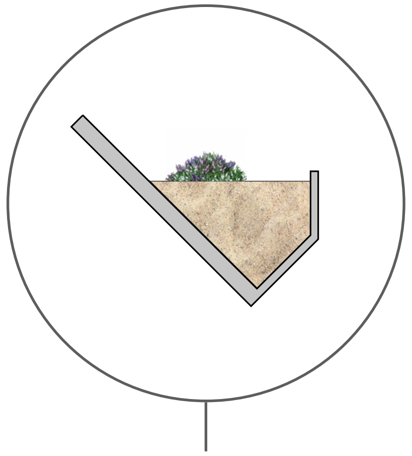
This paragraph will go into solutions and analyses of the biodiversity design problem.



WATER BOWL

- 🟢 Creates a variety of life
- 🟡 Will dry out during a hot summer
- 🔴 Mosquitos close to people

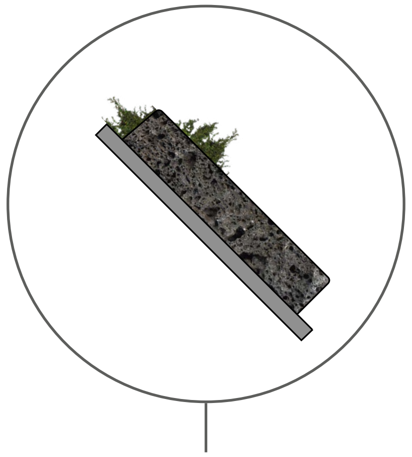
Water is the main source of life. Collecting it on roofs in open water bins will generate mosses, algae, and plants automatically. Birds can drink from it and insects can lay their eggs in it. Wet parts of the world, like swamps and wetlands are rich on biodiversity, so can be an open water roof. However, these bowls cannot collect enough water to keep it wet during a hot summer, it can become full of algae such that no other species can live in it and mosquitos can become a problem for users of a building.



SAND BOWL

- 🟢 Provides opportunities for nature
- 🟡 Will insects and plants move to a roof?
- 🟡 Will wind blow sand away?

Pioneering plants grow on places scarce of food, under hard conditions. A bowl of sand or earth can become a new location of these plants. It provides opportunities nature can fill in itself. Next to plants, insects can use these bowls to lay their eggs. But how do plants and insects move to a roof, does wind blow sand away and how much water can it collect? Also, this idea can improve biodiversity but can form an issue for users of the building too.

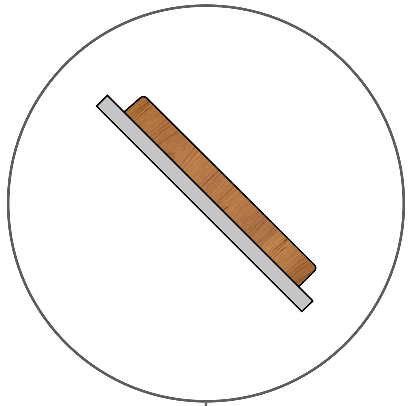


POROUS STONE

- 🟢 Creates opportunities
- 🟡 Creates a chaotic roof
- 🟡 Will insects and plants move to a roof?

Improving biodiversity can be done in two ways. Opportunities are generated and nature is filling it in itself, or people manage which plants can grow where. A roof made of porous stone is using first tactic, generating opportunities for plants to grow and insects to hide. Its holes collect seeds from the wind, making plants sprout.

A disadvantage of the first tactic is chaos. It is not possible to know how a roof is developing and how it will look within a few years. Besides that, it is hard to know if a system works because wind needs to bring right seeds on right moment to right location.

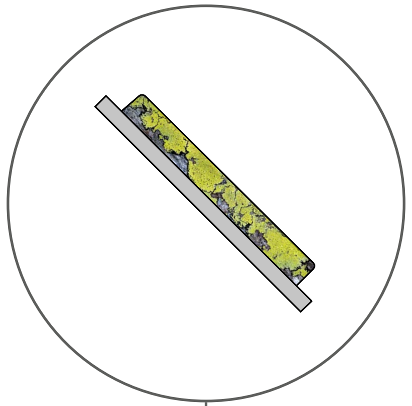


WOOD

- 🟢 Creates diverse life on a roof
- 🟡 How does a wooden roof look like after a few years?

In nature, dead trees form a nursery of new life. Molds, insects, and plants grow on or in it. Wood used in buildings is protected to all these threats with chemicals, paint, or smart design. But what if a wooden roof is developed to putrefy on purpose? Within a few years a roof is full of life. Different wood species can be used to generate a variety of molds, plants, and insects.

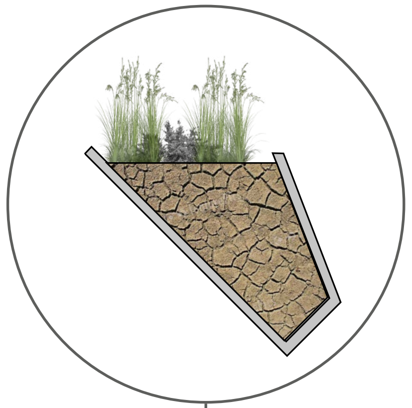
Underneath the wood, a waterproof layer is protecting rest of the building to molds, insects and plants, because it is important to keep them where planned.



LICHENS STONE

- 🟢 Creates a colourful roof in patterns
- 🟢 Creates a basis for other species to grow

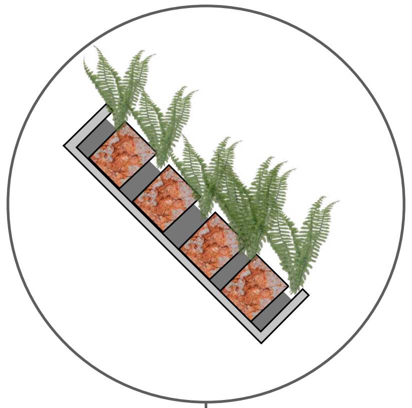
On current roof tiles, mosses and lichens are growing, especially on north sides of buildings. Often, people remove it because it looks sloppy. However, mosses and lichens can generate multiple colors and patterns. Using roof tiles designed for it can become an architectural feature. Instead of painting roof tiles, mosses and lichens can grow on it. Next to aesthetics, mosses and lichens keep roof tiles humid, generating possibilities for other species to grow. Therefore, it benefits biodiversity.



HERBS ROOF

- 🟢 Significant impact on biodiversity
- 🟢 Cools and filters air
- 🟡 Can roof structures hold enough substrate?

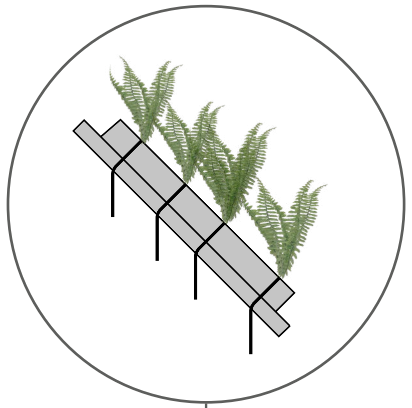
An ideal green roof has herbs, flowers, and grasses. However, these plants need more water and substrate than roof structures can hold. A solution can be a different way of placing substrate. Current green roofs are 100 percent green if you look at it, using sedum. Herbs roof solution is placing substrate in planters, so green is divided into containers. In this way more substrate and water can be used by fewer plants. With this construction, it is possible to create a low weight green roof out of herbs, flowers, and grasses.



WALL PLANTS

- 🟢 Creating opportunities for wall plants
- 🟡 How to stay humid and what is total weight?
- 🔴 Only suitable for roof orientated north

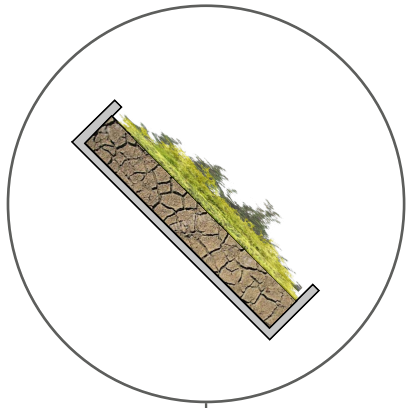
A slanted roof of 45 degrees, is that a roof tilted down, or a wall tilted up? If you can think of a wall tilted up, possibilities arise. Ancient cities have walls covered with mosses, ferns and ivy. Why can a roof not be? Especially north sides are suited for it. Making a roof structure with similar elements as a wall, such as stones and mortar can generate life to plants. Two aspects are important, how to collect enough water and total weight.



CAVITY

- 🟢 Making use of other aspects of a roof
- 🟡 Difficult solution and unknown if it works

The cavity is an improved version of wall plants. By placing wall plants on a roof, water management is critical. This idea uses the cavity behind roof tiles. Within normal circumstances, this cavity is humid which can be used to water plants. Small pieces of fabric are hanging into the cavity collecting water damp and transporting it to the roots of ferns. Theoretical this can work; however, it is not known if cavities are humid enough in hot, dry summers.

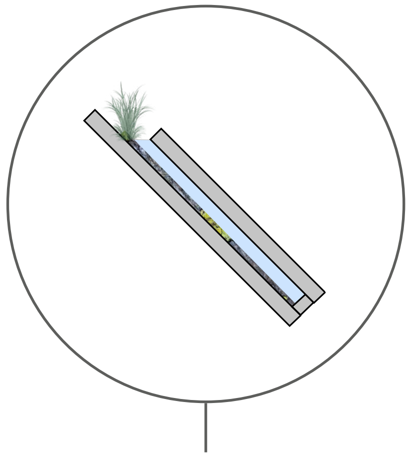


SEDUM ROOF

- 🟢 Survives extreme conditions
- 🟢 Green roof with low weight
- 🔴 Sedum has low biodiversity impact

As said before, use of sedum does not have significant impact on biodiversity. However, sedum has its benefits such as cooling down air, aesthetics, surviving most circumstances and low weight. Besides that, it is the only alternative which is used on roofs nowadays.

The goal of this research is to have a bigger impact on biodiversity than sedum roofs. This sedum idea is added to create a reference point other alternatives can be compared with.



ENVELOPE

- 🟢 Improving biodiversity while looks of a roof remain
- 🟡 Will insects and plants move to a roof?
- 🟡 Will the envelope not become too hot/dry during summer?

Everyone has experienced a burst of life by removing a pavement tile. Insects are rushing for a place to hide, collecting their eggs on the way. This is the idea of an envelope. Making a roof tile with an extra layer for insects, mosses, and plants. From outside, a roof looks similar to a conventional roof, while inside generates life.

However, how do insects reach the top of a building, do roof tiles not get too warm and does the extra layer stay humid during a summer? Answers can determine whether this idea works or not.

CONCLUSION

Next page shows the overview of scores. Herbs roof scores most points because it scores good on all aspects. On one hand, it creates gradients, it is diverse, and its impact on biodiversity is significant. On the other hand, cooling effect, water storage, acoustics and aesthetics are also good. Other ideas such as wood, porous stone, liches stone and envelope are only good at biodiversity and not at cooling down air or acoustics. Some ideas will not have the impact needed (water and sand bole) or will probably not work at all (wall plants and cavity). Sedum roof scores sixth place because it is working, has impact, stores water and scores two on almost all criteria.

Process time is the only 1 for herbs roof because plants need to grow. This can be different if seeds are planted on roofs, however a green result will take weeks after installation.

Having substrate in a planter means people cannot see it. Therefore, a roof looks clean in winter as well. Other alternatives will have a brown roof if plants die.

To conclude, the concept of herbs roof scores good on all biodiversity criteria, has extra environmental benefits (cooling, water storage, acoustics, air filtration), is adaptable, can be produced in large batches and can be made aesthetically pleasing. So, this idea will be developed further into a design.

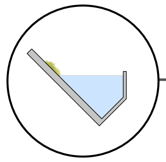
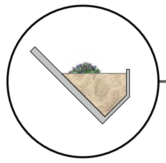
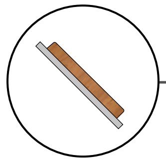
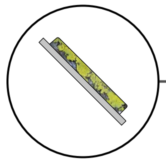
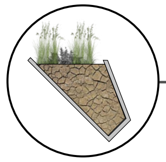
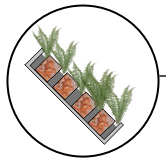
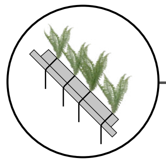
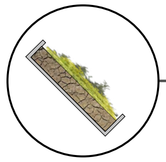
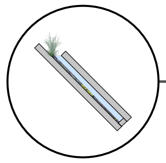
	FIRE SAFETY	WEIGHT	PITCHED ROOFS	DIMENSIONS	LIFETIME	GRADIENTS	DIVERSITY	OPPORTUNITIES	NATIVE FLORA AND FAUNA	IMPACT	ENVIRONEMTAL IMAPCT	END OF LIFE	BATCH SIZE	SCALABILITY	PROCESS TIME	ADAPTABILITY	MAINTENANCE	AESTETICS	FREEDOM OF DESIGN	COOLING EFFECT	WATER STORAGE	ACOUSTICS	AIR FILTRATION	MARKETABILITY	COSTS	**TOTAL**
	🟢	🟠	🟠	🟠	🟠	2	2	2	3	1	2	2	3	3	3	1	3	2	2	2	2	1	1	2	2	85
	🟢	🟠	🟠	🟠	🟠	2	2	3	3	1	2	2	3	3	3	1	3	2	2	2	2	1	1	2	2	88
	🟢	🟢	🟢	🟢	🟢	3	3	3	3	2	2	1	3	3	3	1	3	2	3	1	2	1	2	2	3	99
	🟠	🟢	🟢	🟢	🟠	2	2	3	3	2	3	2	3	3	3	1	3	2	3	2	2	1	1	2	3	98
	🟢	🟢	🟢	🟢	🟠	2	2	2	3	2	2	1	3	3	3	2	3	3	2	1	2	1	2	2	3	94
	🟢	🟠	🟠	🟠	🟠	3	3	2	2	3	2	2	3	3	1	3	2	3	2	3	3	3	3	3	2	107
	🟢	🟠	🟠	🟢	🟠	2	3	2	2	2	2	1	2	3	1	2	2	2	1	2	2	2	3	2	2	85
	🟢	🟢	🟠	🟢	🟠	2	3	2	2	2	2	2	2	2	1	2	2	2	1	2	2	2	3	2	1	85
	🟢	🟢	🟠	🟠	🟠	2	2	2	2	2	2	2	3	3	1	3	3	2	2	2	2	2	2	3	2	91
	🟢	🟢	🟢	🟢	🟢	3	3	3	3	2	2	1	3	3	3	1	3	2	2	1	2	1	2	2	3	98

Table 4.3 | Scores biodiversity concepts (own)

4.4 CONSTRUCTION

This paragraph will go into solutions and analyses of the construction design problem.

PV PANEL CONSTRUCTION

- 🟢 Standard parts and tools
- 🟢 Less strict on drainage
- 🔴 Cannot be used in combination with herbs roof

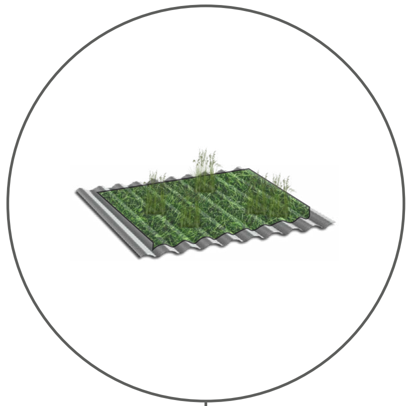
Placing PV panels is one of the few moment people are on their roofs. While doing that, it is possible to use the same aluminum construction to hold a green roof module. This module has same size and connection method as standard PV panels. So, only standard parts and tools are needed for this construction. Besides that, requirements regarding drainage are less strict because normal roof systems (tiles) are still there.

A standard PV panel weights between 10 and 25 kg per square meter. This is low compared to a square meter of substrate, water, and plants. Therefore, a solution of a herbs roof cannot be used in combination with a PV panel construction.

ROOF TILE

- 🟢 Can cover a conventional roof 100 percent
- 🟢 Replaces any number of conventional roof tile
- 🟢 Low weight and easy connection with conventional roof tiles

Most slanted roofs of the Netherlands are covered with roof tiles. Therefore, making a construction as a roof tile is convenient. First, because of its size, having a green roof system made of roof tiles always fits on every roof. It would be possible to take any number of roof tiles out and replace them with green roof tiles. In this way an investment can stay low (it is not necessary to replace a complete roof). Second, because of connection, a green roof system needs to connect with conventional roof systems, and that is easier if a green roof is shaped as a roof tile. Third, because of weight and size, weight is low and size is easy to handle.



CORRUGATED ROOF

- 🟢 Low costs and fast mounting
- 🟢 Covers a big area in once
- 🟡 Weight
- 🟡 Connection with conventional roof systems

Corrugated roofs are placed if costs are leading. It is cheap, fast and can cover big areas in once. A green roof system out of corrugated roof panels will also be placed fast and cheap. Connection with conventional roof systems can be a challenge because corrugated roofs are normally not mixed with roof tiles. Also, weight can become a problem, because of its size.

GUTTER

- 🟢 Enough substrate and water for herbs and flowers
- 🔴 Adjustements needed in building construction

The gutter will function as a planter, holding substrate and water for plants. Standard gutters have a similar form compared with balcony planters. An integration of these two products can form a functional green roof system. Instead of one, a gutter gets two containers. One filled with plants and second works as overflow. Water only goes to a sewer system if plants are saturated. In this system hanging plants can be used as well, giving houses a green, natural look.

Current gutters are lightweight and therefore is their suspension. If a gutter construction is used, building construction needs to be adjusted too.

DOWNSPOUT

- 🟢 Reduces stress on sewer system
- 🟢 Bigger plants can be used
- 🟡 Difficult solution with technical challanges

All water falling on a roof goes through a downspout. Instead of moving water to a sewer system as fast as possible, it can also be collected and used. The downspout becomes a water barrel, collecting all rainwater and using it for plants on top. Because large amounts of water can be stored and construction is standing on the ground, bigger plants can be used, even small trees. A small overflow pipe is transporting water to the ground if downspout is full.

CONCLUSION

Next page shows the overview of scores. Roof tile construction scores most points because it scores good on all criteria. Having a roof tile with plants on it connects with conventional roof systems, it is possible to place different number of modules, it is scalable, does not require extra components or knowledge and can fill 100 percent of a conventional roof. PV panels often mismatch with dormers, chimneys and antennas resulting in unpleasant located rectangles. However, it scores second place because of freedom of design, tolerances, and end of life. As said before, weigh is an issue and PV panel construction cannot be used in combination with herbs roof, similar to corrugated roof. Both gutter and downspout score low because of complex systems and adjustments needed to building construction.

To conclude, a roof tile as construction connects best with current systems, has the right size, can function in combination with herbs roof and can fill a roof 100 percent without odd looking corners. So, this concept will be developed further into a design.

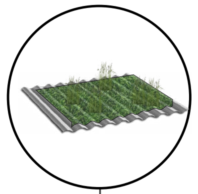
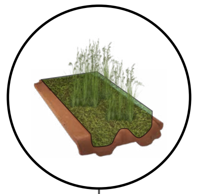
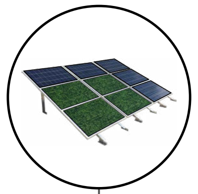
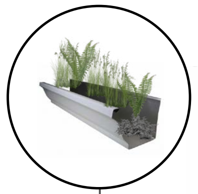
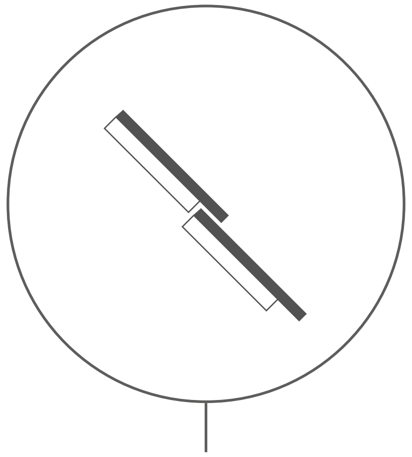
					
STRUCTURAL SAFETY	🟢	🟢	🟢	🟡	🟡
FIRE SAFETY	🟡	🟡	🟢	🟢	🟢
DRAINAGE	🟢	🟢	🟢	🟡	🟡
WEIGHT	🔴	🟡	🔴	🟡	🟡
PITCHED ROOFS	🟢	🟢	🟢	🟢	🟢
EXISTING SYSTEMS	🟢	🟢	🟢	🟢	🟢
EXISTING ROOF TILES	🟡	🟢	🟢	🟢	🟢
LIFETIME	🟢	🟢	🟢	🟢	🟢
MAINTENANCE	3	3	3	3	3
AESTETICS	2	3	2	3	2
FREEDOM OF DESIGN	2	2	3	2	2
TOLERANCES	2	2	3	2	2
ENVIRONMENTAL IMPACT	2	2	2	2	2
BUILDING SPEED	3	3	2	2	2
NUMBER OF COMPONENTS	3	3	2	2	2
END OF LIFE	2	2	3	2	2
BATCH SIZE	3	3	3	3	3
SCALABILITY	3	3	3	3	3
PROCESS TIME	3	3	2	2	2
MARKETABILITY	2	3	3	1	1
COSTS	3	3	2	2	2
TOTAL	57	62	58	52	49

Table 4.4 | Scores construction concepts (own)

4.5 CONNECTION MODULES

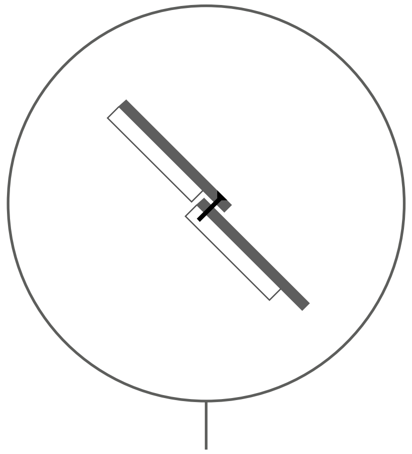
This paragraph goes into solutions and analyses of connection modules design problem.



OVERLAPPING

- 🟢 Simple, easy and cheap
- 🟢 Disassemble and reuse without adjustments
- 🟡 Structural safety

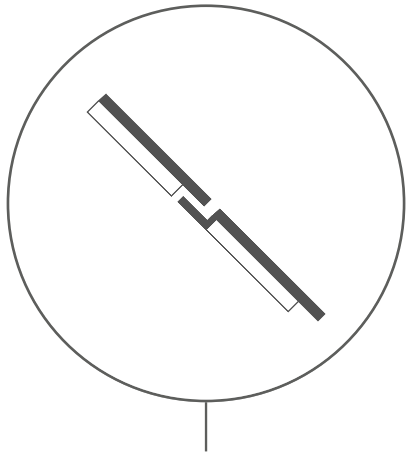
Simplest way to connect two modules rainproof, is overlapping. Because green roof systems are placed on a slanted roof, overlapping is possible. Roof tiles are connected this way, similar as other (ancient) roof systems made of stone, steel, or wooden plates. Because modules are not connected, it is possible to disassemble and reuse the system without adjustments or holes. On the other hand, it is less structural safe because wind can lift it from a roof.



OVERLAPPING CONNECTED

- 🟢 Structural safe
- 🟡 Creates higher tolerances and less movement

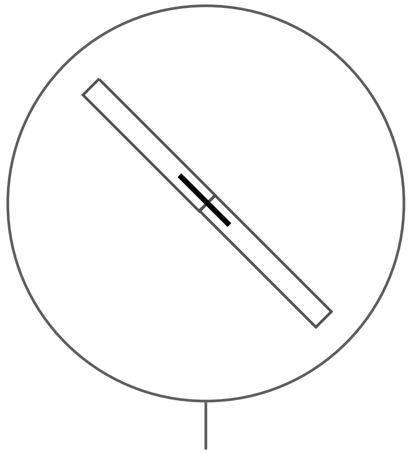
Because structural safety of overlapping modules is less, this alternative is developed. A watertight screw is used to connect modules in a structural way. Because of screws, less movement is allowed between modules, creating higher tolerances.



OVERLAPPING FORMED

- 🟢 Aligned modules
- 🟢 Disassemble and reuse without adjustments
- 🟡 Production costs

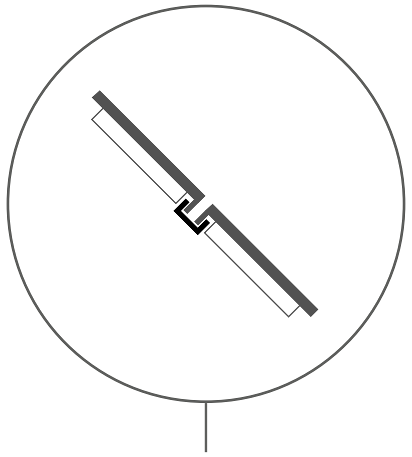
An overlap between modules can also be formed by folding back the top of it. In this way, elements are aligned, and system stays watertight. Disassembling and reusing a single module is possible without making adjustments/holes. Depending on production process, a formed overlap can increase production costs.



CONNECTION PLATE

- 🟢 Aligned and smooth outer surface
- 🟡 Requires wet seals
- 🔴 Disassemble and reuse single module not possible

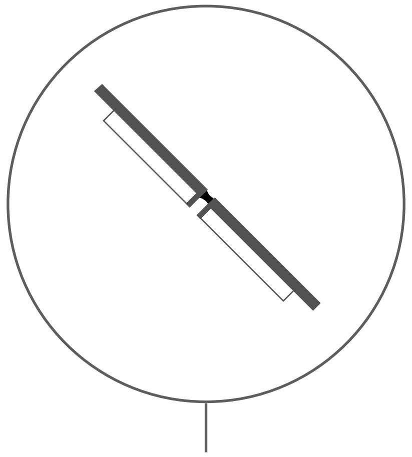
An aligned and smooth outer surface can be generated by a connection plate. This plate is put into slots on both modules. Making this system watertight requires extra wet seals. Therefore, disassembling and reusing of a single module is not possible without adjustments.



CAP

- 🟢 Modules similar on all sides
- 🟢 Flat outer surface
- 🟡 Extra parts
- 🟡 Complex building sequence

Another option to create a waterproof connection between modules is a gutter system behind it. In this way, modules can be similar on all sides with a flat outer surface. Also, tolerances are less strict and adjustments can be made on site. However, it requires extra parts and building sequence complexity.



WET SEAL

- 🟢 Watertight connection with smooth and flat outer surface
- 🟡 Less complexity of modules
- 🔴 Disassemble and reuse single module not possible

By using a wet seal, for instance silicones, a watertight connection between modules can be realized. Besides that, a smooth and flat outer surface is created. Complexity of modules is less; they can be the same on all sides and wet seal systems do not require a certain panel layout. Downside of wet seal systems is disassembly because components cannot be reused without cleaning or adjustments. Besides that, it needs time to dry and it cannot be assembled at certain circumstances.

CONCLUSION

Overlapping scores most points (34) because loose tolerances can be used, assembly time is low, no extra components needed, and it does not impact production time or costs negatively. It is the system conventional roof tiles are using, so it makes it easier to integrate both green roof system and roof tiles. Structural safety can become an issue if connection with roof structure is not strong enough. However, standard parts such as tile hooks could be used to improve it.

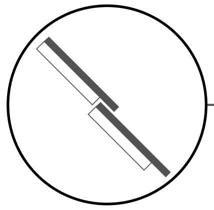
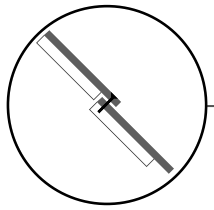
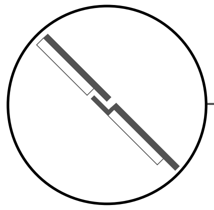
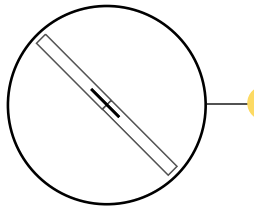
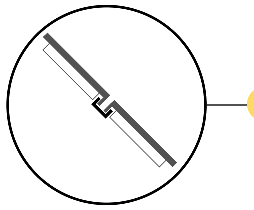
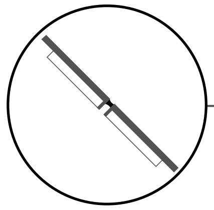
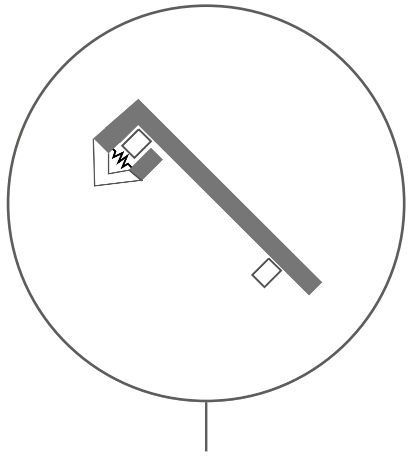
	DRAINAGE	PITCHED ROOFS	EXISTING ROOF TILES	STRUCTURAL SAFETY	LIFETIME	TOLERANCES	BUILDING SPEED	NUMBER OF COMPONENTS	END OF LIFE	BATCH SIZE	SCALABILITY	PROCESS TIME	COSTS	**TOTAL**
	🟢	🟢	🟢	🟡	🟢	3	3	3	2	3	3	3	3	34
	🟢	🟢	🟡	🟢	🟢	1	2	2	2	3	3	3	3	30
	🟢	🟢	🟢	🟡	🟢	2	3	3	2	3	3	2	2	29
	🟡	🟢	🔴	🟢	🟡	2	2	2	2	3	3	1	2	25
	🟡	🟢	🔴	🟢	🟢	2	2	1	2	3	3	1	1	22
	🟢	🟢	🔴	🟡	🟡	1	1	3	1	3	3	2	3	26

Table 4.5 | Scores connection modules concepts (own)

4.6 CONNECTION ROOF STRUCTURE

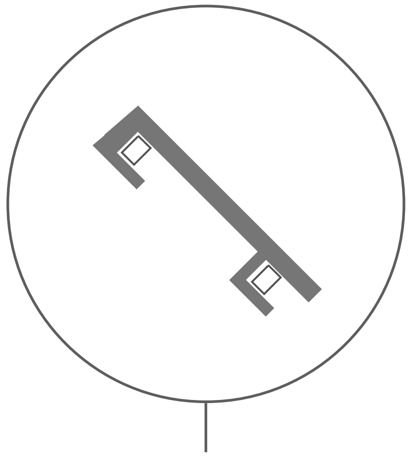
Conventional roof structures are made of horizontal beams (purlins) and vertical beams (rafters). Roof systems and tiles are connected to purlins by gravity (hanging), screws or special roof tile hooks. In this paragraph, solutions made for a green roof system are explained and analyzed. These solutions all make use of conventional purlins.



CLAMP

- 🟢 Strong connection with reconnection possibilities
- 🟡 Compex product
- 🟡 Strenght connection decreases over time

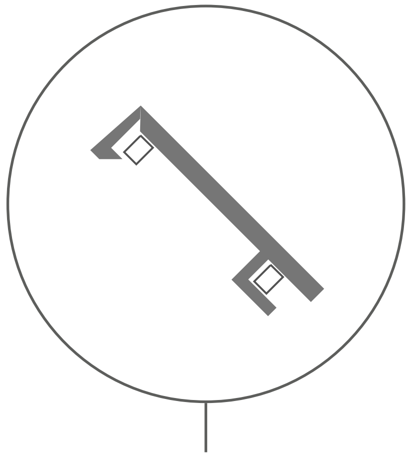
Connecting a green roof system to purlins can be done in multiple ways. Clamps provide a strong connection which can be reconnected. On site, tolerance errors can be tuned, and multiple purlin sizes can be used. A clamp increases the number of components and complexity of product. A spring is sensitive for fatigue, so strength of connection can decrease over time.



FIXED SHAPE

- 🟢 Strong and locked connection
- 🔴 Dissassembling single module not possible

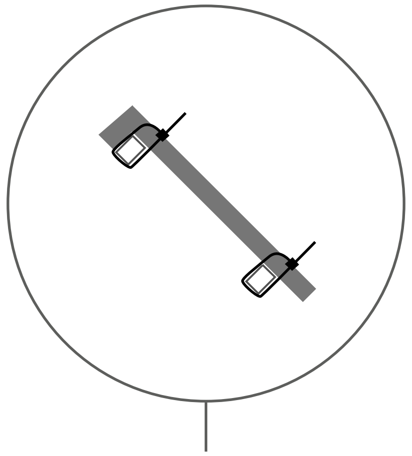
Buildup of a conventional roof starts from right bottom corner up to left upper corner. This sequence can be used to lock tiles in their position. With a fixed shape, which can only be removed upwards, all roof modules are secured by modules above. By extra securing upper row, whole roof is fixed without any additional components. Downside of this system is disassembling; it is not possible to replace one tile without disassembling whole roof.



CLICK SYSTEM

- 🟢 Fast connection without aditional components
- 🟡 Complex dissassembling
- 🟡 Tight production and purlin tolerances

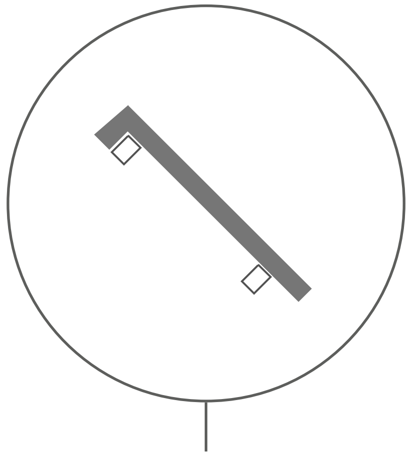
A fast way of connecting parts is a click system. It is easy to put modules in place and secure it by one push. However, disassembling is more complex if a click system is hard to reach. A click system needs tight production tolerances and constant distance between purlins. On the other hand, it does not require extra components and connection can be made rigid.



TIE WRAP

- 🟢 Cheap, easy to handle and replacable
- 🟢 Dissassembling single module possible
- 🔴 Holes and slots reduce waterproofness
- 🔴 Fire safety

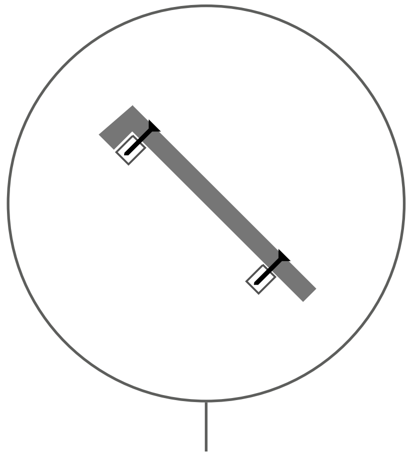
Tie wraps are used in a variety of applications, all with a function of connecting and securing something. They are cheap, easy to handle and can be replaced. Disassembling a single module is possible without removing or replacing other modules. They allow loose tolerances and diversify distances between purlins. However, holes or slots are made to connect tie wraps to modules which reduces waterproofness of total system. Besides that, tie wraps melt during a fire which reduces fire safety.



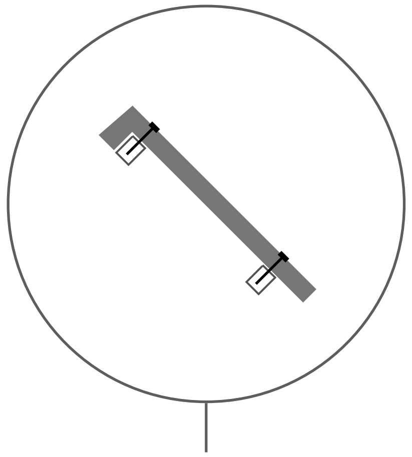
HANGING

- 🟢 Cheap, easy and fast
- 🟢 Dissassembling single module possible
- 🟡 Structural safety

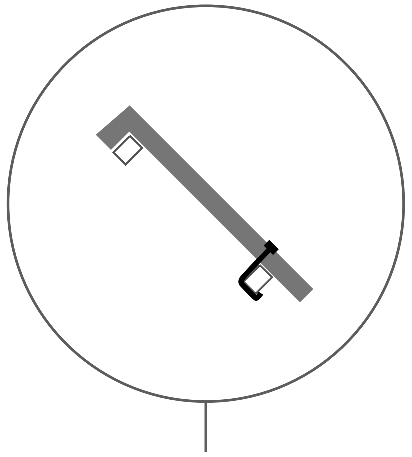
Easiest and simplest way to connect a roof system to purlins is hanging. Gravity and friction are keeping modules in place. Most roof tiles use this system, allowing for replacing one tile independently from others. No holes are drilled through a panel, making it 100 percent waterproof and it allows for a variety of distances between purlins. No tight production tolerances are required, and geometry of module is simple, reducing costs. If total mass of system is high enough, it is structurally safe. However, extra security can be necessary in some cases.



SCREW



NAIL



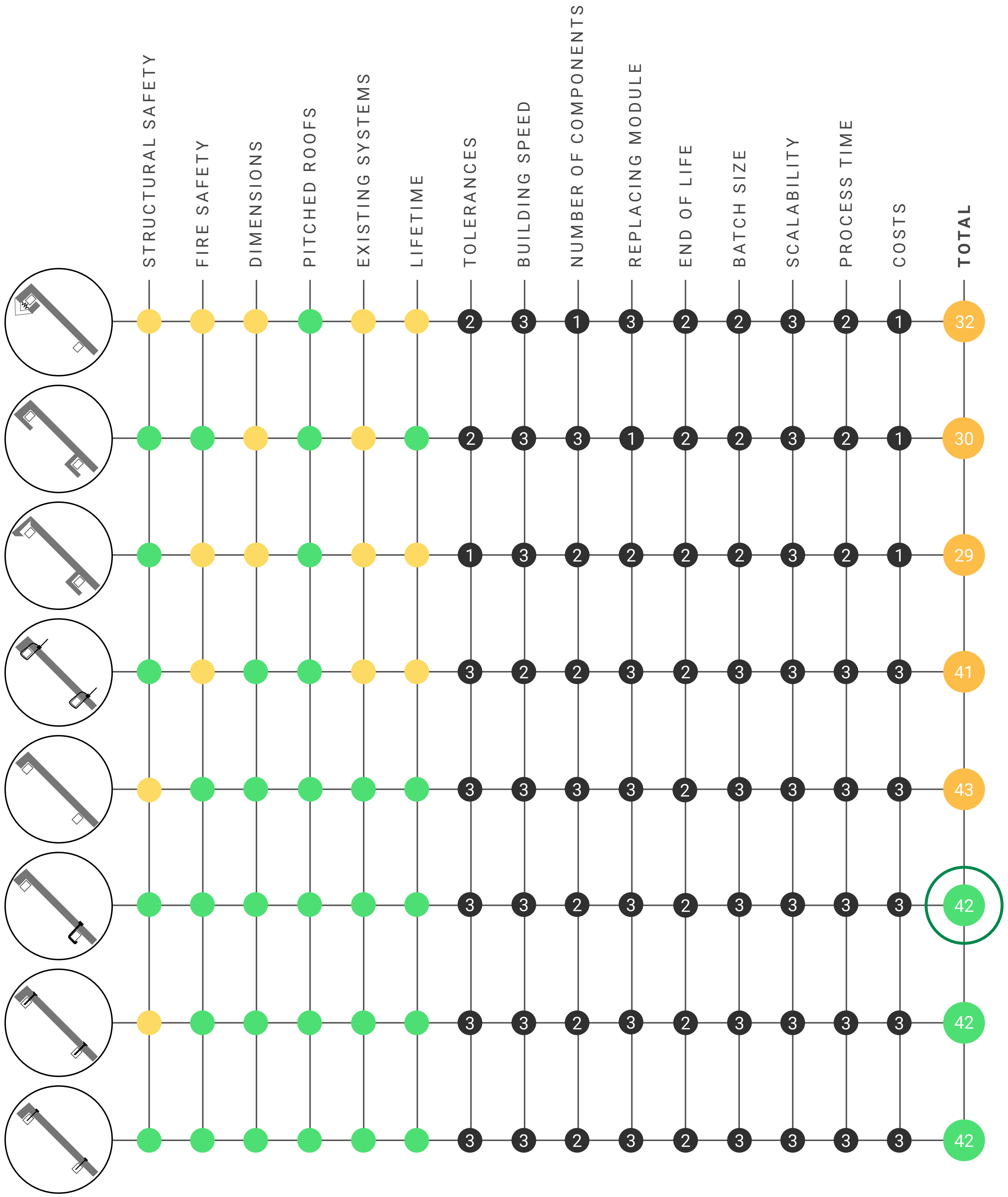
TILE HOOK

SCREW, NAIL, TILE HOOK

- 🟢 Cheap, easy and fast
- 🟢 Dissassembling single module possible
- 🟢 Structural safe

As explained at Hanging system, extra security might be necessary at some cases. Adding screws, nails or tile hooks secure a system to purlins. The hanging system transfers all vertical loads to roof structure, while screws, nails or tile hooks are dealing with horizontal loads. A screw connection is stronger compared to nail connection and easier to remove. Bigger screws require a pre-drilled hole, increasing assembling time, nail connections do not. Both make use of a hole or slot, reducing waterproofness of system.

Therefore, special tile hooks are made. They are a combination of a hook and a nail. It uses geometry of a roof tile to connect and it is nailed into a purlin. Because they are specially designed for roof tiles, the costs are higher (compared with screws or nails) but compared with the other systems it is still cheap (therefore, it scores a 3 as well).



STRUCTURAL SAFETY	FIRE SAFETY	DIMENSIONS	PITCHED ROOFS	EXISTING SYSTEMS	LIFETIME	TOLERANCES	BUILDING SPEED	NUMBER OF COMPONENTS	REPLACING MODULE	END OF LIFE	BATCH SIZE	SCALABILITY	PROCESS TIME	COSTS	**TOTAL**
🟡	🟡	🟡	🟢	🟡	🟡	2	3	1	3	2	2	3	2	1	32
🟢	🟢	🟡	🟢	🟡	🟢	2	3	3	1	2	2	3	2	1	30
🟢	🟡	🟡	🟢	🟡	🟡	1	3	2	2	2	2	3	2	1	29
🟢	🟡	🟢	🟢	🟡	🟡	3	2	2	3	2	3	3	3	3	41
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🟢	🟢	🟢	🟢	🟢	🟢	3	3	2	3	2	3	3	3	3	42

Table 4.6 | Scores connection roof structure concepts (own)

CONCLUSION

Replacing one individual module without removing all others is a criterion on which click system and fixed shape fail. Clamp system has too many components, is complex and sensitive for fatigue. Tie wraps have advantages, however, it reduces building speed and fire safety.

Hanging, screws, nails, and tile hooks score similar. Hanging has highest score because no extra components are needed. However, structural safety can become an issue. Therefore, it is not the best solution. Screws, nails, and tile hooks all apply extra safety in a simple and cheap way. People know how to use it and it does not influence assembly time much. Tile hook is preferred option because it is specially designed for its task, can be used on multiple designs and no holes are required. Waterproofness could become a problem with nails or screws.

4.7 CONCLUSION CONCEPT DEVELOPMENT

Ten biodiversity concepts, five construction concepts, six connection module concepts and eight connection roof structure concepts are developed and analyzed. Next step is to integrate preferred solutions.

A green roof system with herbs roof scores most points because it has significant impact on all criteria. This system will be placed on a roof tile because of its low weight and small size. With this roof tile system, all corners of a roof can be used without adjustments of the system. These green roof tiles overlap each other, mimicking conventional roof tile structures. Overlapping is most useful, cheap, and fast way to make a slanted roof waterproof. Lastly, Green roof tiles will hang on a roof structure (purlins), keeping in place by gravity and friction. Tile hooks will secure the modules to make it structurally safe.

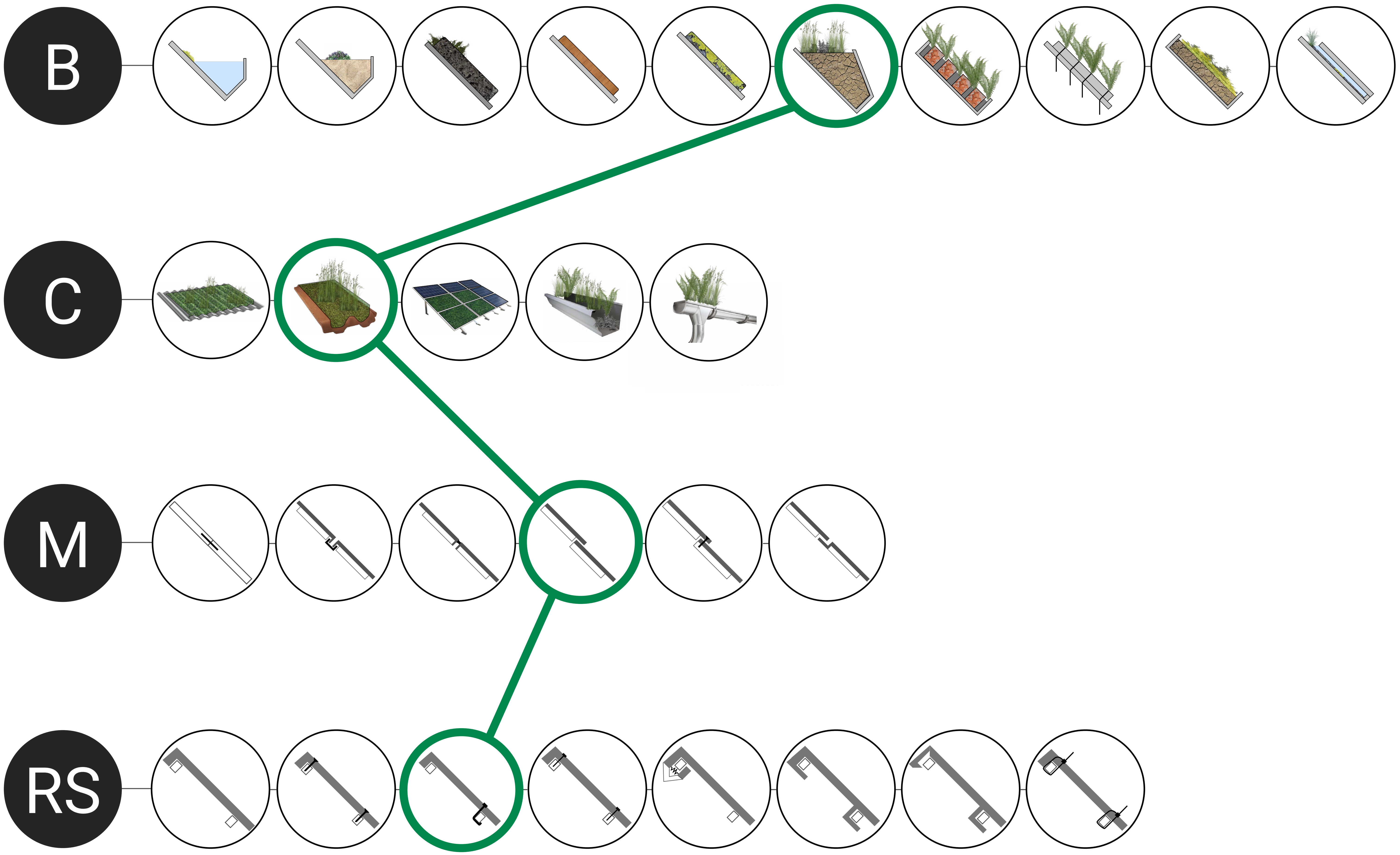


Table 4.7 | Overview concepts (own)

DESIGN DEVELOPMENT

The overall concept is developed into a design. This design consists of two parts, a universal roof tile and a planter. Roof tiles create a lightweight, waterproof layer on which planters can be attached. Standard products are used as part of design or as inspiration, reducing complexity and costs. With the use of a 3d-printer, prototypes on a scale of 1:4 and 1:1 are made. These prototypes are used to evaluate its design. A FMEA, SWOT, and injection molding design guide are made to take design to its final stage.

5.1 APPROACH

As described in previous chapter, an herbs roof will be combined with a roof tile. These will be overlapping to make it waterproof. These modules hang from purlins secured by roof tile hooks. Together, the four concepts start the design development.

Design revisions are developed using Solidworks as design tool (3d modeling). With this design tool, 3d models are analyzed on connections, overlapping, strength, and assembly sequence. Connections are analyzed between designs itself and with conventional roof tiles. For this, VHV and OVH roof tiles are used, see appendix B. These are the most used roof tiles within the Netherlands (Kamps, G., January 2021).

Inspiration has been gained from desk research, focusing on conventional solutions for roofs and planters.

Prototypes have been produced using 3d-printing on a scale of 1:4. These prototypes are analyzed on connections together and with conventional roof tiles (also printed 1:4). 1:1 prototypes are printed to optimize final design revisions.

FMEA and SWOT analyses are implemented to find points of improvement and an injection molding guideline is made to optimize design for production.

Improvements are done step by step, using strong points of last designs revision and updating weak points. Program of requirements is used as guide to improve design into right direction.

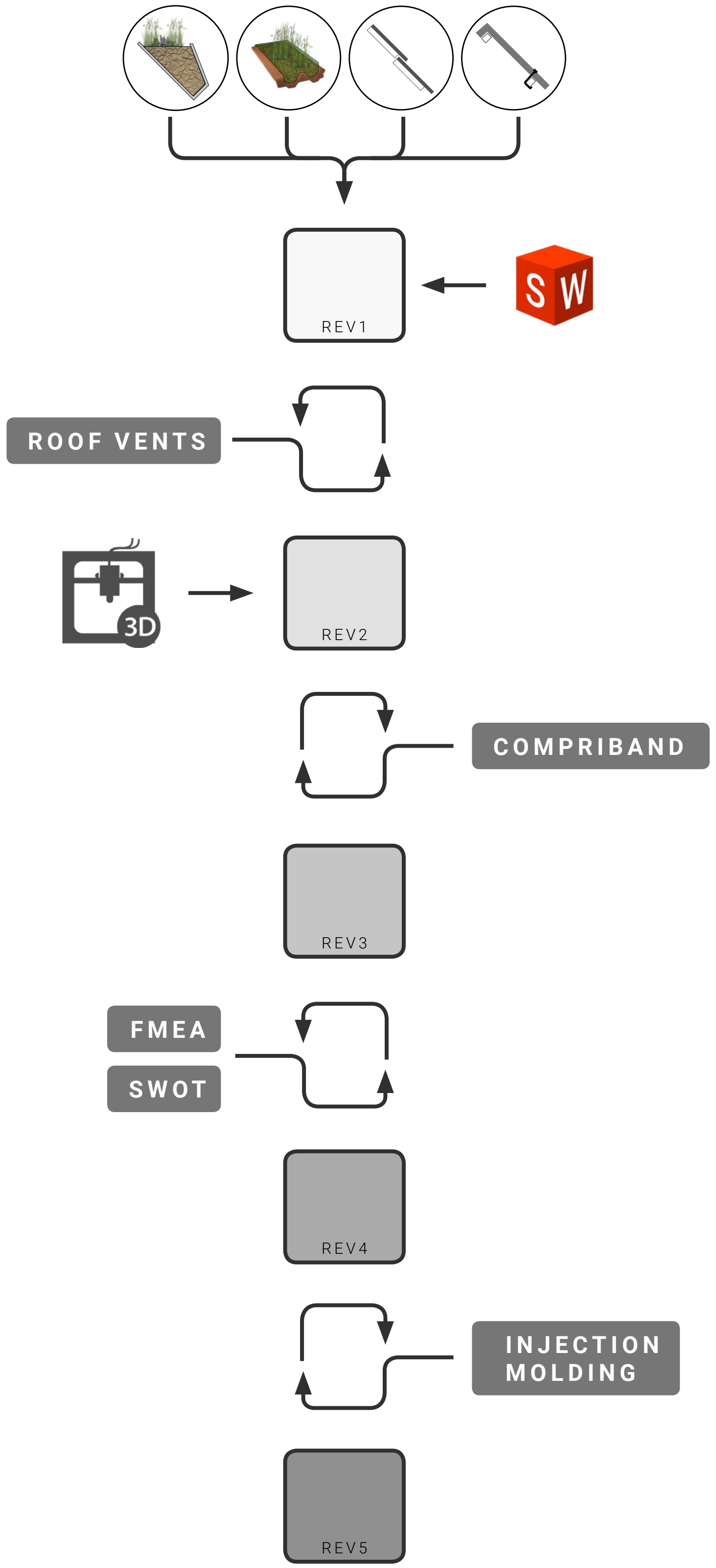


Figure 5.1 | Design development (own)

DESIGN REV 1.1

Conventional roof tiles overlap a roof tile on one side and are being overlapped on the other side. This idea is the start of design revisions. A planter is designed with upstanding edges [1]. These edges are under an angle to create a waterproof connection. Lower right corner [2] has an indentation to make sure four green roof tiles fit into one corner. Two dotted lines [3] indicate conventional roof tiles. One is going over lower edge, other is going underneath upper edge.

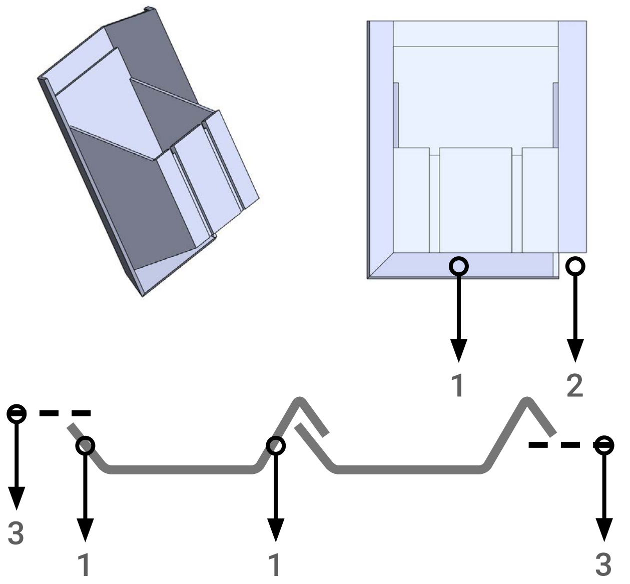


Figure 5.2 | Design revision 1.1 (own)

DESIGN REV 1.2

A separation is made between planter and Green roof tile. In this way, both can be designed and optimized for their own purpose. Disconnecting the two parts makes the whole system more flexible, a planter can be replaced or removed without replacing or removing a Green roof tile.

Rev 1.1 has not enough clearance between upper and lower edge. Therefore, only VHV roof tile could fit and OVH not because its different geometry. Instead of a declined upper edge, it is made straight [1], creating more clearance.

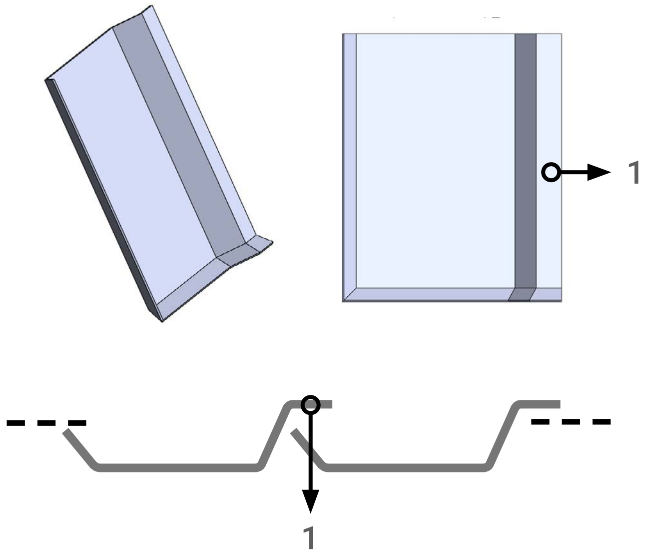


Figure 5.3 | Design revision 1.2 (own)

DESIGN REV 1.3

Rev 1.2 has tight connections with conventional roof tiles, but clearance between modules itself is too much. Rainwater may go through it. Therefore, edges of rev 1.3 [1] are both overlapping conventional roof tiles and making a tight connection between modules [2]. In this way, a bin is created automatically and only a front plate is needed. The geometry at the bottom left and upper right corner [3] is to make sure four modules fit into one corner.

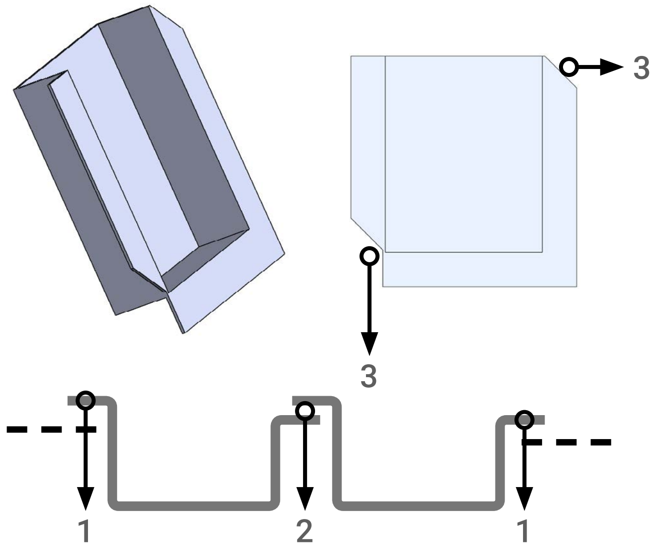


Figure 5.4 | Design revision 1.3 (own)

DESIGN REV 1.4

Straight walls create problems at injection molding, therefore slanted sides are made [1]. Besides that, holes are drilled for screws [2]. These screws secure the system to purlins instead of tile hooks. Tile hooks cannot be used because the edges are too wide [3]. Lastly, an overflow is created [4], guiding rainwater from one module to another.

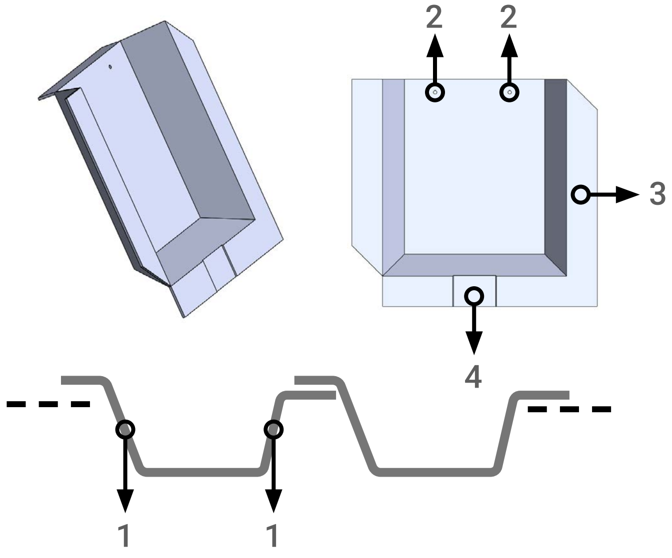


Figure 5.5 | Design revision 1.4 (own)

5.2 ROOF VENTS

All four design revisions do not fulfill the requirements. Waterproofness is not guaranteed because of high clearances. These clearances are necessary to connect with multiple conventional roof tiles.

At this point, a desk research is performed to investigate conventional products with similar criteria (waterproof connection with multiple conventional roof tiles). Hereby, roof vents are analyzed. These roof vents are universal (one product can be used for multiple roof tile systems) and they create a waterproof connection.

Two parts create this waterproof connection. First, a flexible ridge made of rubber, plastic or foam connects to overlapping roof tiles [1]. This ridge is cut or pushed into right shape. Second, a flexible part overlaps roof tiles at the bottom side [2]. This part can be formed into position by hand. An adhesive strip at the backside [3] makes sure this part keeps its form and does not disconnect from roof tiles.

Both ideas are used into next designs revisions.

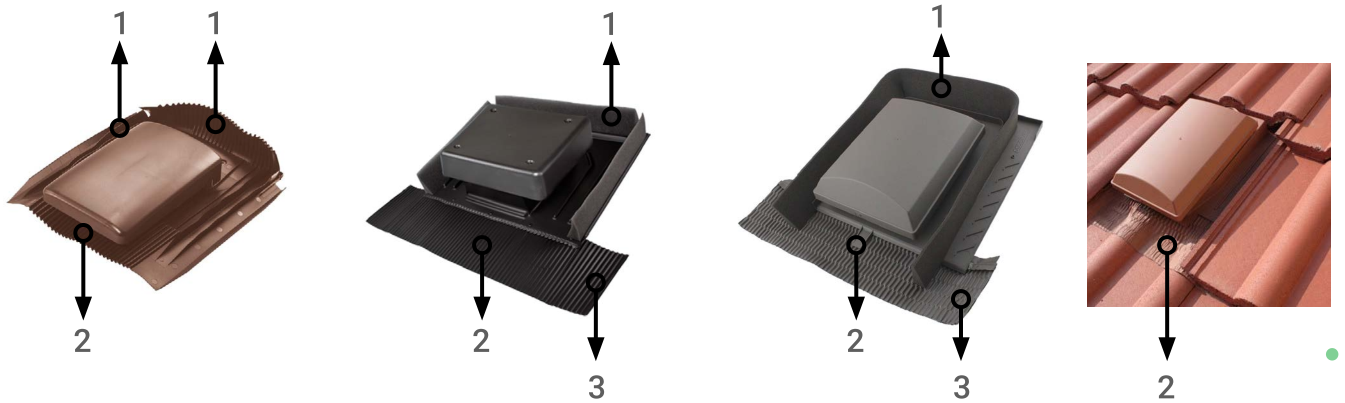


Figure 5.6 | Roof vents (roofingOutlet, Iconbp)

DESIGN REV 2.1

Similar to universal roof vents, this design goes underneath conventional roof tiles on both sides [1]. Between modules, overlapping takes place, whereby left panel is overlapping right one [2]. Left, right and upper side have a slot in which an extra part can be placed [3]. This part is a foam strip, closing off gabs between Green roof tiles and conventional roof tiles [4]. This foam guarantees a closure independent from roof tile geometry.

Green roof tile revision 2.1 hangs from purlins [5] and secured by screws. These screws are located at the top side at which another panel is overlapping [6]. Therefore, these screw holes do not influence waterproofness of product.

At the front, four holes are made [7]. These holes do not go through the product, so waterproofness is guaranteed. They are made to connect with a planter.

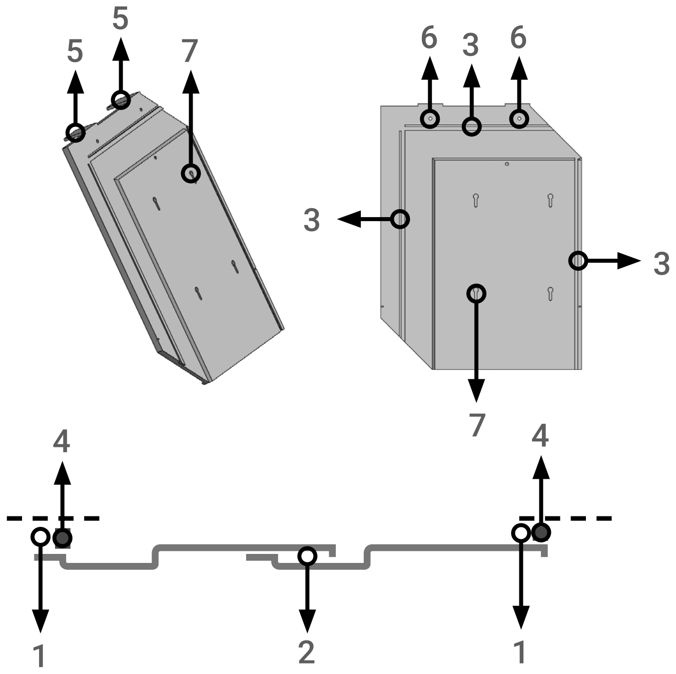


Figure 5.7 | Design revision 2.1 (own)

DESIGN REV 2.2

As described in paragraph Planter, planters will be divided over four Green roof tiles. Because these tiles can move relative to each other, slots are used instead of holes [1]. A planter is hanging at the upper two tiles and secured by screws. These screws will be positioned at the small horizontal slot above the main horizontal slot [2]. A vertical groove is made to remove water accumulating at the horizontal slots [3].

This design is made more compact and left bottom and right upper corner have a different indentation [4]. This is done for better overlapping of all four tiles at every corner.

Lastly, besides using screws at the top, it is also possible to use a tile hook at the left bottom corner. A notch is made at which a tile hook can be connected [5].

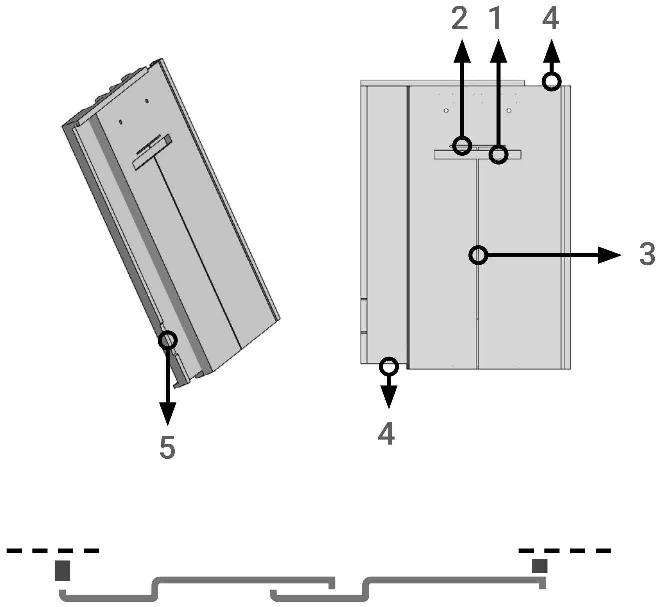


Figure 5.8 | Design revision 2.1 (own)

DESIGN REV 2.3

Another horizontal slot is created compared to rev 2.2 [1]. This slot is used to secure a planter at the bottom side as well. So, it will only be used at the bottom two tiles.

Small details are important. As can be seen in figure 5.9, left detail (rev 2.2) has an undercut [2] and right detail (rev 2.3) does not. Both details have a similar function, they are used to guide a foam strip. Left detail is expensive to produce relative to right detail, making use of injection molding. All slots have been updated to reduce production costs.

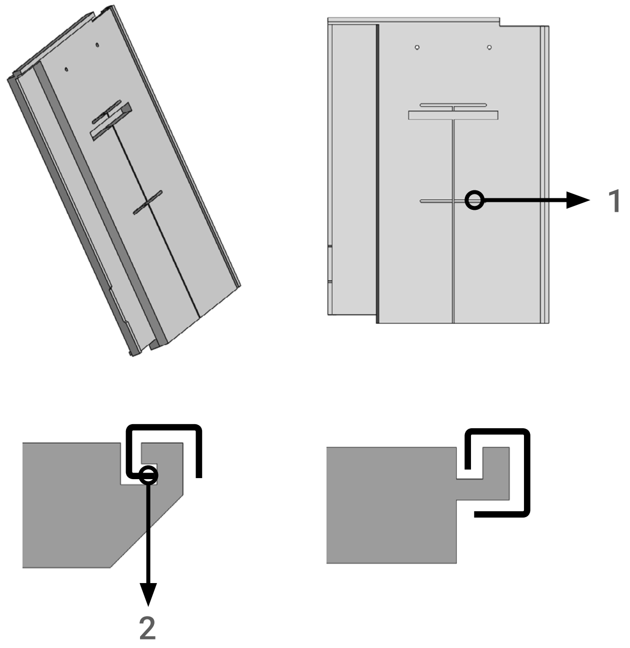


Figure 5.9 | Design revision 2.3 (own)

DESIGN REV 2.2B, 2.3B

From design rev 2.1 onward, all designs are overlapped by conventional roof tiles on both sides. Combined with a foam strip, this creates a waterproof connection able to use with big clearances. However, bottom side creates a problem. If Green roof tiles are going underneath conventional roof tiles at the bottom side, water will go through the roof. Universal roof vents solve that with a flexible part which can be formed into a right shape on top of conventional roof tiles.

Rev 2.2b has such a flexible part in its design [1]. However, it is not possible to use HDPE for that because it is not a flexible material. Injection molding two materials into one mold is complex and reduces ability to recycle these products. Therefore, another option is created.

At the top of a roof (ridge), similar systems are used as describes above. A flexible material, an Ondervorst (traditionally lead, currently aluminum or plastics), is placed underneath ridge tiles [2]. This material is shaped onto the upper row of roof tiles by hand, creating a watertight connection. A standard roll of

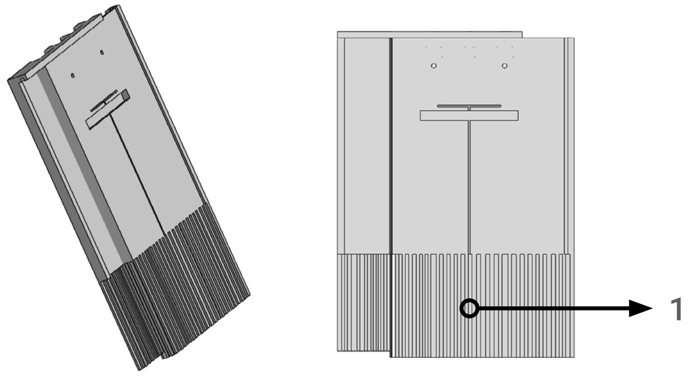


Figure 5.10 | Design revision 2.2B (own)

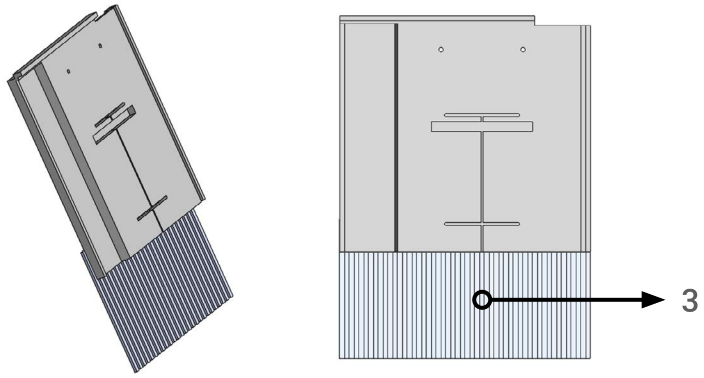


Figure 5.11 | Design revision 2.3B (own)

aluminum Ondervorst is used at design rev 2.3b. This aluminum [3] is cut into pieces and screwed at the back. In this way, a connection with lower roof tiles is developed using standard products, reducing complexity and costs.

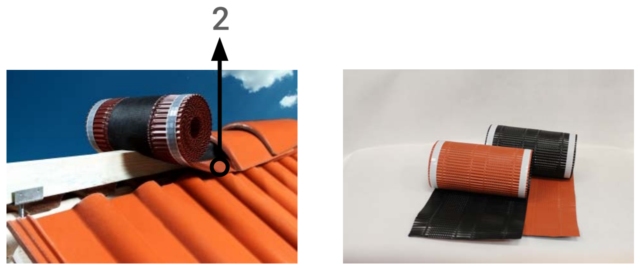


Figure 5.12 | Ondervorst, Alurol (Ondervorst Arisda BV)

5.3 CONNECTION CONVENTIONAL ROOF TILES

Up to revision 2.3, a foam strip has been designed as a custom part sliding on three sides of a Green roof tile. However, the question arose whether this part is the best solution for its function. A comparison is made between six alternative solutions. Their positive (green), negative (red) and points of improvement (yellow) are written down below.

Instead of a custom foam strip, which is expensive and requires good management on construction site, a foam tape is the best option. Foam tapes are standard products on construction sites, it is a simple, easy, and cheap connection. It shapes itself, making it possible to be used with multiple conventional roof tiles. Glue residues will not become a major problem because foam tapes will not be disassembled regularly, and glue residues can be removed if necessary.

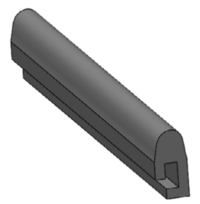


Figure 5.13 | Custom part (own)

CUSTOM PART

- 🟢 Tight connection with green roof tile and conventional roof tiles
- 🟢 Easy disassembling without glue residues
- 🟡 User does not know product, risk on mistakes or wrong assembly
- 🟡 No improvisation possible if there are no or too little foam strips
- 🟡 High costs due to custom part
- 🟡 High costs due to different production technique compared to Green roof tile

Figure 5.14 | Compriband, foamtape (Kitcentrum)

COMPRIBAND/FOAMTAPE

- 🟢 Tight connection to a variety of roof tiles
- 🟢 Simple and easy connection
- 🟢 Standard part, low costs
- 🟢 User knows product, less risk on mistakes
- 🟢 Cutting right length on site, so good connection and room for improvisation
- 🟢 Available on a roll, so compact transportation (especially compriband)
- 🟡 Possible glue residues at disassembling

Figure 5.15 | Preformed foam (corrugatedroofelog)

PREFORMED FOAM

- 🟢 Tight connection with roof tiles
- 🟢 Simple and easy connection
- 🟡 Different products needed for different roof tiles
- 🟡 Tight alignment with roof tiles
- 🟡 Possible glue residues at disassembling
- 🟡 No compact transportation

Figure 5.16 | Roof vent (Iconbp)

CUTTING AWAY EDGE

- 🟢 Cutting right size on location, so good connection with roof tiles
- 🟢 Watertight connection because it is one part
- 🟢 Low costs because no extra part is needed
- 🟡 Two types of green roof tile needed because this is only necessary at the edges
- 🟡 It generates waste
- 🟡 Flexible material needed

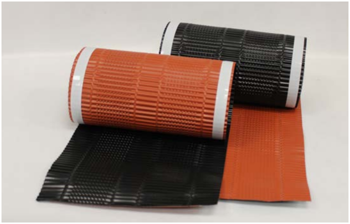


Figure 5.17 | Alurol (Ondervorst Arisda BV)

BENDED ALUMINUM

- 🟢 Tight connection with roof tiles because aluminum is shaped on location
- 🟢 Standard part, low costs
- 🟡 Standard part is too big, so material is unused or it needs to be cut into custom shape
- 🟡 Assembling of roof is slow because all green roof tiles need to be shaped on site

Figure 5.18 | PUR (Bison)

PUR

- 🟢 Watertight and airtight connection
- 🟢 Easy and fast assembling
- 🟢 Cheap product
- 🟢 User knows product
- 🔴 Roof tiles are glued together, so no disassembling possible

DESIGN REV 3.1

Instead of a slot for a custom foam strip, a 20 mm wide recess is placed on top and two sides [1], this corresponds with a 20 mm wide Compriband. This foam tape can be placed on roof tiles at any moment, before assembling, during, or at last stage. Foam will swell up to 45 mm within an hour, closing gabs between Green roof tiles and conventional roof tiles.

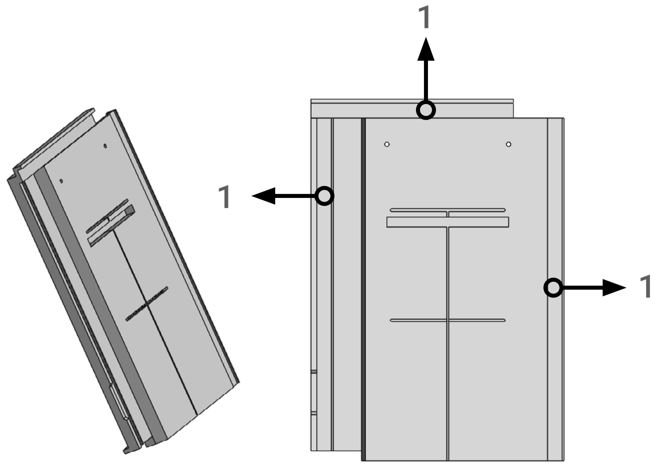


Figure 5.19 | Design revision 3.1 (own)

DESIGN REV 3.2

During process of design development, 3d printed prototypes are made on a scale of 1:4. These prototypes are used to analyze functionalities and connections of Green roof tiles and planter. Up to design revision 3.1, a planter is connected to two green roof tiles hanging on horizontal slots. Because of production method (injection molding), it is not possible to make undercuts. Therefore, horizontal slots are not a safe connection. Instead of a slot, a hole is made at the top of the Green roof tile [1]. Planters have a hook going through these holes and hanging on the Green roof tiles. Hooks are secured by screws, placed in horizontal slot [2].

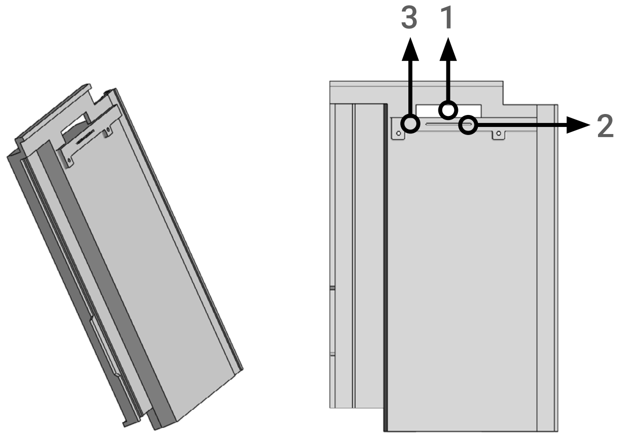


Figure 5.20 | Design revision 3.2 (own)

The hole is made at the top of the product, so it is protected by an overlapping part of a roof tile above. A rime is placed underneath it to prevent water going up [3].

DESIGN REV 3.3

Revision 3.2 has foam tape placed above the hole which is not useful. A foam tape is placed to prevent water going through the roof tiles while a hole does the opposite. At revision 3.3, the foam strip is placed on top of the hole, so it can close it, if needed [1].

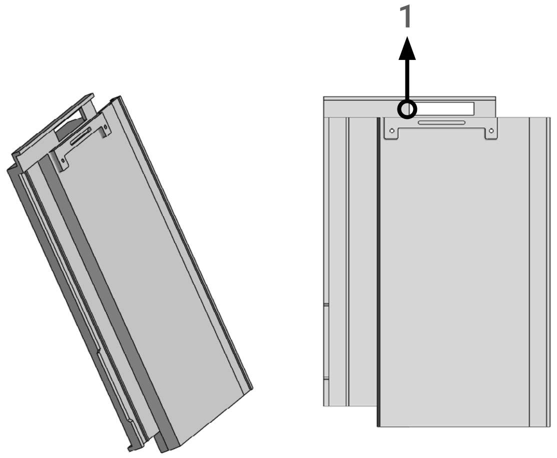


Figure 5.21 | Design revision 3.3 (own)

5.4 FMEA ANALYSIS

At this stage, a Failure Mode and Effect Analysis (FMEA) is made. This analysis ranks all possible risks by their Risk Priority Number (RPN). This number is a multiplication of three factors all given a number 1 to 5. These factors are probability of a risk (1 = low probability, 5 = high probability), urgency of that same risk (1 = low urgency, 5 = high urgency), and chance of detection if that risk occurs (1 = fast detection, 5 = slow detection).

A standard FMEA gives numbers 1 to 10 and action is needed if a risk gets a RPN of 120 or more (Bureautromp, n.d.).
However, at a design stage it is more useful to give a score up to five and instead of a certain number, a certain percentage decides if action is needed. Adding all Risk Priority Numbers times 0.80 gives 80 percent. Risks causing this 80 percent are the ones to focus on, they are marked red.

Risk	Consequence	Probability	Urgency	Detection	**Risk Priority Number**	Conclusion/design change
Installation						
1. Screws roof tile not installed	Roof system can fall from roof	3	5	4	**60**	Write clear manual
2. Screws planter not installed	Planter can fall from roof	3	4	4	**48**	Write clear manual
3. Panhaak not installed	System is less structural safe	3	3	4	**36**	Write clear manual
4. Compriband not installed	Roof system is not waterproof	3	3	4	**36**	Write clear manual
5. Roof tiles are not possitioned well on roof	Leakage	2	4	4	**32**	Write clear manual
6. Protection not removed adhesive layer aluminum part	Aluminum part can come loose from roof tiles	3	2	4	**24**	Write clear manual
7. Installed on steep roof > 60 degrees	System not structural safe	2	5	1	10	
8. Installed on flat roof < 20 degrees	System not waterproof	2	4	1	8	
9. Purlins bigger or smaller than standard	Green roof system cannot be installed	2	3	1	6	
10. Roof tile installed wrong way around	System does not function or falls from roof	1	5	1	5	
11. Aluminum part not bent into form roof tiles	Connection less waterproof	2	2	1	4	
12. Turned screw	Replace part is laborious	4	1	1	4	
Damage						
1. Hook planter detaches	Planter falls from roof	2	5	4	**40**	Secure hook with screw
2. Aluminum part not strong enough to keep roof tile in position	Leakage and not structural safe	2	5	4	**40**	Test 1:1 prototype
3. Holes planter clog	Roots plants can rot	4	3	3	**36**	Include more holes and increase diameter
4. Screws break	System can fall from roof	1	5	5	**25**	Use strong screws
5. Screws rust	Screws become weaker and can break	1	5	5	**25**	Use stainless steel screws
6. Hook planter break	Planter falls from roof	2	5	4	**20**	Make hook planter stronger
7. Planter leaks	Negative effect on development plants	1	4	5	**20**	Make planter out of one part and use right material
8. Roof tile breaks	Leakage and not structural safe	1	5	4	**20**	Make roof tile strong enough
9. Adhesive compriband dissolves in water	System not waterproof	1	3	5	15	

Risk	Consequence	Probability	Urgency	Detection	Risk Priority Number	Conclusion/design change
External factors						
1. Brittle material due to UV-light	Material can become weak and breaks	2	5	5	**50**	Select right material
2. Extreme wet winter	Roots of plants can rot	4	3	3	**36**	Include more holes and increase diameter
3. Autumn leaves on roof	Too much water and nutrients in planter	4	3	3	**36**	Include more holes and increase diameter
4. Something heavy hits roof	Part of system breaks	3	4	2	**24**	Make hooks planter and roof tile strong enough
5. Someone cleanes roof with high-pressure cleaner	Roof system can be damaged or breaks	3	4	2	**24**	Write clear manual
6. Someone cleanes roof with chemicals	Roof system can be damaged or breaks	3	4	2	**24**	Write clear manual
7. High temperature due to sunlight or close to chimney	Negative effect on development plants	2	3	3	18	
8. Fire	Roof system melts or deforms	3	5	1	15	
9. Storm	Roof system breaks and falls from roof	3	5	1	15	
10. Extreme dry summer	Plants dry out or die	4	3	1	12	
11. Electric cable hits roof	Nothing happends	2	1	3	6	
12. Water in planter freezes	Open system, so no consequences	5	1	1	5	
13. Snow on roof	Snow load included in calculations	5	1	1	5	
14. Earthquake	Roof system breaks and falls from roof	1	5	1	5	
External factors plants						
1. To much nitrogen in soil	Negative effect on development plants	3	3	5	**45**	Include chalk in substrate
2. Only one green roof tile system on roof	Roof becomes warm and has negative effect on development plants	5	2	4	**40**	Select right plants
3. Mold and algea grow in planter	Negative effect on development plants	2	3	4	**24**	Use opaque material
4. Ant nest in planter	Negative effect on development plants	2	3	4	**24**	Replace planter if needed
5. Wrong substrate	Negative effect on plants/system too heavy	1	4	4	16	
6. Substrate washes away by rain	Not enough substrate for plants	2	3	2	12	
7. Wrong plants	Less impact on biodiversity	1	2	4	8	

5.5 SWOT ANALYSIS

Next to FMEA analysis, a SWOT analysis is made. Goal of this analysis is to find strengths weaknesses, opportunities, and threats of a product. Especially weaknesses and threats are interesting at this stage in design development because they can define design changes and solutions.

Strength

1. Simple and clear design
2. Uses standard parts
3. Universal design - large application area
4. Replaces conventional roof tiles 1:1
5. Injection molding - cheap production process
6. Many plant species, nature decides which grow best in every situation
7. Solution with high quality green for slanted roofs

Weakness	Conclusion/design change
1. Opening in roof tile for planter hook - not 100 percent water proof	Raise rime before opening
2. Screws required to ensure structural safety	Write clear manual
3. Small planter - little substrate	Test 1:1 prototype
4. Replacing roof tile is laboriously	Possibility to slide up one roof tile
5. Maintenance and cleaning on slanted roof is laboriously	As little maintenance needed as possible

Opportunity

1. Position of holes decide how much water remains in planter
2. Roof tile can be used for products for birds and insects too
3. Product on roof, so no perfect finish necessary

Threats

1. Hooks planter fragile	One hook can hold a planter, so no concequences if other breaks
2. Too little water during hot and dry summer days	Test 1:1 prototype
3. Compriband does not foam enough	Select right compriband
4. Panhaak does not fit	Make enough room for panhaak
5. Aluminum part does not work	Test 1:1 prototype
6. Material is not sustainable/circulair/recyclable	Select right material
7. Material gets brittle due to UV-light	Select right material

DESIGN REV 4.1

Both FMEA and SWOT analyses have design changes as conclusion. FMEA analysis points out strength of a Green roof tile, selection of right parts, design changes for planter, right material selection, and writing a clear manual. SWOT analysis makes clear that 1:1 tests, selection of right parts, and writing a clear manual are important too. An important conclusion is the possibility to slide one roof tile up without removing other roof tiles. At design revision 3.3 and lower, this was not possible due to upper left corner. Lowering that part [1] makes it possible to slide green roof tiles vertically, independently. Because of that geometrical update, the notch of upper right corner [2] is not needed anymore.

Two types of Green Roof Tiles are needed, one as shown in figure 5.22 and another one adjacent to conventional roof tiles (see design rev2.2B and 2.3B). To make both products cheaper, they make use of the same injection molding mold. When sideplates are needed, a filler piece is placed in the mold, preventing lower part to be made. Because both types are made with the same mold, final design is a combination of both functionalities. For instance, at the back of the product, two slots are made [3], these slots are used to screw an aluminum part to the sideplate.

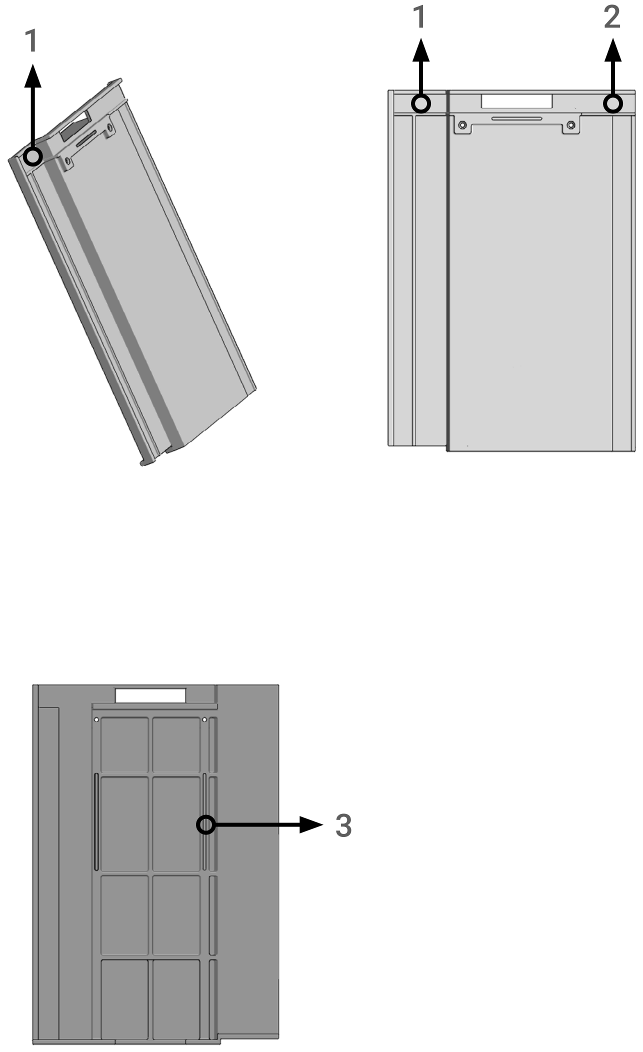
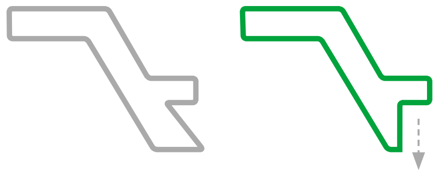


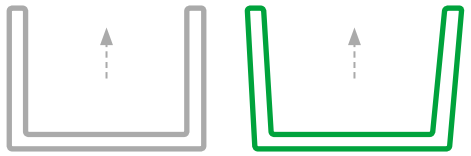
Figure 5.22 | Design revision 4.1 (own)

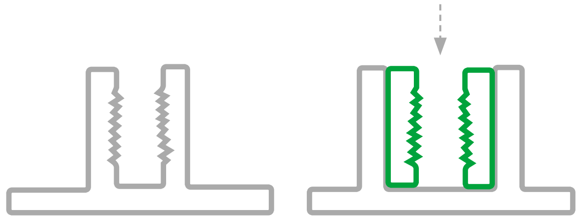
5.6 INJECTION MOLDING

As described earlier, injection molding will be the production process of Green roof tiles and planter. This is because of low costs, selected material, product complexity, and production volume. To design a product for injection molding, some criteria are required otherwise this production process is not possible. Other criteria are important to consider to reduce costs. A list of design parameters is made to optimize injection molding products. Green roof tile and planter are optimized using this list.

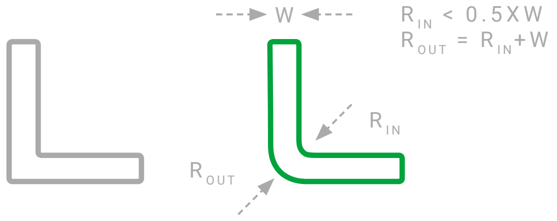

AVOID UNDERCUTS


USE SHUT-OFFS


ADD DRAFT ANGLES


USE THREADED INSERTS

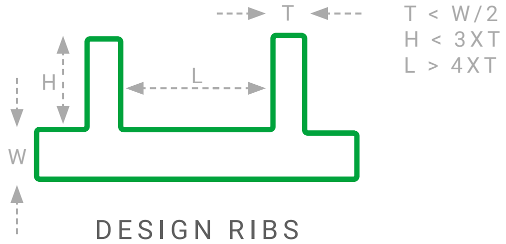

USE CONSTANT WALL THICKNESS



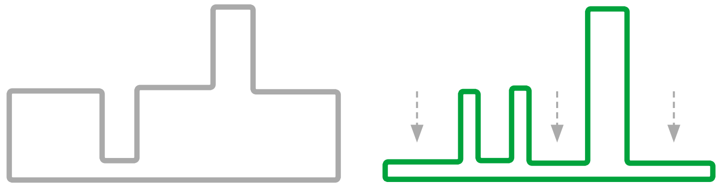
ROUND ALL EDGES

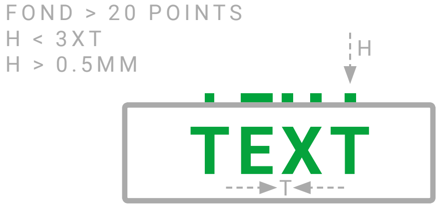

ADD SMOOTH TRANSITIONS

CONSIDER SECONDARY OPERATIONS

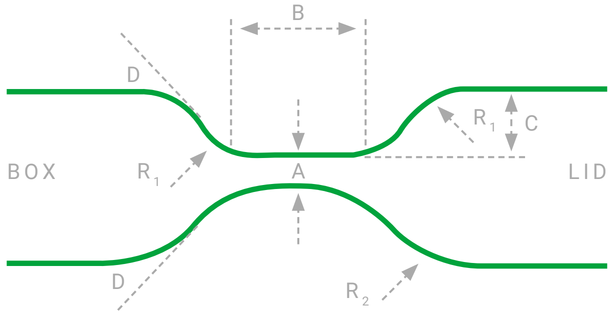


DESIGN RIBS

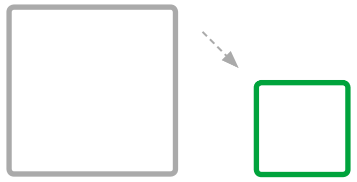

MINIMIZE PART VOLUME

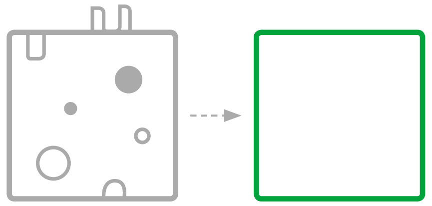


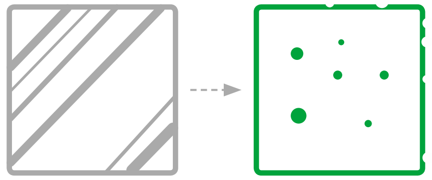
DESIGN TEXT AND SYMBOLS



DESIGN FLEXIBLE HINGES


MAKE PART SMALLER


AVOID SMALL DETAILS


USE LOWER GRADE FINISHES

A = 0.20-0.35MM
B = 1.5MM
C = 0.25MM
D = 45°
R_1 = 0.25MM
R_2 = AS LARGE AS POSSIBLE

DESIGN REV 5.1

Many small details haven been changed, all to optimize product for injection molding:

- All rimes and edges have a draft of 2 degrees to improve removal of product from the mold [1]
- A constant wall thickness of maximum 4 mm is realized by removing surplus material and making parts hollow [2]
- Part volume is minimized by removing surplus material [3]
- Ribs are designed based on design guide [4]
- All edges are rounded [5]
- By adding rounded edges, smooth transition between parts is realized [6]
- Text is designed based on design guide [7]
- Low grade finish is used to reduce mold expenses [8]

5.7 CONCLUSION

Design development of Green roof tile is done step by step, changing and improving shape from revision 1.1 to 5.1. Development is done based on examples, experience of designer, feedback from supervisors and design analyses. Prototypes are made on a scale of 1:4 and 1:1 to test ideas, functionalities, and connection methods. Lastly, design is optimized to its production method, injection molding. This all makes it a product that can be realized, produced, and used on slanted roof of the Netherlands.

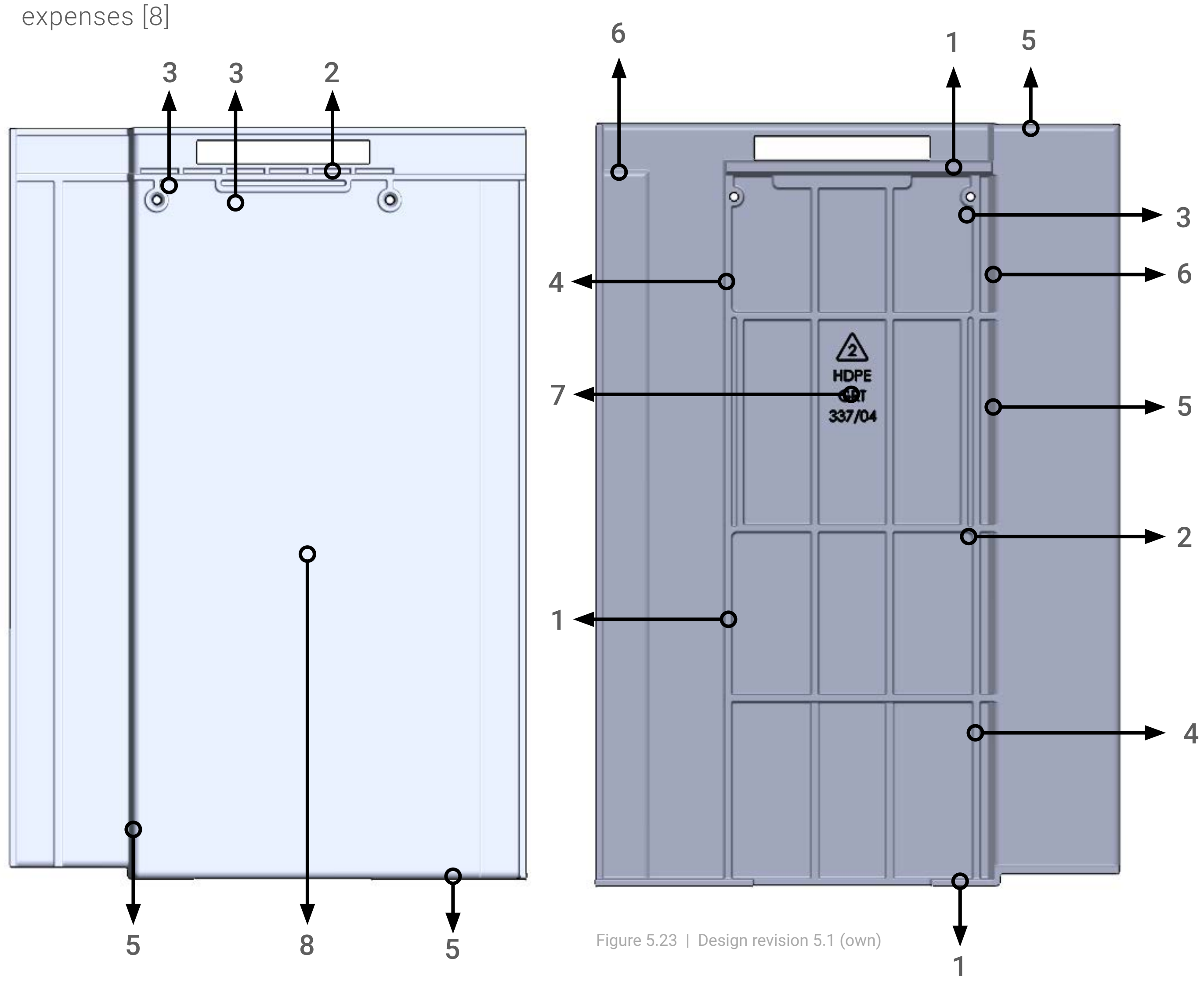


Figure 5.23 | Design revision 5.1 (own)

5.8 PLANTER

Core of Green roof tile's function is a planter. This holds earth, water, and plants used to improve biodiversity, cleans air, and reduces energy use. Key aspect of a planter is holding enough substrate and water to let plants grow. Three versions are made to indicate size. First, a planter is designed to connect with one Green roof tile. Second, a planter is designed to connect with four Green roof tiles in a row. Third, a planter is designed to connect with four Green roof tiles in a square.

In consultation with experts from Cruydt hoeck, J. Stam, G. Jager (personal communication February 9, 2021), first two options will not function. These products are not big enough to hold enough substrate and water for the desired plants. Third option could work, but research need to be done (see chapter Test setup).

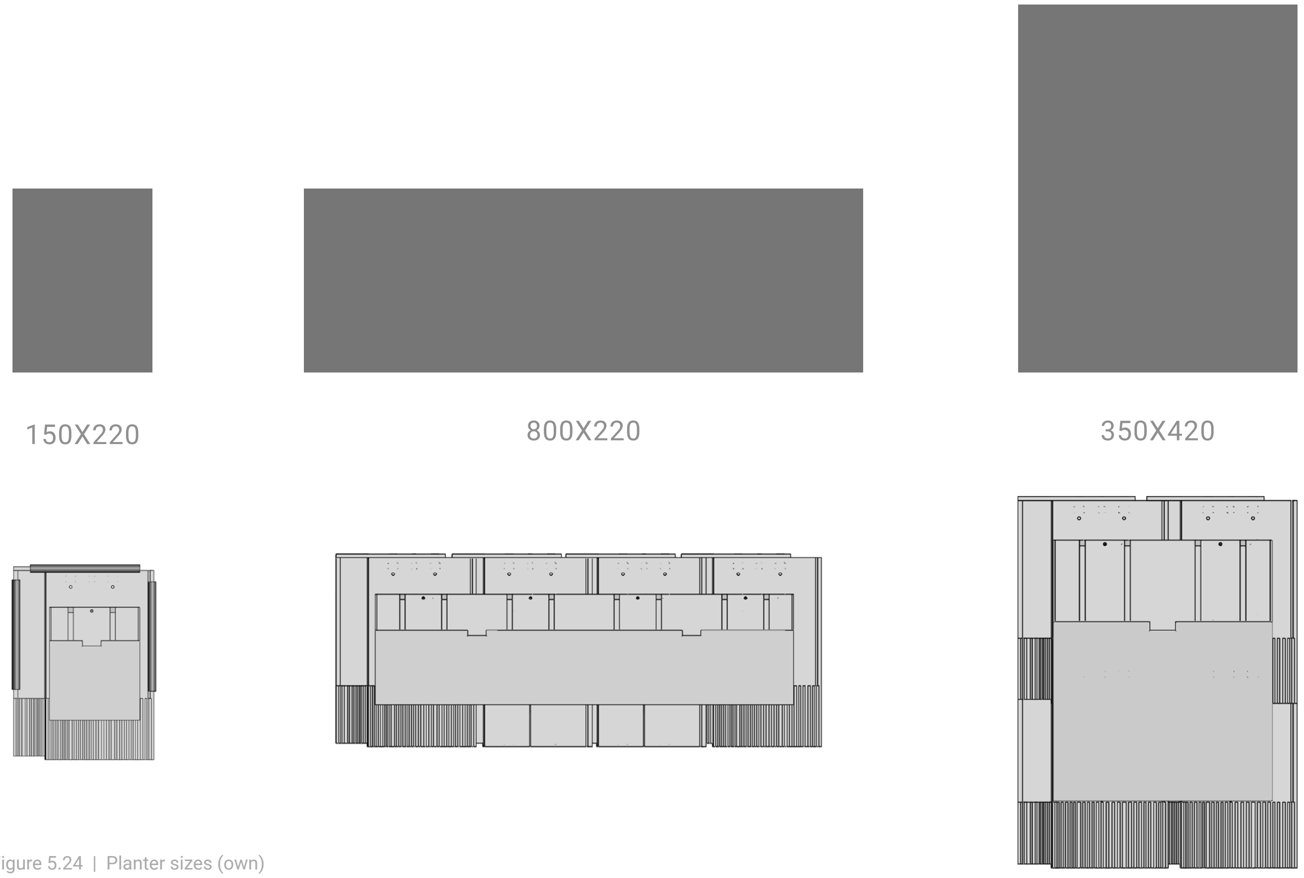


Figure 5.24 | Planter sizes (own)

PLANTER REV 1.1

Ratio between surface and volume is key to let planters work. Chapter Test setup goes into research done concerning this ratio, but main shape will stay similar. A tapering bin [1] makes injection molding possible and sloping top [2] corresponds with 40 degrees (average of slanted roofs, 20-60 degrees). A notch at the front [3] functions as overflow, guiding rainwater down.

At the backside, four screws are not completely crewed into the product [4]. Their head are used to connect with Green roof tile rev 2.1.

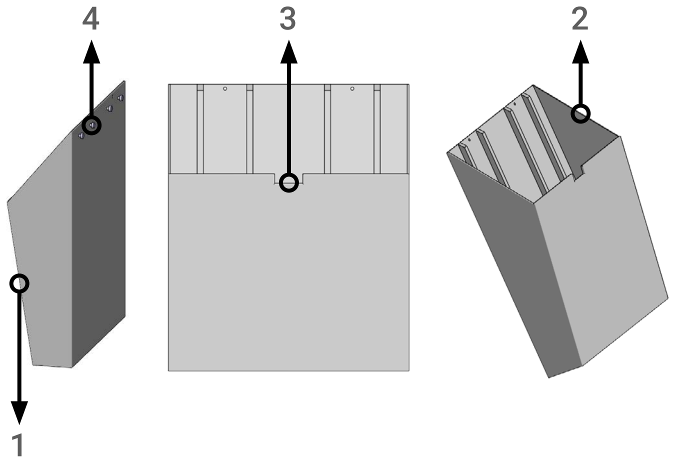


Figure 5.25 | Planter revision 1.1 (own)

PLANTER REV 1.2

Assembling screws halfway such that their head can be used to connect with a Green roof tile is difficult and sensitive to errors. Therefore, two protrusions are made [1], connecting with slots of Green roof tile revision 2.2. Shape of planter rev 1.2 has slightly changed, corresponding with maximum allowed volume (9.4 liter) [2].

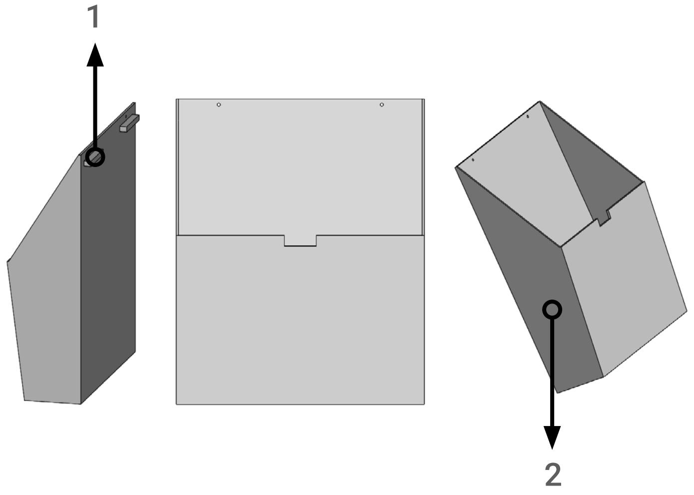


Figure 5.26 | Planter revision 1.2 (own)

PLANTER REV 1.3

Securing planters only at the top with screws will not be strong enough. At the bottom two slots [1] are added for screws to be connected to green roof tiles rev 2.3.

For all four screws, holes are not used but slots [2]. These are possible to make with injection molding without extra production steps or costs.

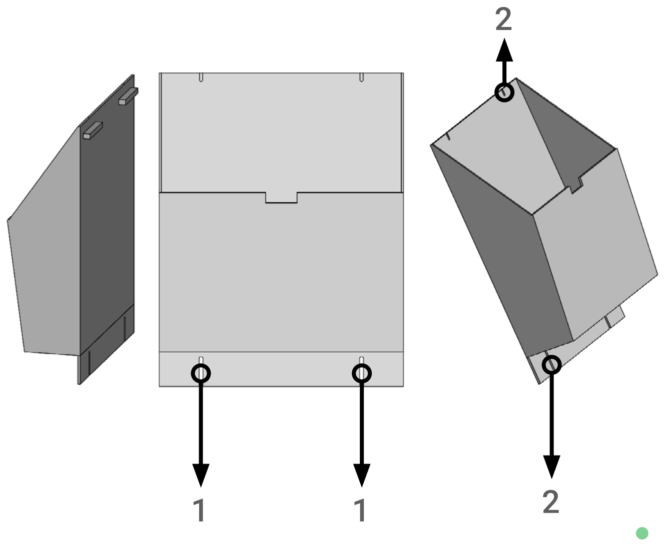


Figure 5.27 | Planter revision 1.3 (own)

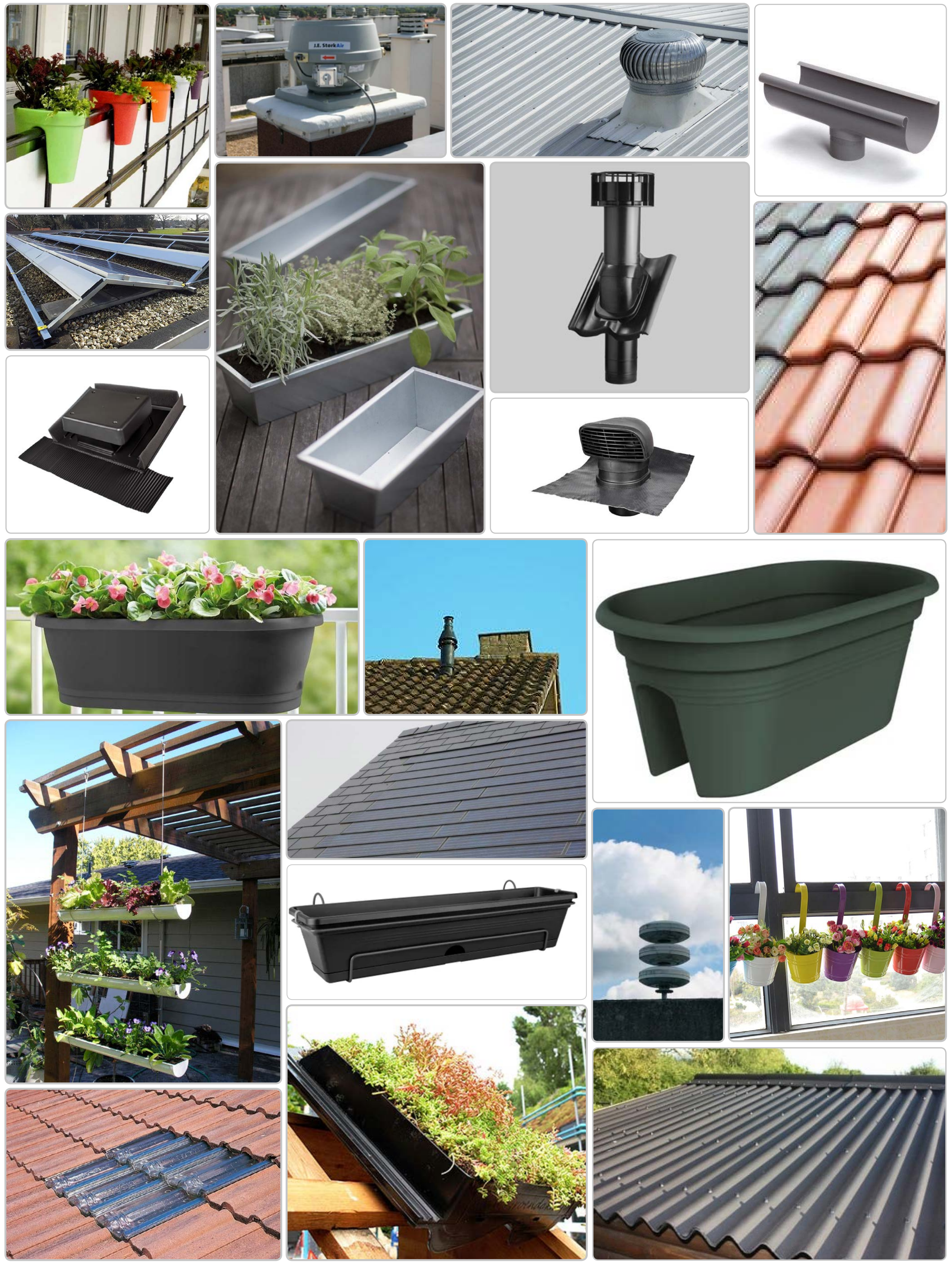


Figure 5.28 | Conventional roof systems and planters (own)

PLANTER REV 2.1, 2.2

Form language and production detailing need to correspond with conventional roof systems and planters. Most products made for roofs are rounded, have large details, no tight tolerances and made as cheap as possible. Because people will only see it from far distance, details can be rough and quality less. Injection molded planters are rounded and have a bended top. This bended top is done to make product stiffer.

To correspond to these products, revision 2.1 and 2.2 are made, both with rounded edges [1]. Revision 2.2 has a bended top to make product stiffer too [2].

Because of its aesthetics, flat backside, and overflow at the front it is not beneficial to have a bended top. This makes the product more complex.

3d printed models concluded that a rim at bottom side [3] does not work, too much space is between rim and Green roof tile. So, it is removed at next revision.

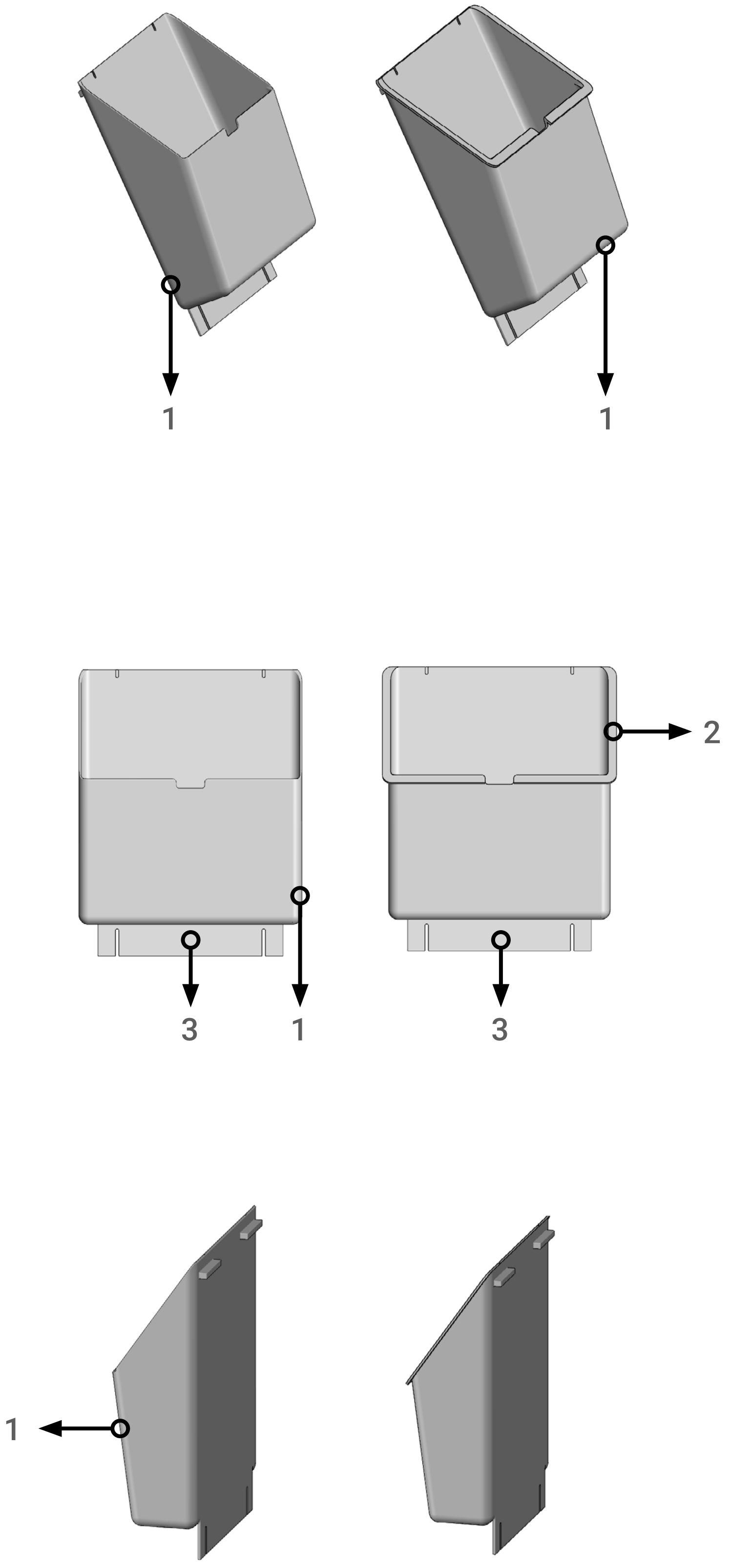


Figure 5.29 | Planter revision 2.1 and 2.2 (own)

PLANTER REV3.1

During process of design development, 3d printed prototypes are made on a scale of 1:4. These prototypes are used to analyze functions and connections of Green roof tiles and planter. Up to design revision 2.2, planters are connected to two green roof tiles hanging in horizontal slots. Because of production method (injection molding), it is not possible to make undercuts. Therefore, horizontal slots are not a safe connection. Instead of a slot, a hole is made at the top of Green roof tiles. Planters have a hook [1] going through these holes and hanging on two Green roof tiles. Hooks are secured by screws [2], placed in horizontal slot of Green roof tiles. To make hooks strong enough, ribs are added [3].

Next to the front, also the sides have a draft angle of two degrees to improve removal from injection molding mold [3]. These sides have holes for water to escape [4]. Hereby, first five centimeter of substrate will stay dry preventing plant roots to rot.

PLANTER REV3.2 - REV3.5

Planter's overall shape did not change from revision 3.1 to 3.5. Improvements were made at the top of the hooks and holes at the sides. Shape of the hooks did follow changes of Green roof tile with first extra material in the corner to make it stronger [1]. At revision 3.5, this material is removed to optimize product for injection molding (constant wall thickness) [2]. Hooks got rounded edges [3] and an angle of 86 degrees [4]. This angle corresponds with Green roof tile's shape.

At revision 3.2 an attempt is made to include holes at the side within the injection mold. Two slots did not work because it makes the planter flexible and weak. Two rims were made to indicate drilling locations for the holes [5]. Therefore, no extra measurements are needed at a secondary production process. However, these rims are removed because it is easier and cheaper to make an external drilling mold. Lastly, more holes are made with a larger diameter to make sure enough water can escape planter if needed [6].

5.9 CONCLUSION

Design development of Green roof tile planter is done step by step, changing and improving shape from revision 1.1 to 3.5. Developments are done based on examples, experience of designer, feedback from supervisors and design analyses. Prototypes are made on a scale of 1:4 and 1:1 to test ideas, functionalities, and connection methods. Lastly, design is optimized to its production method, injection molding. This all makes it a product that can be realized, produced, and used on slanted roof of the Netherlands.

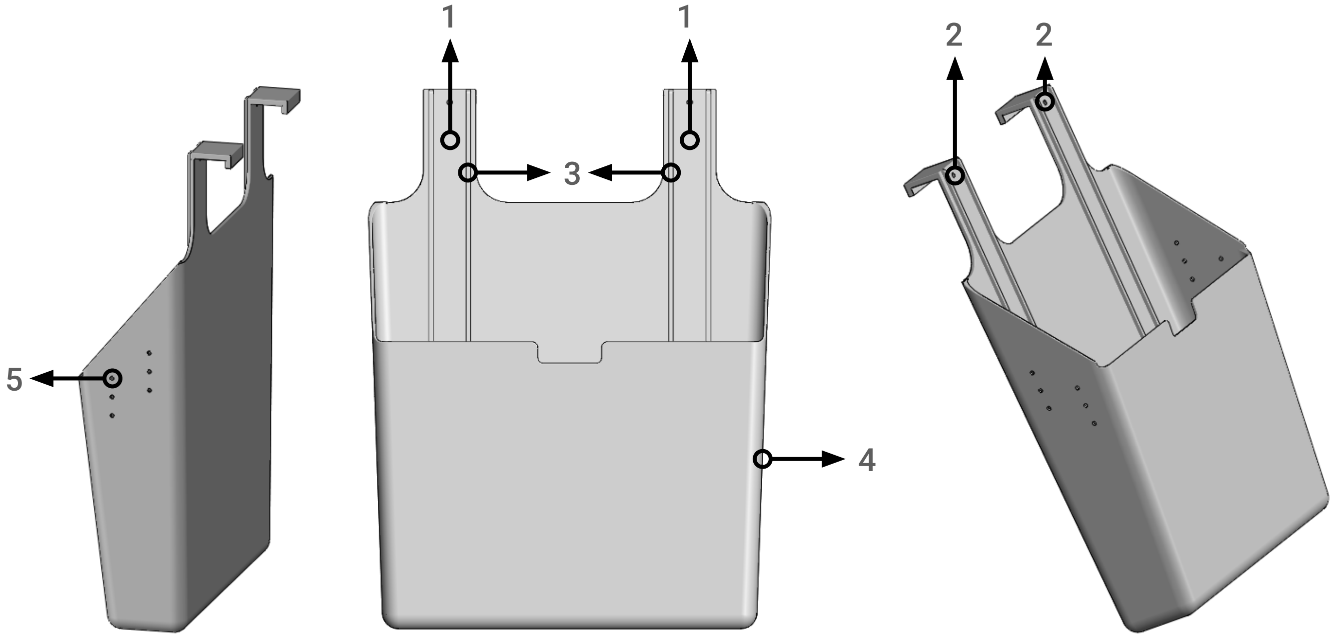


Figure 5.30 | Planter revision 3.1 (own)

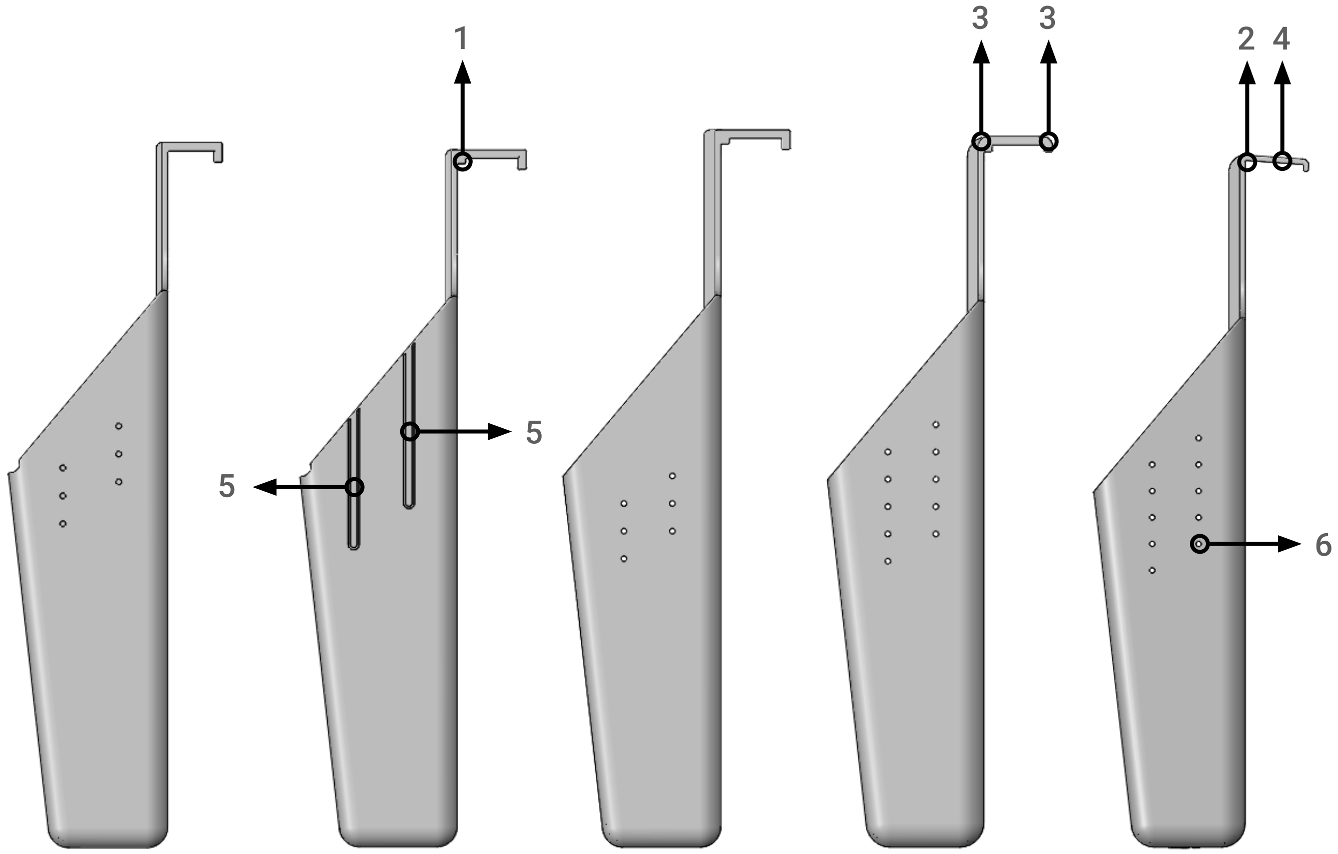


Figure 5.31 | Planter revision 3.2 - 3.5 (own)

5.10 BASEPLATE

Next to a planter, Green roof tiles can be used for other products too. For instance, a breeding box for house sparrows [1] or an insect hotel [2]. With this product family, Green roof tiles do not only improve biodiversity with plants.

A breeding box for house sparrows or insect hotel are two examples of products connected to the Green roof tile baseplate. This baseplate is developed to form a platform for a variety of products connected to a roof. It is not limited to breeding boxes and insect hotels, people can be creative and use a baseplate for their own products.

Baseplate is split into two parts, a hook [3] and a plate [4]. The hook is a steel strip bended twice. This material and production process is selected because it is cheap, functions with an angle less than 90 degrees, and can be produced in small batches. An angle of 86 degrees [5] corresponds with Green roof tiles. Two holes at the top [6] are used by screws to secure baseplate to Green roof tile. Three holes at the bottom connect hook to a plate [7].

A plate is made of 6 mm triplex. Three holes at the top [8] correspond with holes of a hook. Four slots [9] can be used to connect an addition product to the baseplate of various sizes. Holes in middle and on sides [10] have a similar function.

At this stage, the Green roof tile baseplate is designed for a future need. If additional products, like a breeding box or insect hotel, are developed further, design of a baseplate can develop together with it.

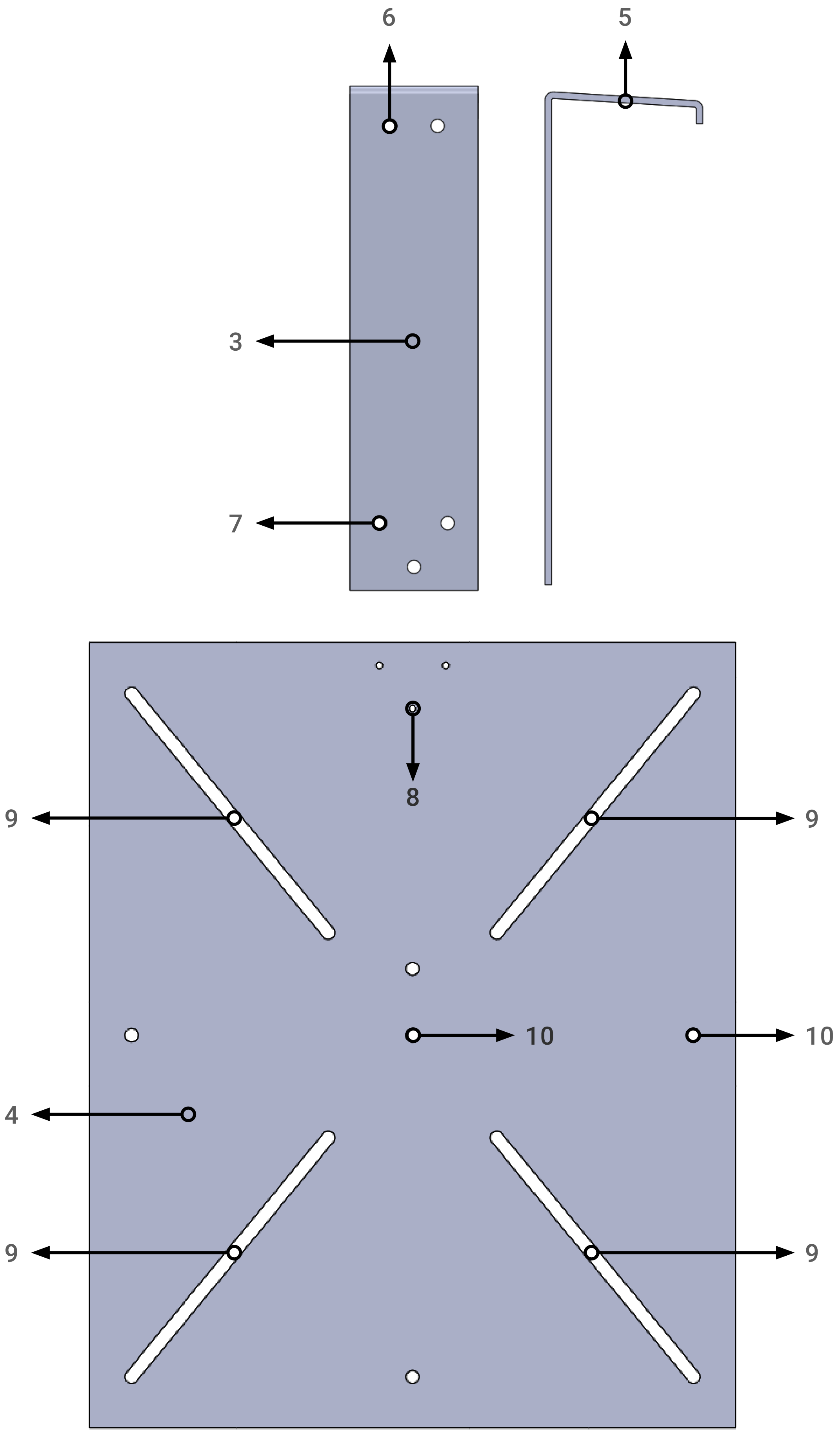


Figure 5.32 | Baseplate (own)

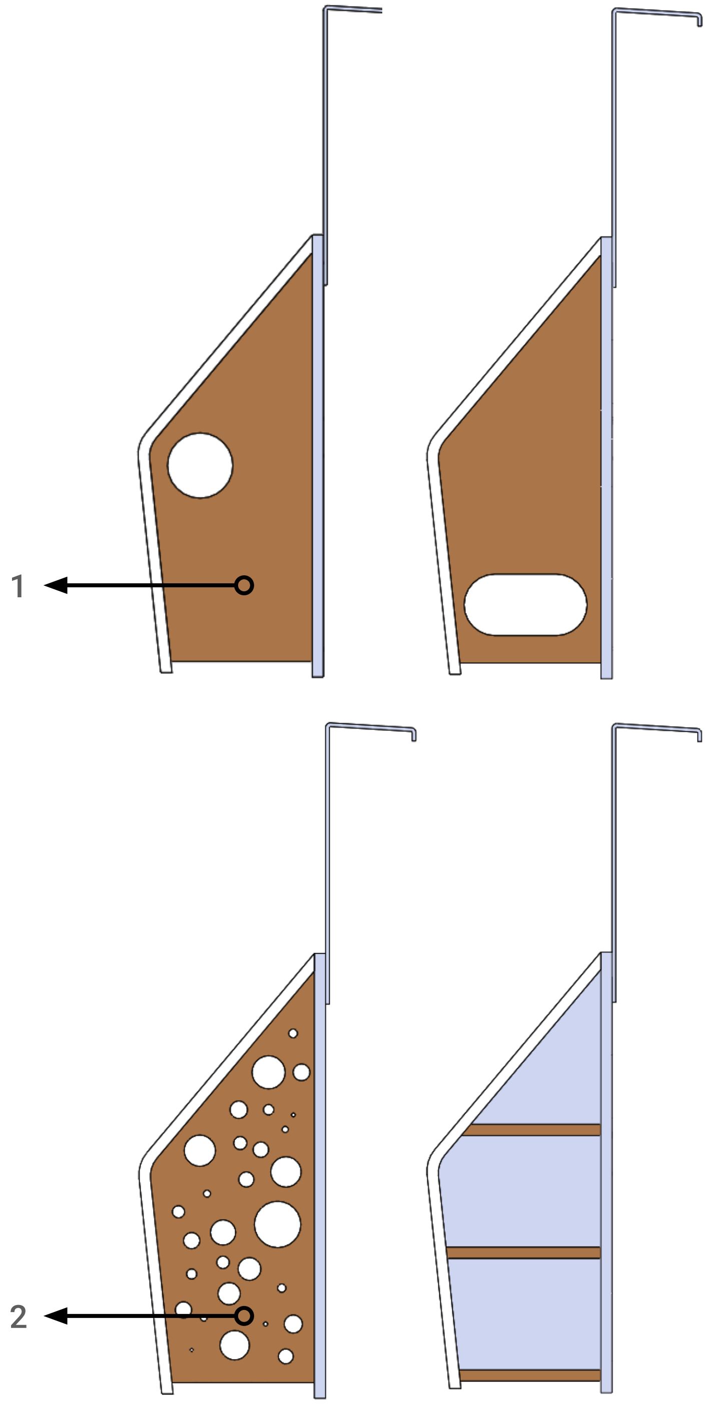


Figure 5.33 | Breeding box bird and insect hotel (own)

PROTOTYPES

To test connections and validate design options, prototypes are made. These prototypes are 3d-printed on a scale of 1:4. A mockup roof is used to test overlapping on a right angle.

MATERIAL SELECTION

A material selection is performed, using material database of CES Edupack 2019. Results are discussed with injection molding experts of Promolding, changing conclusion from PVC to HDPE.

6.1 APPROACH

Material selection is a key part of design. It influences production methods, design parameters, appearance, and costs. Green roof tile is a sustainable design focusing on biodiversity and ecology. Therefore, its material needs to fit in that story as well and needs to be recyclable. This product will stay outdoors up to 10 years, so its durability is important. It needs to protect roofs from rain and can be cleaned with weak acids, alkalis, and organic solvents. UV radiation should not influence technical performance of the Green roof tiles. Slight color change is allowed because these products lay on top of a roof and people do not see it up close. Flammability of material is self-extinguishing or non-flammable to make it a safe product.

As described earlier, production process of Green roof tiles and Green roof tile planter is injection molding. So, selected material needs to be able to do that.

Lastly, sun can heat roofs up to 50-60 degrees Celsius. A green roof will reduce heat production on roofs, but its material still needs to be able to perform at certain circumstances.

Parameters as described above will be input to a CES Edupack 2019 database. Materials will be selected on price, density, and embodied energy. Price is important to make a feasible product, density is a critical factor in design and embodied energy is part of sustainability.

MATERIAL SELECTION CES EDUPACK

Recycling

- Material needs to be recyclable

Durability

- Fresh water: Acceptable; Excellent
- Weak acids: Limited use; Acceptable; Excellent
- Weak alkalis: Limited use; Acceptable; Excellent
- Organic solvents: Limited use; Acceptable; Excellent
- UV radiation: Fair; Good; Excellent
- Flammability: Self-extinguishing; Non-flammable

Production process

- Injection molding

Thermal properties

- Maximum service temperature: 60 degrees minimum

6.2 RESULTS

23 materials fulfill the criteria as described. These materials are plotted in two graphs, one compares price with density and the other price with embodied energy. All three criteria need to be minimized: low cost, low density, and low embodied energy. At the first graph, PVC (rigid, molding and extrusion) has the lowest cost. PCTA (unfilled) and TPU (Ether, aromatic, shore A85, flame retarded) score good as well on price/density ratio.

Second graph shows price/embodied energy ratio. All three variations of PVC perform best to this.

To conclude from this material selection optimized to prize, density, and embodied energy, PVC scores best. This material will be used for Green roof tiles and Green roof tile planters.

6.3 HDPE

To optimize design for injection molding, an injection molding company is consulted (Promolding BV). Next to input related to production costs, they gave input on material as well. PVC is not a stable material, can become brittle and can form hydrochloric acid. Hydrochloric acid can be catalysator for rust on steel. So, in combination with steel screws, PVC is not a good material.

As an alternative they advised to use HDPE (High Density Polyethylene) with UV stabilizer and flame-extinguishing additive. These two factors make that HDPE did not pass previous requirements. By changing these parameters, new graphs are made. Price per kilogram of HDPE (or PE-HD) is lower than PVC. Also, its density is much better, 950 kg/m3 compared to 1400 kg/m3.

Embodied energy of HDPE is more compared to PVC, roughly 60 MJ/kg to 80 MJ/kg.

Lastly, sedum roof tile of Groendakpan is made of HDPE too. So, this material is also in practice the best material for green roof tiles.

To conclude, HDPE with UV stabilizer and flame-extinguishing additive is a better material compared to PVC. Green roof tiles and Green roof tile planters will be made of HDPE.

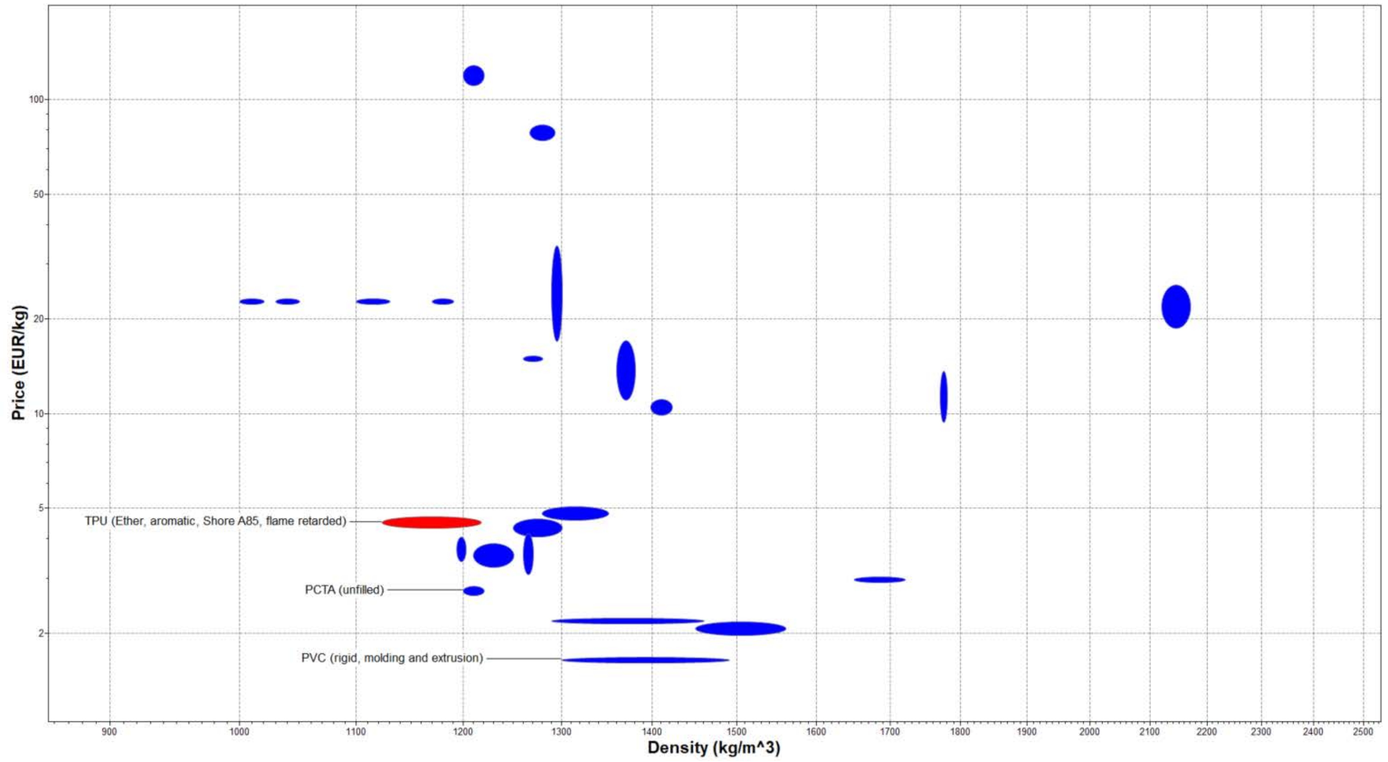


Figure 6.1 | Price/Density PVC (CES Edupack 2019)

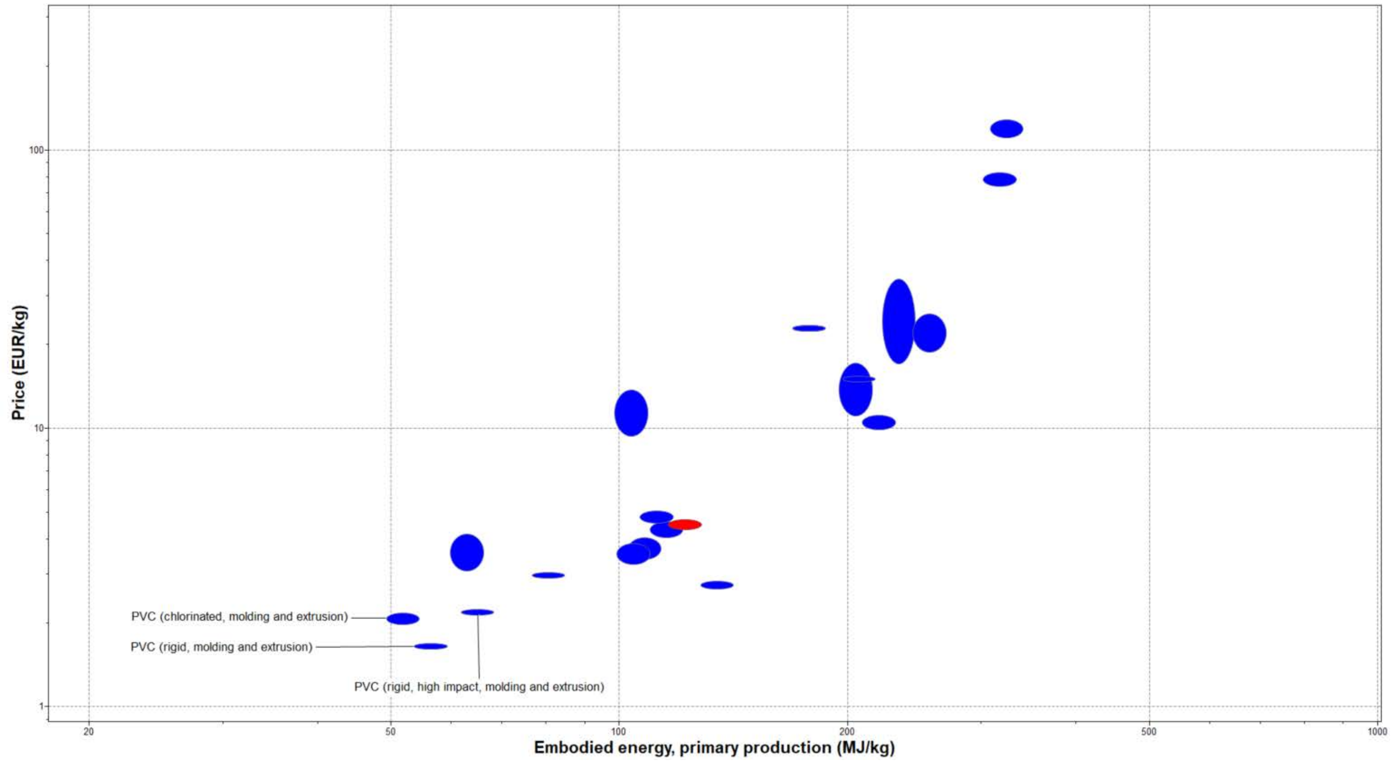


Figure 6.2 | Price/Embodied energy PVC (CES Edupack 2019)

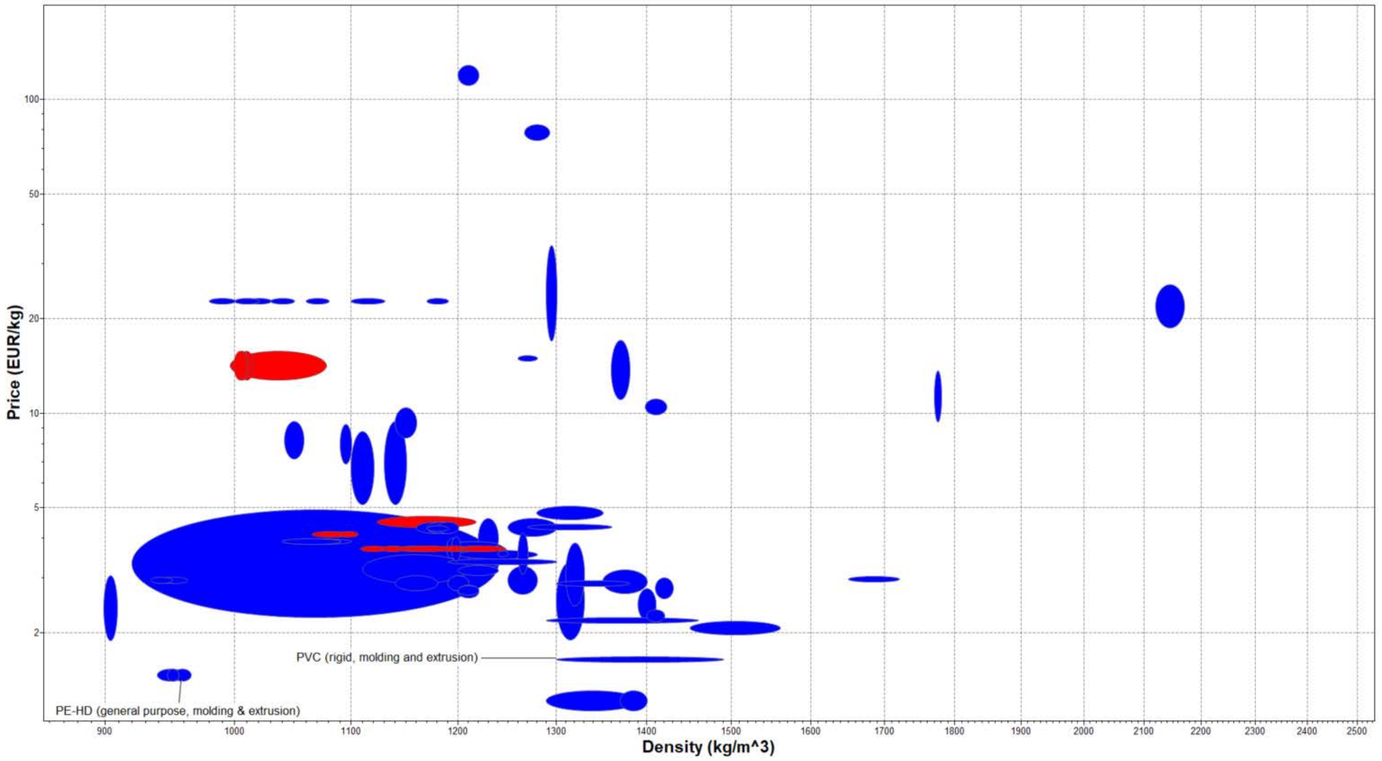


Figure 6.3 | Price/Density HDPE (CES Edupack 2019)

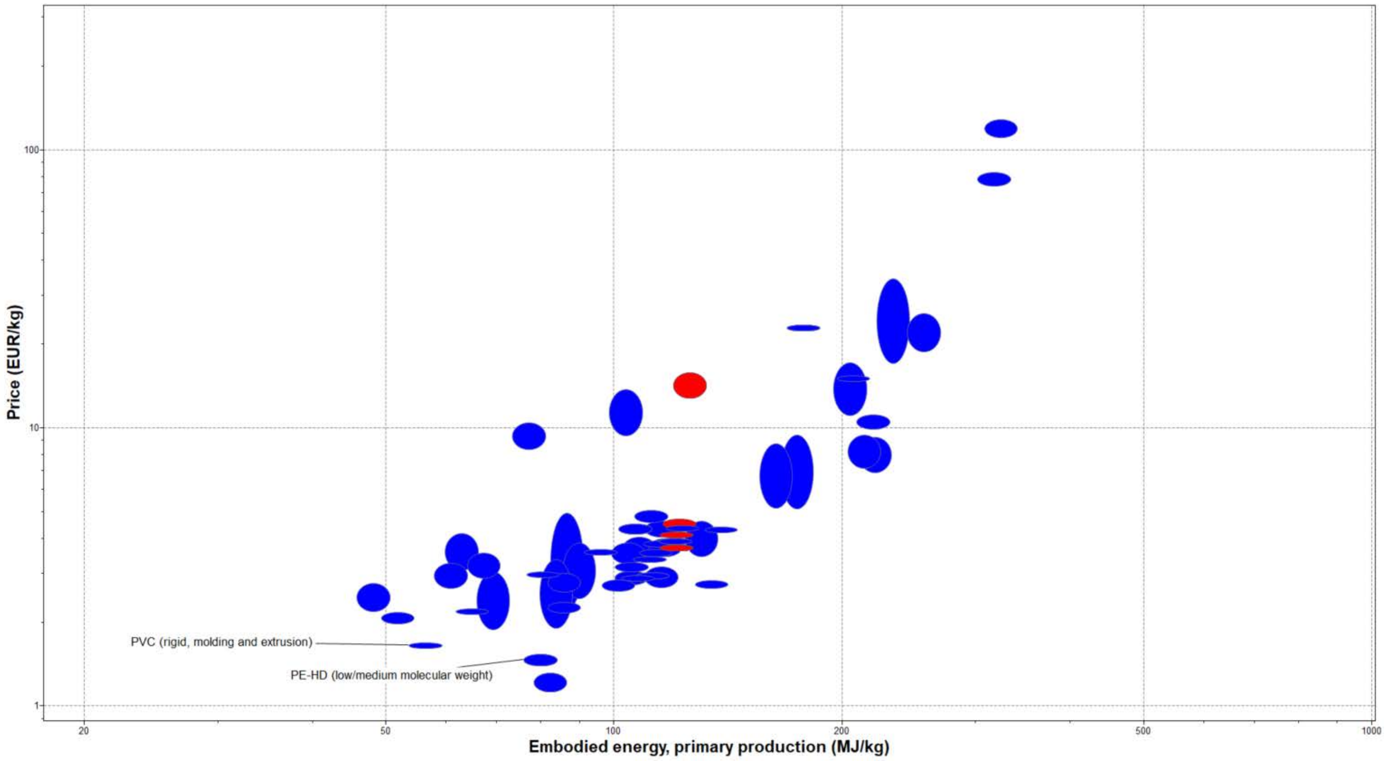


Figure 6.4 | Price/Embodied energy HDPE (CES Edupack 2019)

TESTING

Everything needed to be tested on scale, even plants.

STRUCTURAL PERFORMANCE

Structural performance analyses are executed to indicate strength and stiffness of final design. Results are used for recommendations because these simulations are done at a late stage in design development.

7.1 LOADS

Roof structures and roof systems need to meet national and international standards. Wind load, user load, and snow load are calculated at Research chapter. These values are used to validate Green roof tile design. Results are used for recommendations because simulations are done at a late stage in design development.

Values used for simulations are:

User load	1.5kN/m2
Wind load	- 2.98 kN/m2,
Wind load	+ 1.14 kN/m2
Snow load	0.40 kN/m2
Mass roof system	65 kg/m2

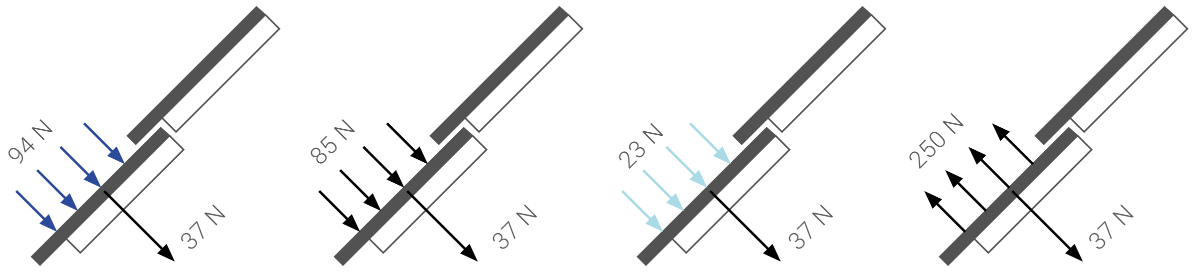
Loads on a single roof tile are highest if less roof tiles are covering a roof. Minimum amount of roof tiles corresponds with a surface area of 250x330 mm per roof tile. Therefore, loads are:

User load	0.12 kN
Wind load	- 0.25 kN,
Wind load	+ 0.094 kN
Snow load	0.033 kN
Mass roof system	5.3 kg

User load, snow load, and mass roof system are perpendicular to the ground while calculations are done with loads perpendicular to the roof (45 degrees). Therefore, these loads are multiplied with sin(45):

User load	85 N
Snow load	23 N
Mass roof system	37 N

In total, four situations are calculated see figure 7.1. Max wind load, user load, and snow load will not happen at the same time. With strong winds, snow will not stay, and people will not walk on a roof. With high snow loads, people will not walk on a roof too. So, these loads are not combined.



a) Positive wind load + mass roof system

b) User load + mass roof system

c) Snow load + mass roof system

d) Negative wind load + mass roof system

Figure 7.1 | Load combinations (own)

7.2 LOAD COMBINATION A, B, AND C

Green roof tiles are connected to purlins. Surface area facing this [1] is cut out with 0.001 mm to be used as fixed area in the model. Lower edge facing another roof tile [2] is fixed too. Multiple load combinations are added to front surface of Green roof tile. Results are focused on displacement and internal stresses. Maximum allowed displacement is 5 mm to keep system waterproof. Maximum allowed internal stress is 22 mpa (CES Edupack 2019) with a safety margin of 2, so 11 mpa (1.1e+07).

Maximum displacements of combinations are:

a) 2.085 mm
b) 1.943 mm
c) 0.964 mm

Because this model works with fixed surfaces, it creates high stresses at the edges of these surfaces [1]. In reality, both purlins and roof tiles deform under load and divide stresses more equally. Therefore, maximum stresses in his model are not realistic. Stresses at locations not adjacent to fixed surfaces give a better indication, such as a rib at the middle of the roof tile [2]. Stresses are an estimation because results are a color scheme.

Maximum stresses of combinations are:

a) 4.4 mpa
b) 4 mpa
c) 2 mpa

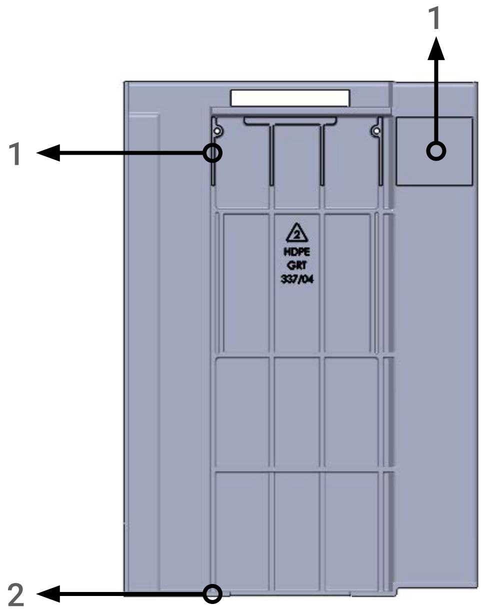


Figure 7.2 | Model adjustments (own)

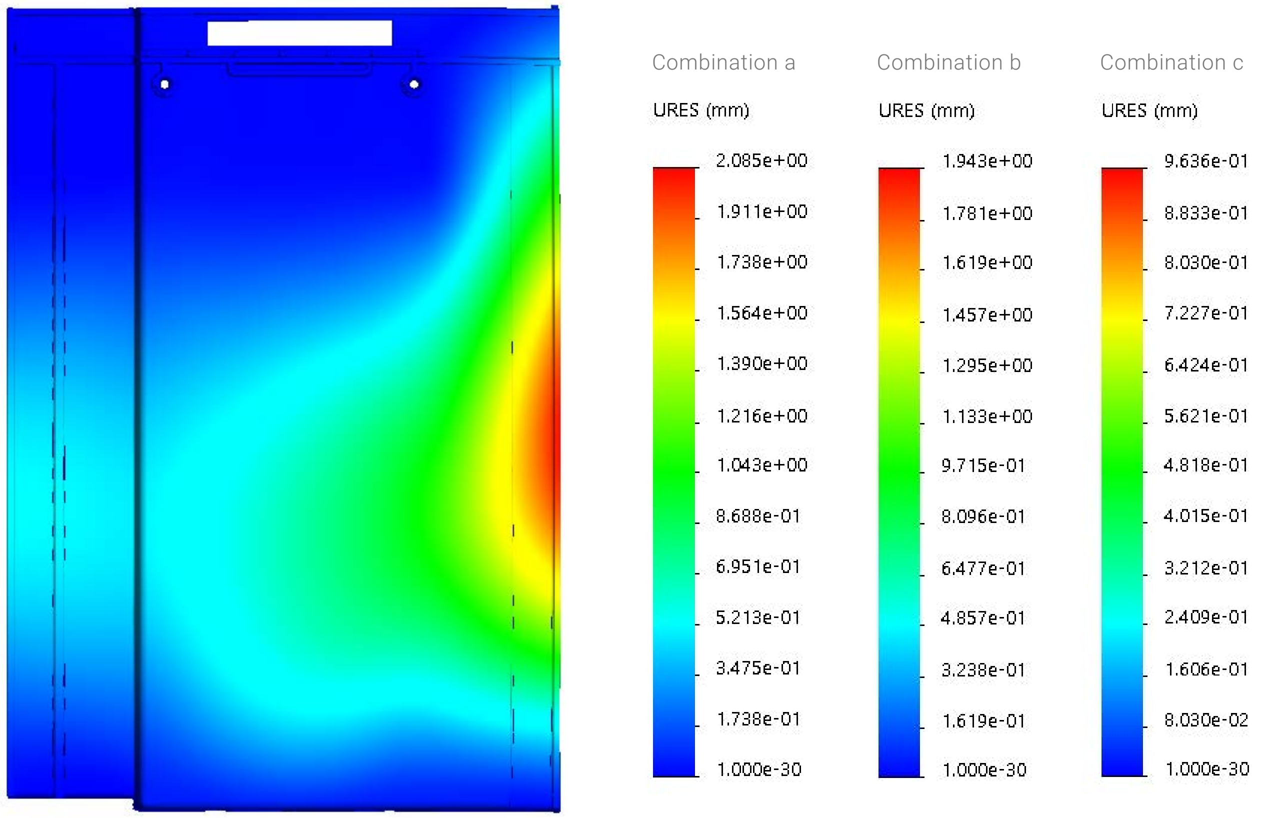


Figure 7.3 | Results displacement load combinations a, b, and c (Solidworks 2019)

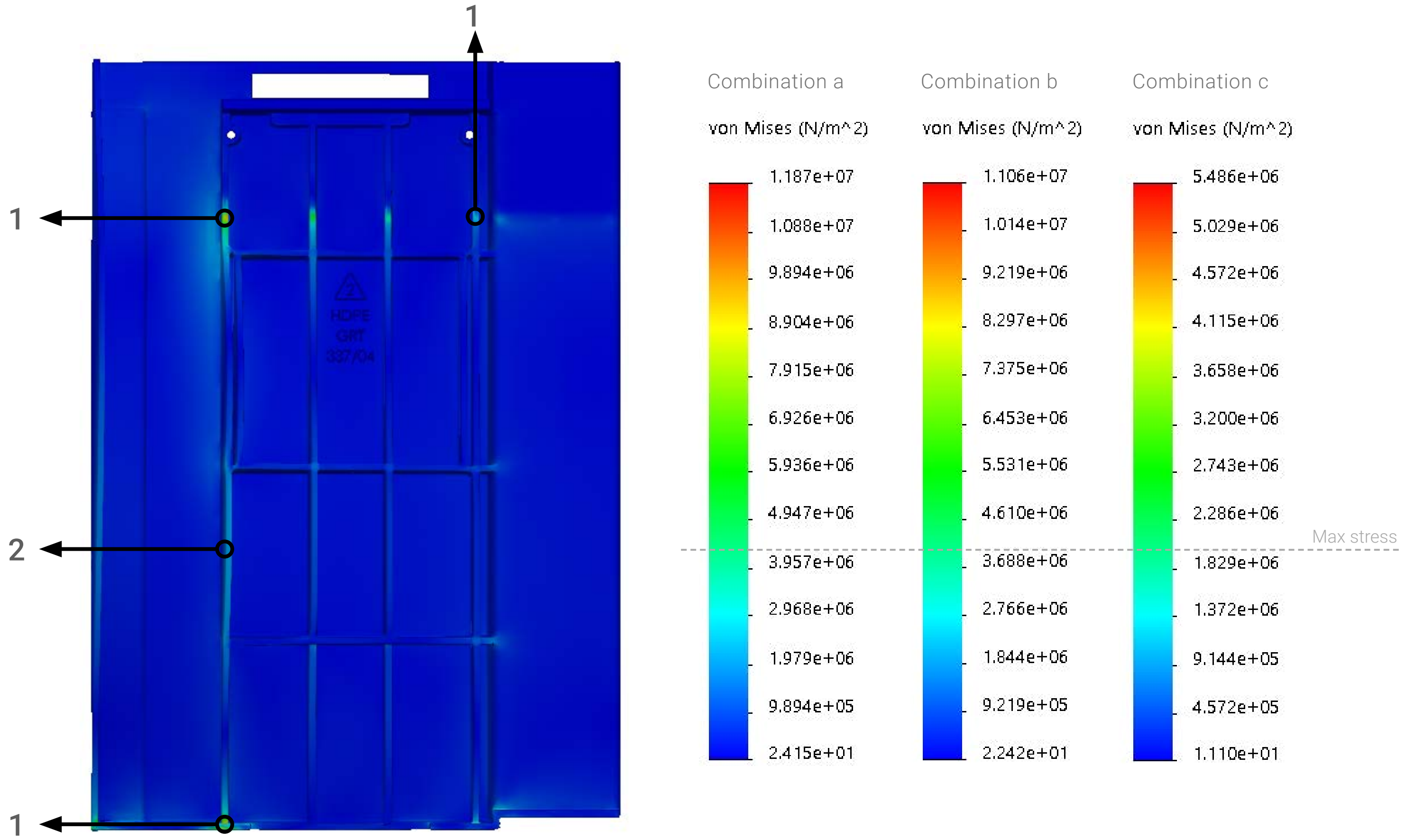


Figure 7.4 | Results internal stresses load combinations a, b, and c (Solidworks 2019)

7.3 LOAD COMBINATION D

At load combination d wind is pulling roof tiles away from roof structure, so its fixation is different. Two screws at the top [1] and a roof tile hook at the left bottom [2] are holding Green roof tile in place. These three points are added to the model and used as fixation points. Similar to stress calculations of load combination a, b, and c highest values are not realistic. Stresses of a rib next to a screw [3] are used as maximum. Results are an estimation because results are a color scheme.

Maximum displacement:
d) 81.98 mm

Maximum stress:
d) 50 mpa

7.4 CONCLUSION

Results of load combinations a, b, and c are below maximum values and show that Green roof tiles can hold user load, snow load, and positive wind load without changes. A realistic test can substantiate this positive conclusion within a future investigation.

Results of load combination d are above maximum values, resulting in broken roof tiles during a storm. Therefore, more realistic analyses and/or tests need to be performed to validate this negative conclusion. If those analyses and tests show high displacements and stresses as well, Green roof tiles design need to be updated.

Possible improvements are:

- [1] Diagonal ribs
- [2] Wider ribs
- [3] More screws at the top
- [4] Roof tile hooks at both sides
- [5] Stronger material

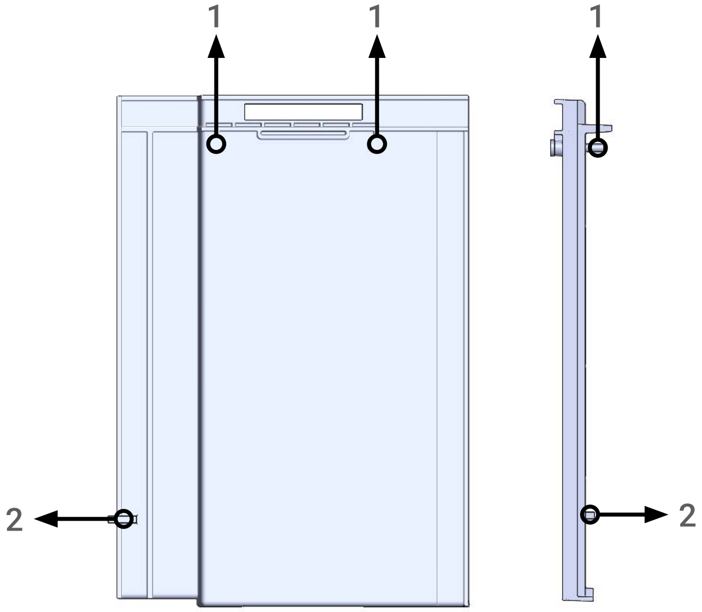


Figure 7.4 | Model adjustments (own)

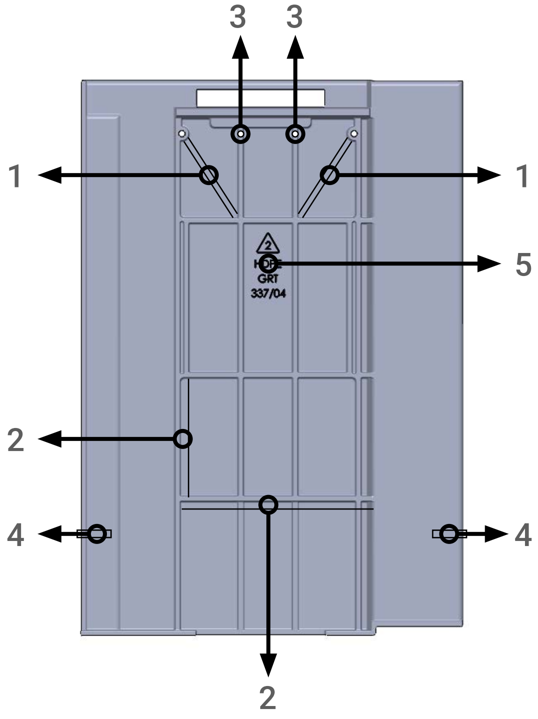


Figure 7.5 | Possible improvements (own)

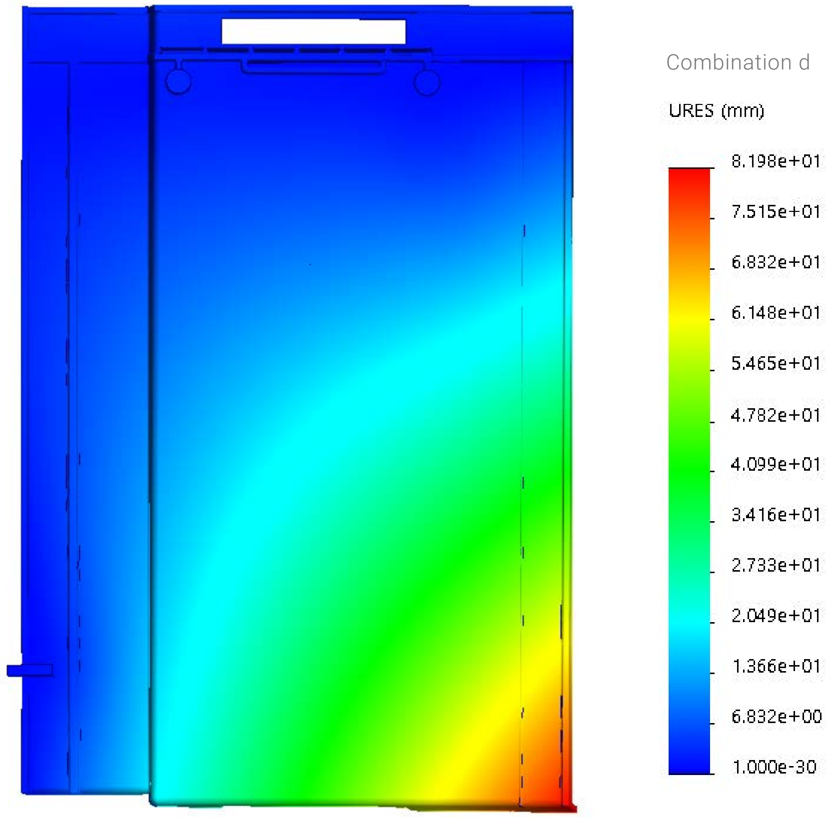


Figure 7.6 | Results displacement load combinations d (Solidworks 2019)

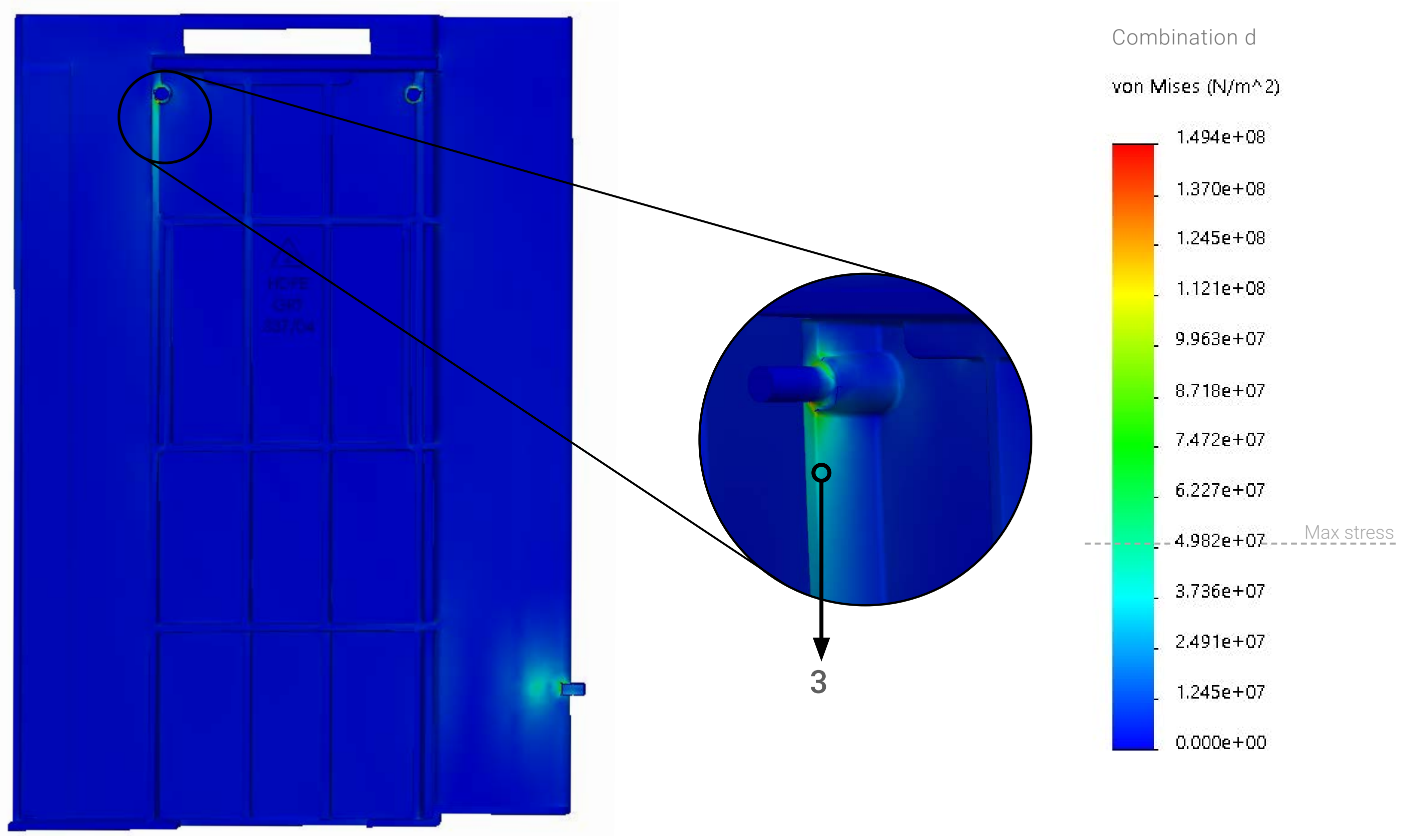


Figure 7.7 | Results internal stresses load combinations d (Solidworks 2019)

SEEDS

28 plant species are used in final design, selected for their ability to survive draught, short floods, and sun.

FINAL DESIGN

This chapter will go into detail about final design of Green roof tile and Green roof tile planter. All design features will be explained step by step. Furthermore, assembly sequence, choice of plants, choice of substrate, color selection, use, maintenance, and end of life are explained.

But first, its parts. Figure 8.1 shows an exploded view of two Green roof tiles, Green roof tile sideplate, Planter and Breeding box for birds. Aluminum part of the sideplate is screwed to injection molding part by 4 screws from the back. Sideplate itself is screwed to a purlin before a breeding box is assembled. This breeding box is screwed on sideplate.

Other Green roof tiles are connected to purlins as well before a planter is screwed to two upper Green roof tiles. Lastly, Compriband is placed on top and sides before normal roof tiles are assembled.

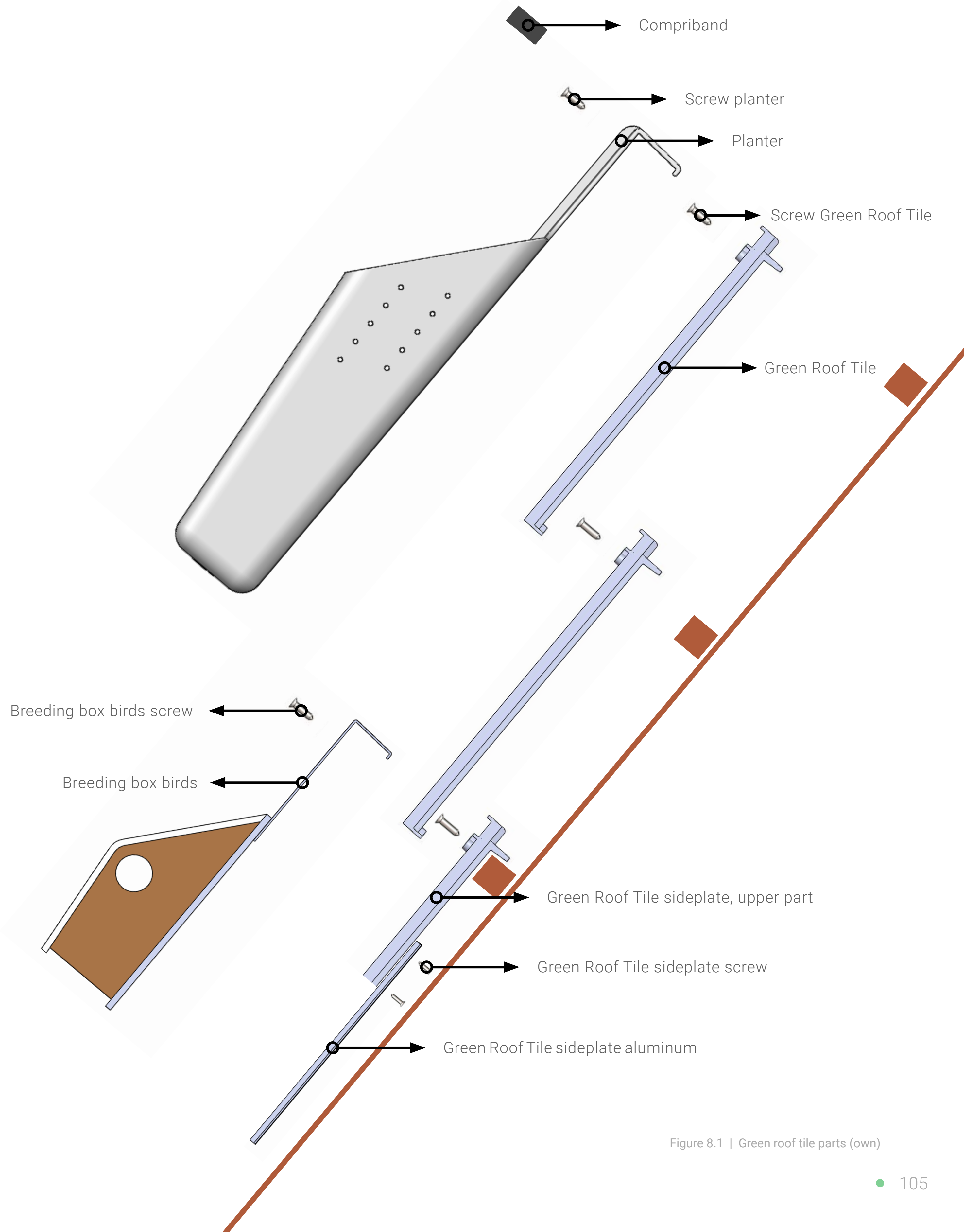


Figure 8.1 | Green roof tile parts (own)

8.1 GREEN ROOF TILE

1. 20 mm wide strips are made to place Compriband
2. Left side goes underneath another roof tile making it rainproof
3. Holes are made to reduce wall thickness of hook
4. A hook of a planter goes through hole at the top
5. A planter is secured by a screw, screwed into horizontal slot
6. Green roof tiles are screwed to a purlin by screws going through two holes
7. A rime is made to prevent water going up
8. A notch is made to make a tight overlapping with another Green roof tile
9. A hook holds Green roof tiles on purlins
10. Ribs are placed to make Green roof tiles stronger
11. Two slots are made for screws of Green roof tile sideplate aluminum
12. Second rib from below is splitting line for a Green roof tile sideplate
13. Material code is part of product to improve end of life recycling
14. A code is part of product revering to a certain production batch in case information is needed
15. A notch is made for a hook of a planter

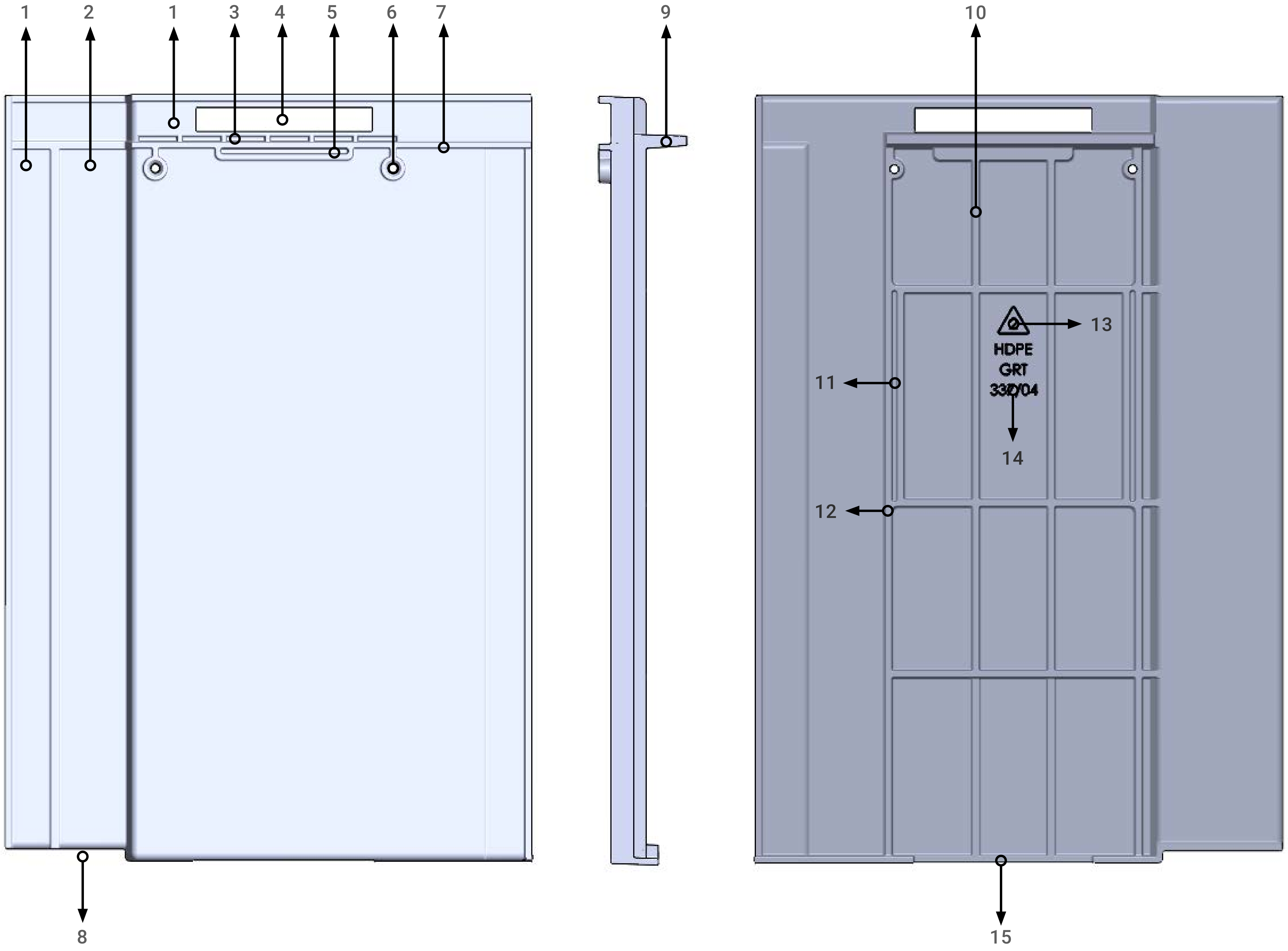


Figure 8.2 | Green roof tile (own)

8.2 PLANTER

1. Hook clamps around Green roof tile and holds planter in place. It has an angle of 86 degrees to match with the angle of a Green roof tile
2. Hook clamps around Green roof tile but not over it because otherwise it will hang on the purlin instead
3. Two ribs make a hook stronger
4. Length of hook is designed such that a planter hangs in the middle of four Green roof tiles
5. Angle is 40 degrees, so it is the average of 20 to 60 degrees
6. Holes let water escape at the first 7.5 cm, so roots do not rot while bottom half can be filled with water
7. Angle reduces total weight without reducing top surface area. It also makes it possible to use injection molding
8. All edges have curves to optimize material flow during injection molding
9. Holes for screws to secure planter on Green roof tile. Holes are made such that it can be produced with injection molding
10. Hooks have a draft angle to improve production process
11. Forces are distributed equally to and from hooks
12. An overflow lets water escape if needed
13. Sides have a draft angle to improve production process

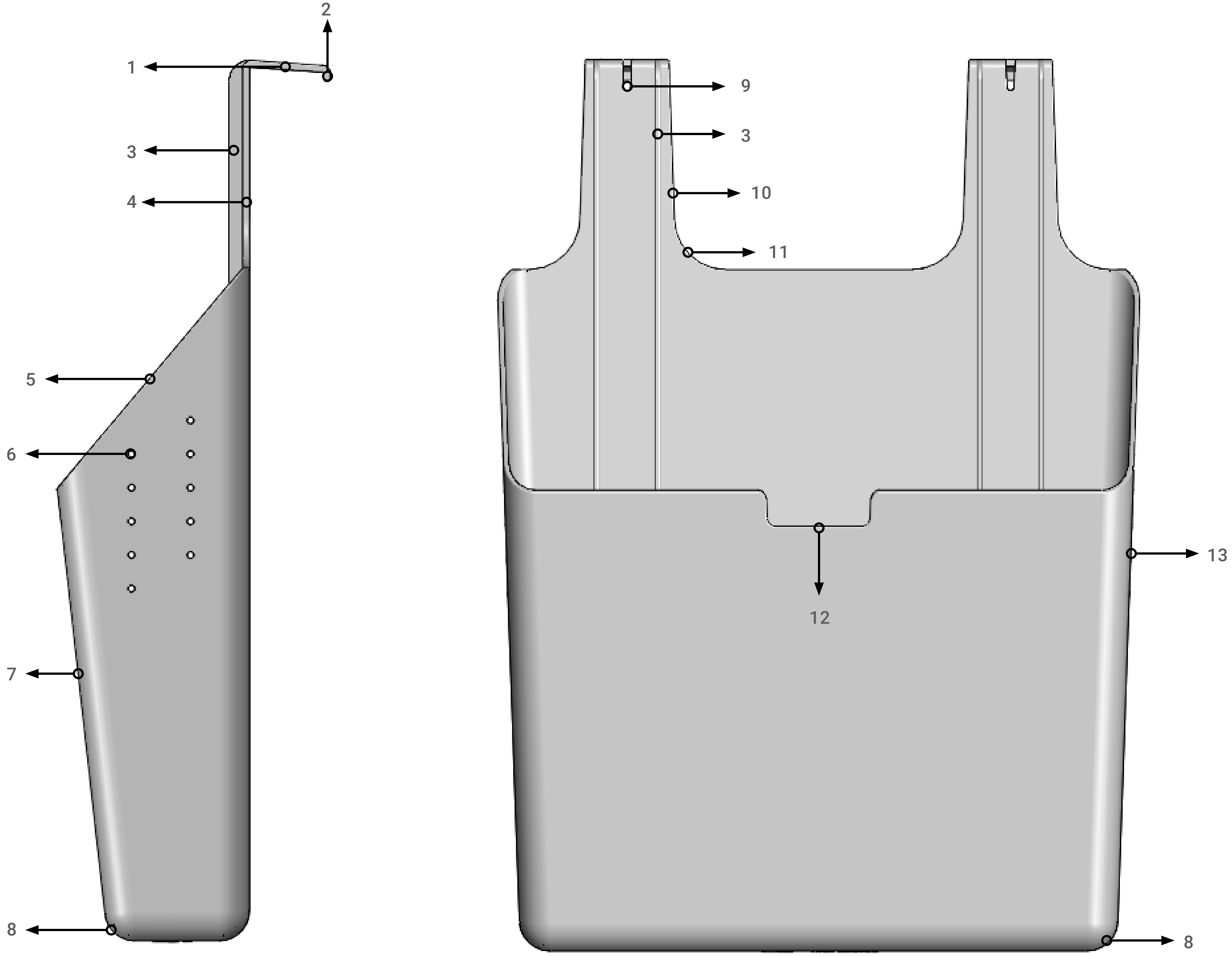


Figure 8.3 | Green roof tile planter (own)

8.3 COLOR

Green roof tiles and Green roof tile planters will be produced in three colors:

Light grey. Recycled HDPE has a natural light grey color. To reduce its environmental impact no extra color coating is added to the material. This results in a light grey Green roof tile and planter.

Anthracite grey. In the Netherlands, most roof tiles are anthracite or natural red. To make a product corresponding to conventional roof tiles, an anthracite grey roof tile is produced.

Natural red. In the Netherlands, most roof tiles are anthracite or natural red. To make a product corresponding to conventional roof tiles, a natural red roof tile is produced.

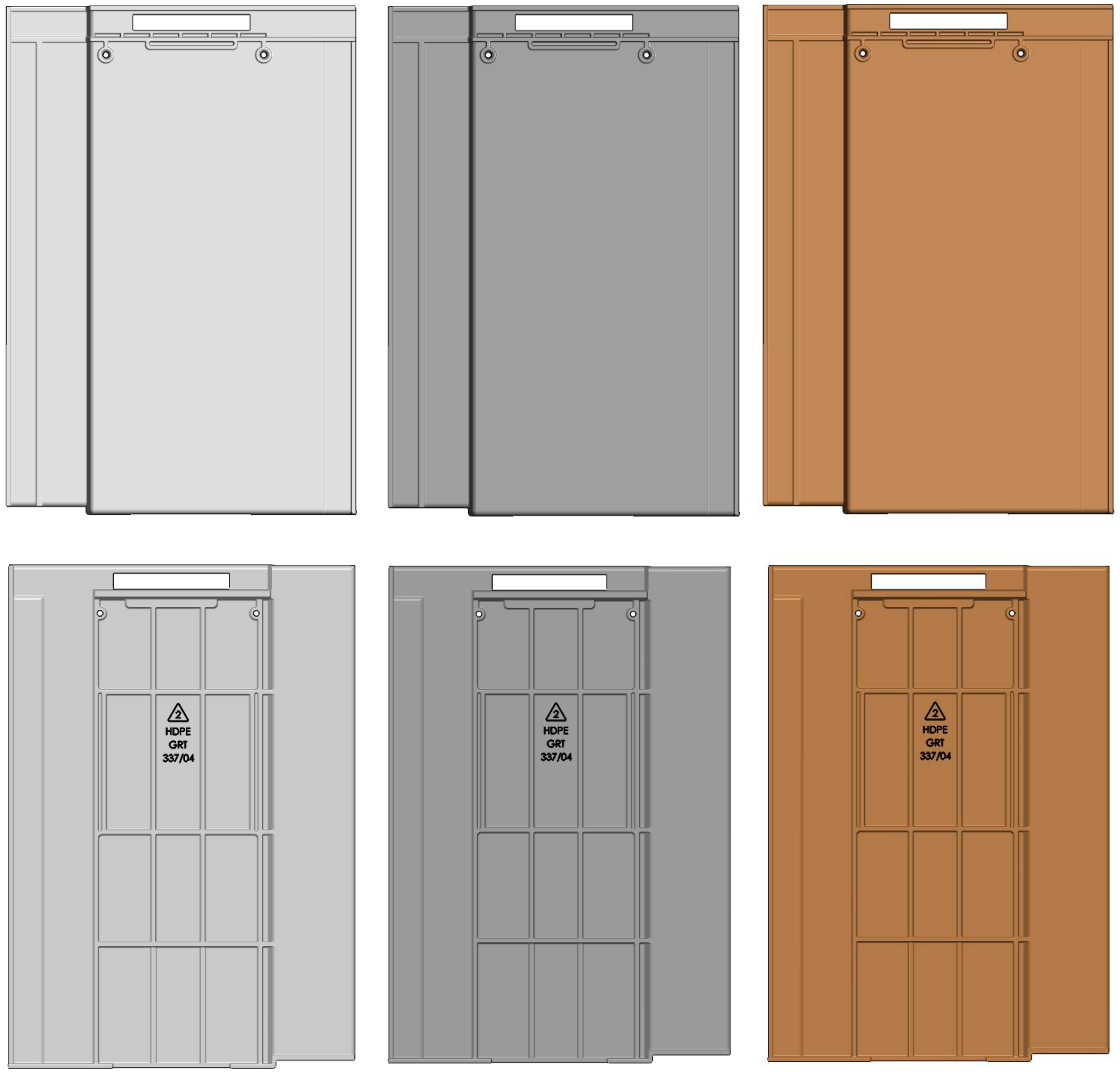


Figure 8.4 | Color roof tiles (own)

Figure 8.5 | Color planters (own)

8.4 SEEDS

Seed mixture used in this design is based on a seed mixture of Cruydt Hoeck (D2 dakmengsel). This mixture has 28 plant species, specially selected for roofs. These plants can withstand dry periods, short floods, and like to grow on a sunny location. Because mixture consists of 28 plant species, nature can select which one grows best on which location. The right species will germinate per circumstance. Therefore, same mixture can be used on north, east, west, and southside; shaded or not. This same principle will be used at Green roof tile planters.
Table 8.1 shows all plant species within Cruydt Hoeck D2 Dakmengel. This mixture is used in test setup too. Within test setup, half of the planters are filled with four plants instead of seeds, these are the colored species.

8.5 SUBSTRATE

Upon recommendations of the employees of Cruydt Hoeck, J. Stam, G. Jager (personal communication February 9, 2021) , a substrate mixture of Optigrun is used. This mixture, Optigrun intensivsubsrat typ I-leicht lose, is produced for an intensive green roof. It is lightweight, nutrient-rich and provided enough space for roots to grow. In final design, an extra component of chalk is added to compensate for nitrogen filtered out of the air by plants.

Achilea millefolium	Duizenblad
Allium Schoenoprasum	**Bieslook**
Anthoxanthum odoratum	Gewoon reukgras
Armeria maritima	Engels gras
Campanula rotundifolia	Grasklokje
Clinopodium vulgare	Borstelkrans
Dianthus armeria	Ruige anjer
Dianthus carthusianorum	Kartuizer anjer
Dianthus deltoides	Steenanjer
Erigeron acer	Scherpe fijnstraal
Erodium cicutarium	Gewone rijgersbek
Festuca ovina	**Schapengras**
Festuca rubra	Rood zwenkgras
Galium verum	Geel walstro
Jasione montana	Zandblauwtje
Linaria vulgaris	Vlasbekje
Lotus cornuculatus	Gewone rolklaver
Origanum vulgare	Wilde marjolein
Pilosella officinarum	Muizenoor
Plantago media	Ruige weegbree
Prunella vulgaris	Gewone brunel
Rumex acetosella	Schapenzuring
Sempervivum	**Huislook**
Sedum rupestre	Tripmadam
Silene vulgaris	Blaassilene
Thymus pulegioides	**Grote tijm**
Trifolium arvense	Hazenpootje

Table 8.1 | Plant species D2 Dakmengsel (Cruydt Hoeck)

8.6 USE AND MAINTENANCE

Green roof tile products will be sold in two ways: directly to a customer or to a housing corporation, renovation company and/or contractor.

A customer can buy a Green roof tile product online per unit. This will be delivered at home. Because it is delivered by mail, substrate and seeds are separate from planter. Consumer needs to assembly it together him or herself. A manual explains all steps from putting substrate and seeds in the planter to assembly on a roof (see assembly sequence). After assembling products on a roof, no extra effort is needed. However, water plants at dry periods, a yearly check and cleaning will improve growth of plants and lifespan. A green roof is similar to a garden: maintenance is not obligated but more effort will have better results.

A housing corporation, renovation company and/or contractor can buy planters separate from substrate and seeds too. However, from a purchase of 25 planters it is also possible to buy them including grown plants. In that case, the products are delivered and assembled by the Green roof tile company. People can maintain their own green roof, but this can also be outsourced to the Green roof tile company. Water plants if necessary, a yearly check and cleaning can be part of a subscription. A good-looking roof without worries.

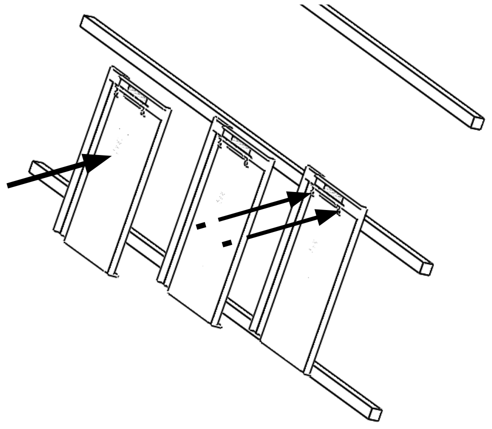
8.7 END OF LIFE

Green roof tile products are designed for easy disassembly. Every product can be disassembled separately without interfering with others. So, if one planter leaks or a roof tile is broken, it can be replaced without disassembling the whole roof. All products can be taken down to pieces of one material. For instance, the roof tile sideplate. This product can be disassembled to an aluminium sheet, 6 screws, 3 pieces of Compriband and its Upper part (HDPE). Screws could be reused, aluminium sheet could be reused or recycled, and Upper part could be reused or recycled. Every part has clear material indications, making recycling easier. Compriband is the only non-reusable or recyclable part at this stage. This could be an improvement of the product.

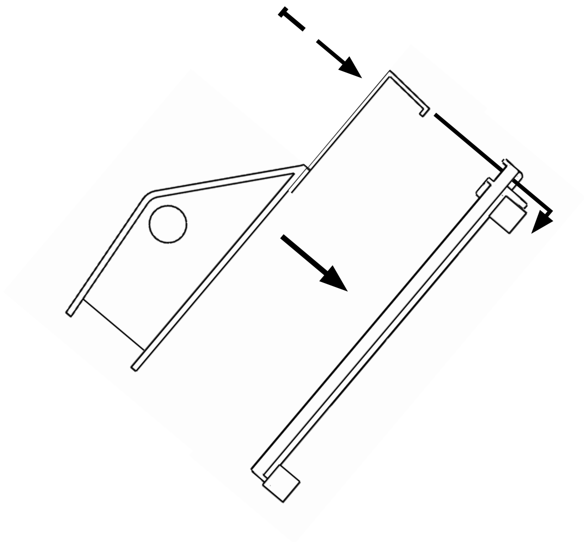
8.8 ASSEMBLY SEQUENCE

Assembly sequence, see next page, is split up into two parts. First, assembly of Green roof tiles with a planter and a breeding box without adjacent conventional roof tiles. Assembly of an insect hotel is similar to a breeding box, so they could be substituted. Secondly, an assembly of a Green roof tile sideplate with conventional roof tiles adjacent on all sides. Both assembly sequences show all possible actions needed to install a green roof.

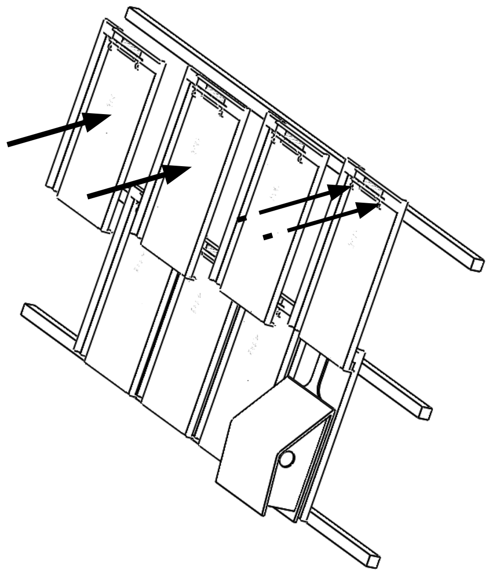
1.1 | Place Green roof tile on purlin
1.2 | Secure Green roof tile with two screws



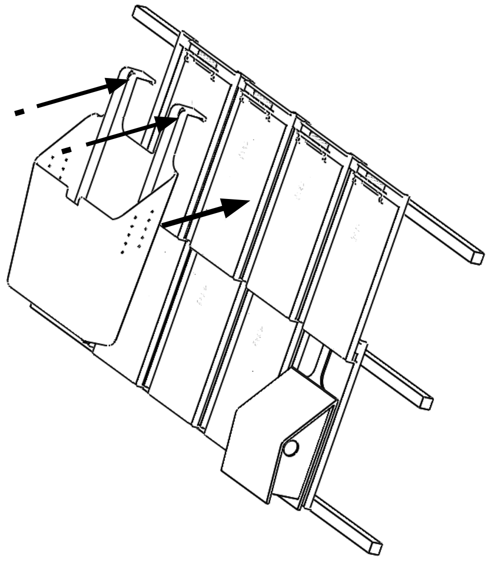
2.1 | Place breeding box on Green roof tile
2.2 | Secure breeding box with two screws



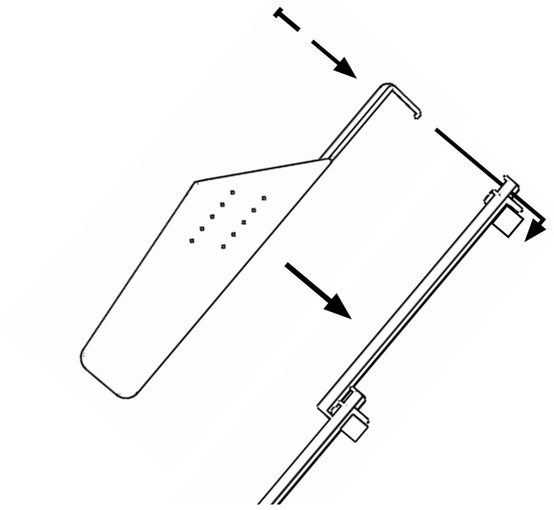
3.1 | Place Green roof tile on purlin
3.2 | Secure Green roof tile with two screws



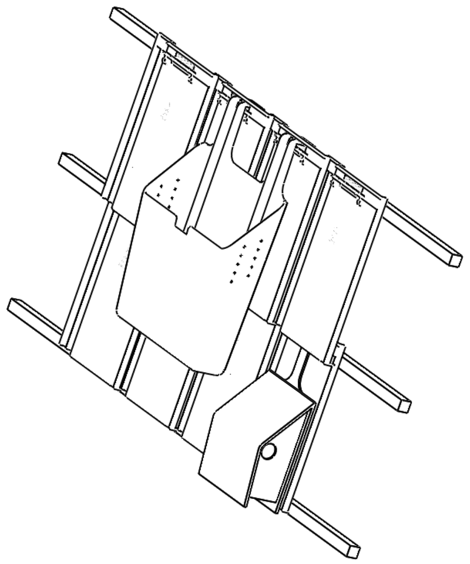
4.1 | Place planter on Green roof tile
4.2 | Secure planter with two screws



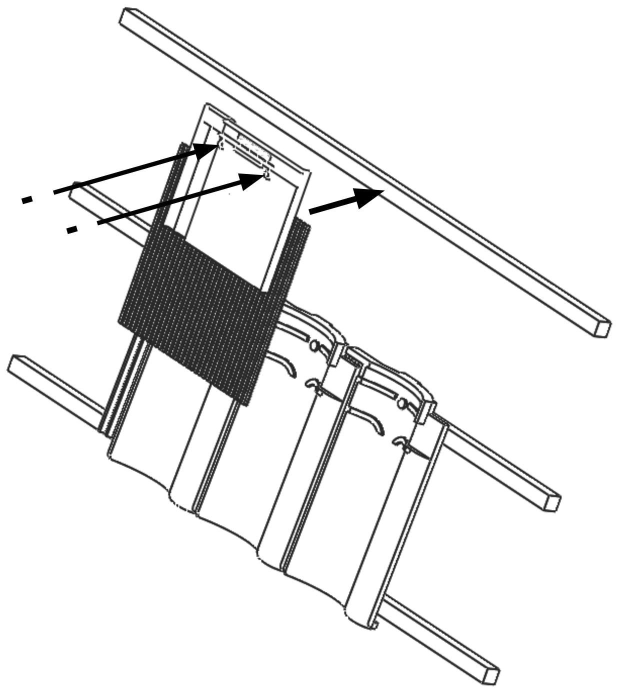
4.1 | Place planter on Green roof tile
4.2 | Secure planter with two screws



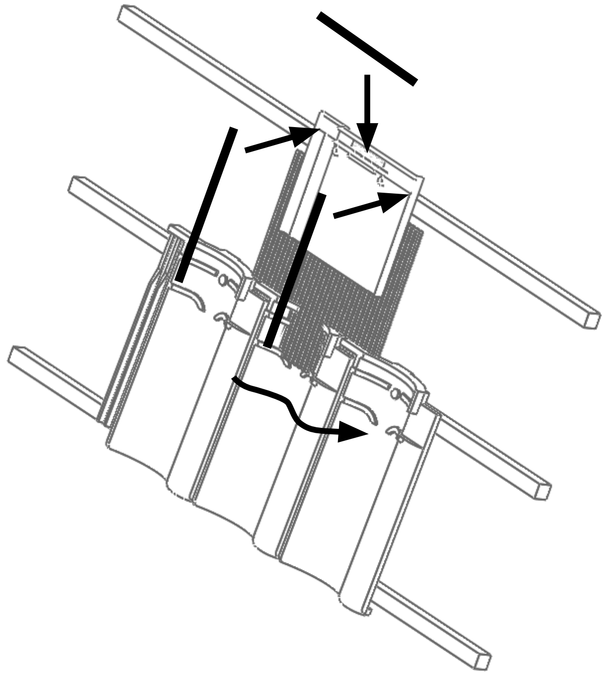
5 | Repeat step 1 - 4



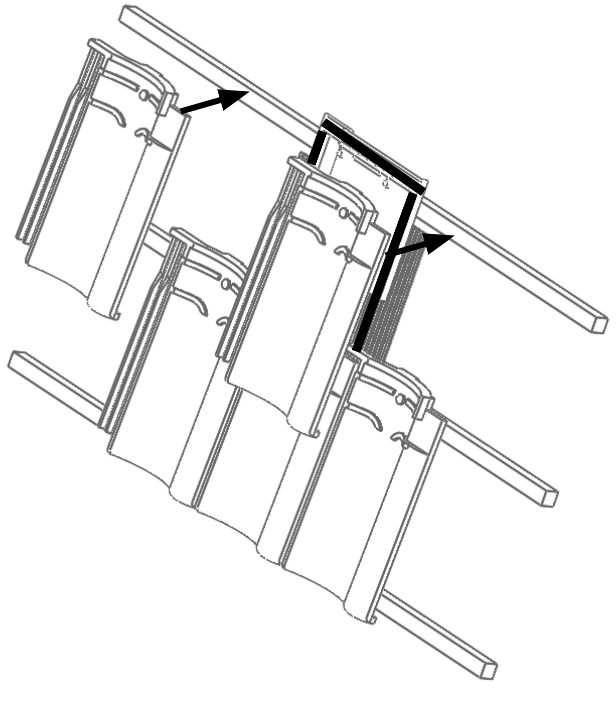
1.1 | Place Green roof tile sideplate on purlin
1.2 | Secure Green roof tile sideplate with two screws



2.1 | Remove adhesive strip protection from aluminum part
2.2 | Form aluminum part to shape conventional roof tiles
2.3 | Place compriband strips on top and both sides



3.1 | Place conventional roof tiles on both sides
3.2 | Let compriband expend and close gap between sideplate and conventional roof tiles



4.1 | Place conventional roof tiles above sideplate
4.2 | Let compriband expend and close gap between sideplate and conventional roof tiles

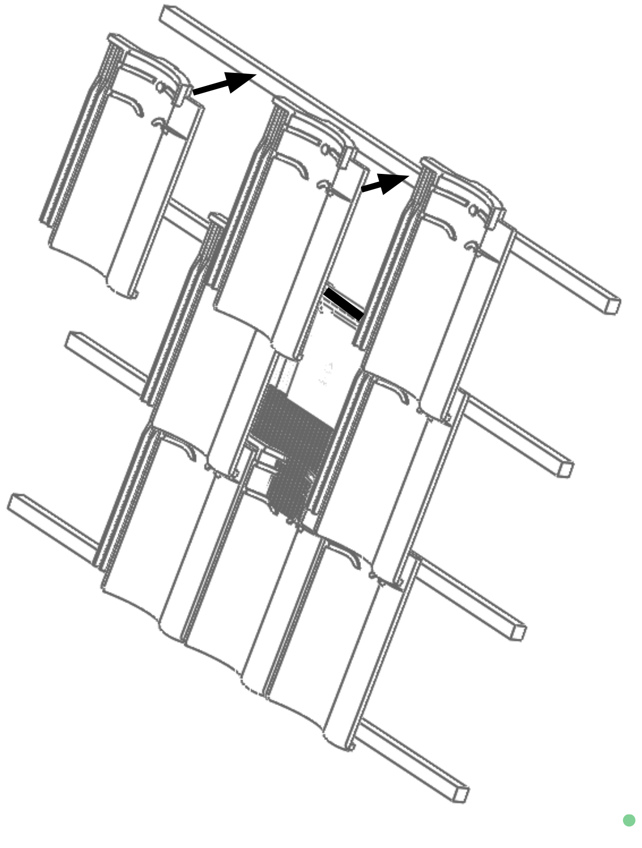


Figure 8.6 | Assembly sequence (own)

FINAL DESIGN

Green roof tiles can be placed on roofs in any way: on a grid, chaotic, or in a certain pattern.

TEST SETUP

To test the feasibility of the Green roof tile concept, a 1:1 prototype is made. This prototype focusses on developing of plants using Green roof tile design. Within this test setup, growth of plants and humidity of substrate is compared in relation to three design options and four orientations. The outcome concludes which design option and orientation performs best. Additionally, it concludes that a Green roof tile concept is working.

9.1 APPROACH

A 1:1 prototype is built to test the Green roof tile concept. It tests if plants can grow and survive during a period of two months, March to May. If that is the case, these plants provide food and shelter for living creatures and therefore increase their living habitat. This test setup functions as proof if a green roof system can improve biodiversity of cities.

In total, 12 planters are produced out of wood, made watertight with garbage bags, and hang on a mockup roof. These planters test two variables: orientation and volume/surface ratio. They are filled with Optigrun roof substrate provided by Berry Zaad, Van Ginkel Groep. Half of the planters contain grown plants: chives, fescue, houseleek, and large thyme. The other half are sown with a roof mixture D2 of Cruydt Hoeck.

Test setup is located at the Green Village on the Technical university of Delft. Test period started at the 25th of March and ended at 11th of May.

This research ends at the beginning of summer, so it is not possible to test long periods of draught or showers. However, small tests indicate planters' performances during a period of three weeks.

Figure 9.1 | Test setup West orientation (own)

Figure 9.2 | Test setup South orientation (own)

9.2 RESEARCH QUESTIONS

This test setup is made to give answer on following main question:

Does the concept of a Green roof tile work?

Next to the main question, test setup is made to answer two sub-questions as well:

- Does orientation influence growth of plants?
- What volume/surface ratio works best for plants?

9.3 METHODOLOGY

Growth of plants can be tested quantitative and qualitative. Both methods are used to give answer on the research questions. Quantitative research is done by measuring substrate humidity every day. Its humidity provides insight whether circumstances are too wet, good, or too dry. Measurements are done by hand with an analog measurement device. This device gives a humidity from 1 to 10 with steps of 0.5. By measuring every planter, a comparison can be made.

Qualitatively research is done by making pictures every Monday. These pictures give an overview of growth of every planter. Comparing these pictures gives insight in growth per circumstance.

9.4 TEST SETUP

In total 12 planters are made, 6 planters contain seeds, 6 contain plants. Every situation has two planters, one with seeds and one with plants. This is done to have results of grown plants too, within the given timespan. Germinate of seeds takes a few weeks and before they are grown, this research ends. 6 planters are orientated south, 2 Small planters, 2 Medium planters and 2 Large planters. These sizes correspond with a volume/surface ratio, see figure 9.3. 2 Medium planters are orientated west, 2 Medium planters are orientated north, and 2 Medium planters are orientated east.

Next to the test setup, in the ground, same four plants are planted, and seeds are sown. This is done to function as reference.

During test period, no adjustments are done, and no water is given. Only pictures are taken and substrate humidify is tested.

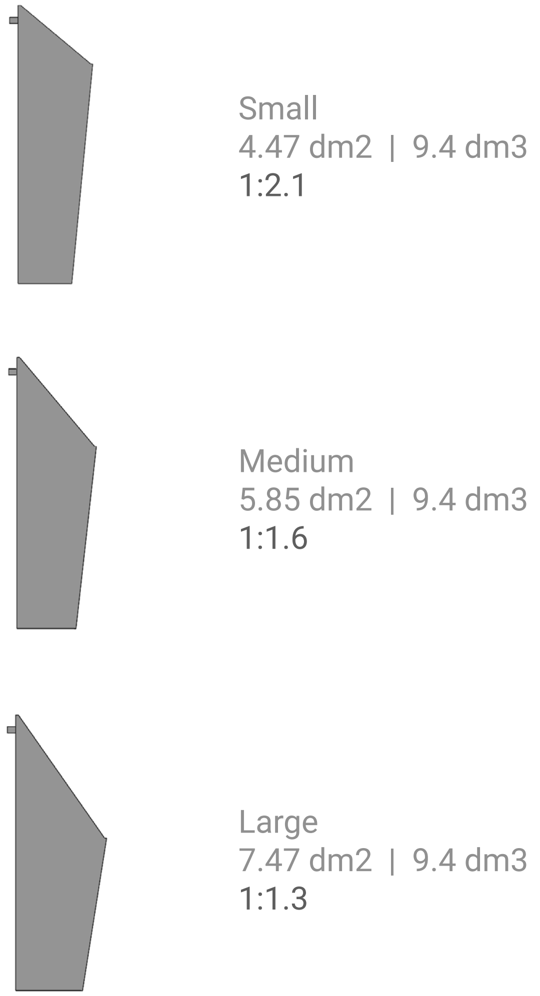


Figure 9.3 | Volume/surface ratio (own)

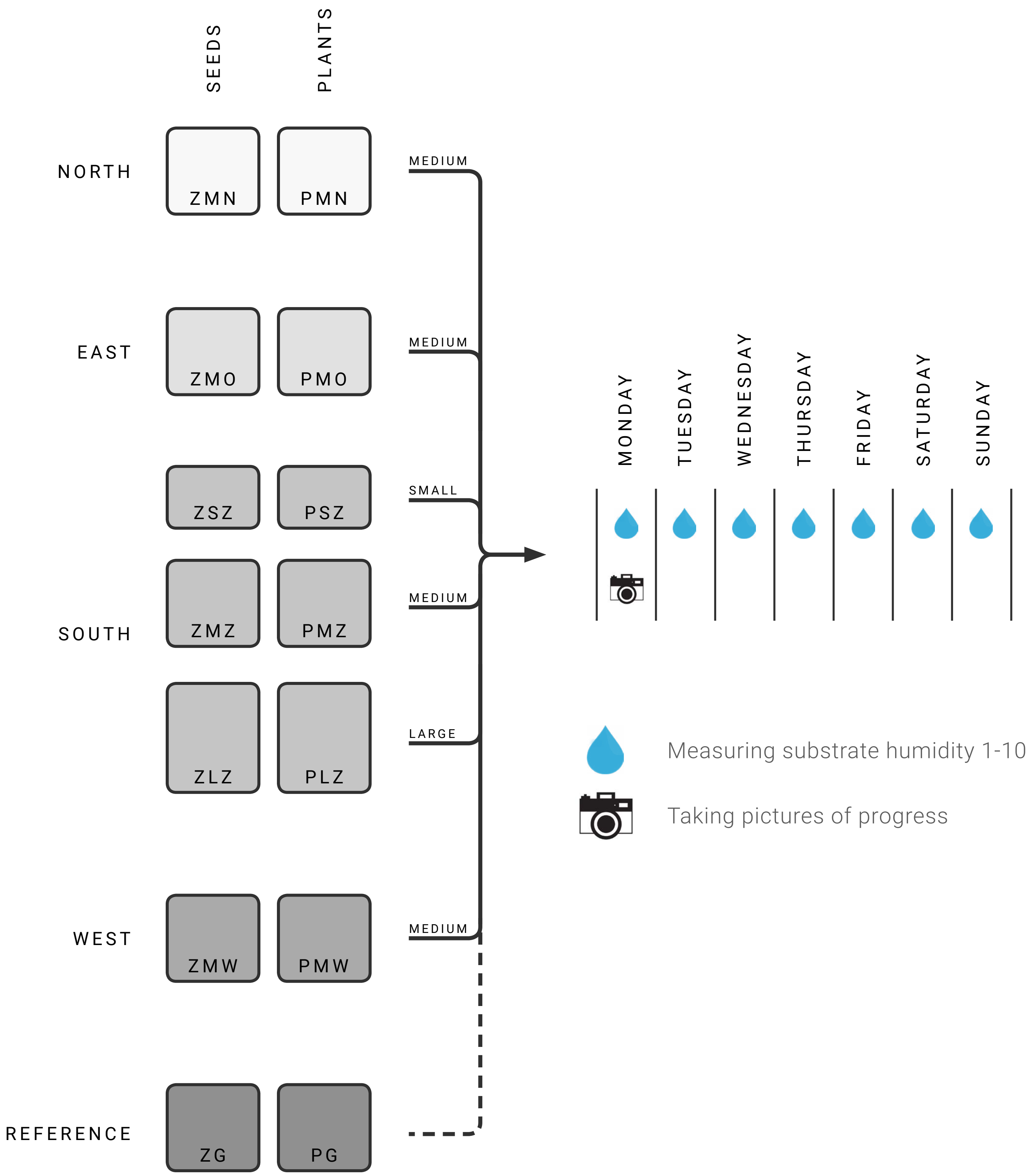


Figure 9.4 | Test setup (own)

9.5 RESULTS

Figure 9.5 shows results of all planters including reference seeds and plants in the ground (ZG and PG). Because measurement device has a scale from 1 to 10, top of graph results into a flat line [1]. Another measurement device would give more specific results at that stage, see recommendations.

Blue bars [2] represent rainfall in mm per day in Delft. So, first twelve days, with exception of 27th of March, was dry followed by a wet period. Within this first dry period, substrate humidity stayed constant and increased by the rain at the 6th and 7th of April. After that, range between the top [3] and bottom line [4] increased. First, the difference was 3 while later, the difference increased to 6. This is due to the difference between seeds and plants, see next paragraph.

9.6 SEEDS AND PLANTS

Six planters are filled with seeds and six with plants. For every situation there is one planter with seeds and one planter with plants. Figure 9.6 and 9.7 show a difference between substrate humidity. After rain on the 6th and 7th of April most seed planters stayed wet with a score of 10. Only ZSZ has a different result due to its volume/surface ratio and ZG because it is the reference measurement in the ground.

On the other hand, substrate humidity of plants did increase at the 6th and 7th of April too. However, most planters did not score a 10 and their scores fluctuated more. These results can be explained by the fact that plants absorb water and release it through transpiration. Seeds, and later small plants did not have the ability to absorb water from the bottom half of the planter and release it.

Seed planters give a view on its behavior from the moment these planters are assembled on a roof while plants give an insight on its behavior on longer term.

As long as plants are small, they have not the ability to reduce planter's humidity. This substantiates the necessity of holes at sides of a planter. These holes make sure water can escape from the first 7.5 cm, preventing roots to rot. Grown plants have that ability themselves. However, multiple days are scored too wet (a score >8), so holes are beneficial for grown plants too.

A period of 12 days with little rain, 15th of April to 27th of April, results in an average decline (plants) of 0.9 substrate humidity. This indicates the ability to function during a longer period of draught. However, normally, a longer period of draught is not directly preceded by a wet period (scores >8). So, its functionality during a hot and dry summer is part of a future investigation.

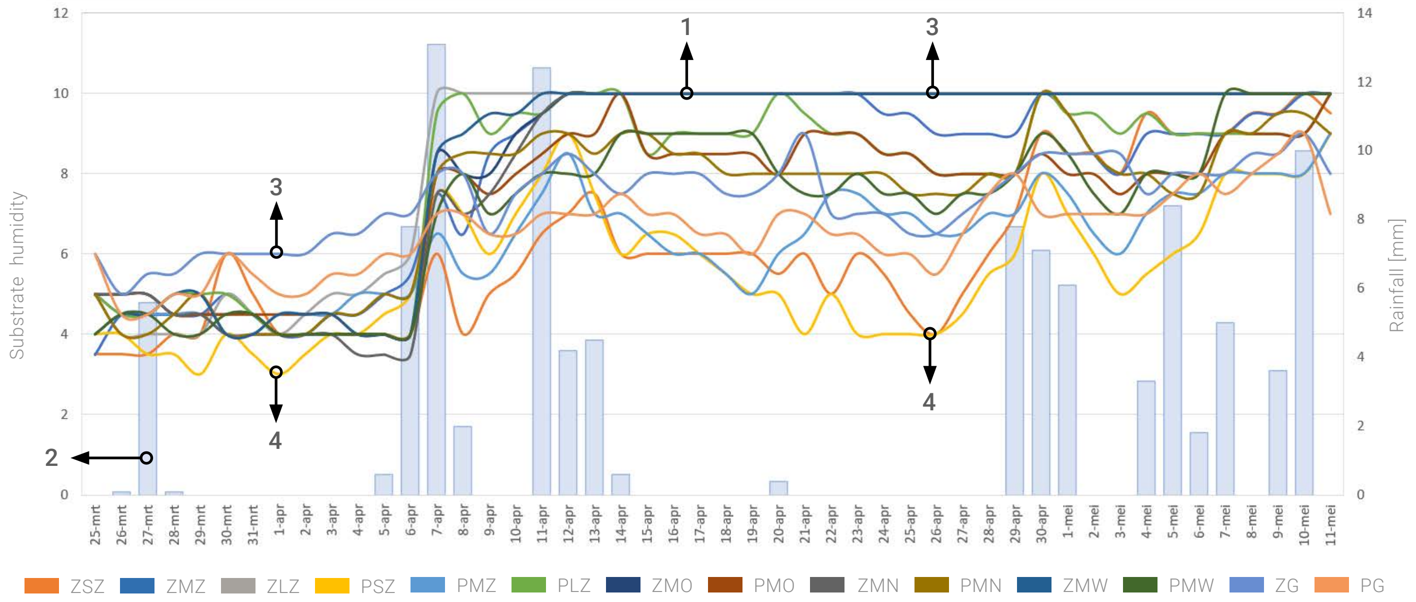


Figure 9.5 | All data (own)

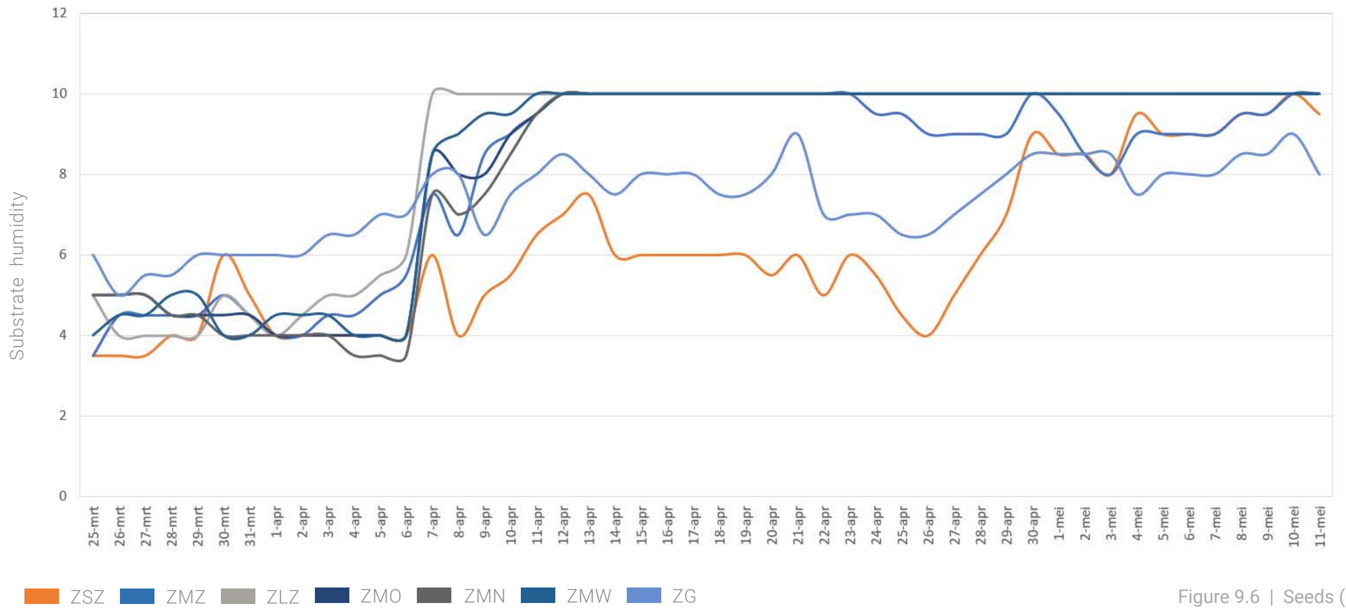


Figure 9.6 | Seeds (own)

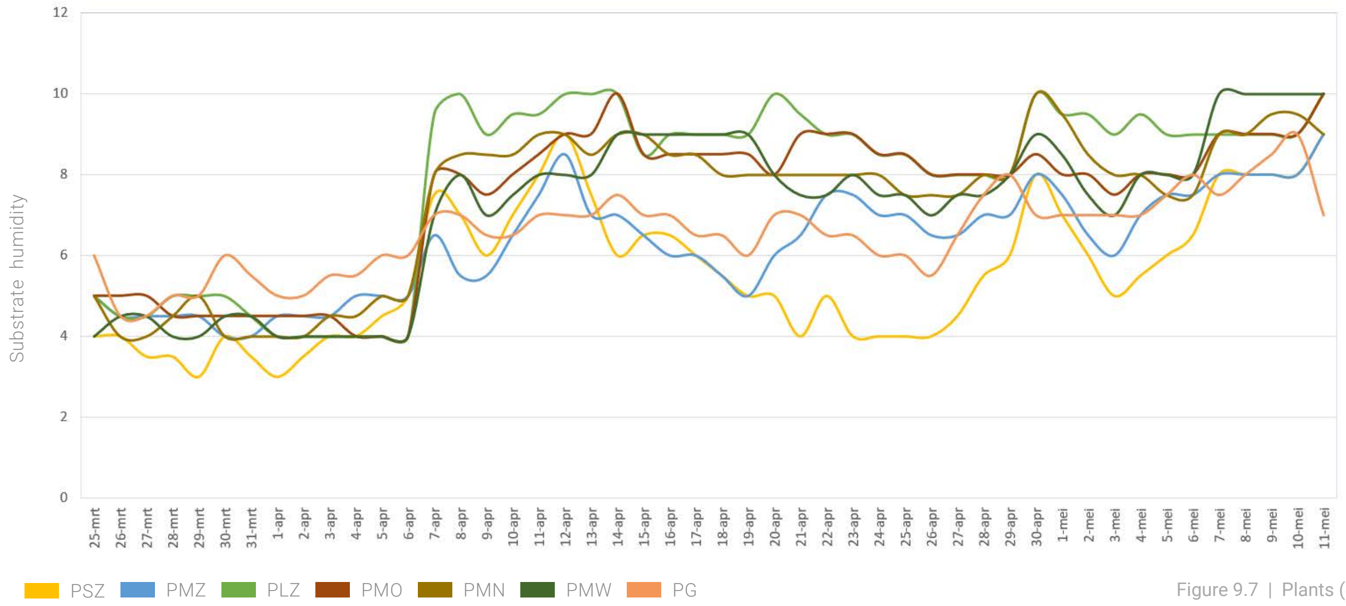


Figure 9.7 | Plants (own)

9.7 ORIENTATION

Figures 9.8 to 9.11 show substrate humidity per orientation. At every orientation, planters with seeds follow a similar pattern; first week stable around 4, increasing to 10 at the end of week 2. From that moment their scores continue to be 10. Only south orientation [ZMZ] has a slightly different line. Increase at the end of week 2 is less and it does not score only tens at the end. For other orientations, no significant difference can be measured. Same can be concluded form planters with plants. Their substrate humidity is more fluctuating but follow a similar pattern. South orientated planter with plants [PMZ] has a different path too, with less increase at the end of week 2 and a dryer period at week 4.

To conclude, south side is drier compared to other orientations while east, west and north have no significant differences. Because a score between 3 and 8 counts as good (below 3 as too dry and above 8 too wet) a south orientated planter is better during period of testing. Other planters stayed too wet. If a south orientated planter is a better option during a dry period is part of a future investigation.

9.8 SHAPE

Figures 9.12, 9.13 and 9.14 show substrate humidity of different shaped planters (Small, Medium, and Large). These planters are all orientated south.

Small planter's humidity (both seeds and plants) increases at the end of week 2 and decreases at week 3 and 4. Scores are low and fluctuate a lot.

Medium planter's humidity of seeds [ZMZ] increases at the end of week 2 and scores an 8 or higher until the end of this test period. Humidity of plants [PMZ] fluctuates between a score of 5 and 8 most days.

Humidity of both seeds and plants of the Large planters [ZLZ] [PLZ] score an 8 or higher from 6th of April to 11th of May. Seeds scores only 10s in this period.

Small planters stayed dry compared to others, during period of testing. Within this period, they scored between boundaries of too wet (>8) and too dry (<3). However, during a period without rain this can become a problem. On the other hand, Large planters scored too wet most days. During a period with more rain, Large planters will remain wet for too long resulting roots to rot. Medium planter with plants [PMZ] has scores fluctuating between 5 and 8 which is desirable at this stage. Also, its seeds [ZMZ] shows ability of drying out, resulting in better circumstances for small plants to grow. So, a Medium planter has the best volume/surface ratio.

To conclude, a large planter collects to much water and stays too wet during a long period. A small planter collects not enough water and will become too dry during dry periods. So, a Medium planter is the best design in relation to substrate humidity during period of testing.

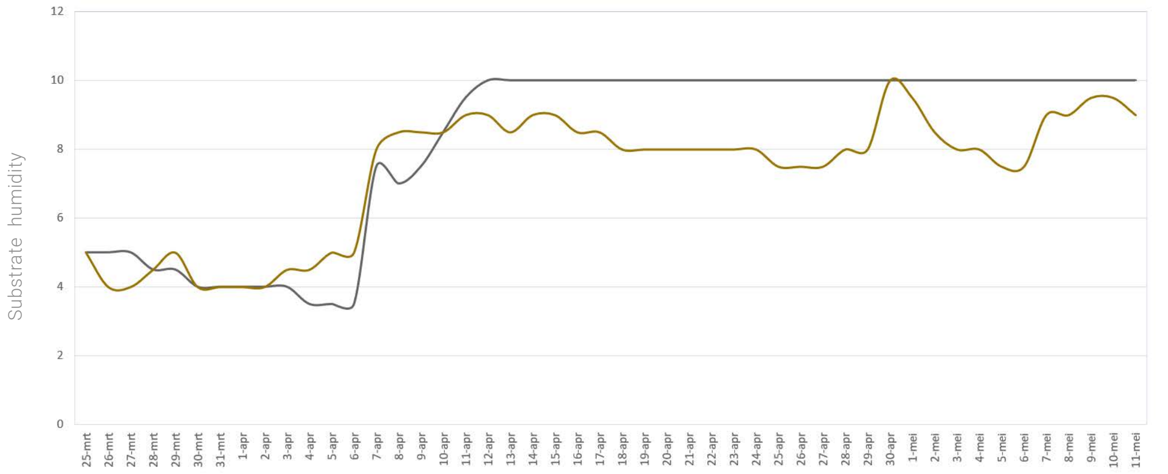


Figure 9.8
North (own)

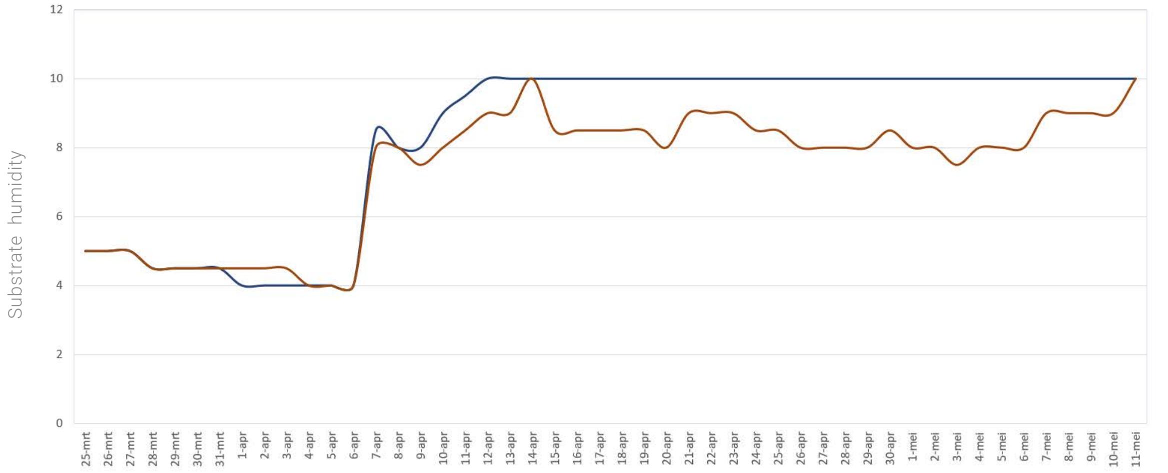


Figure 9.9
East (own)

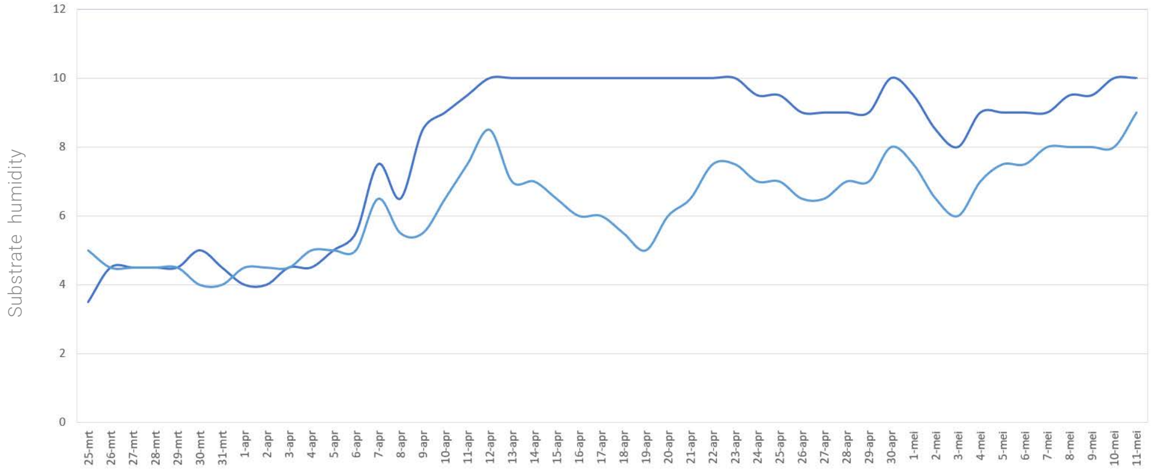


Figure 9.10
South (own)

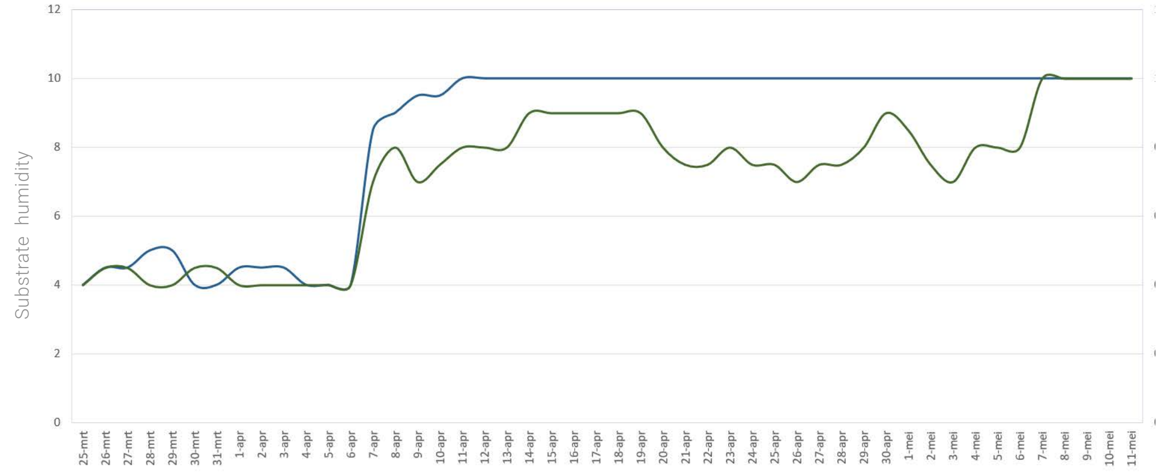


Figure 9.11
West (own)

Figure 9.12 | Small (own)

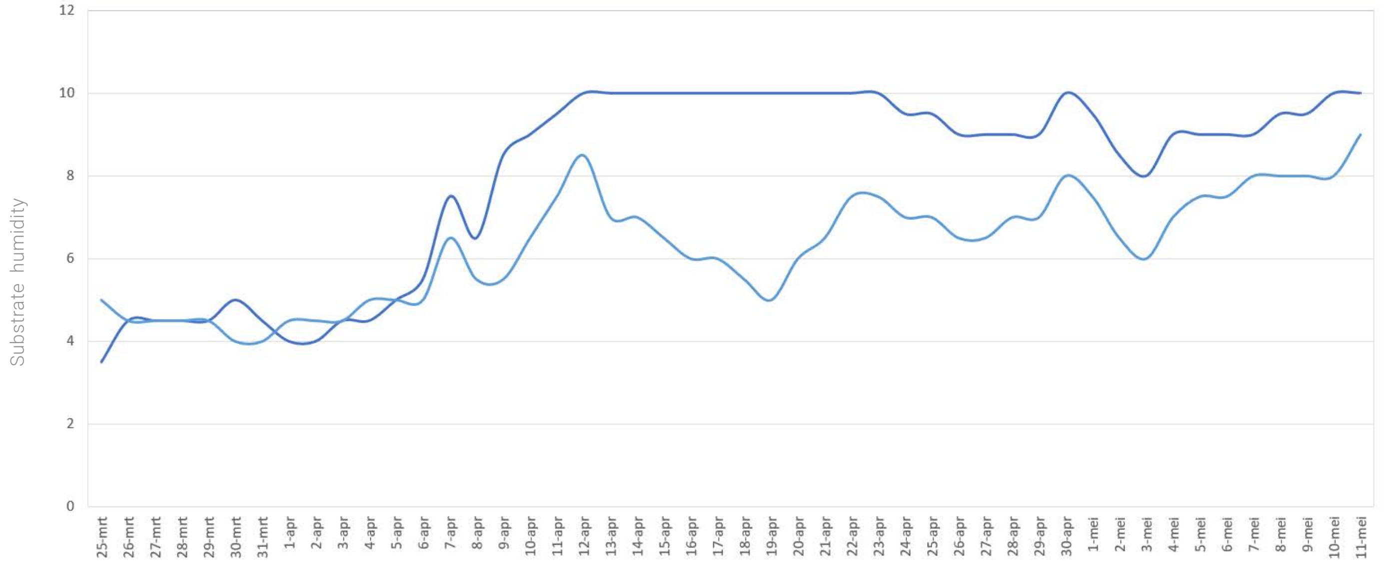


Figure 9.13 | Medium (own)

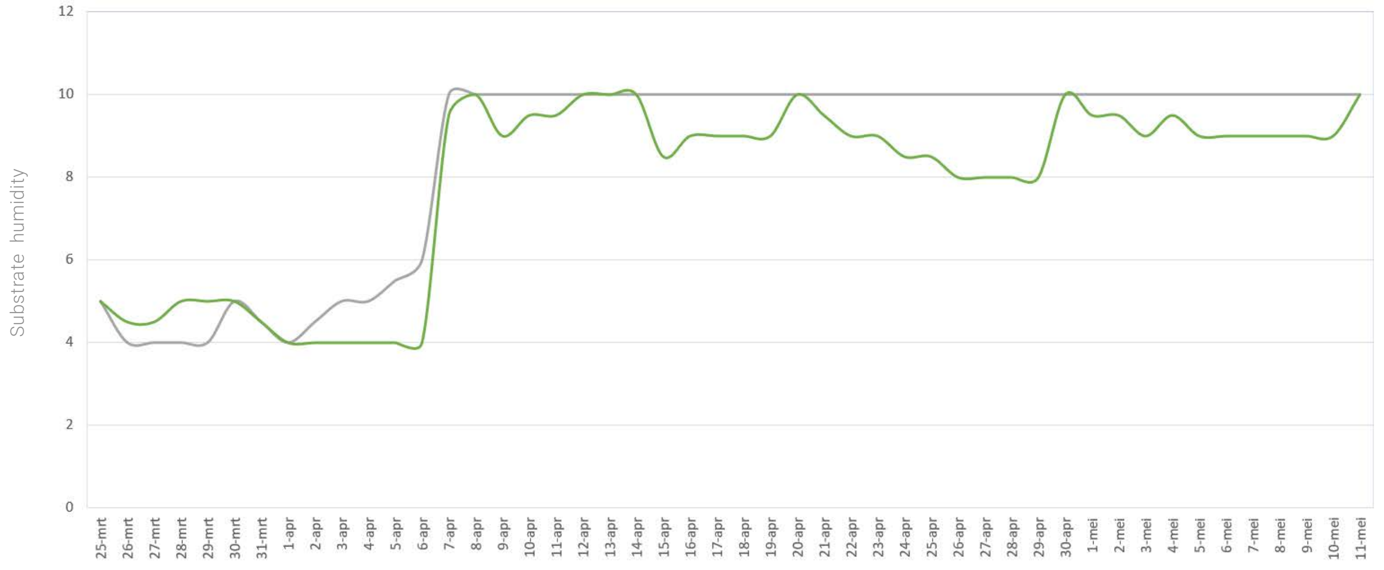


Figure 9.14 | Large (own)

9.9 PICTURES

Next two pages, figure 9.15 and 9.16, show pictures taken every Monday. Because week two and three were cold, including snowfall, growth of plants and germinating of seeds are inhibited. That can be a reason that no significant difference can be measured between Small, Medium, and Large planters. Similar conclusion can be made between the four orientations.

However, some dissimilarities can be perceived; houseleek at PSZ, PLZ, PMO, and PMN is spouting, this is not happening at houseleek planted in the ground [PG]; fescue located in the ground seems smaller in relation to fescue located in planters; and shives at PMZ, PMW and PG are blooming.

No significant differences in size can be measured between plants growing from seeds. Only reference seeds are different [ZG]. Plants germinating at the ground are not the same compared to planters. Other plant species, located in the ground are growing faster than seeded species.
Lastly, water level within seed planters has been rising up to 3 cm below substrate level. This substantiates the necessity of holes at the sides.

Altogether, no conclusion can be made which planter performs best based on qualitatively research. However, conclusion can be made that all plants grow during period of testing. So, Green roof tile concept is working.

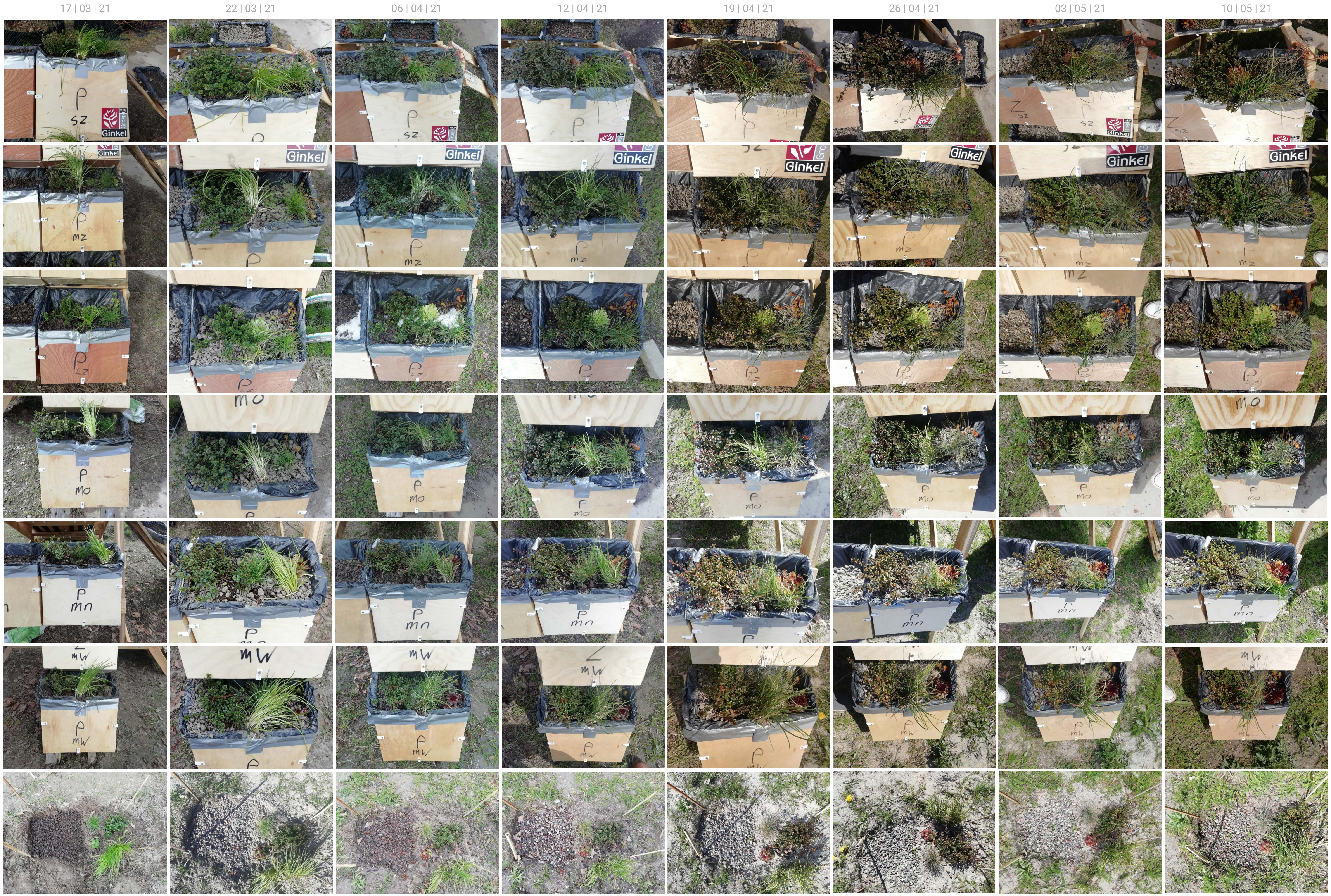


Figure 9.15 | Test setup plants (own)

Figure 9.16 | Test setup seeds (own)

9.10 CONCLUSION

A 1:1 test setup is built with 12 planters, 6 with plants and 6 with seeds. Every day, substrate humidity is measured and once a week pictures are made. These quantitative and qualitative test methods are used to answer the following question:

Does the concept of a Green roof tile work?

Answer on this question is yes. Plants are growing, and seeds are germinated. No significant difference can be measured between plants and seeds located on Green roof tile planters and the ones located in the ground.
Due to rain, substrate humidity is too high most days, resulting in a water level up to 3 cm below substrate level at some planters. This substantiates the necessity of holes at sides. However, no consequences can be seen because of that.

Next to main question, the two following sub questions are answered:

- Does the orientation influence the growth of plants?
- What volume/surface ratio works best for plants?

During period of testing, planters orientated south have better growing conditions. Other orientations stayed too wet during test period. Whether south side is still working best during a period of draught is part of future investigations.

A volume/surface ration of 1:1.6 is best (Medium planter). A ratio of 1:2.1 collects not enough water (Small planter) and a ratio of 1:1.3 stays too wet during testing period (Large planter). A 1:1.6 ratio will be used at the final planter design.

9.11 RECOMMENDATIONS

This test is done on a small scale to give a first impression of Green roof tile planters. A bigger scale test is needed to validate results. This test needs to be performed on a conventional roof where circumstances are similar to final product circumstances. This will influence air temperature for instance. air temperature on a roof is higher than on the ground. This influences evaporation of water and growth of plants.

It was not possible to perform a long-term test, including dry periods, because of the timespan of this research. These dry periods will have an impact on performance of Green roof tile planters. This test will be needed to validate if the concept works during a hot and dry summer.

During such a long test it could be interesting to see if different plant species grow under different circumstances. This can give information about performance. At current test, a seed mixture is used with 28 species. These plants are geminating, but it is not possible to identify them at this stage.

Current test setup is performed during a period of rain. However, what happens during a storm or a downpour? Will planters be flooding? For how long does water stay in a planter? Do holes at the sides clog? Such tests could improve design.

All planters are filled with similar substrate (roof substrate of Optigrun). However, other substrates could perform better within these circumstances. A test with different substrates could improve overall design.

A measuring device is used measuring substrate humidity on a scale of 1 to 10. Most planters with seeds scored tens for a longer period. Differences between these planters could not be measured. A device with a bigger scale, or with absolute values could improve results.

9.12 EXTRA TESTS

Between end of testing and final presentation are three weeks. These weeks are used to perform some smaller test with the same planters. These tests give a performance indication on a dry period, wet period, downpour, and shadow. For the test of a wet period, holes are drilled at the sides such that the planters function similar to final design.

9.12.1 DRY PERIOD

One planter with plants and one with seeds are located inside so they are protected from rain. These two planters did not get any water during a period of three weeks and temperatures were rising to 30 degrees Celsius.

Figure 9.17 shows the results. Both plants and seeds are performing well. Substrate is dry, but the plants are green, and chives and fescue are flowering. This test shows that these species can survive a period without rain and high temperatures of at least three weeks.

9.12.2 WET PERIOD

One planter with plants and one with seeds are tested on a wet period. Every day both planters got 1.2 liters of water. This is based on the wettest period of 2020, 24th of September to 14th of October, with 189 mm rain in total (Royal Netherlands Meteorological Institute, April 2021).

Figure 9.18 shows the results. Plants and seeds are green and growing. Because holes were drilled at the sides, the upper 7.5 cm staid dry. This test shows that planters function during a period of rain.

9.12.3 DOWNPOUR

The two planters tested on a wet period get 1.2 liters water per day. This water is given at one moment, so it simulates a downpour. At this moment water flows out of the planters through holes at the sides. Therefore, the planters will not flood, and the upper 7.5 centimeters substrate will stay relatively dry. Roots of plants are not rotting because of these holes.

At the beginning, water coming out of planters is brown, while later this water is clearer. This suggests that small particles are removed from planters. This could lead to a loss of nutrients. Results of that cannot be seen in this short time span. However, it is something for future investigations.

9.12.4 SHADOW

At roofs, some parts are always protected from the sun. These shaded parts can influence growth of plants. One planter with grown plants is located underneath the test setup such that it is always in a shadow. Figure 9.19 shows the results of a planter in shadow for three weeks whereby the plants grow similar to others. So, no significant difference can be seen between plants located in shadow or in sun.

9.12.5 CONCLUSION

These four tests are done with a sample size of one or two within a period of three weeks. This is too short and with too little samples to give reliable conclusions. However, they give an indication of a planters functionality in dry and wet periods, during a downpour and without direct sunlight. At all four tests, plants were growing well, so it indicates that a concept of planters does function during draught, rain, and shadow for at least three weeks.

Figure 9.17 | Dry period (own)

Figure 9.18 | Wet period (own)

Figure 9.19 | Shadow (own)

TEST SETUP

12 planters, 125 liter substrate, two pallets, 286 screws and 7 gram seeds were used to make a test setup. This setup compares four orientations, three design options and validates the overall concept.

BUSINESS CASE

Within this business case, an overview is given of production costs, product margins, and selling prices. Calculations are done based on a startup of two persons and 8.750 product sells per year. Selling prices are compared with existing products, showing its economic feasibility.

10.1 APPROACH

A Green roof tile can be an addition to product portfolio of a company such as Faunaprojecten or Groendakpan. On the other hand, it can be a product for a startup. This business case focusses on a startup because that gives highest product prizes. Within a startup, a Green roof tiles need to finance all expenses while that is not the case in a company. If Green roof tile product prizes are realistic at a business case of a startup, it shows the feasibility of this concept.

Product prizes are split up into two parts. First, production costs and secondly product margins. Production costs are split up into all product parts (for instance: mold, substrate, screws, and wood), production or assembly time, and external startup costs. External startup costs are costs to setup production, assembly, and distribution.

Engineers from Promolding, an injection molding company located in The Hague, are consulted considering production costs of injection molding parts (Personal communication, April 19, 2021). Costs are based on technical drawings of a Green roof tile and Green roof tile planter, see appendix D.

Other production costs are based on customer prizes found on websites of retailers.

10.2 PRODUCT MARGIN

Because Green roof tile products need to finance all expenses of a startup, its product margin is significant. Product margins covers all expenses per month. These expenses are based on a startup of two people:

- Salary two persons: 5000
- Office space: 1000
- Storage and distribution: 1000
- Investment costs: 1000
- Permanent charges: 500
- Traveling costs: 500
- Overhead: 1000

Investment costs are costs to let a startup grow. Permanent charges are fixed costs such as a website, database, software, and insurances. These prizes are an estimation based on two online tutorials (Business Finance Coach, 2020) (Slidebean, 2019).

Total product margin is 10.000 euros per month which is divided over all products:

	Sales/year	% of margin	€/product
Green roof tile planter	1.250/year	20%	19.20 euro/product
Green roof tile	3.000/year	30%	12.00 euro/product
Green roof tile sideplate	2.000/year	20%	12.00 euro/product
Breeding box bird	1.250/year	15%	14.40 euro/product
Insect hotel	1.250/year	15%	14.40 euro/product

Table 10.1 | Margin division (own)

Selling 5.000 roof tiles a year is comparable with one complete roof a month, based on a standard terraced house.

10.3 CONCLUSION

Selling prices of Green roof tile products are:

Planter	€29.95
Roof tile	€19.95
Roof tile sideplate	€19.95
Breeding box bird	€24.95
Insect hotel	€24.95

These prices can be compared with conventional products on the market. Mass produced products such as conventional roof tiles (€1.52) and planters (€6.89) are cheaper because of their production volume. Special roof tiles, for instance for ventilation openings (€23.95), have a comparable price. This shows that a Green roof tile could be financially feasible. Same conclusion can be made with product prices of breeding boxes by Faunaprojecten (€24.95) or insect hotels by Natuurmonumenten (€23.99). Green roof tiles made by Groendakpan have a low product price (€11.31) because it is a side product of company Groendak. Therefore, most company costs are financed by other products and product margins are low.

Green roof tiles can be sold individually or as a service. Price as calculated is for individually selling at an online web shop. The whole setup is delivered at people's house in separated bags. Therefore, planter, substrate, and seeds need to be assembled before putting it on a roof. This means that a green roof will take a few weeks, depending on the moment people are buying it.

Green roof tiles can also be bought as a service. The Green roof tile company places, maintains, and repairs the roof tiles and planters. Planters are placed on a roof including grown plants such that the roof is green immediately. Costs for such a subscription is not calculated because it is depending on multiple unknown factors.

Costs	Planter 1.250/year		Roof tile 3.000/year		Roof tile sideplate 2.000/year		Breeding box bird 1.250/year		Insect hotel 1.250/year		Source
	Total costs	Costs/ product	Total costs	Costs/ product	Total costs	Costs/ product	Total costs	Cost/ product	Total costs	Cost/ product	
Mold	30.000	2.40	12.500	1.00	12.500	1.00					Promolding
Injection molding		5.00		4.00		3.00					Promolding
Substrate		0.93									Groendak
Seed		0.17									Cruydt hoeck
Screws		0.08		0.30		0.08		0.08		0.08	rvs-paleis
Compriband						0.43					Kitcentrum
Ondervorst						0.83					EPDM
Baseplate								3.00		3.00	-
Wood								1.00		1.00	goedkoop bouwmaterialen
Paint								0.50		0.50	goedkoop bouwmaterialen
Insect hotel infill										0.50	-
Production/Assembly		0.75				0.50		4.25		4.25	25 euro/uur
External startup costs	2.000	0.16	2.000	0.07	2.000	0.10	1.000	0.08	1.000	0.08	-
Total prod. costs		**9.49**		**5.37**		**5.94**		**9.63**		**10.13**	
Product margin		19.20		12.00		12.00		14.40		14.40	
Product price		**28.69**		**17.37**		**17.94**		**24.03**		**24.53**	
Selling price		29.95		19.95		19.95		24.95		24.95	

Table 9.2 | Green roof tile product costs (own)

11.31 6.89 1.52 23.95 24.95 23.99

Figure 10.1 | Conventional product costs (Groendakpan, Intratuin, debouwmarktshop, aboutroofing, Faunaprojecten)

BUSINESS CASE

Green roof tiles can be sold individually so people can place them on roofs themselves or the Green roof tile company can provide green roofs as a service by placing, maintaining, and repairing it.

CONCLUSION

CONCLUSION

World's population of human species is increasing. Also, Dutch population is growing. More and more people are moving to urban areas. All these people are part of ecosystems in a city. These ecosystems are under stress because of global problems such as diseases, pests, and climate change. To make future cities a liveable place, ecosystems need to be healthy and resilient. Biodiversity of a ecosystem is a serious indicator of health and resilience of that ecosystem. Therefore, nature needs to be included into building environment and form a natural symbiosis with people in it. To do so, right locations need to be divined where nature can grow without intervention of people. Good locations are above our heads, roofs, in particular pitched roofs. Therefore, main research question is:

"How can a Green roof system improve biodiversity of pitched roofs in Dutch cities?"

Several sub-questions form a basis on which the main research question can be answered.

IMPROVE BIODIVERSITY

Answering sub-question: How will a green roof system improve biodiversity of Dutch cities?

Measuring biodiversity and biodiversity improvement is difficult, especially focusing on small creatures, mosses, and plants. Therefore, another definition is used: “if plants grow on a slanted roof and they can survive a hot and dry summer and cold and wet winter, they provide food and shelter for other living creatures. Therefore, they increase living habitat of these species creating opportunities for population growth or new inhabitants. In that case, local biodiversity has improved.”

1:1 tests give insight in growth of plants during period of this research. This test concludes that a roof system with planters works during a dry and wet period. Therefore, it improves local biodiversity.

STATE-OF-THE-ART

Answering sub-question: What is state-of-the-art of biodiversity improvement in cities?

Based on point systems made by municipalities, a list of interventions is made. These interventions improve biodiversity in different ways. All interventions are scored on area and impact on different species. This list gives an overview of state-of-the-art on biodiversity improvements. From this list can be concluded that flat roofs have multiple interventions while slanted roofs do not. Therefore, a system such as a Green roof tile is needed.

TYPE OF ROOFS

Answering sub-question: What type of roofs are most appropriate for a Green roof system?

A green roof system has most impact if it can be implemented on all roofs of the Netherlands. However, some boundaries are needed. A slanted roof between 20 and 60 degrees is required with a roof structure related to conventional roof tiles.

INTERNATIONAL STANDARDS

Answering sub-question: What are national and international standards for roof systems?

Standards related to roof systems are user loads (distribution load is 0, concentrated load is 1.5 kN/m2), wind loads (-2.98 kN/m2 and +1.14 kN/m2), snow loads (0.40 kN/m2), rain loads (0.023 l/s/m2) and fire safety (Broof$_{t1}$). These values are part of design development. Next to this, conventional roof structures are designed to hold a distributed load of 65 kg/m2. Planters are designed according to this weight.

BENEFITS

Answering sub-question: What are benefits of a green roof system for owners of a building?

A precursor of Green roof tile, Groendakpan, is sold mainly for its cooling effect. Additionally, sustainability and aesthetics are reasons to buy a green roof too. Lastly, a green roof extends lifespan of a roof which reduces maintenance costs.

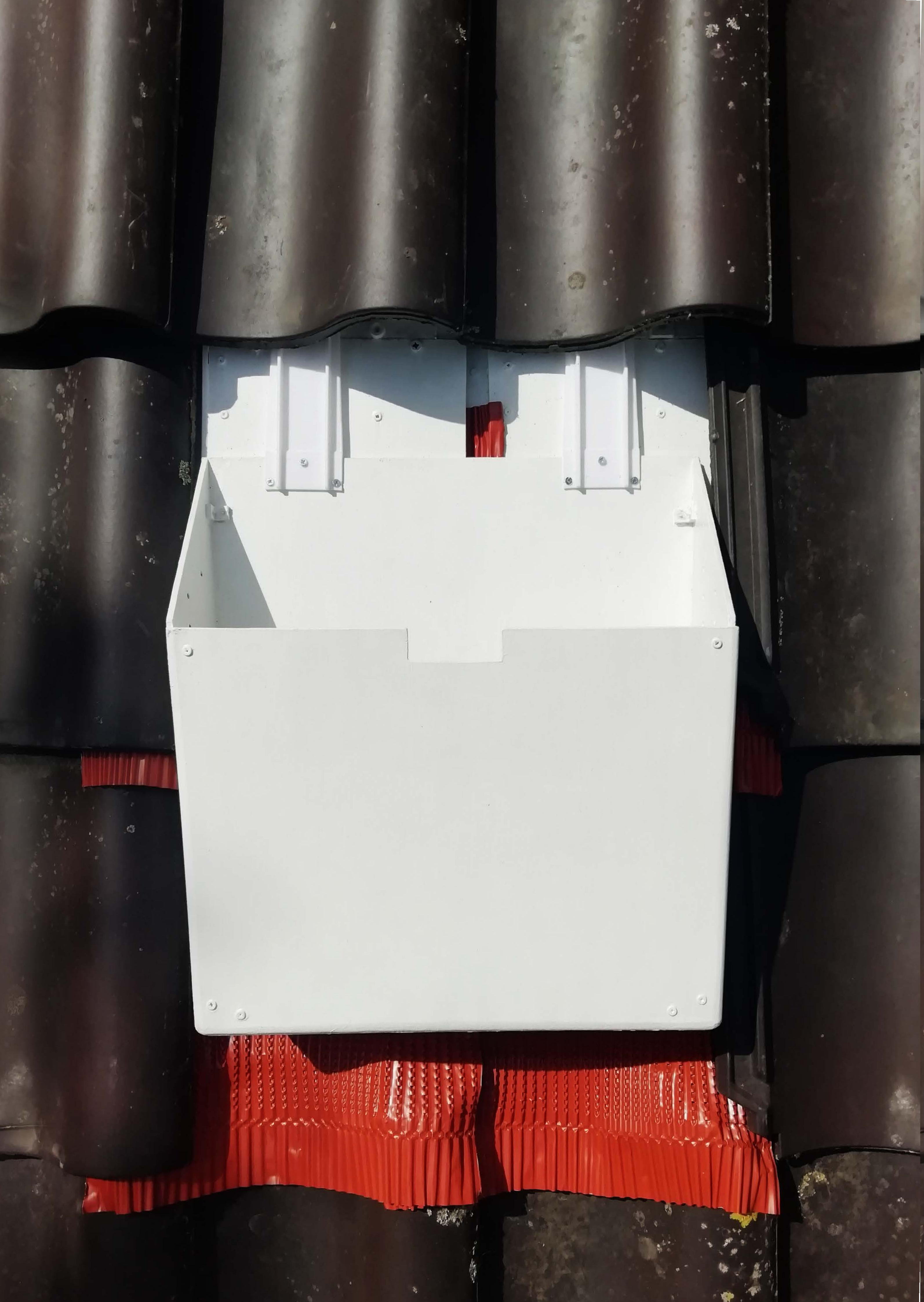
MAIN QUESTION

Main question is answered by research by design. First, a concept is developed based on methodology introduced in research report of Jeroen van Veen (2016). This concept is developed into a design step by step using strong points of the last design revision and updating weak points. Conventional products are used as inspiration or as part of design. Analyses such as FMEA and SWAT are performed to improve the product. Lastly, Green roof tile and planter are optimized for injection molding. This design has been tested in a 1:1 test for seven weeks, giving insight in substrate humidity, growth of plants, orientation, and volume/surface ratio.

Altogether, the product family of a Green roof tile answers the main question. Biodiversity of pitched roof in Dutch cities can be improved by:

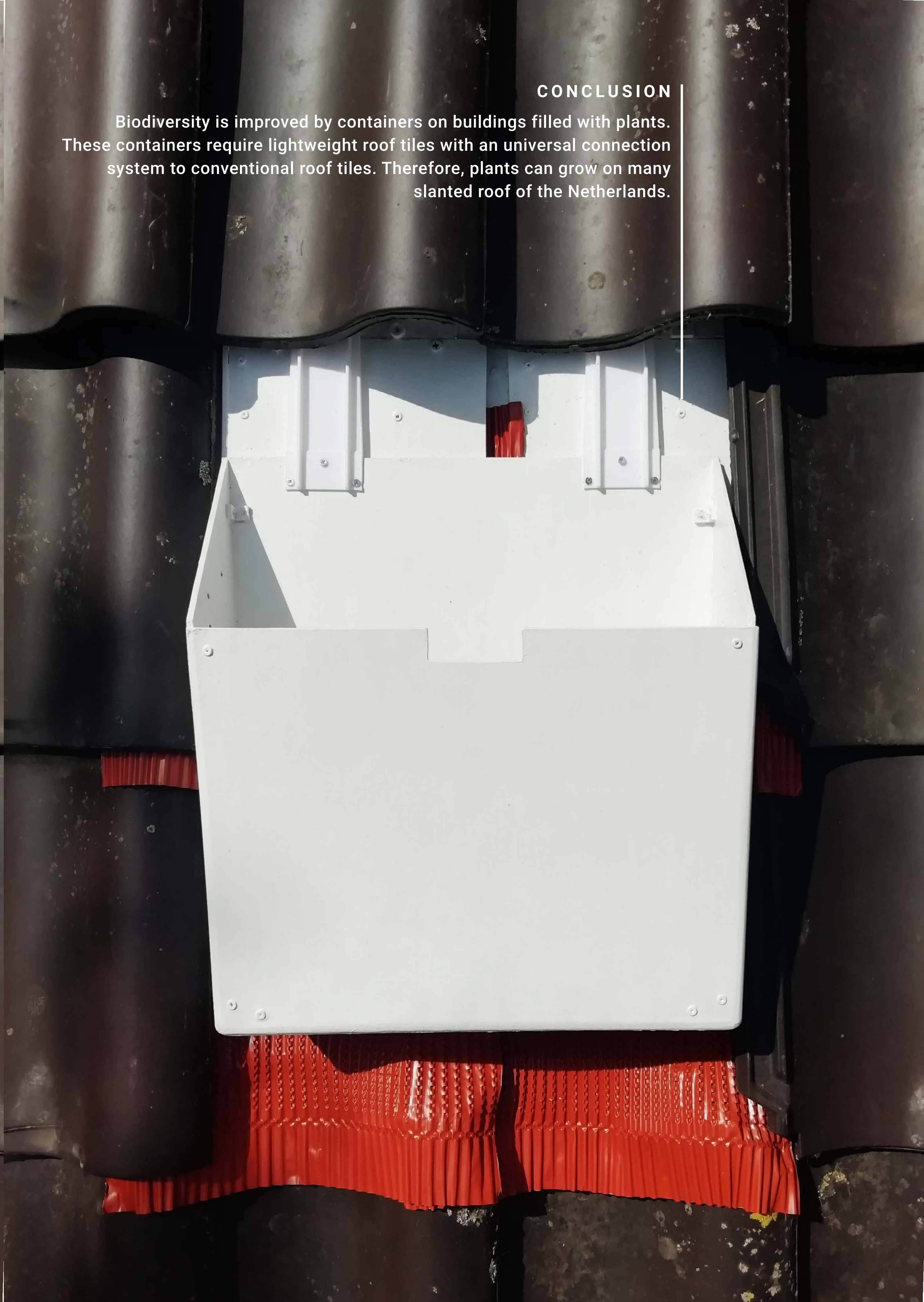
- Plants growing in Green roof tile planters providing food and shelter for other living creatures
- Birds breeding in Green roof tile breeding boxes
- Insects nesting, feeding, and hiding in Green roof tile insect hotels
- Other solutions created by people based on Green roof tile baseplates

These solutions are placed on top of Green roof tiles. These tiles connect solutions to roof structures and conventional roof tiles. They provide a strong and waterproof layer and form a technical and functional bedding required to improve biodiversity.



CONCLUSION

Biodiversity is improved by containers on buildings filled with plants. These containers require lightweight roof tiles with an universal connection system to conventional roof tiles. Therefore, plants can grow on many slanted roof of the Netherlands.



RECOMMENDATIONS

TEST SETUP

As explained at chapter Test setup a long-term test is needed to investigate Green roof tile planter performances during a hot and dry summer and cold and wet winter. This information verifies if the concept works all year. This test needs to be performed on a conventional roof to have similar circumstances as final products have. Within this test seeds have time to geminate and grow, resulting in a green roof as intended, giving input on aesthetical factors too.

SUBSTRATE

Current design and test setup makes use of one substrate. This substrate is selected on advice of Cruydt Hoeck experts. However, other substrates could perform better within this design. So, a substantiated substrate selection can improve this product.

AESTHETICS

Green roof tile, Green roof tile sideplate, planter, baseplate, breeding box, and insect hotel are designed for performance: form follows function. This results in a decent, simple, and substantiated design. However, roofs are part of architecture and need to have aesthetical appearance. These products can be improved on that aspect, making it something special, something people would like to put on their roofs, a feature architects use to distinguish their building.

NEXT STEP

The Green roof tile concept has been developed to a final stage. However, extra steps need to be done to make it a real product. Are people, housing corporations, renovation companies, and contractors interested in a green roof and willing to pay something extra? What business model fits best? What is the best production, assembly, and distribution strategy? What investments are needed? This could be an interesting deliberation together with a company experienced with comparable products such as Faunaprojecten or Groendakpan.

NATIONAL AND INTERNATIONAL STANDARDS

As described in chapter Research a water impermeability test needs to be performed following procedure as described in EN 491, 2011. This test concludes whether a roof tile system is waterproof or not. Additionally, products need to pass fire safety tests (B-roof$_{t1}$) as well. Test setups, product parameters, and results need to be discussed with experts.

Green roof tiles perform well with load combinations a, b, and c. However, structural performance is not sufficient with load combination d. Extra analyses and tests are necessary to validate this result. Possible improvements could be: diagonal ribs, wider ribs, more screws, extra tile hook, and stronger material.

SMALL PRODUCTION BATCH

Investing 50.000 euros into injection molding molds is a risk, especially if product purchases are uncertain. Starting with a small and flexible production batch can be a solution. This makes it possible to change design, implement stakeholder requirements, and optimize product. However, it also requires another production process, increasing production costs, and changing design. A good trade-off needs to be made between extra costs and flexibility.

TRANSPORT

Without a car, some other transport was required to move test setup from my house to university campus.

RELEVANCE

Nature within a city is not only about plants and animals, people play a major role in it too. We are depending on plants and animals for food and healthy air. Plants help cities cool down during hot summers and lower stress on sewer systems during rain showers. Nature can have a positive impact on self-perceived health of people by stress-reducing ability of nature, sound absorbing effect of plants, and physical activity people tend to do in nature. Additionally, we maintain plants in our gardens and make nesting places for birds and small mammals. So, a city without nature is not a healthy city.

City ecosystems are under stress because of global problems such as diseases, pests, and climate change. To make future cities livable places, ecosystems need to be healthy and resilient. Biodiversity of an ecosystem is a serious indicator of the health and resilience of that ecosystem and therefore important to be researched. Improving biodiversity will lead to a healthier ecosystem and therefore a healthier place to live for people.

A green roof tile is a small piece in the puzzle of ecosystems of cities. On its own, its impact is neglectable. But when implemented on all applicable roofs it creates a green landscape larger than Utrechtse Heuvelrug. It gives people and companies a green solution which can be implemented on slanted roofs without use of sedum. Such a solution does not exist and therefore it creates new opportunities for flora and fauna. It can become a small step forward to a green and healthy city.

Product itself is made of HDPE which is a recyclable material. Therefore, its carbon footprint is minimized. Besides that, all products can be separated, reused, and recycled without loss of material. Only Compriband need to be replaced by reassembly.

Green roof tile, Green roof tile sideplate, and Green roof tile planter are developed to a final stage. These products can be produced and sold without many adjustments. In case a company is interested, this could become a real solution, having impact on biodiversity within a year.

ACKNOWLEDGEMENTS

Together with this master thesis, chapter student-life is closed. Seven years has been all about meeting new people, learning how to cook, organizing activities, playing chess at Asterion, building a hydrogen car, discover Trondheim, and moving from Enschede to Delft. But above all: studying, learning intricacies of design from kitchen machines to skyscrapers.

This Green roof system is my masterpiece. A simple but effective product. A product ready to be implemented and change roofs of the Netherlands. I want to thank my main mentor Marcel Bilow for his guidance, clear suggestions, and practical insights on the topic of design for buildings. I want to thank my second mentor Nico Tillie for his knowledge about ecology, plant species, and his view of the bigger picture, especially at moments I keep discussing tiny details in my Solidworks model.

I want to thank all my friends and roommates for an amazing seven years of my life. I want to thank my parents, Constance and Frans, for their unconditionally support whether I am moving to Norway for my minor, to Leeuwarden for my bachelor thesis or Delft for my master.

I will always look back with a smile!

Jorrit Parmentier
Delft, June 2021

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APPENDIX

A. ROOF SURFACE NETHERLANDS

Actueel Hoogtebestand Nederland (AHN3) and BAG Panden are used to calculate surface area of flat and pitched roofs within every municipality of the Netherlands (Atlasleefomgeving, 2018). This overview shows the percentage flat roofs (blue) and pitched roofs (red). Percentages are based on surface area in km^2. In total, the Netherlands include 1281 km^2 roof in which 617 km^2 is flat and 645 km^2 is slanted (20 km^2 is unknown). Offices, greenhouses, and industrial premises cover most flat roofs and slanted roofs are mainly located within city boundaries.

B. ROOF TILES

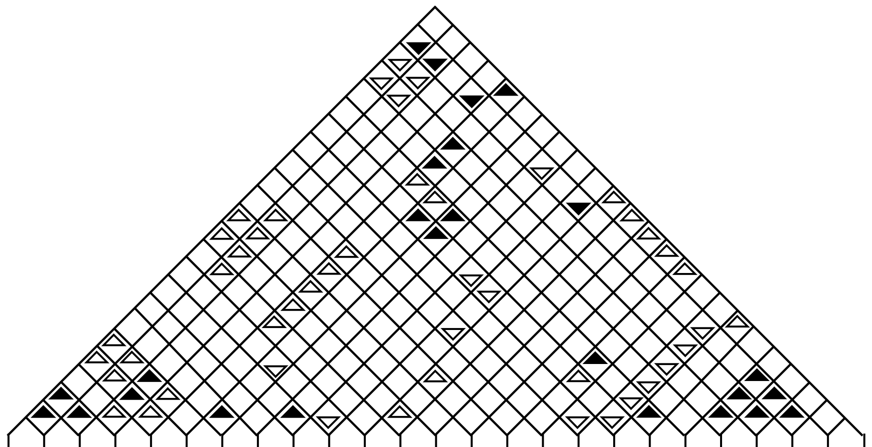
Green roof tiles are universal, connecting with multiple conventional roof tiles. Roof tiles of BMI Monier are used as references, see overview (BMI Monier, n.d.). Size, weight, and purlin distances are used within design development of the Green roof tile.

	Roof tile	Material	Size [mm]	Weight [kg/m2]	Purlin distance [mm]
	Achat 10	Ceramic	450x280	43.7	335 - 370
	Aerlox	Concrete	420x332	33.9	295 - 345
	Belmont	Ceramic	465x326	48.79	300 - 370
	Bretagne	Ceramic	350x244	54.08	240 - 255
	Utrechter	Concrete	380x230	50.12	280 - 305
	Nieuwe Hollander-V	Ceramic	420x267	43.84	325 - 355
	Grote Romaanse	Ceramic	344x256	49.59	285 - 295
	Neroma	Concrete	420x332	47.46	295 - 345
	Oude Holle	Ceramic	343x242	35.86	304 - 306
	OVH 206	Ceramic	372x268	39.00	311 - 315
	Renova	Ceramic	421x267	44.80	325 - 345
	Rubin 11v	Ceramic	443x280	43.18	338 - 373
	Sneldek	Concrete	420x332	47.46	295 - 345
	VH variabel	Ceramic	361x256	41.08	288 - 300
	Vlakke Mulden	Ceramic	418x244	44.64	338 - 350

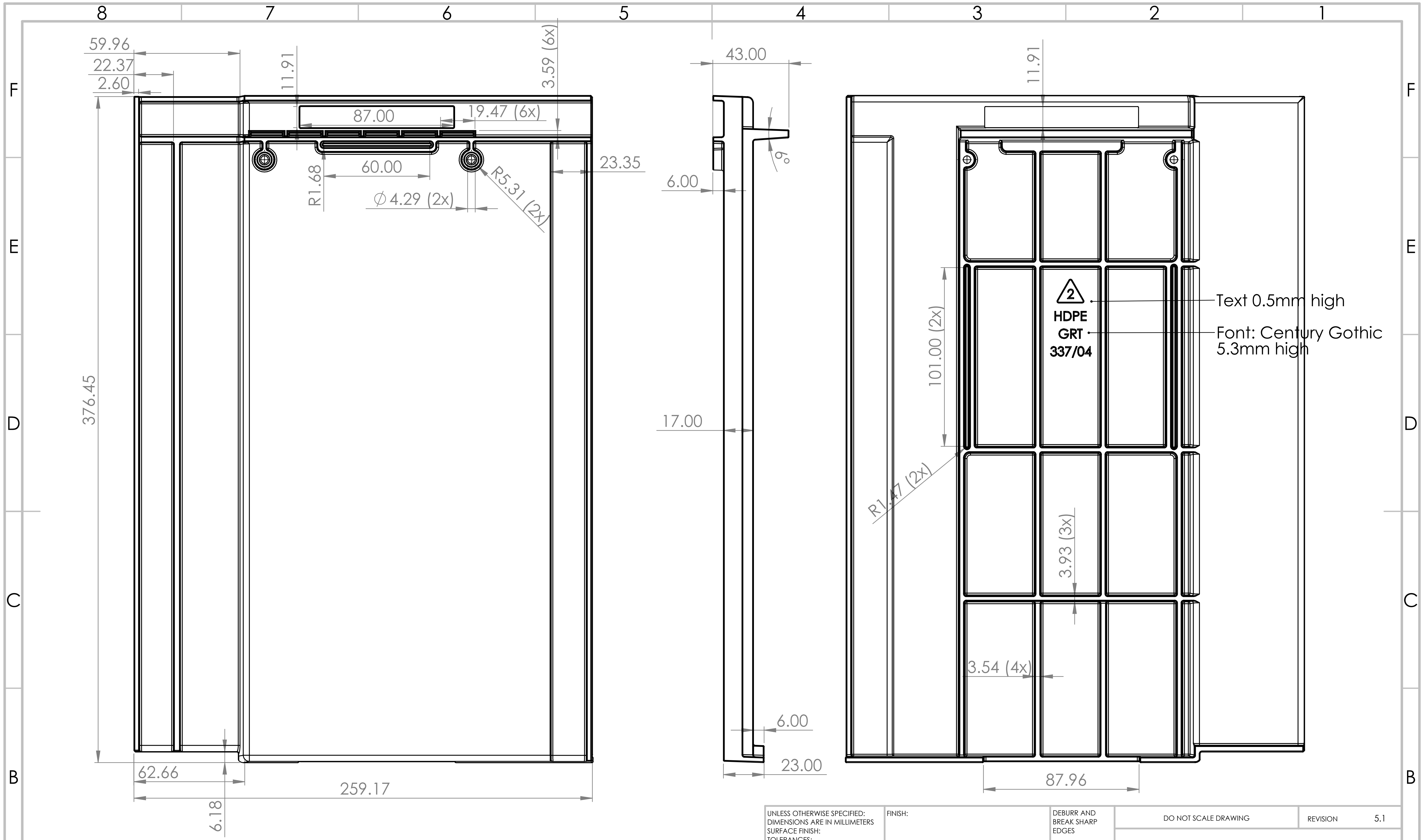
C. WEIGHT VALUATION

All criteria are listed and weighed. Criteria influencing each other get a 1. Total scores show the importance of a criteria. A higher score means more influence on other criteria. Scores of 12 and higher get a weight of three, scores of 7 to 11 get a weight of two, and a score of 6 and lower get a weight of one.

Triangles on top show a very positive relation (▲), a positive relation (△), a negative relation (▽) or a very negative relation (▼) between criteria.



		Gradient	Diversity	Opportunities	Native flora, fauna	Impact	Adaptability	Maintenance	Aesthetics	Freedom of design	Tolerance	Cooling effect	Water storage	Acoustics	Air filtration	Environmental impact	Building speed	Number of components	Replacing modules	End of life	Batch size	Scalability	Process time	Overall costs	Marketability	**TOTAL**	**WEIGHT**
BIODIVERSITY	Gradient	■	1	1	1	1	1	0	1	0	0	0	1	1	0	1	0	0	0	0	0	1	1	1	0	12	●●●
	Diversity	1	■	1	1	1	1	0	1	0	0	1	1	1	1	1	0	0	0	0	0	1	1	1	0	14	●●●
	Opportunities	1	1	■	**1**	1	1	0	1	0	0	1	1	1	1	0	0	0	0	0	0	1	1	0	0	12	●●●
	Native Flora, Fauna	1	1	1	■	1	1	1	1	0	0	0	0	0	0	1	0	0	0	1	1	1	1	1	0	13	●●●
	Impact	1	1	1	1	■	1	0	1	0	0	1	1	1	1	1	0	0	0	1	1	1	0	0	1	15	●●●
USE	Adaptability	1	1	0	0	1	■	1	1	1	0	1	1	0	0	1	0	0	1	1	0	0	0	0	0	11	●●
	Maintenance	0	0	0	1	0	1	■	0	0	1	0	0	0	0	1	1	1	1	1	0	0	0	0	0	8	●●
DESIGN QUALITY	Aesthetics	1	1	1	1	1	1	0	■	1	0	0	0	0	0	0	0	0	0	1	1	1	0	1	1	12	●●●
	Freedom of design	0	0	0	0	0	1	0	1	■	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	4	●
	Tolerance	0	0	0	0	0	0	1	0	1	■	0	0	0	0	0	1	0	1	0	0	0	0	1	0	5	●
	Cooling effect	0	1	1	0	1	1	0	0	0	0	■	1	0	1	0	0	0	0	0	0	0	0	0	1	7	●●
	Water storage	1	1	1	0	1	1	0	0	0	0	1	■	0	0	0	0	0	0	0	0	0	0	0	1	7	●●
	Acoustics	1	1	1	0	1	0	0	0	0	0	0	0	■	0	0	0	0	0	0	0	0	0	0	1	5	●
	Air filtration	0	1	1	0	1	0	0	0	0	0	1	0	0	■	0	0	0	0	0	0	0	0	0	1	5	●
MATERIAL	Environmental impact	1	1	0	1	1	1	1	0	0	0	0	0	0	0	■	0	1	1	1	0	0	0	0	1	10	●●
ASSEMBLY	Building speed	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	■	1	1	0	0	0	0	0	0	4	●
	Number of components	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	■	0	1	0	0	1	1	0	6	●
	Replacing module	0	0	0	0	0	1	1	0	1	1	0	0	0	0	1	1	0	■	1	0	0	0	0	1	8	●●
	End of life	0	0	0	1	1	1	1	1	0	0	0	0	0	0	1	0	1	1	■	0	0	0	0	1	9	●●
PRODUCTION	Batch size	0	0	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	■	1	1	1	0	6	●
	Scalability	1	1	1	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	■	1	1	0	9	●●
	Process time	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	■	1	0	8	●●
COSTS	Overall costs	1	1	0	1	0	0	0	1	0	1	0	0	0	0	0	0	1	0	0	1	1	1	■	1	10	●●
	Marketability	0	0	0	0	1	0	0	1	0	0	1	1	1	1	1	0	0	1	1	0	0	0	1	■	10	●●



MATERIAL: HDPE
SURFACE ROUGHNESS: Ra 0,8
GENERAL TOLERANCE: +_0,1mm,
unless otherwise specified.

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION 5.1

	NAME	SIGNATURE	DATE
DRAWN	J. Parmentier		18-05-21
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL: HDPE
SURFACE ROUGHNESS: Ra 0,8
GENERAL TOLERANCE: +_0,1mm,
unless otherwise specified.

DWG NO.

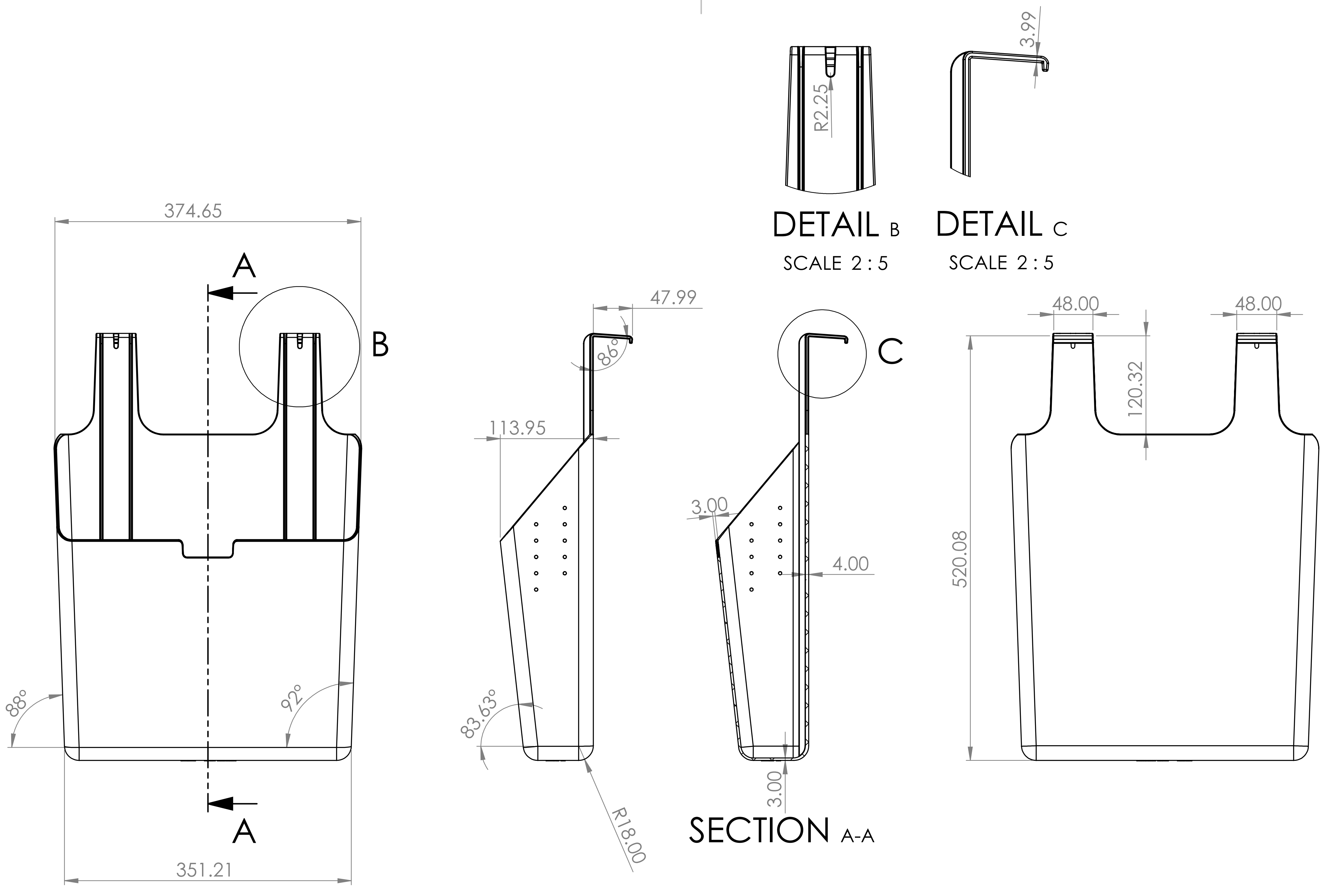
Green roof tile

A3

WEIGHT:

SCALE:1:5

SHEET 1 OF 1



MATERIAL: HDPE
SURFACE ROUGHNESS: Ra 0,8
GENERAL TOLERANCE: +_0,1mm,
unless otherwise specified.

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:		DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION 5.9
	NAME	SIGNATURE	DATE		TITLE:
DRAWN	J. Parmentier		18-05-21		
CHK'D					
APPV'D					
MFG					
Q.A			MATERIAL: HDPE SURFACE ROUGHNESS: Ra 0,8 GENERAL TOLERANCE: +_0,1mm, unless otherwise specified.	DWG NO. Green roof tile planter	A3
			WEIGHT:	SCALE:1:5	SHEET 1 OF 1