

# Redesigning the Groundfridge underground cellar

Designing a nature-inspired, user-centred,  
passive thermal system





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# Preface

Throughout my studies I have developed a strong passion for sustainable design, that genuinely contributes to a more liveable and beautiful world. To me, sustainable design goes beyond the materials and manufacturing of a product. It is embedded deeply in the user’s perception and experience of systems. This interaction between the user and products foster a connection that is just as important, thereby creating an understanding of nature and the environment. This insight supported my choice to focus my graduation project on a nature-inspired and user-centred product, pushing the boundaries of what sustainable design can be in practice.

Redesigning the Groundfridge system offered a valuable experience. It required exploring technical solutions while simultaneously focussing on interaction design, finding ways of embedding a deeper connection with nature into the product experience.

This project has challenged and developed my passion for holistic, sustainable design. I hope that The Living Groundfridge will encourage others to take Mother Nature as a genuine partner in design.

Iris de Bree  
23th June, 2026

A handwritten signature in black ink, which appears to read 'Iris de Bree', written over a light blue background.



*figure 0.2: the Living Groundfridge. Source: Oep Schilling*



# Executive summary

Long before refrigeration existed, people used the earth to store their food and keep it cool. The Groundfridge revives this principle: a prefabricated underground root cellar designed for off-grid living and passive food storage. It relies on the stable temperature of the surrounding soil to passively cool its contents, but exposure to atmospheric conditions causes its internal temperature to fluctuate during warmer periods.

This graduation project explores how the Groundfridge can become an integrated system by reconnecting the product, its user, and Mother Nature with each other. It embraces the power of natural processes to create value for both the system and its users. The project aims to improve the thermal performance of the Groundfridge by thoroughly analysing its working principles. This is done by investigating how conductive, convective, and radiative heat transfer can be optimised through a redesign, while embedding user needs and sustainability. Rather than treating cooling as a purely technical challenge, the design seeks to create a system in which environmental processes become visible, understandable, and meaningful to the user.

The project followed a *Double Diamond* structure, discovering the thermal behaviour and operating conditions through literature review and thorough analysis. These findings were defined into thermal challenges and insights into user needs emphasised a desire for a deeper understanding of the project. Through iterative ideation and brainstorming, these insights formed the foundation of the *Research-through-Design* process, in which a wide range of concepts and interventions were prototyped and tested. The resulting takeaways from this and earlier phases are integrated in the final design implementation.

The **Living Groundfridge** consists of two complementary interventions:

- The **Climate Gate**, a redesign of the door assembly that increases the thermal resistance from 2.2 to 3.7 Rc, addressing the thermal weaknesses into a protective thermal barrier points of the current product. The redesign of the door decreases conductive exchange and prevents radiative heat from entering the Groundfridge
- The **Groundflow** system, a self-regulating water supply system combined with a temperature-regulating vegetation plan. By leveraging evapotranspiration, the system actively reduce the temperature in the Groundfridge hill. Beyond its cooling function, the Groundflow makes these processes visible and understandable, encouraging users to engage with the environmental conditions that influence food preservation.

Together, these two interventions improve thermal stability while strengthening the relationship between the Groundfridge, its user, and the surrounding environment. By making natural cooling processes tangible and intuitive, the design transforms passive food storage into an interactive experience. The Living Groundfridge demonstrates how designing with nature, rather than against it, can create solutions that are thermally effective, ecologically beneficial and create meaningful interaction with its user.

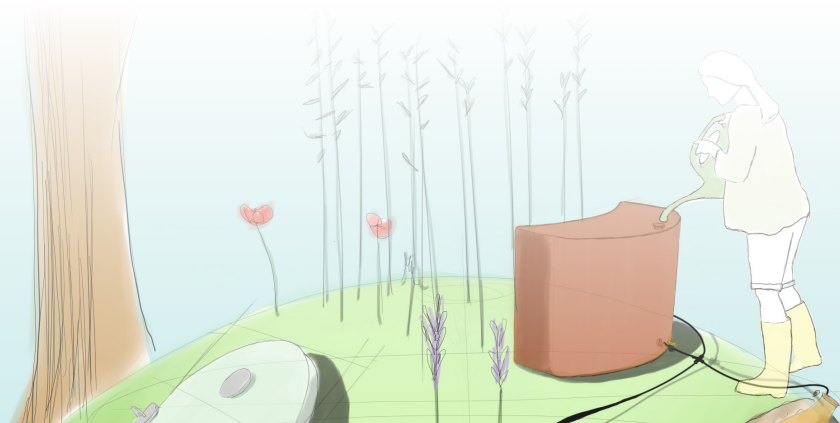


figure 0.2: the Living Groundfridge. Source: author

# Acknowledgements

Designing is looking around you and gathering all the pieces to create something with value. Inspiration flows from one person to another, and that is why I want to express my acknowledgements to the people that helped me in this project. First of all, I would like to thank my supervisory team consisting of Stefan, Caroline and Oep! Without much discussion, they altogether knew what I needed to be encouraged to explore the best version of myself.

Stefan, thank you for the wise words you gave me, with all the anecdotes that gave me the visionary insights about my process. You always gave me a good feeling about what I was doing, and you pointed me towards the tools and especially the mental space to explore all the ideas that I had.

Next, I want to thank you Caroline for asking the right questions in a concise and grounded way. By means of these questions, you sharpened the vision of my ambitions and goals during the project. You are truly a magnificent person to be mentored by.

Then, Oep! Next to all the concrete and less concrete ideas you had about this project and how I should engineer the process of it. I want to thank you for reflecting my personal traits in this stage of my life. Your mentoring, both the praise and advice you have given me, will stay with me.

Of course, I also want to thank Floris, Lianne, Jannes, Mark and Roel from the Groundfridge team for all their insights, ideas and help during this project. From the beginning, I felt very welcome in this team and supported exploring what this project would be.

Then, thank you Fiction Factory for letting me ask a million questions and helping me out with realising and physically building all the ideas that I came up with. Especially, Chris, thank you for being patient with me and letting me experience all the mistakes I made during this project.

Beppie, thank you for sharing your knowledge about plants and their purpose. This was meaningful information for the vegetation plan. Also, this rekindled my own inspiration in integrating more nature in this project as well as my personal life.

Phi, thank you for helping me out with the co-creation, ideation and above all your support to help me formulate my thoughts and ideas.



figure 0.3: Inside Fiction Factory. Source: author



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figure 0.4: Garden context. Source: author

# Glossary

|                     |                                                                                               |
|---------------------|-----------------------------------------------------------------------------------------------|
| Conductive heat     | Heat transfer through a material or object via direct contact                                 |
| Convective heat     | Heat transfer between a material or object and a fluid, like air and water                    |
| Design with nature  | Using nature as inspiration for designing products and systems                                |
| Emissivity          | The efficiency of a material or object to emit thermal radiation                              |
| Evapotranspiration  | Combined proceess of evaporation of soil and transpiration of vegetation                      |
| Olla                | An unglazed terracotta pot, functioning as a self-watering system                             |
| Radiative heat      | Heat transfer in the form of electromagnetic waves requiring no contact.                      |
| Reflectivity        | The efficiency of a surface material to reflect radiative heat                                |
| Regenerative        | Approach to minimise environmental harm and restoring natural systems                         |
| Rootcellar          | A (partially) underground storage to preserve fresh foods over a longer period of time        |
| Thermal performance | The efficiency of a material or object to manage heat, by retaining, blocking or allowing it. |
| Thermal resistance  | The efficiency of a material or object to resist the heat flow through it.                    |
| User value          | The perceived benefit the user gets from usage of a product/system                            |

# Abbreviations

|     |                         |
|-----|-------------------------|
| BOM | bill of materials       |
| FF  | Fiction Factory         |
| GF  | Groundfridge            |
| MRO | main research objective |
| RO  | research objective      |
| RtD | Research-through-Design |





This introductory chapter sets the scene for this graduation project about underground cooling and highlights the need to improve thermal stability. It connects the current product to the project and its purpose, before providing an overview of the process this project will follow.

# 1 Introduction

*figure 1.0: The Groundfridge in the garden context. Source: Groundfridge.com, n.d*

## 1 Introduction

|            |                      |
|------------|----------------------|
| <b>1.1</b> | <b>Introduction</b>  |
| 1.1.1      | Product introduction |
| 1.1.2      | Raison d'être        |
| 1.1.3      | Project purpose      |
| 1.1.4      | Assignment           |
| 1.1.5      | Research objectives  |
| 1.1.6      | Process              |



# 1.1 Introduction

## 1.1.1 Project introduction

“Groundfridge is a brand new, super-old idea that keeps fresh produce deliciously fresh without any electricity” (Groundfridge, n.d.)

Designed by Floris Schoonderbeek, who is inspired by activities that connect people with nature, and produced by Fiction Factory, a company that builds all interiors you can imagine, Groundfridge is a cooling cell that keeps food cool without the use of electricity. It is created for people who aspire to an off-grid lifestyle and people who live self-sustaining lifestyles.

The cooling cell is placed underground and uses nature’s insulating properties to keep the temperature between 8–15 °C, as it takes advantage of the natural cooling characteristics of the ground. The ground works as an insulating layer, making it a passive cooling system. It can cool up to 3000L of space. This sustainable alternative to a fridge is inspired by root cellars that were used in the past and is innovated into a modern version, with a focus on authentic interactions.

With minimal help from a ventilator, the GF (Groundfridge) circulates cool and warm air during the night. During the day, the insulating capacity of the soil maintains a stable temperature. However, in summer the moisture in the ground warms up, which accelerates the rise in temperature too quickly to maintain stability at all times.

## 1.1.2 Raison d’être

Floris Schoonderbeek’s idea of designing the Groundfridge evolved from the idea of creating a preservation method that is part of a holistic lifestyle. The concept of a root cellar has existed for centuries, and Floris wanted to bring it back to life. The GF is designed to shorten the chain between the farmer and the consumer. Since a farmer has a large quantity of the same crops, consumers need a way to store these products over a longer period, in a natural and efficient way.

Additionally, outdoor temperatures in the Netherlands are often below the temperatures of a refrigerator. The Groundfridge uses this advantage by making use of this mechanism of nature to store food, and function as a contemporary, accessible solution.

In comparison to building a full cellar, the GF is more cost-effective and a prefab solution. It requires minimal construction and most often no permits, making sustainable food storage accessible.

Ultimately, it reconnects users with the natural cycle of the earth, supports local food networks and creates a conscious and resilient lifestyle.



## 1.1.3 Project purpose

This project is performed as a graduation assignment within Groundfridge, a part of Fiction Factory, combining industrial design engineering with hands-on experience. Working in an organisation offers an opportunity to understand design in a real-life context.

This project aims to deepen the understanding of the Groundfridge system in order to design valuable implementations. These insights will be developed through a thorough analysis of the context and the technical principles of the cooling mechanism. The project goal is achieving more stable temperatures inside of the Groundfridge.

These meaningful design opportunities will be driven by insights from the needs of current users and to identify where the product is lacking. The goal is to develop designs that add value at multiple levels: adding practical value, by improving the product in terms of performance and functionality, and enhancing emotional value, improving the product experience. Input from multiple analyses and broad contextual understanding will be the foundation in order to ensure desirability, feasibility and viability.

On a personal level, this graduation project will be an opportunity to translate real-life human needs and problems into concrete design implementations, within the timespan of 20 weeks. This process will be a valuable experience within a company that combines design and manufacturing of products and projects.

## 1.1.4 Assignment

**Assignment**  
This project aims to develop and prototype a design that stabilises the internal temperature of the Groundfridge. The project will focus on feasibility, and will also assess desirability and viability.

The project seeks to define the working principles of the product and map the context of the Groundfridge system in order to develop, prototype, and test potential design solutions that are both meaningful and grounded in reality, ultimately leading to a final concept.

This report documents the exploration of complex design opportunities throughout the graduation project. It reflects the various aspects of Integrated Product Design engaged during this process.

**Problems and opportunities**  
The assignment creates a meaningful design challenge: to not only improve temperature stability, but to enrich the experience of owning and using a Groundfridge. There is an opportunity to add physical features and broader experiential qualities, such as feedback mechanisms, guidance, interaction and rituals, that turn the GF from a passive product into something users can engage with, learn from and build a relationship with over time.

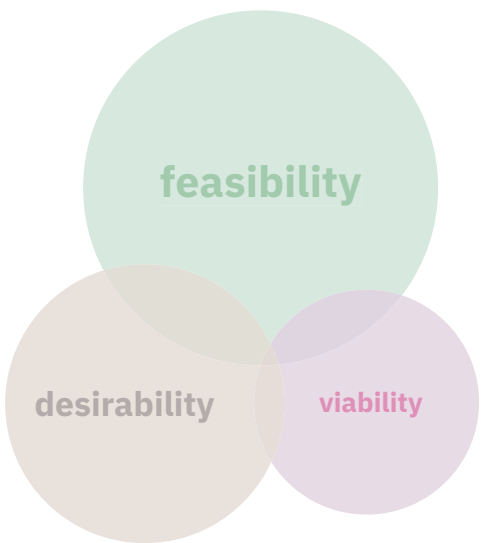


figure 1.1.3: Visual of focusses of this project



1.1.4 Research objectives

Main Research Objective

MRO: Improving the thermal performance of the Groundfridge.

*How can a redesign of the Groundfridge control conductive, convective, and radiative heat transfer to improve internal thermal stability in comparison to the existing solution?*

Sub-objectives

RO1: Analysis of thermal behaviour of the current product

*What is happening in the current Groundfridge, in terms of conductive, convective and radiative heat, and where are challenges and problems?*

RO2: Increasing user value of the Groundfridge

*How can the Groundfridge be integrated more intuitively into the lives of users by making its invisible thermal system tangible?*

RO3: Ecological and systemic sustainability

*How can the design implementations in the Groundfridge system become ecologically grounded by eliminating energy dependency and contribute positively to its environment?*

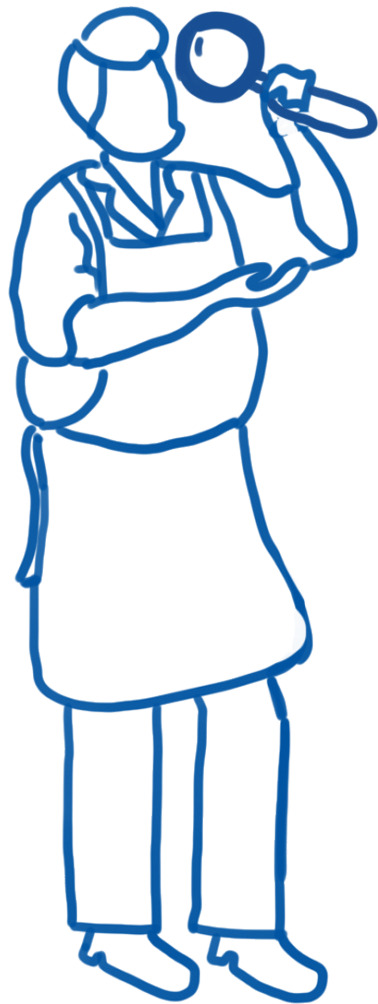
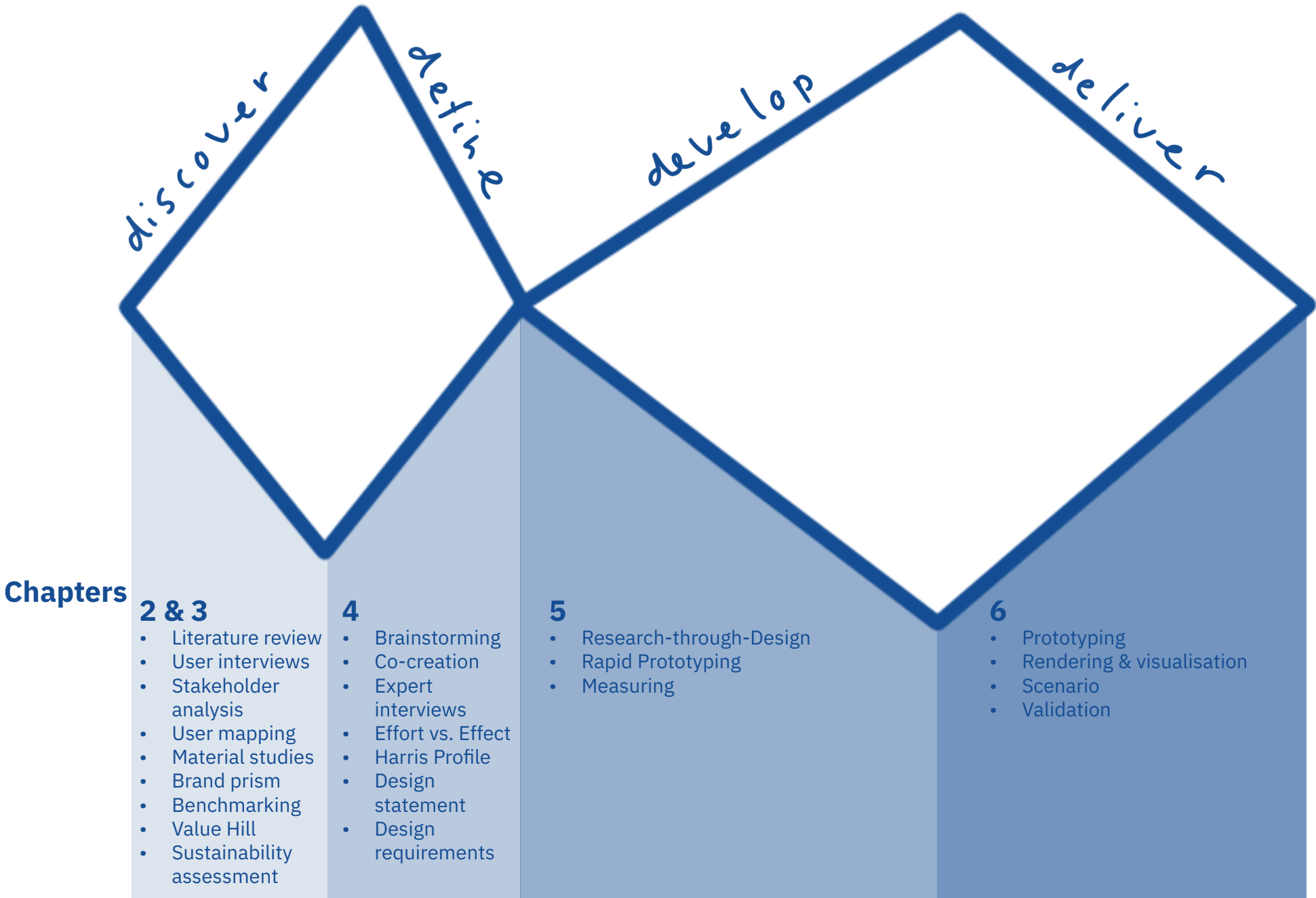


figure 1.1.4: Research Objectives visual. Source: author

1.1.5 Process

This page visualises the design process that was completed in this graduation project. The Double Diamond was used as method to keep a focus during the project, and connecting the takeaways from all the phases to a design solution.





A large, white, cylindrical Groundfridge unit is being transported on a truck. The unit is secured with straps and is positioned on the truck's bed. The truck's cab is visible on the left, with the word 'MAX' on the side. The background shows some greenery and a clear sky.

In the introduction, the assignment is described. To understand its opportunities, the context chapter explores the product in its current form, its interaction with the user and stakeholders and the world its inhabiting. The Groundfridge’s intention is more than a product: it is a choice for a simpler and more conscious lifestyle. The subchapters examine the motivations behind purchasing and using the Groundfridge, the technicalities of the product, and the message the brand seeks to convey.

## 2 Context

*figure 2.0: The GF going on transport. Source: author*

## 2

### 2.1

#### 2.1.1

#### 2.1.2

#### 2.1.3

#### 2.1.3

#### 1.1.4

### 2.2

#### 2.2.1

#### 2.2.2

#### 2.2.3

### 2.3

## Context

### Product

Why a Groundfridge?

Current design

Production

Installation

Methodology

### System

Stakeholders

User types

Groundfridge brand

### Context takeaways



# 2.1 Product

## 2.1.1 Why a Groundfridge?

As outlined in the Raison d’Être (1.1.2), the GF was developed on the principle of utilizing natural soil temperatures for food storage, while supporting local food production to close the food chain. These core values resonate strongly with the GF’s target audience: people with an affinity for outdoor living and a sustainability- driven lifestyle. GF owners typically aspire to live self-providing lives, growing their own crops and preserving them on-site. This was confirmed during user visits, where every GF owner was actively growing produce they intended to store in their GF. They share a deep interest in nature and carry a desire to understand and play into natural processes. The product embodies this philosophy by using the soil itself as a cooling mechanism, making it a natural extension of the way users already want to think and live.

The product’s off-grid characteristics emphasizes this appeal. Since the GF is free of energy consumption, it aligns with the self-providing ambitions of users. Owners want to live a self-sustaining life-style by living independently from the energy grid.

A less obvious but equally significant motivation became apparent during user interviews: for many, the GF is simply a more practical and affordable alternative to a traditional concrete cellar. Since the GF is a prefabricated product, it eliminates the costs associated with custom design, digging and building the cellar, expenses that often accompany a cellar of which much of the space may go unused. The GF arrives ready to install and can be fully operational within a single day. It is also engineered in order to withstand high water tables, due to the waterproof, boat-like construction, preventing flooding when the groundwater rises. Beyond the lower upfront cost, the GF offers an important regulatory advantage, since in comparison to a permanent cellar, it most often does not require a building permit to install.



figure 1.1.4.2: Interior of the Groundfridge. Source: (left) Groundfridge, n.d., (middle and

## 2.1.2 Current design

The current design of the Groundfridge is visualised in the render in figure 2.1.2.1 on this page and components are visualised in the exploded view (figure 2.1.2.2)

### Form

The spherical shape is constructed in order to distribute the forces of the soil that is laying on top of the GF. With a circumference of 2.3 meters, it is big enough for a Dutch man to stand upright. The tunnel is attached, and functions as the connection between the GF and the outside, allowing a person to enter it upright as well. This tunnel also ensures that the GF can be installed at lower depths, where the temperatures are more stable.

### Shelves and handles

The shelves are milled out of birch-wood, and allow storage of up to 3000 litres. The shelves are manufactured in a way that they are locked in place by the plate at the bottom. The stair railing and the handles are also made with birch-wood, to ensure a luxury yet natural experience.

### Fixtures and details

The fixtures of the shelves, handles and hinges are made of stainless steel, so they will not erode in moist environment. Other details, like the ventilation cover plates are made of stainless steel as well, as they are exposed to the wear of the weather.

### Ventilation

On the inside, at the bottom of the door, a ventilation unit is placed. This ventilation will ensure a better air circulation to prevent mould and circulate cold outside air. The ventilation can be installed to circulate air into the GF during the night, in order to circulate cold air from outside into the GF.

### Solar panel

To accommodate the ventilation system with power, an additional solar panel is placed on top of the GF. On sun-rich days, the solar panel will transform this radiation into energy that is stored in a battery inside of the ventilation system. That way, the ventilation works off-grid.

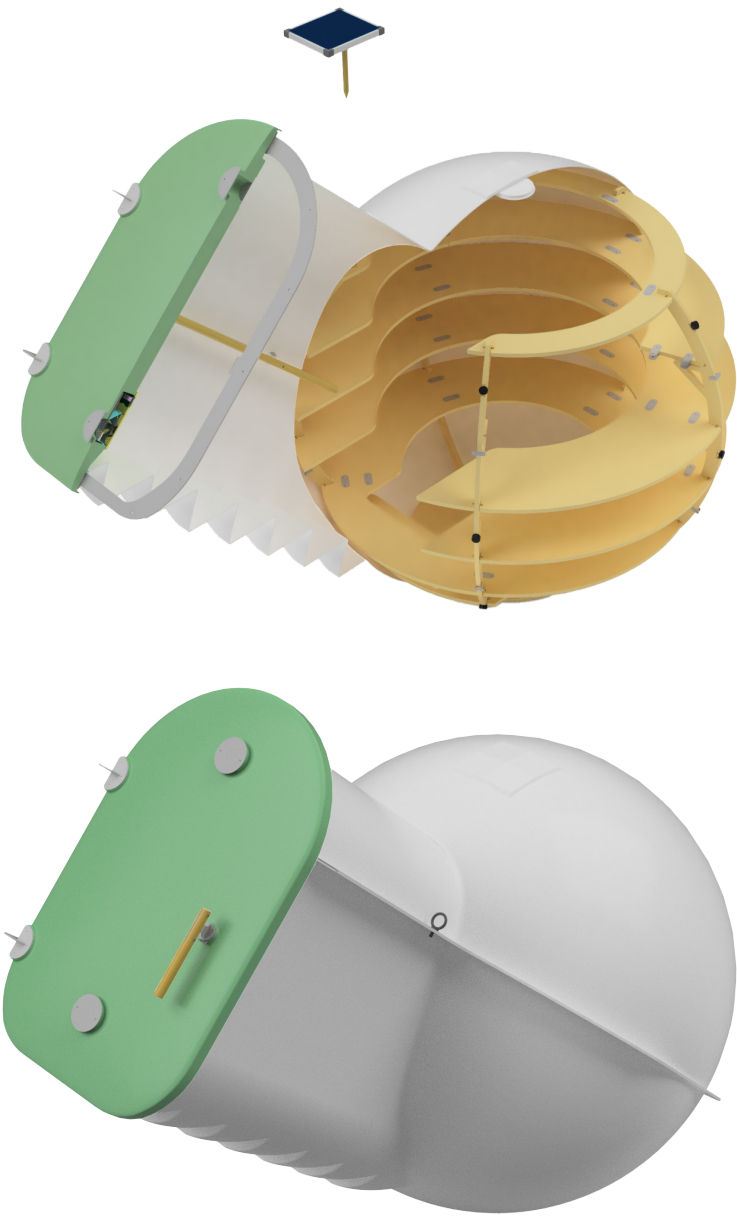
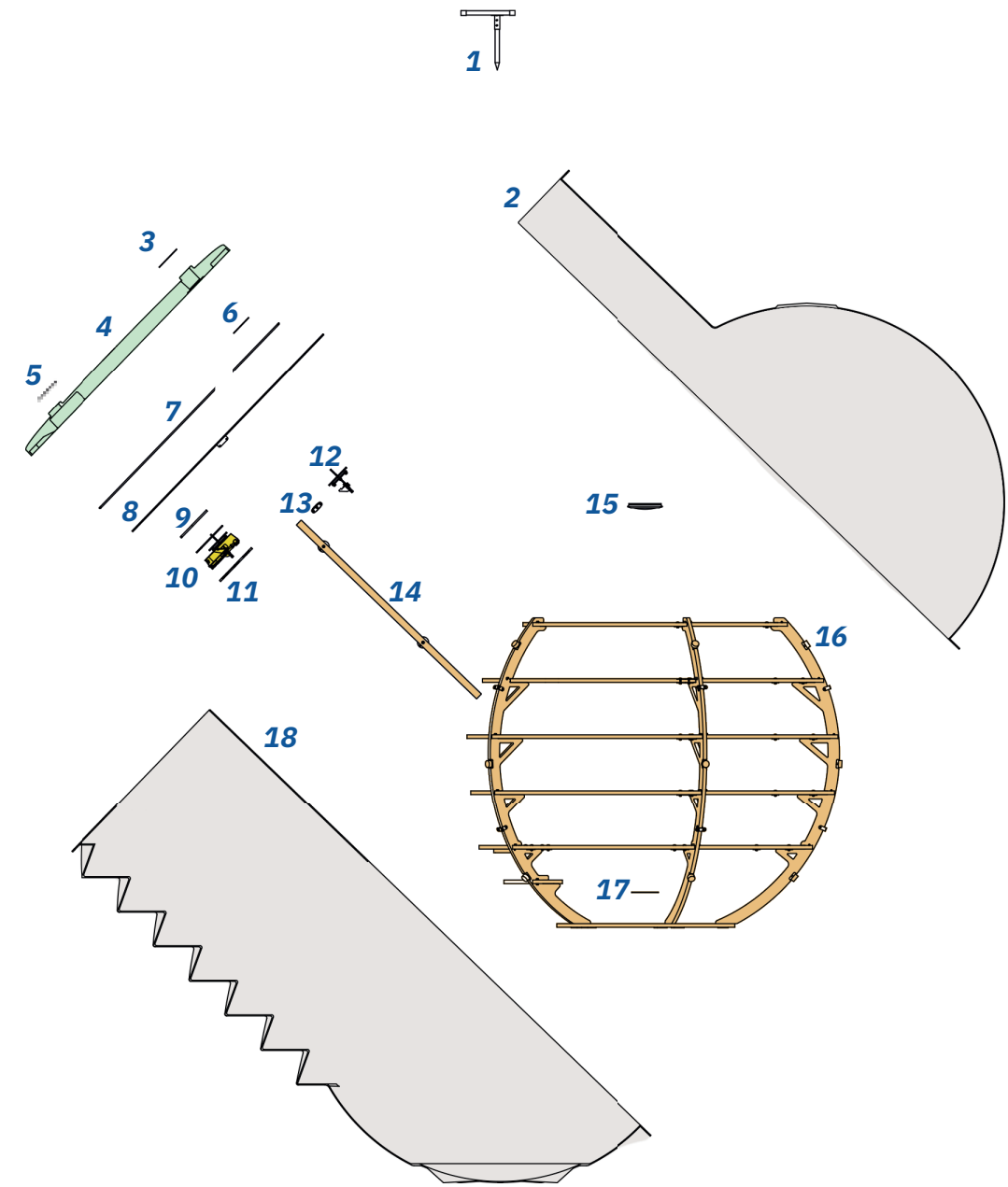


figure 2.1.2.1: Renders of the Groundfridge. Source: author (with Autodesk Fusion 360)



# Exploded View



- 1 Solar Panel
- 2 Upper Half
- 3 Ventilation Cover 1 Plate Outside
- 4 Door
- 5 Ventilation Cover 2 Plate Outside
- 6 Ventilation Cover Plate Inside
- 7 Closing Rubber
- 8 Door Frame
- 9 Ventilation Screwplate
- 10 bequiet! Ventilation System
- 11 Ventilation Cover Plate
- 12 Hinge
- 13 Door Closing Plate
- 14 Handrail
- 15 Ceiling Light
- 16 Shelves
- 17 Well cover
- 18 Bottom Half

figure 2.1.2.2: Exploded view of the Groundfridge. Source: author (with Autodesk Fusion 360)



figure 2.1.2.3: Chris assembling the GF. Source: author



2.1.3 Production

The GF is produced by Wentech in Poland, the components created by this organisation are visualised in figure 2.1.3.2 To create the GF, two half spheres are formed. A top half (c) and a bottom half (d) are created with two moulds. Reinforced fibreglass mats are placed on top of the mats and then they are baked in order to harden them. The two halves are connected using resin, and in between the flanges, all around, a rubber band is placed in order to make the GF waterproof.

To manufacture the door, there are two shells of fibre reinforced composite (6mm) with a layer of Rockwool in between (72mm). The shells are made of 2 chopped strand mats (CSM),150 g/m^2 and 450g/m^2, made by Krosglass. These mats are made of powdered glass with a polyester binder. Reinforced with a XM core, these layers are bonded with a polyester resin, shaped by a mould and then heated until they are hardened. Then, a layer of Rockwool is put inside of the two layers and with resin the shells are connected. After this, the shells are coated with a layer of polyester resin (gel-coat Maxguard GN in RAL 6021 SA). This method is derived from the boating industry, which is the sector that Wentech produces for.

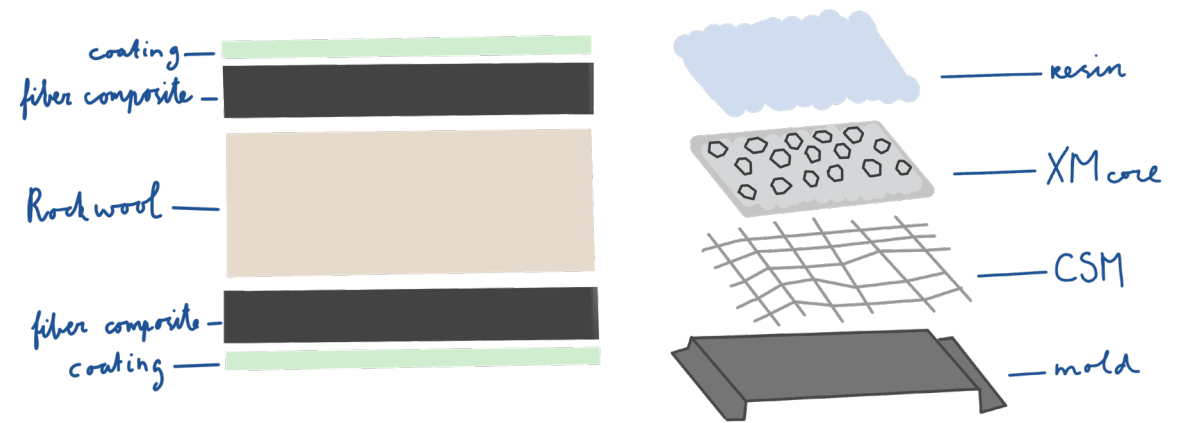


figure 2.1.3.2: Door cross section. Source: author figure 2.1.3.3: Production visual. Source: author

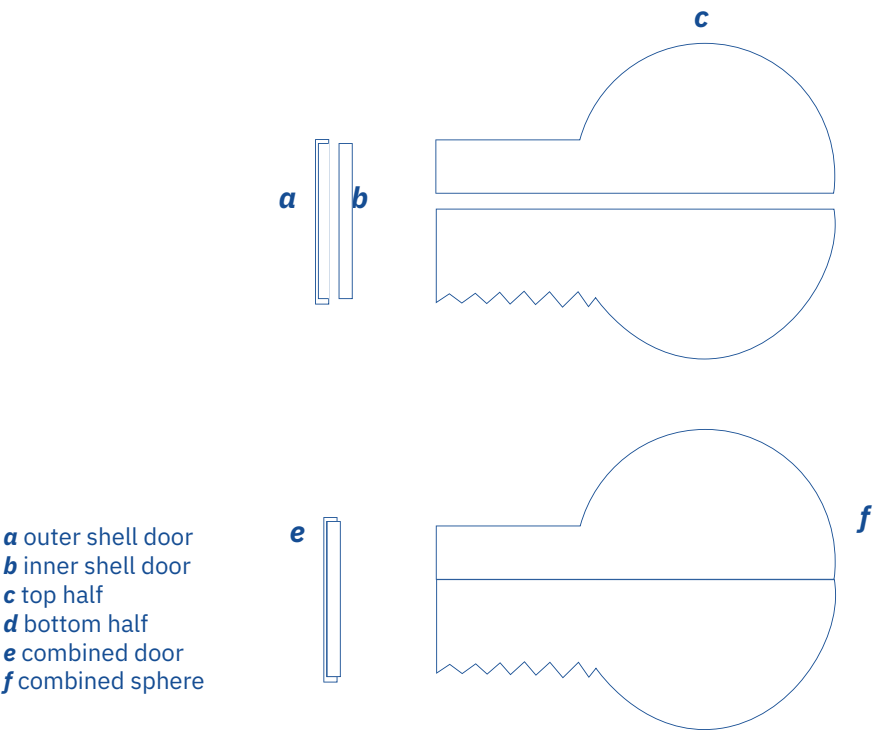


figure 2.1.3.1: Production visual. Source: author

2.1.4 Installation

Installing the GF needs some preparation, but takes no more then a single day. However, some considerations have to be made in advance.

Instalment location

Where the GF is installed can change the management of temperature quite a bit. First, it is recommended to pick an easily accessible and safe place. A site of five meters in diameter is required to install the GF. Second, it is recommended to pick a site where there is shadow, to prevent the GF from being exposed too much to the sun.

Orientation

The door of the GF should be placed in the direction of the North (in locations above the equator). This is to minimize the amount of direct sun exposure.

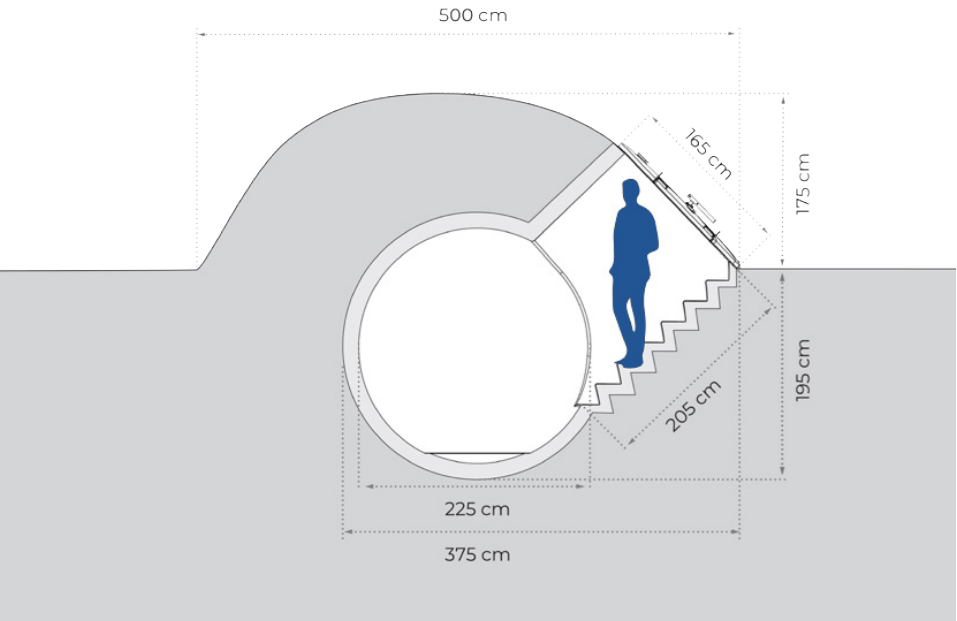


figure 2.1.4.1: Installation measurements. Source: Groundfridge,n.d.

Installation day

To install the GF, an excavator is needed to dig a hole of 1.85 meters in a square shape form. Users are refered to the installation manual, available on the official Groundfridge website. The GF is lifted into the hole and levelled on an extra layer of white sand. An additional layer of approximately 1 meter soil is used on top of the GF.

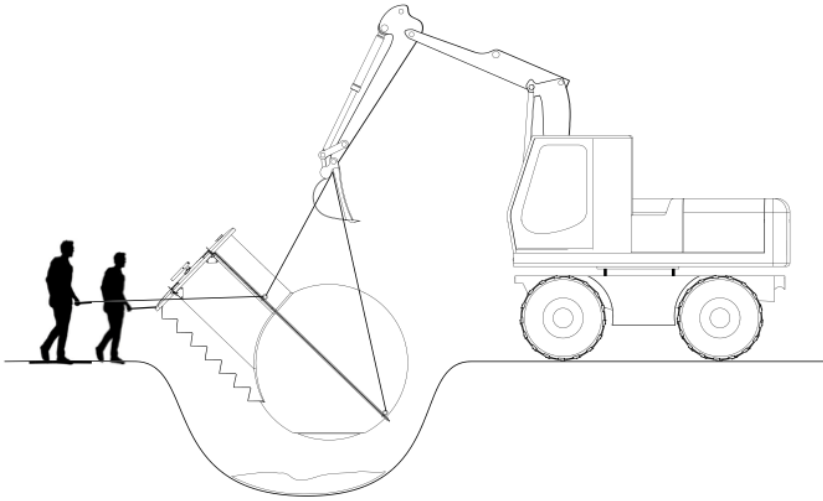


figure 2.1.4.2: Installation visual. Source: Groundfridge,



# 2.2 System

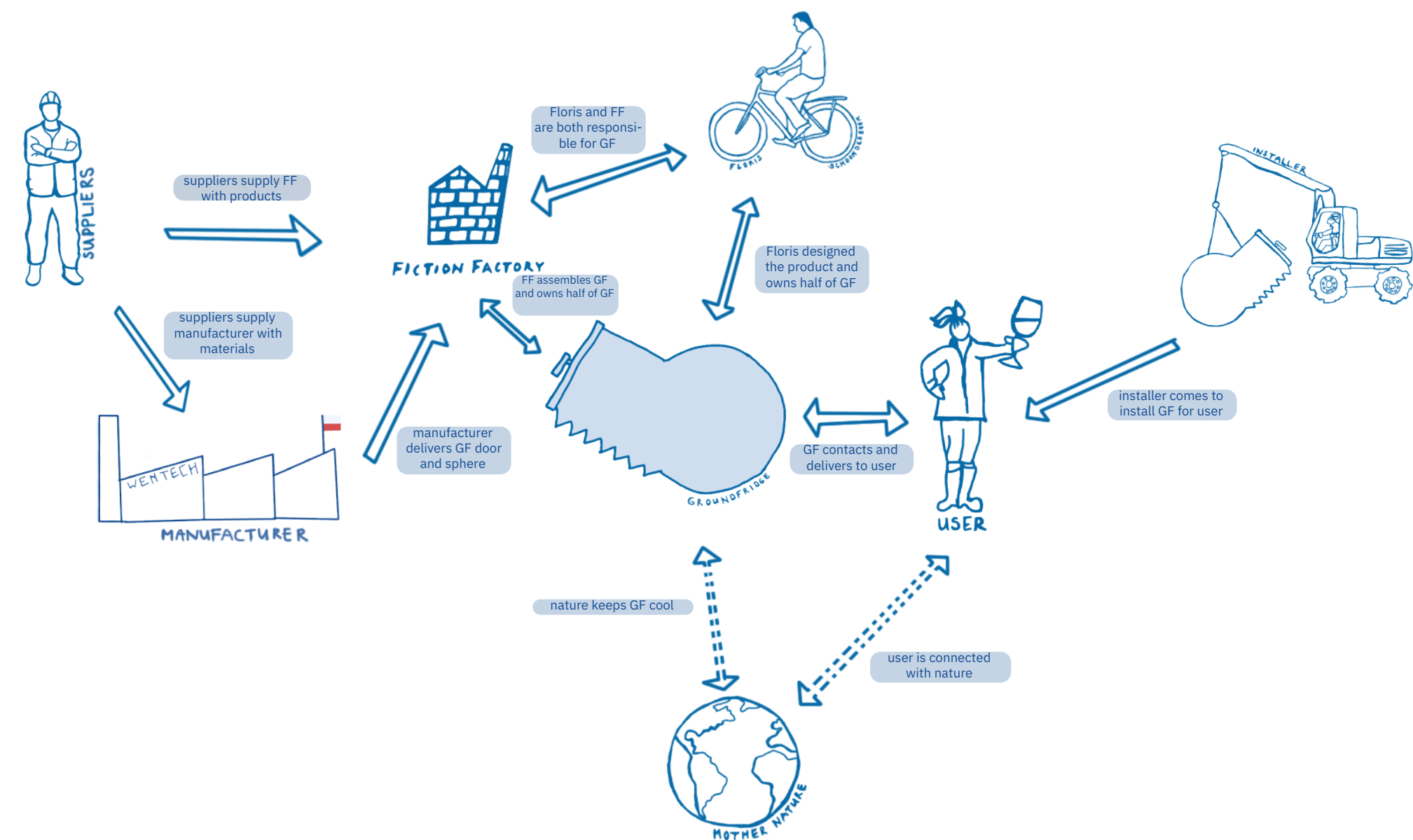


figure 2.2.1: Stakeholders and their relatedness. Source: author

## 2.2.1 Stakeholders

### Groundfridge

Groundfridge is the company that makes the root cellars for the users. They are improving the design, responsible for marketing and the supply chain of the Groundfridge. The company is co-owned by 2 parties: Floris Schoonderbeek and Fiction Factory. Also, they have multiple employees that are responsible for running the organisation on the aspects of managing, sales and customer service.

For the organisation, the focus lies on the functionality and economic feasibility of the design.

### Floris Schoonderbeek

Floris Schoonderbeek is the designer of the Groundfridge and nowadays he is half the owner of Groundfridge. Floris is a designer, focussing on authentic and nature-inspired products, and he is involved in the company on all aspects.

### Fiction Factory

The other half of the company belongs to Fiction Factory, they bought half of the company from Floris Schoonderbeek. Fiction Factory is an interior design and building company in Amsterdam. Fiction Factory focusses on the contact with the manufacturing and also assembles the GF. They are installing the shelves, the door, the ventilation and other components of the GF.

### Manufacturer (Wentech)

The two separate parts are manufactured by Wentech, located in Poland. Wentech is a manufacturing company specialised in building boats, as well as the Groundfridge. They manufacture the parts of the Groundfridge, and send these to Fiction Factory in the Netherlands. It is important to understand how the GF can be improved on technical aspects.

### Suppliers

Then there are several suppliers that deliver parts to both Wentech as Groundfridge, like the gel coating, the CSM mats, the solar panel and hinges.

### User

The person that orders and receives the Groundfridge. As it is a product, the GF will be delivered to the user. However, if there are issues, the user can address the organisation to fix the problems. The user is the stakeholder to be kept satisfied and their needs should be understood.

### Installer

When the user has ordered a GF, the installer is recommended by Groundfridge to install the product. The installer is a third party that ensures the transportation from Fiction Factory to the user as well as the instalment of the GF.

### Mother Nature

This is not a person, however, nature and the product are tightly related in this graduation project. The GF is placed under the soil, vegetation is growing on top of the product and the GF's temperature is mainly regulated by nature. Therefore, it is a crucial stakeholder and it is important that the product does not deteriorate the nature.



# System map

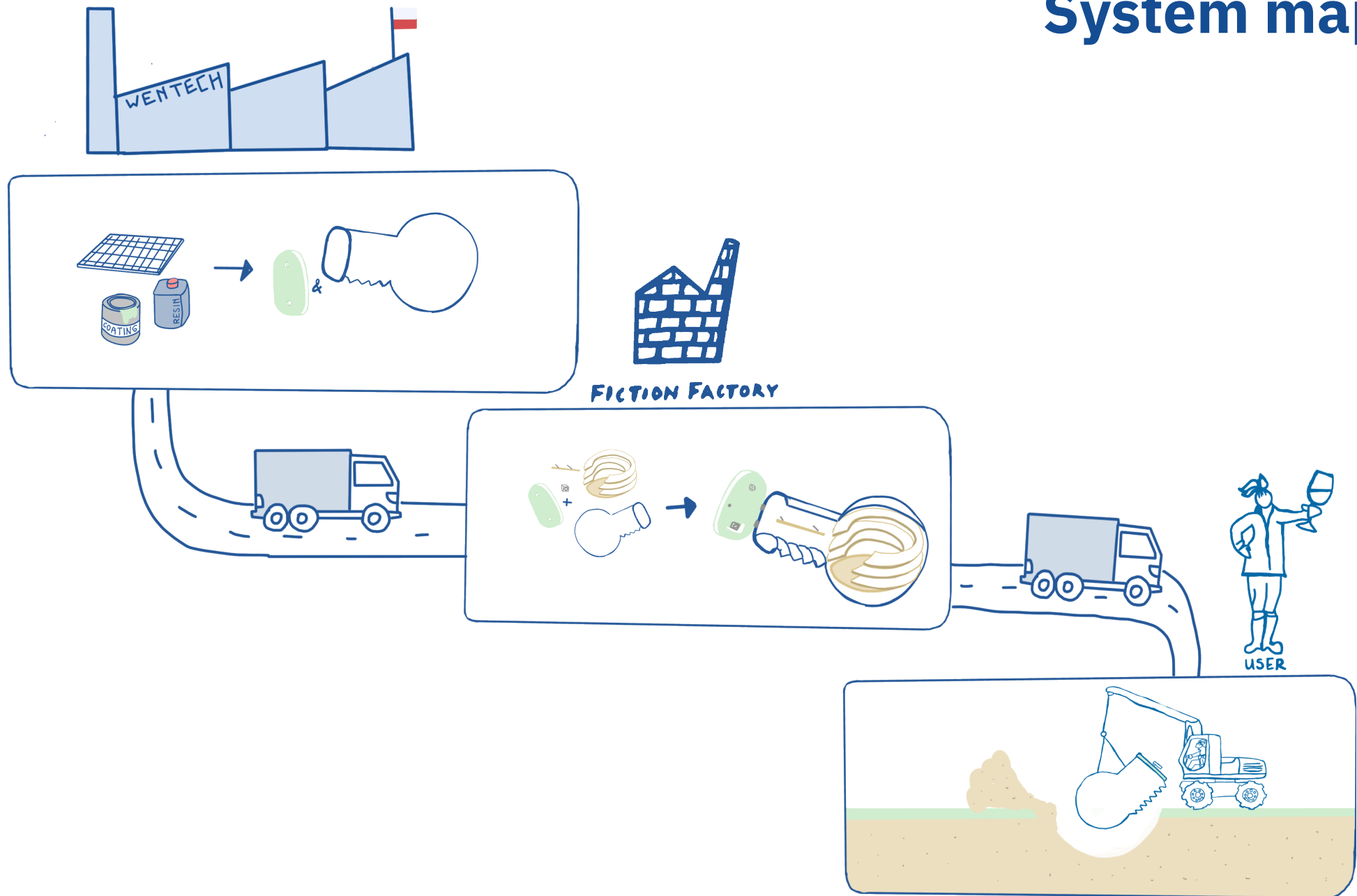


figure 2.2.2: Production roadmap. Source: author

## 2.2.2 User types

In order to understand the purpose of the Groundfridge, it is important to understand the user of it. This target audience of the GF can be divided into a typology. Multiple types emerged from combined insights of Groundfridge,

### Connoisseurs

These are people who collect fine delicacies such as wine, cheese and other goods. They use the GF for their personal collection to enjoy and experience quality food and drink. They take great pride in what they store and enjoy opening the door for others to take a look, whether that is pouring a well-aged wine or cooking a special meal for their loved ones. The GF offers stable and consistent temperatures that are particularly important for the ripping of sensitive products.

### Homesteaders

Homesteaders purchase the GF out of a desire to live independently from the grid. They are drawn to nature’s own mechanics rather than relying on artificial systems. The GF matches their ideology for a self-sustaining lifestyle.

### Outlanders

Unlike homesteaders, Outlanders are drawn to the GF primarily for practical reasons rather than ideological ones. This group owns holiday homes, farms or off-grid cabins where access to a stable energy supply is scarce. The GF offers a reliable solution to store their goods, that is maintenance free and works regardless of how long and far away they are from their homes.



### Forest gardeners

Forest gardeners, along with other small scale farmers and gardeners, use the GF to store their own produce. Their approach to the garden is holistic, guided by the vision of food consumption that is regenerative and sustainable farming, deeply connected to the land. The GF is buried underground and does not disturb ecosystems and can also offer a habitat for insects to live on top of the hill.



### Restaurateurs

People with a restaurant with an environmentally driven vision make use of the GF in order to accommodate storage for their restaurants and cafés. This group also includes festival organisations like “Into The Great Wide Open”, where the Groundfridge was already used in a pop-up restaurant. This is suitable for temporary purposes, since installation is easy, as well as remote restaurants that want to keep things cool without energy. The GF could also be a marketing asset, communicating its sustainable values to customers, which is a big demand in the market.



figure 1.1.4.2: User drawings. Source: author, inspired by Groundfridge drawings



2.2.3 Groundfridge Brand

Meeting with the team were done in order to understand the values within the organisation.

Brand Prism

In order to understand the personality of the brand, a Brand Prism (Kapferer) explained by Crawford (2025) framework was used to illustrate this personality. Figure 2.2.3.1 visualises the outcome of this method. An understanding of the brand can be advantageous in design choices, and understanding whether concepts and designs fit this personality.

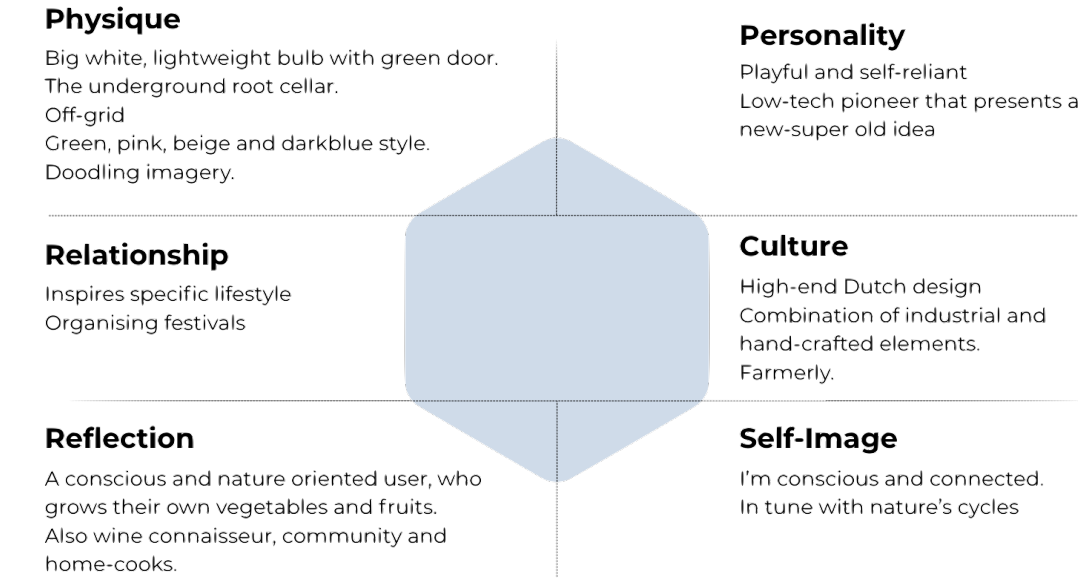


figure 2.2.3.1: Kapferer Brand Prism. Source: author

Competition

In figure 2.2.3.2 is visualised how the Groundfridge is placed in the market compared to other pre-fabricated root-cellar, based on a price-quality matrix. It is clear that the Groundfridge is high in quality in comparison, as well as it is the most expensive in its category.

However, in comparison to other prefab cellars, Groundfridge is in lower price segments and is therefore a fairly reasonable choice for underground cooling.

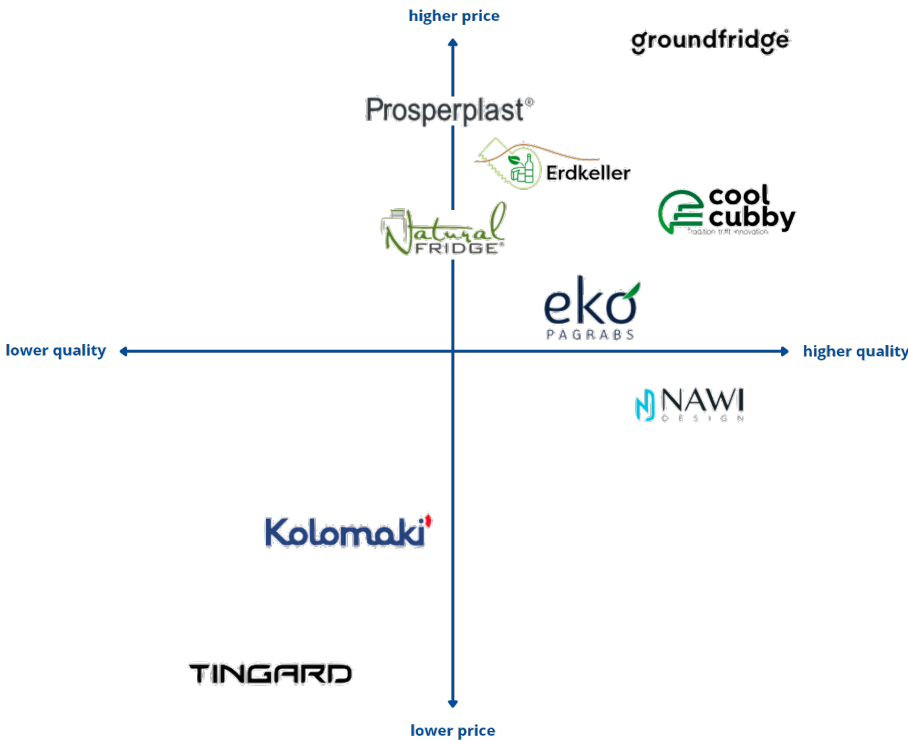


figure 2.2.3.2: Price/quality matrix. Source: author

2.3 Context takeaways

MRO

Improving the thermal performance of the GF.

1

Temperatures fluctuate due to external and seasonal factors

R01

Analysis of the thermal behaviour of the GF.

2

The GF is unpredictable in its thermal behaviour due to its natural context

R02

Increase user value of the GF.

3

The user aspires a more sustainable and integrated lifestyle.

4

The GF is a low effort product that can be installed within a single day

R03

Ecological and systemic sustainability

5

The GF is supposed to be part of a sustainable lifestyle.





Building on the context established in the previous chapter, this chapter looks beneath the surface of the Groundfridge, both literally and figuratively. In order to understand the behaviour of the product, it examines the conditions and temperature behaviour within and the challenges these present. Beyond that, it also analyses opportunities that increase value on an experiential level, connecting the product’s performance to its users’ needs.

# 3 Analysis

figure 3.0: The GF in the “Wikkeltuyn” at Fiction Factory. Source: author

|        |                                            |
|--------|--------------------------------------------|
| 3      | <b>Analysis</b>                            |
| 3.1    | <b>Terminology</b>                         |
| 3.2    | <b>General conditions</b>                  |
| 3.2.1  | Underground conditions                     |
| 3.2.2  | Atmospheric conditions                     |
| 3.3    | <b>Temperature within the Groundfridge</b> |
| 3.3.1  | Main temperature sources                   |
| 3.3.2  | Temperature helpers                        |
| 3.3.3  | Behaviour                                  |
| 3.4    | <b>Challenges</b>                          |
| 3.4.1  | Thermal resistance                         |
| 3.4.2  | Airflow                                    |
| 3.4.3  | Ventilation control                        |
| 3.5    | <b>Existing thermal systems</b>            |
| 3.6    | <b>Door analysis</b>                       |
| 3.7    | <b>Material studies</b>                    |
| 3.8    | <b>User interaction</b>                    |
| 3.8.1  | Current interaction                        |
| 3.8.2  | User needs                                 |
| 3.9    | <b>Interaction values</b>                  |
| 3.10   | <b>Sustainability</b>                      |
| 3.10.1 | Value hill                                 |
| 3.10.2 | Further opportunities                      |
| 3.11   | <b>Analysis takeaways</b>                  |



### 3.1

# Terminology

This section introduces terms that are relevant to this project from a theoretical perspective. These phenomena occur in the behaviour of the Ground-fridge (GF).

#### Temperature

In the context of this project, maintaining a stable temperature inside the GF is central. It is worth noting that ‘cooling’ is not a proper term from a thermophysical perspective. Two objects both contain a certain amount of thermal energy, and when they are in physical contact with a difference in thermal energy between them, they will always seek to reach thermal equilibrium (Energy Education, n.d.). When an object is “cooled,” it is in fact transferring some of its thermal energy to another object. Temperature is therefore the proper indication of the amount of thermal energy within an object or substance.

#### Heat transfer

To understand how heat is transferred between substances, it is important to know that there are three types of heat transfer: conduction, convection, and radiation (Simscale, 2023).

*Conduction* is the transfer of heat between two solid objects that are in direct contact with each other. Thermal energy is exchanged directly between them as they aim to reach a state in which both objects have the same amount of thermal energy.

*Convection* also aims to reach thermal equilibrium, but differs from conduction in that it occurs between a solid and a fluid. The heat transfer is influenced by the movement of the fluid.

*Radiation* is the third type of heat transfer. It is the phenomenon by which a body emits electromagnetic waves that carry thermal energy, thereby affecting surrounding substances.

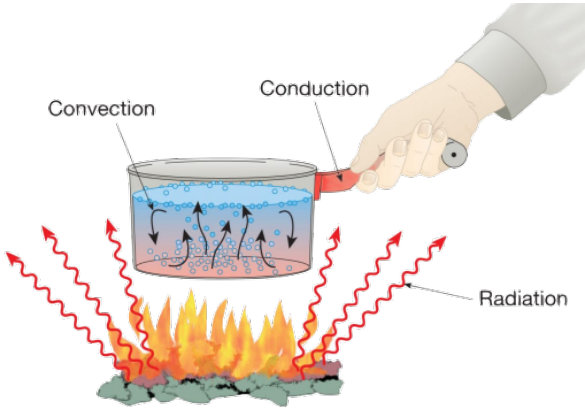


figure 3.1.1: Convection, conduction and radiation visualised (Wattco, 2026)

#### Thermal mass

Thermal mass refers to the ability of a material to absorb, store and gradually release heat (Energy Education, n.d.). A material with a high thermal mass encapsulates a lot of thermal energy within the material and is able to slowly release this heat to its surroundings.

#### Thermal stratification

Thermal stratification refers to the phenomenon of warm air rising and cold air sinking, causing vertical temperature variations within an enclosed system (Ryckewaert, 2024). Air with a lower amount of thermal energy has a higher density and consequently sinks to the bottom, while air with higher thermal energy will rise. As a result, air naturally separates into distinct temperature layers.

#### Thermal load

Thermal load quantifies the total thermal energy of internal and external factors on a system. It is used to assess how thermal energy behaves around a system and how different factors influence this.

#### Thermal conductivity

Heat transfer occurs at different rates in different materials. The property that determines this is referred to as thermal conductivity, the ability of a material to conduct or transfer heat through its body without any movement of the body itself. Thermal conductivity is represented by  $\lambda$  (lambda) or  $k$  (Stewart, 2026).

#### Thermal Insulation

According to Merriam-Webster (n.d.), thermal insulation is defined as a material that slows the transfer of heat between two or more systems, and thereby reducing the flow between them. Insulation helps a body to maintain temperature for a longer period of time. This is based on the thermal conductivity of materials.

#### Thermal transmittance

Thermal transmittance is the rate at which heat passes through a complete building element. The unit that is used is the U-value ( $W/m^2 \cdot K$ ).

#### Evaporation

During evaporation, a fluid undergoes a phase change from a liquid state to a gaseous state. This phase change requires a large amount of thermal energy, which the fluid absorbs from its surroundings. As a consequence, the surroundings lose thermal energy and decrease in temperature.

#### Reflectivity

Reflectivity determines the ability of a material to redirect solar energy or light back to the environment instead of absorbing it (Family & Menguc, 2018). If a surface has a high reflectivity ( $>0.7$ ), it is good at reflecting radiation back to the outside. This ensures that radiative heat is kept outside of the surface. If this reflectivity is low, the thermal energy passes through this material layer and enters the inside of the GF.

#### Emissivity

This refers to the measurement of a material’s surface property to release internal heat as thermal radiation (Sun et al., 2022). If the emissivity of a material is high, it releases a lot of thermal energy towards other connecting materials. This is compared to a perfect black-body, which has an emissivity of 0, and a perfect emitter with an emissivity of 1.

It is important to note that emissivity is based on radiative heat transfer and only is applicable on surface areas, as after this, thermal energy is continued in conduction and convection.

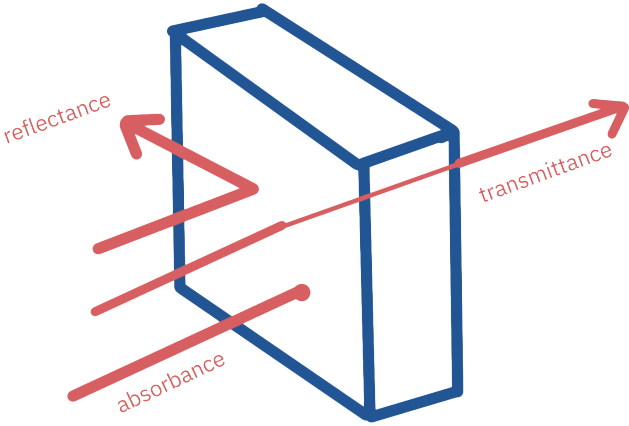


figure 3.1.2: reflectance, absorbance & transmittance visualised. Source: author



### 3.2

# General conditions

The Groundfridge is buried underground and relies on natural temperature regulation rather than electricity. The GF utilises multiple phenomena to stabilize internal temperature. However, this is not straightforward. The thermal behaviour is dependent on a complex interplay between underground and atmospheric conditions. To understand how these conditions are of influence on the GF, this literature review section examines the thermal working principles that form the GF’s thermal system.

### 3.2.1 Underground conditions

**Soil**  
The GF is installed underground because the soil has a lower and more stable temperature than the above-ground environment. The underground temperature at a depth of 1 meter is visualised in figure 3.2.1 (KNMI, 2026). This is the lowest point of which the KNMI measures soil temperatures, and the closest to the depth at which the GF is installed. Daily fluctuations are minor, but throughout the year the temperature ranges between 7 and 18 °C.

**Groundwater**  
Beneath the soil surface, groundwater flows at a temperature between 10 and 12 °C at a depth of 15 meters (Visser, 2024). It is noticeable that the groundwater at higher depths fluctuates more due to seasonal changes. Groundwater is a main cold source, as it is thermally quite stable and has a high thermal conductivity. Its thermal mass helps the GF to remain a stable temperature. Therefore, the height of the groundwater table is important because if the water table is higher, it brings the groundwater closer to the GF, increasing the heat transfer rate. For that reason, the GF will maintain a temperature close to the temperature of the groundwater.

The groundwater table is determined by a lot of factors, including soil type. Different types of soil have different permeability and water behaves accordingly. In highly permeable soil, the ground is more likely to be saturated with groundwater and will have a better conductivity, and thus will transfer heat between the GF and the groundwater.

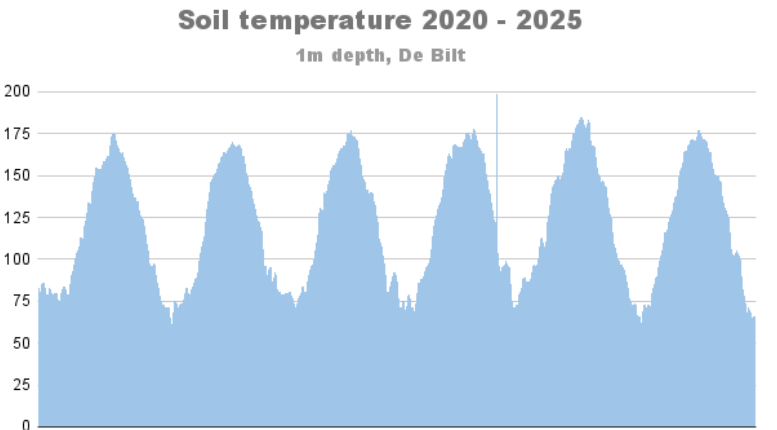


figure 3.2.1: Soil temperatures from 2020-2025, measured in de Bilt. (KNMI, 2026)

| temp (°C)    | jan | feb | mar  | apr  | may  | jun  | jul  | aug  | sept | okt  | nov  | dec |
|--------------|-----|-----|------|------|------|------|------|------|------|------|------|-----|
| average min. | 8.0 | 8.0 | 8.0  | 5.5  | 7.3  | 12.3 | 13.3 | 12.2 | 10.2 | 9.0  | 4.6  | 2.9 |
| average max. | 6.0 | 7.2 | 13.5 | 17.1 | 19.5 | 23.3 | 24.0 | 24.0 | 19.8 | 15.0 | 10.6 | 8.7 |

figure 3.2.2.1: Average atmosphere temperatures throughout 2025. Source: KNMI, 2026

### 3.2.2 Atmospheric conditions

**Air circulation**  
The atmospheric temperature tends towards a stable temperature. In the GF, there are layers with different temperatures. Although the stratification of the air within the GF, various factors will disturb this balance. As an effect, air with higher thermal energy will flow toward areas of lower thermal energy, resulting in natural air circulation within the GF

**Atmospheric temperature**  
In the Netherlands, notable differences exist between daytime and night-time temperatures. In figure 3.2.2.1, an overview of the average atmospheric temperatures throughout the year 2025 are visualised (KNMI, 2026). These temperatures directly influence the behaviour of the GF. As it is stated that the GF temperatures should stay between 8 -15°C, it is important to notice that the temperatures during the day and night are both lower and higher than the goal temperature of the GF. The GF should be able to perform up to the standards of this temperature goal, despite the atmospheric fluctuations.

**Rain**  
Rain also has an influence on the thermal stability of the groundwater. As water has a higher thermal conductivity, the rain that falls from the atmosphere will reach a temperature close to the atmospheric temperature and when it penetrates the soil, it will influence the soil temperature (Veldhuizen et al., 2020). During summer, the average atmospheric temperature is higher than the temperature of the groundwater, and so the soil temperature will increase as a consequence of that. Since the GF relies on a stable groundwater temperature, rainfall during summer has quite an influence on the temperature within the GF.

**Atmospheric transparency window**  
The sun emits a broad spectrum of wavelengths. However, not all the electromagnetic waves generated by the sun can pass through the Earth’s atmosphere. The atmospheric transparency window refers to the band of electromagnetic radiation that can penetrate through the atmosphere of the earth (Meriktas et al., 2021). Figure 3.2.2.2 visualises the spectrum of electromagnetic wavelengths that pass through the atmosphere.

This atmospheric transparency window can be broken down into three types of wavelengths, that are all responsible for a specific quantity of heat. Visible light accumulates approximately 47% of the heat, ultraviolet (UV) 2% and infrared (IR) 51% (Center for Science Education, n.d.). That means that infrared is accountable for about half of the heat that is generated by the sun. This has a big influence on all the parts of the GF directly exposed to the sun.

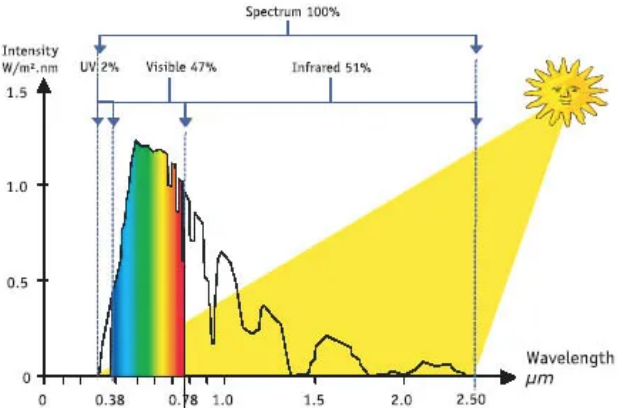


figure 3.2.2.2: Atmospheric window, (NOAA, n.d.)

**Infrared**  
There are three types of infrared radiation in regards to infrared wavelengths. These are direct, diffuse, the major radiance types, and albedo radiation (Marino et al., 2024) (figure 3.2.2.3). Direct radiation, or beam radiation, refers to the direct rays of infrared waves from the sun which are unhindered and directly are projected onto surfaces. This radiation follows one path directly from the sun onto the earth. Secondly, there is diffuse, or sky radiation, which is the radiation that is reflected and scattered by the Earth’s atmosphere and its nanoparticles, like clouds, aerosols, and vapour. The path of this radiation is non-uniform and arrives onto the surface from all directions. Lastly, there is albedo, which refers to the radiation that forms as a consequence of reflection of other surfaces, such as snow and other reflective surfaces.

It is very dependent on the climate, clouds, pollution and how much direct and diffuse radiation there is. On a clear day, the amount of direct radiation is much higher than the diffuse radiation. On the contrary, on a day packed with clouds, the amount of direct radiation significantly lowers. Unlike direct sunlight, this downwelling atmospheric radiation reaches surfaces even at night or under overcast conditions.

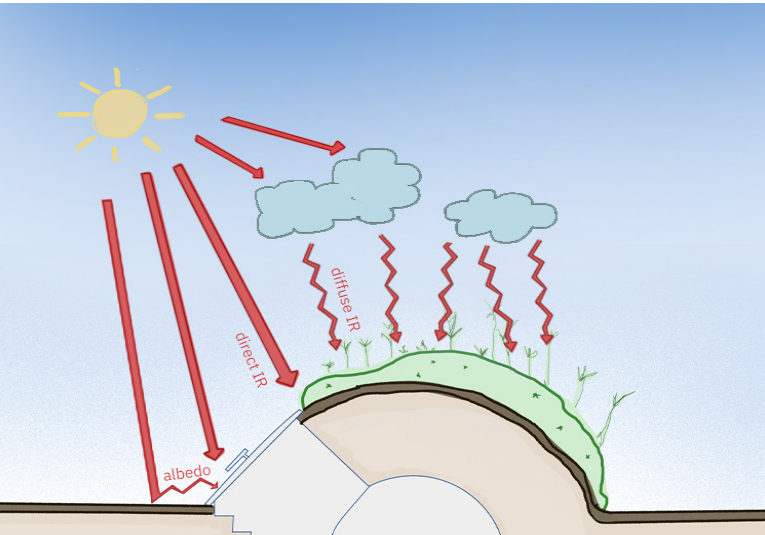


figure 3.2.2.3: Radiation types: direct, diffuse and albedo. Source: author



The atmosphere in the Netherlands is often filled with clouds. In figure 3.2.2.4 is visualised how the solar energy is divided into diffuse and direct sunlight. These are measurements that are performed during 10 years, from 2011 to 2020 in de Bilt, the Netherlands. The amount of diffuse and direct solar radiation is measured and put into a graph. As visualised, the global energy is significantly higher during summer than during winter. Consequently, the amount of diffuse and direct light are both higher as well. From the graph it is visible that during summer, the amount of direct sunlight is about half of the global amount. Therefore, the infrared intensity is also higher.

Although it will be different from the Netherlands, Rossi et al. (2018) report that direct radiation has a content of approximately 51% infrared radiation, while diffuse radiation has a content of approximately 38%.

### Humidity

Relative humidity refers to the ratio of water vapour in the air in comparison to the maximum amount of water vapour the air is able to hold (Cordulus, 2025). In the atmospheric environment in the Netherlands, there is a relative humidity of 80 - 84% (KNMI, n.d). As the ventilator of the GF draws air from the atmosphere, it is important to notice that this air has a relatively high humidity. Consequently, higher humidity has a higher heat capacity (Luo et al., 2024) and so the temperature of the atmospheric air that is moved into the GF will influence the inside temperature of the GF.

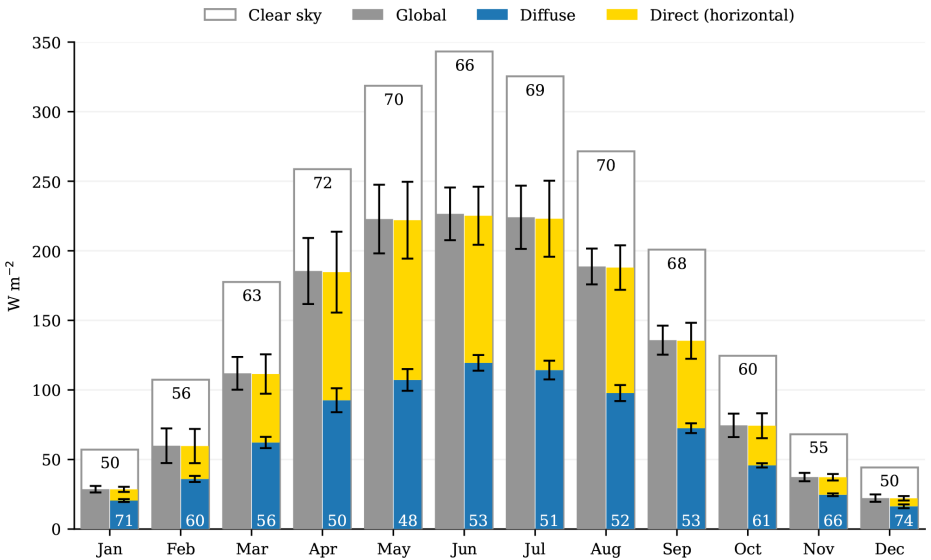


figure 3.2.2.4: Surface irradiance 2011 - 2020. Source: EESD

### 3.3

## Temperature within the Groundfridge

There are multiple factors in the context of the GF that influence the inside temperature. They can be divided into different types of factors: main temperature sources, temperature helpers and behaviour.

### 3.3.1 Main temperature sources

#### Soil temperature

Firstly, the soil temperature is very important. The material of the main part of the GF is made of fibreglass and the product is placed underground, making it a very good conductor between the soil and the inside of the GF. Therefore, the temperature of the As mentioned in section 3.2, the soil temperature will determine largely what temperature the GF is.

#### Groundwater temperature

Also, the groundwater plays a significant role in the temperature of the soil. Especially when the groundwater table is high, the water will conduct thermal energy between the GF and the surroundings. Since the groundwater temperature is relatively stable, it will have a positive effect on the GF. However, if it rains a lot during summer, the groundwater temperature will most likely be warmed, and this will negatively influence the temperature within the GF.

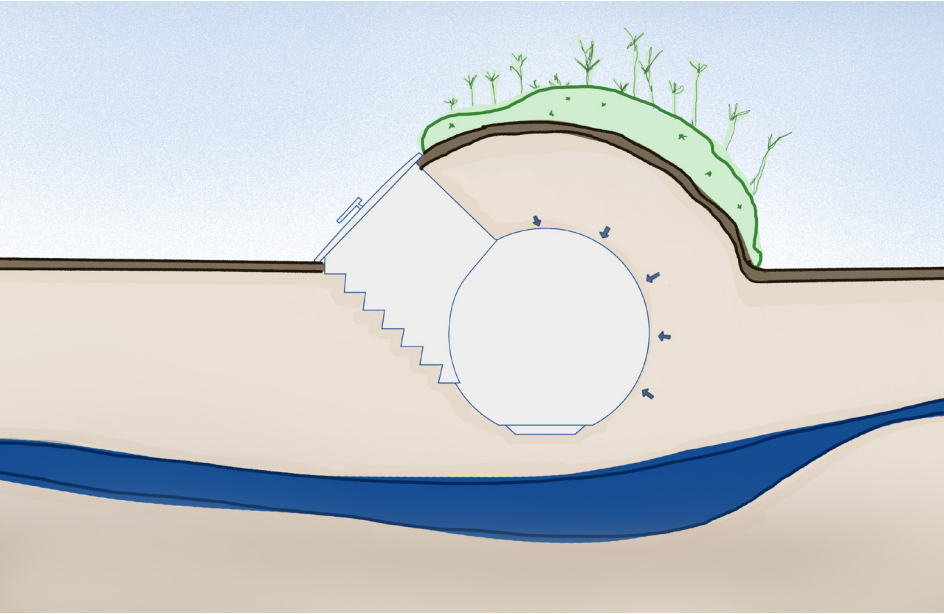


figure 3.3.1.1: Soil temperature. Source: author

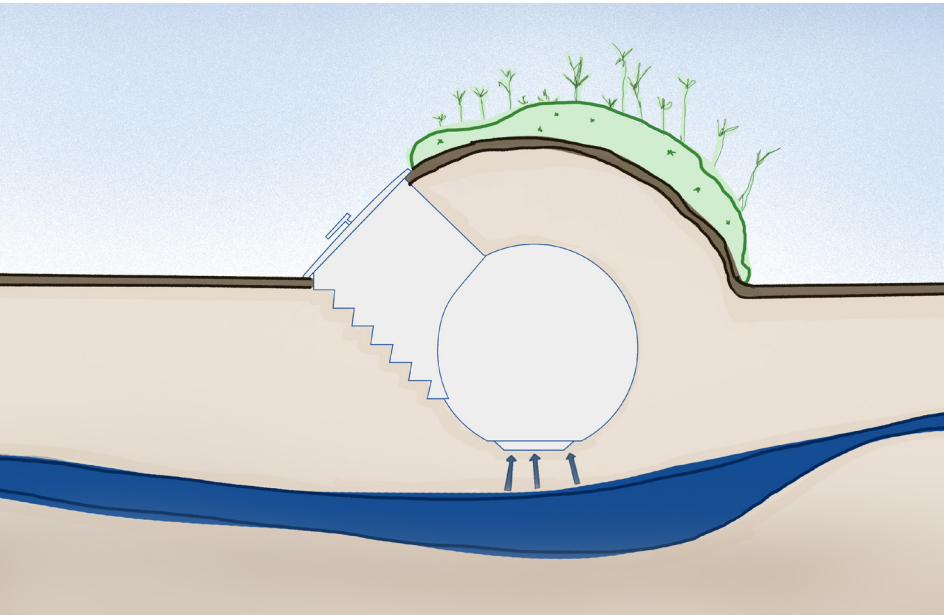


figure 3.3.1.2: Groundwater temperature. Source: author



### 3.3.2 Temperature helpers

Additionally there are smaller sources that will support the cooling effect of the GF. These are not as influential as the main cold sources but also significant. The temperature helpers are described in this section.

#### Ventilation system

In the door of the GF, a ventilation system is installed that is responsible for air circulation. Its purpose is to draw in cold air from outside and replenish the warmer air inside the GF. The ventilation can be programmed to start working at the coldest temperatures, mainly during the night. During these hours, outside air is forced into the GF and it will push other air out. As the interior warms, the warmer air rises and accumulates at the top of the GF. Thus, an additional ventilation opening is placed at the highest point of the door, functioning as an outlet for the warmest air. Beyond temperature regulation, air circulation also plays an important role in hygiene. As discussed earlier, moving air helps suppress the growth of bacteria, pathogens and microbes inside the GF (Lin et al., 2022).

#### Soil insulation

In addition to the main temperature source, the layer of soil on top of the GF functions as an insulating layer. It slows down the transfer of heat generated in the upper soil layer by the sun during summer. In winter, when the soil temperature drops below that of the GF interior, heat will transfer outward through the GF wall into the surrounding soil. In both cases, the soil layer acts as a thermal buffer, moderating the heat exchange between the interior of the GF and its outside environment.

#### Door insulation

As visualised in section 2.2.1 (Production), inside of the door there is a layer of Rockwool that functions as an insulative layer. This layer functions as a heat transfer buffer between the tunnel of the GF and the outside temperature. The heat transfer between the atmospheric air and the air trapped within the GF is decreased in order to stabilize the temperature.

#### Vegetation

On top of the GF, there is a layer of vegetation growing as a result of plants growing in the soil. There are multiple reasons why this vegetation influences the thermal stability of the GF. Firstly, the vegetation reduces the amount of direct sunlight on the GF as it creates a layer of shadow on top. Additionally, the evaporative characteristics of the vegetation enables water to evaporate from the soil into the atmosphere as the plants transpire (Tan, et al., 2018). The vegetation draws heat away from the GF from the soil between and releases it as water vapour. Lastly, the vegetation stabilizes temperature as it traps air between its stems and a layer of static air is formed. This reduces convection by the atmospheric air around the top of the GF.

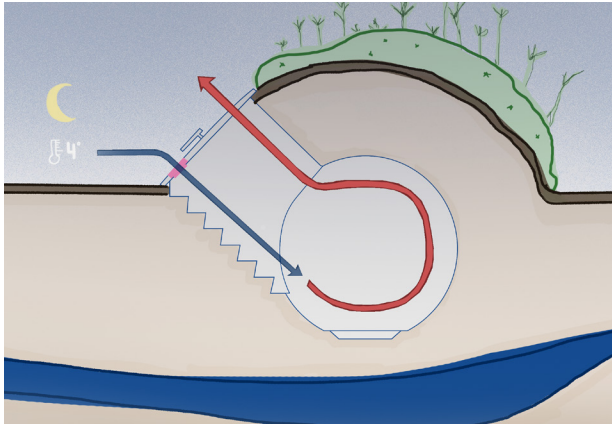


figure 3.3.2.1: Ventilation in night. Source: author

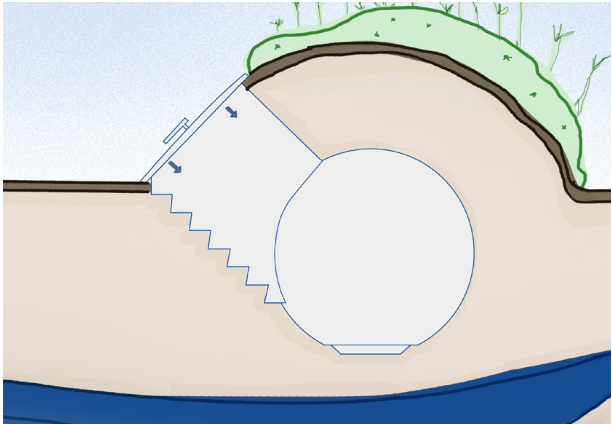


figure 3.3.2.2: Insulation of door. Source: author

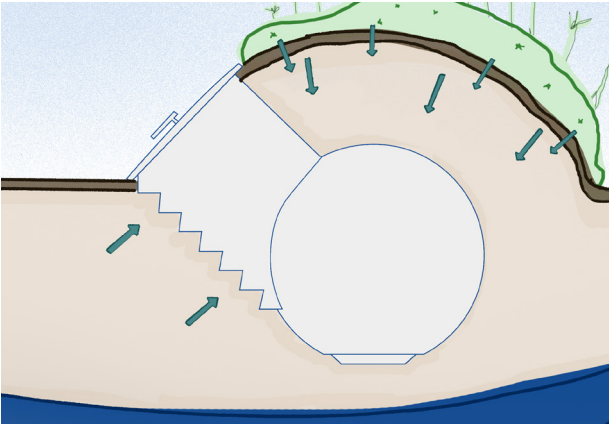


figure 3.3.2.2: Insulation of vegetation and soil. Source: author

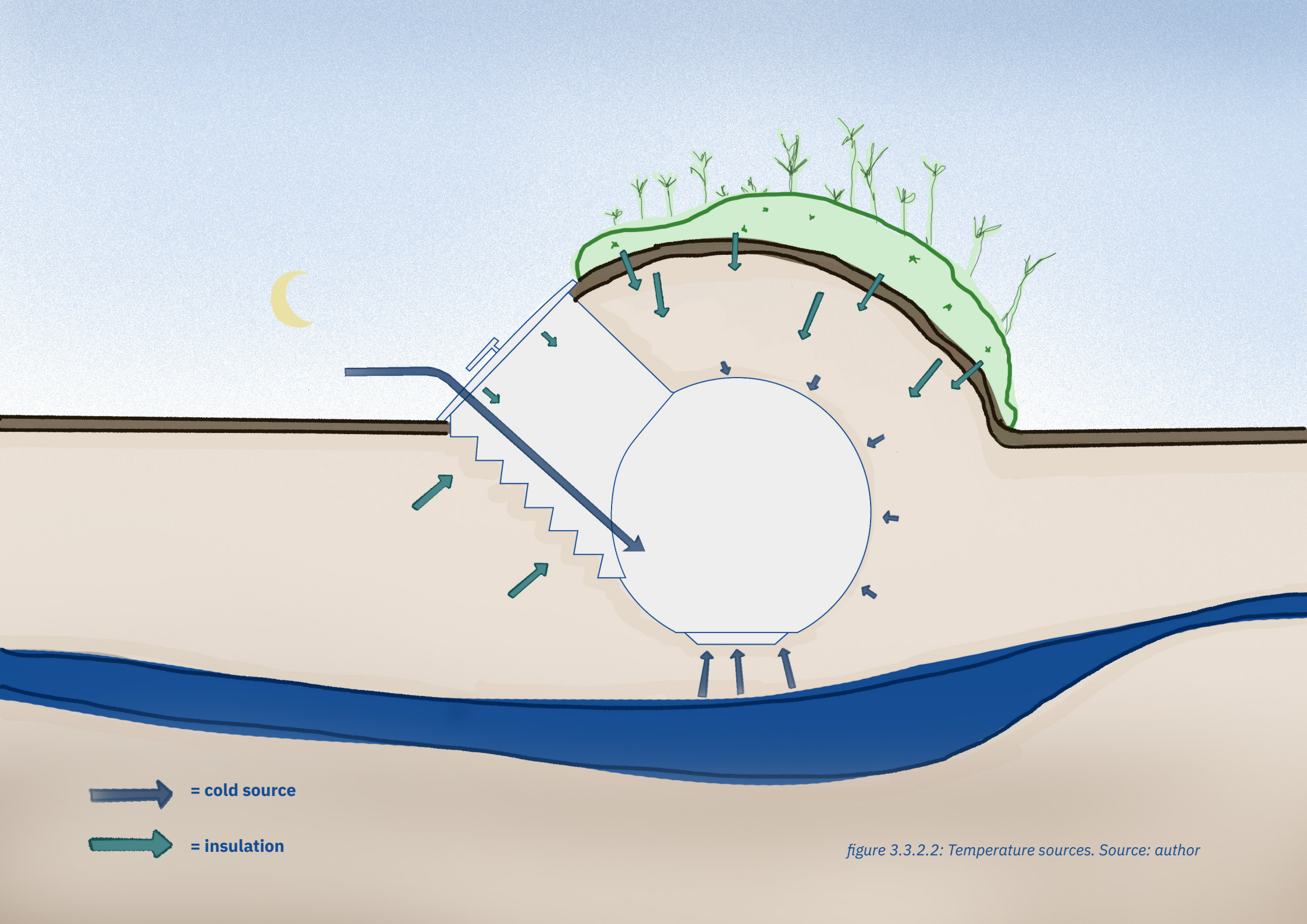


figure 3.3.2.2: Temperature sources. Source: author



### 3.3.3 Behaviour

Then there is behaviour of the GF, that will influence the temperature of the GF. These can be described as the habits a user has, in the usage of the GF. Some of these are:

#### Frequency of opening the door

The door closes the GF for the outside and works as an airflow blockage. Every time upon opening the door, it enables inside and outside air to mix and therefore destabilizes the temperature. It is better for a stable temperature to open the door as little and efficiently as possible.

#### Harvesting

A habit that influences the temperature in the context of harvesting is field heat. This is the vegetable's temperature at time of harvest. If the harvest is done during mornings, when the outside temperature is low, the crops will have a lower temperature as well. As you bring this cold into the GF, the GF will have a lower temperature as a result. The contrary works for harvesting in the afternoon, so if the crops harvested are warmer, this heat will also be introduced into the GF.

#### Amount and type of products

The thermal mass of what is stored inside the GF influences how it behaves. With a filled GF, the overall thermal mass is higher than an empty GF. Hence, changes in temperature will affect the GF more slowly. Due to a difference in thermal mass of products, the types of products stored also have an influence on the thermal system and products with a higher thermal mass will have the same effect.

#### Location of stored goods

Another influencing factor is the location of specific stored products. Storing high-moisture contents at the bottom, which have a higher thermal mass, will remain colder and maintain this temperature inside. This is based on temperature stratification and heat capacity. Within the GF, the coldest air accumulates near the bottom of the sphere, while warmer air will move towards the top. If users ensure that products with higher moisture content will be stored at the bottom of the GF, it will ensure a lower thermal mass which can function as a buffer for temperature increases over time.

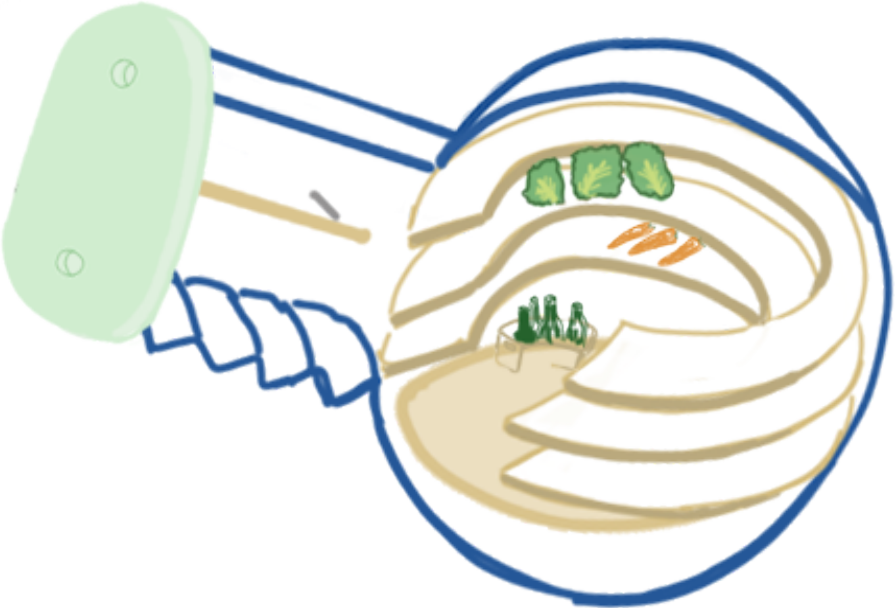


figure 3.3.3: Storing crops. Source: author

### 3.4

## Thermal challenges

Based on the previous sections (3.2 & 3.3), there are some main thermal challenges that withhold the GF of maintaining a stable temperature. This section presents an overview of challenges that are encountered in stabilizing the temperatures inside the GF. These challenges can be divided into 3 sections: thermal resistance, airtightness and ventilation control

#### 3.4.1 Thermal resistance

This section describes the challenges in preventing heat transferring through the material and structure of the Groundfridge.

##### Warming of the soil

As stated in the general conditions (section 3.2), the soil temperatures in summer are higher than in winter. Since the temperature of the GF is mainly regulated by the temperature of the soil, it will affect the GF. This results in warming of the GF.

##### Warm summer rain

In summer, when it rains, the water absorbs the heat of the summertime and surrounds the Groundfridge. Because water has a higher heat capacity, the Groundfridge is exposed to more heat for a longer period of time, which interferes with the cooling cycle of the Groundfridge, leading to an unstable temperature and energy inefficiency.

##### Direct exposure to sun

As the door is the entrance of the GF, it is attached to the tunnel and located at the outside of the hill dug for the GF. Therefore, it is the only part of the GF that is exposed to the atmospheric environment, in comparison to the rest of the GF, which is covered by the soil. This is substantiated by the fact that the door is the warmest spot within the GF (appendix A). The door is the only part that is exposed directly to the sun, making it prone to increased temperature due to the warmth generated by sun radiation. In a solar simulation (appendix I), a simulation of the sun path in the Netherlands is created. From this it can be concluded that the door is exposed quite often to the sun, and with that IR radiation. The materials used in the door (section 2.1.2), are not blocking this radiation.

Additionally, it is exposed to air, while the other part of the GF is insulated by a layer of soil. Air is a very good thermal conductor, and therefore the door is exposed to quicker temperature rises in comparison to the other parts.

##### Lack of insulation around tunnel

In the current design, the GF is installed partially underground, and covered with approximately one meter of soil on the top of the dome. However, the location where the tunnel and door are connected, the end of the tunnel is not covered with soil and therefore exposed to the outside environment. At this location, no insulation is used to regulate the temperatures.

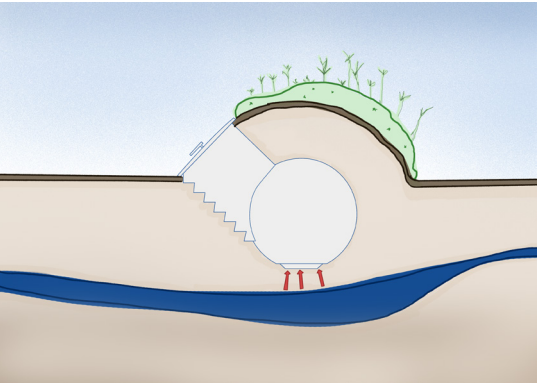


figure 3.4.1.1: Warmer soil entering the GF. Source: author

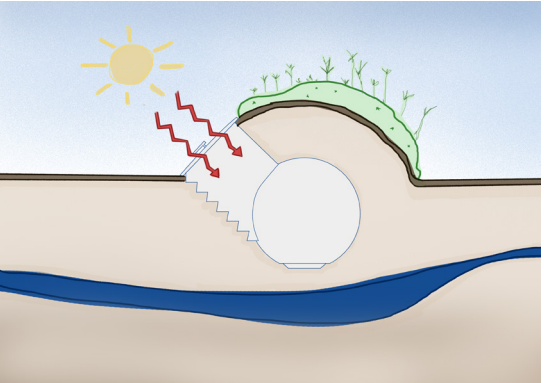


figure 3.4.1.2: Solar radiation entering the GF. Source: author

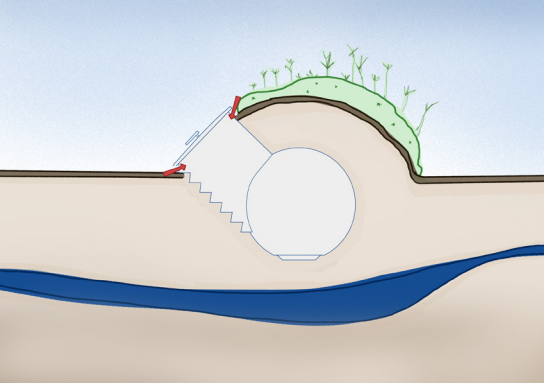


figure 3.4.1.3: Heat entering the GF through exposed neck.



Insulation type

The only insulation used in the product is located in the door. The door is fabricated by two shells, an outer shell and an inner shell. These shells are pressed together with soft insulating rock wool in between and finished with an epoxy kit. Since it is pressed together, there is a decrease in static air, which is one of the insulation factors.

3.4.2 Air flow

This section covers the prevention of heat exchanges through gaps and leak-ages.

Ventilation holes

When looking at the door, it is noticeable that there are two holes located in the door. These are part of the ventilation system, so the ventilation can draw outside air into the GF. However, these holes are a source of air leak-age and therefore thermal exchange. In figure 3.4.2.3, it is visible that these holes are significantly different in temperature in comparison to the rest of the door.

Opening the door

Since the door is opened in order to enter the GF, a lot of thermal exchange is happening in this moment. That is substantiated by the fact that there is a major rise in temperature when opening the door (figure 3.4.2.2 & appendix A).

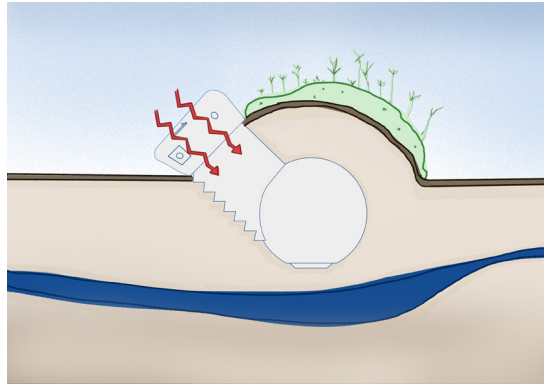


figure 3.4.2.1: Heat entering the GF while opening the door. Source: author

3.4.3 Ventilation control

Ventilation

With use of multiple tests and simulations (appendix C & D) is tested how well the performance of the ventilation system is. The smoke test shows that there is an airflow and the smoke mixes with the air inside of the GF. However, during user interviews (appendix B), it became clear that there is no insight in this ventilation flow and there is no control of it. It is said to be set on working during the coldest hours in the night, but if it is automatically powered, it can happen that the set hours are actually not the coldest hours of the night and as a result the GF is warmed up.

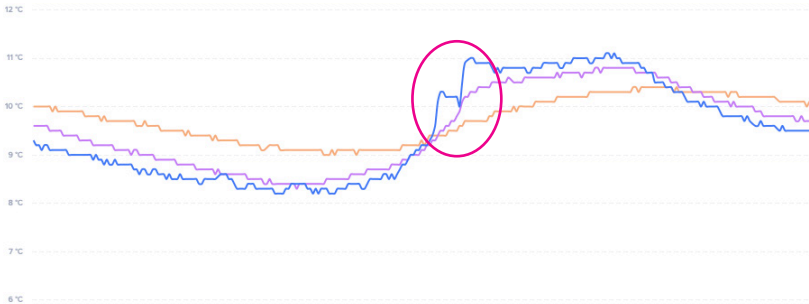


figure 3.4.2.2: Temperature rise during opening door. Source: author

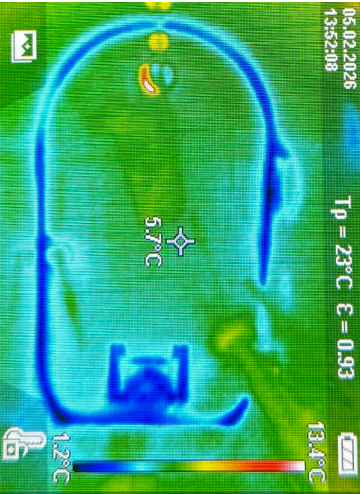


figure 3.4.2.3: Temperature of the back of the door, measured with a thermal camera. Source: author

3.5

Existing thermal systems

To review the state of the art in cooling systems, this section compares existing systems for thermal regulation. The complete review is described in appendix G, while the existing thermal systems that are used in the final design are described in the next paragraphs.

Daytime radiative cooling

Daytime radiative cooling is an energy-free and therefore passive technique that enables a surface to reduce its temperature below that of the environment around (Sun et al., 2022). This passive cooling material emits thermal radiation and reflects sunlight into outer space. It is based on two mechanisms, solar reflection and thermal emission.

For solar reflection, the material should have a very high solar reflectivity across the solar spectrum in order to prevent the object from absorbing solar energy and therefore heating up.

The other mechanism is thermal emission, meaning that the material also should have a high emissivity in an infrared range, known as the atmospheric transparent window. This is the band in which the Earth’s atmospheric radiance is emitted. Therefore, the thermal energy can pass through the material, directly into the atmosphere, functioning as a heat sink.

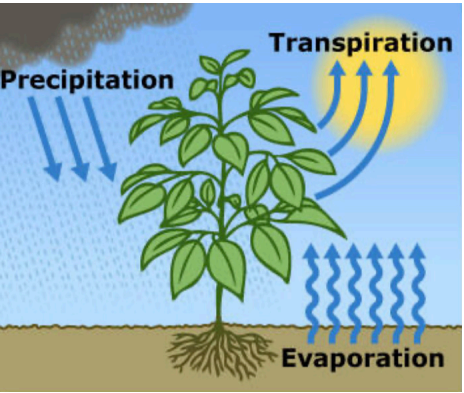


figure 3.5.1: Evapotranspiration. Source: USGS.gov

Roof surface evaporative cooling

A roof evaporative cooling system is a passive cooling method that utilizes the evaporation of water on or near the roof surface to lower the temperature of the building (Berardi et al., 2018). In the context of the GF, applying water or a pool of water on top of the dome can help the GF release heat by evaporation.

Evapotranspiration

Evapotranspiration is the combined process of moisture evaporating from the earth’s surface, water being converted into vapour, and transpiration of plants, where the water in the soil is absorbed by the roots of the plants and released as vapour through their leaves (Allen et al., 1998). This process is endothermic and latent heat is drawn away from the surface by the creation of vapour. For the GF, it can be interested how to create ways of evapotranspiring water via pools and plants in order to passively cool the hill and the GF underneath.

Stratification segments

In the terminology (section 3.1) stratification is explained. Stratification of buildings and objects like the GF can be a strategic way to reduce the air-flow, and maintaining colder and warmer areas. This can be done by dividing the area into distinct horizontal and vertical zones, with each section functioning as areas with different storage temperatures for different products.



# Door analysis

## Thermal Resistance

To understand the thermal performance of the current door, the thermal resistance should be calculated. The current shells (6mm) are fabricated by a chopped strand matt 150 + 450 of Krosglass, a XM core and polyester resin (Lantor B.V., 2024), with a layer (72mm) of Rockwool insulation in between.

$R_c = \text{thickness} / \lambda$   
**Rc(shell) = 0.006/0.117 = 0.051**  
**Rc(Rockwool) = 0.072/0.034= 2.118**

$R_c = (2 * \text{shell}) + \text{Rockwool}$   
**Rctotal = (2\*0.051) + 2.118 = 2.220**

This is a relatively low thermal resistance value, and heat will transfer easily through the door.

## Reflectivity

The green gel coating has a low reflectivity of about 0.4, which is fairly low. After the surface layer, the radiative heat is passed through to the underlying layers of the door construction.

## Emissivity

The door coating has an approximate emissivity of 0.95, just like most polyester materials (Gardon, 1956). As a result, majority of the radiation heat is absorbed and passes through this coating and is conducted to the layers beyond. Since emissivity also only applies to the surface material, the heat will pass into the GF and back.

## Thermal Bridges

Thermal bridging, like hinges and the ventilation valves, are potential sources of reduced thermal performance. Hinges made of steel and uncovered air gaps enable conductive and convective heat to flow into the door. Furthermore, the Rockwool is compressed in the door (figure 3.6.1), decreasing the insulating performance by reducing static air.

## Door versus sphere

It is assumed that the door contributes to approximately 20 - 40% of the heat gain. This is based on the following calculation:

$A_{door} \approx 0.91 \text{ m}^2$   
 $U_{door} \approx 0.4 \text{ W}/(\text{m}^2 * \text{K})$   
 **$G_{door} = U_{door} * A_{door} = \approx 0.4 \text{ W}/\text{K}$**   
 $A_{soil} \approx 3 \text{ m}^2 \approx 10-15 \text{ m}^2$   
 $U_{soil} \approx 0.05-0.15 \text{ W}/(\text{m}^2 * \text{K})$   
 **$G_{soil} \approx 0.6 \rightarrow 1.8 \text{ W}/\text{K}$**   
**Door fraction  $\approx 20 \rightarrow 40\%$**

However, the door is the only part exposed to the sun, meaning on very warm days, this is the first part to let heat in.

## Conclusion

Analysing the door reveals the thermal resistance of the current door to be 2,2 [Rc]. The Rockwool accounts for majority of this, as an insulator. However, since the Rockwool is pressed into the door, the amount of static air, the main insulator probably is lower. Additionally, this Rc is based on the whole door, without taking the air valves into account.

An Rc of 2,2 is moderate insulation regarding a cellar construction in the Netherlands. A standard thermal resistance for ground surfaces is 3.7 Rc (Rijksoverheid, 2024), so this will be the aim of the design.

Moreover, since the coating has a high emissivity and low reflectivity, the radiation heat will pass through the surface towards the inside of the GF. Additionally, reflectivity is low of all the products, meaning there is little reflection of the solar radiation.

## Takeaways

- The reflectivity of 0.4 is low and therefore conducts radiative heat through the door
- The emissivity of 0.95 is absorbing heat
- An appropriate Rc would be 3.7
- The doors heat ingress fraction is 20 - 40%
- For short-term heat peaks, the soil is a major influence, for longer term, the soil is a bigger player.

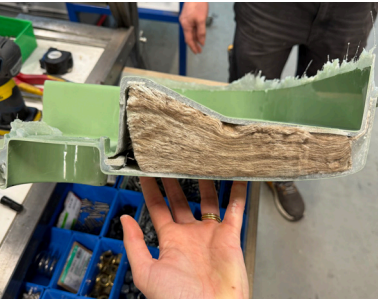


figure 3.6.1: Door cross section picture. Source: author

# Material studies

A material study was conducted in order to identify suitable materials for a layered door design. Insulation materials like Rockwool, flaxwool, XPS, Steicoflex, sheep’s wool and Bluedec were analysed for their low thermal conductivity values ( $\lambda$ ). The materials have different properties, and therefore have different considerations when integrating them into a design.

For a reflective layer, materials like aluminium, Mylar film, low-e coatings and metallised polypropylene were considered for their high reflectivity values (r). To counteract radiative heat transfer, highly reflective foils are commonly integrated into constructions like walls and doors. These materials, like the ones mentioned above, reflect incoming infrared radiation back towards the heat source instead of emitting it (Lee et al., 2016). In order to function efficiently, the foil must be constructed to face an air cavity, as the reflective effect operates across an open gap and not via conduction. Research indicates that an air gap of 20 mm represents an optimal construction in applications like the door (Pourghorban et al., 2020).

In order to further research the passive cooling techniques, materials like TiO2, SiO2, CaCO3, Chitin and ceramic aerogel were evaluated for their unique passive cooling characteristics, combining high reflectivity and emissivity ( $\epsilon$ ) to reflect visible and invisible light. These materials reflect radiative heat, created mostly by solar energy in the visible spectrum, while emitting heat generated during the day into the invisible spectrum.

A comprehensive list of materials are found in the appendix M.



figure 3.7.1: Flax wool insulation. Source: author



figure 3.7.2: Cork on GF door. Source: author



3.8

# User interaction

The previous sections highlighted the thermal behaviour of the GF and the technical challenges regarding the product. However, design is about more than solely function. A good design creates value beyond its functionality, it invites people to interact with it. This interaction forms an emotional connection and the user will perceive it as more than just a cooling system. The following sections explore the current interaction of the Groundfridge and explore opportunities to grow from a passive product into an interactive system with increased user value.

## 3.8.1 Current interaction

The current GF is sold as a prefabricated product, and therefore the moments in which a user interacts with the product are few but significant. The user experience map (figure 3.8.1.1) visualises the current interaction of the user with the Groundfridge and its pain points. The insights are gained from analysis of use and interviews with customers (appendix B).

### Ordering the GF

The customer gets in contact with the Groundfridge organisation to arrange the purchase of the product. The customer already has to think about where to place the GF. Due to production and assembling of the GF, or sometimes the water table being unfavourable, the lead times can be a little long. This is the moment where expectations begin to form about the use of the GF.

### Installing the GF

The GF is installed in the garden of the user. This is the moment where the user sees the product in real life, before it is buried underground. The location and orientation of the product is decided in these moments, where after this is set. When installing the GF, the ventilation system of it is set to a specific schedule. However, there is no way of understanding and verifying whether the system is functioning and what it does.

Users sometimes also do not want to put the GF in the location that is recommended, and for example still want to place the door in another direction

than facing the north. This is also the moment in which the user plants the vegetation they would like. Sometimes, they are advised by a gardener but sometimes they do not have an idea what kind of plants to put on top.

### Putting products in GF

As the GF is functioning as a root cellar, the user is going to put products inside of the product in order to store and preserve. This can be anything like fresh crops, wine, cheeses, pickled goods, dry products, drinks and many more things.

### Storing of products

As the GF is a passive product, the user does not have to look too much after the GF after installation. The soil, groundwater, vegetation and ventilation do the work. The seasonal change takes place, and temperatures will fluctuate. Since the temperature and moisture level are crucial conditions of the GF, it is important to understand how these are within the GF, however, the feature of this are not added to the product. Insights about temperature, moisture or ventilation are lacking in the storing time of the product. On a very warm, summer day finds place, the temperature can rise above the desired temperatures. This can cause products to spoil and rot, which causes user dissatisfaction.

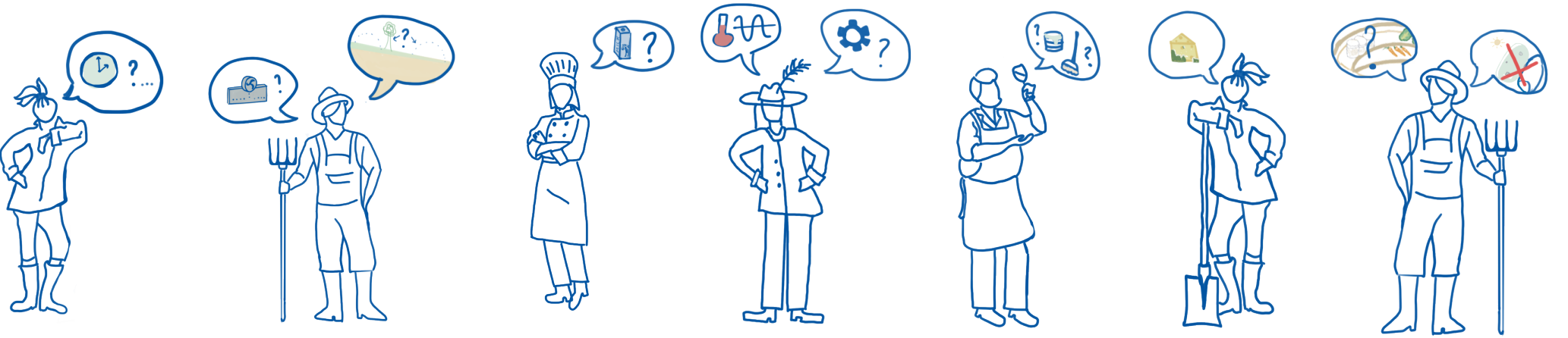
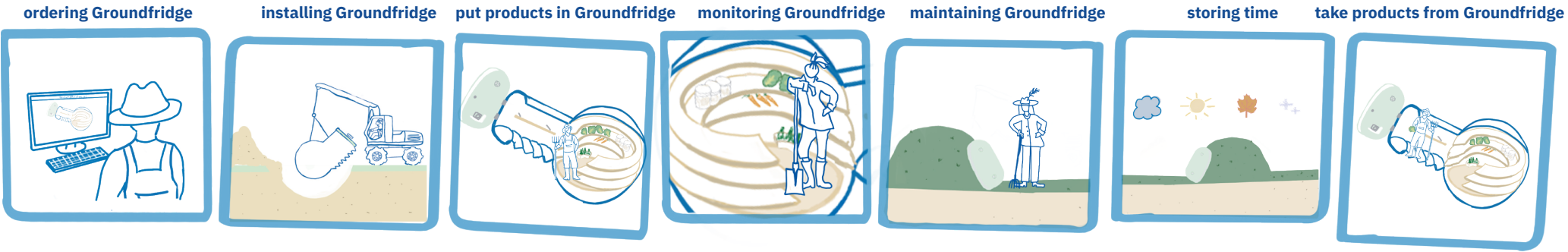
### Monitoring and maintaining the GF

Over time, the user needs to monitor the GF by checking whether everything is going well inside the GF. Customers now have purchased separate systems to monitor the temperature and moisture, to get an understanding what is going on. Just like every product, the GF needs regularly cleaning and maintaining. Users said to dislike that the handle of the door will deteriorate due to the weather over time.

### Take products from the GF

Every time the user needs something from their storage, they have to go inside of the GF. However, since the product functions most often as a long-term storage, the users are not constantly aware of the state inside of the GF. They also tend to forget what products they put in. Additionally, the GF is preferred to be opened during cooler times of the day rather than during peak temperatures.

# User experience map



#### pain points:

- sometimes it takes a while to get the GF, as the groundwater table is too high

#### pain points:

- location choice does not always have the recommended factors
- installing ventilation, without know-

#### pain points:

- user does not know what can be stored inside and what not

#### pain points:

- no insight in fluctuations of temperature
- no insight whether ventilation system is working

#### pain points:

- user does not know how to maintain the system

#### pain points:

- stored produce can go rotting (due to fluctuations of temperature)

#### pain points:

- tend to forget what is inside
- opening of the door can not be done in too high temperatures

figure 3.8.1.1: User experience map. Source: author



# Customer insights

“I lose track of what I have stored inside.”

“It would be very interesting to know more about the storing temperatures of products.”

“I understand that there are fluctuations in temperature, but I want to understand this better.”

“A thermometer or visualisation of temperature would be very useful.”

“We purchased the Groundfridge as an alternative for a cellar.”

figure 3.8.1.2: Customer insights. Source: author

## 3.8.2 User needs

On the previous page (figure 3.8.1.2), the insights gained from user interviews are visualised. These interviews highlighted some important takeaways for interesting design opportunities. Overall there is a lack of information and guidance around the installation, monitoring and maintaining the product.

### Monitoring the product

The most notable takeaway is the fact that people are aware of the product having fluctuations, meaning users are genuinely interested in learning from the GF system and creating an understanding of what is happening during the variations of the season. In that way it becomes more integrated in their lifestyle rather than just a product.

### Seasonal awareness

Users are interacting with the product differently during the year, storing different products and visiting in different frequencies. A user needs to be able to adapt and anticipate to the occurring seasonal changes, and connecting this to the current design can be an opportunity to educate the user.

### Sustainable lifestyle

As the GF is said to be fitting a sustainable lifestyle, this is something that can be enhanced in the design of the GF. Sustainability is getting more and more important in peoples lives, and so the GF should play into that expectation of the user.

### Connection to garden

Since a most of the user types are deeply connected to their garden, the GF could be integrated better into this. The GF system could reflect and support the relation between the garden and the user.

### Product with pride

Since this is a contemporary product, people are actually proud of the GF. Therefore, the product should be something that is working without hesitation or at least with an understanding. The aesthetics of the product and the hill around should be fitting the brand and the lifestyle of the GF.

### Effortless functioning

As the product works based on the passive cooling of the earth, the whole product should feel effortless. The maintenance should be low, or very enjoyable so that it is not a user's concern.

### Organisation of inventory

The user now struggles with remembering what is stored inside the GF, and where. Therefore, a better way to organise the inventory is desired.

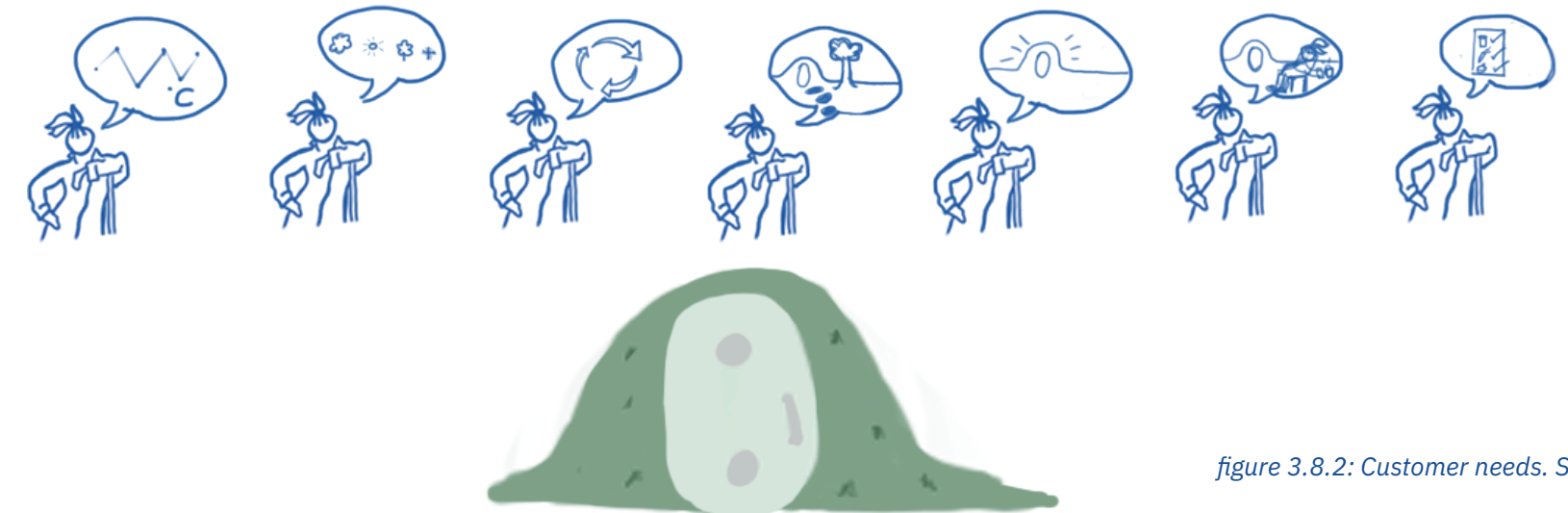


figure 3.8.2: Customer needs. Source: author



### 3.9

# Interaction value

From the previous section, 3.8.2, it is clear that there are some user needs that should be fulfilled. These needs can be understood as interaction needs, reflecting a desire for greater engagement. In order to incorporate these needs into the design, it is significant to understand product experience and what makes a product valuable and how interaction with the Groundfridge contributes to increasing this value.

#### 3.9.1 Product value

A product is more than the function solely. Desmet and Hekkert (2007) describe product experience as all affective responses that a person experiences when interacting with the product, from aesthetic experience, to meanings and emotional experience. Together, these layers determine how a product is perceived and valued and decide what makes a product genuinely valuable to its user. This value can be divided into multiple dimensions, that will contribute different aspects to a design.

Building on this, Van den Berge et al. (2021) built a five-dimension framework based on the research of Shet et al. (1991), that introduces functional, social, emotional, epistemic and conditional value. Functional value refers to how well a product fulfils the purpose of it. In the case of the GF it refers to maintaining a stable temperature to store the food inside. Conditional value is about the performance of the product within its specific context and the influence that these circumstances have on the product. Emotional value refers to the feelings that the product evokes, such as making the user feel excited, satisfied and proud of the product. This should form a connection between the user and the product. Then there is epistemic value, that is the value that is enabled to knowledge gain and understanding of the product. This value is about the curiosity it evokes. Lastly, there is social value, referring to the role of the product in a community or collective context.



figure 3.9.1: Interaction in garden. Source: author

### 3.10

# Sustainability analysis

A key focus of this project is sustainability, and since the GF is buried underground, it inherently interacts with its natural surroundings. Additionally, users expect the product to align with their sustainable lifestyle. To improve future iterations, it is essential to evaluate the sustainability of the current design in order to improve the future design. Sustainability in product design goes beyond material use and energy consumption, and it requires a more holistic approach by designing for the entire lifecycle of the system. This section reviews the current GF system through the lenses of the Value Hill and reviews further opportunities for sustainable design.

#### 3.10.1 Value Hill

The Value hill (figure 3.10.1), established by the Ellen MacArthur Foundation, visualises a product’s circularity across three stages of its life: pre-use, use and post-use. The framework is created as a strategy to keep a product at the highest possible level of value. Strategies located near the top of the hill ensure that the product keeps the most value, strategies further down the hill recover the least product value.

##### Pre-use phase

The GF is produced by using energy intensive materials, including fibre reinforced composites, polyester resin and Rockwool, carrying high environmental costs. Especially the door, consisting of an encapsulated combination of these materials (section 3.6), has a significant impact on the system. The composite door parts are bonded by means of epoxy and filled with Rockwool, and therefore is extremely hard to recycle. Thus, it is important that the value of the door is prolonged. Additionally, fibreglass composite can be a toxic substance due to its epoxy bondings, and working with it may be harmful due to its microscopic glass particles. The exploded view (section 2.2.1) shows, that the system contain few electronic devices. In general these devices have a high impact due to their resource-intensive materials. The ventilation solar panel and ventilation system therefore have a big environmental impact.

##### Use phase

During this phase of the cycle, the whole system works passively and without energy input. Sustainability wise, this is a great strength. However, the door is the weakest spot of the product, not only in terms of thermal performance. This door is exposed to UV, the weather and mechanical wear over time. It became clear that the handle deteriorates over time, and the gelcoat fades in colour. Additionally, the lack of thermal performance does not contribute to the energy efficiency of the GF. Moreover, users currently receive no information or guidance in maintaining the product or monitoring its behaviour. This means that preventable deterioration is unaddressed.

##### Post-use phase

The post-use analysis is the most concerning from a sustainability perspective. The layered composite construction makes the product extremely difficult to disassemble and recycle. This means that the whole GF will probably end up as landfill or incineration in the end-of-life phase of the product.

##### Conclusion

Since the passive, energy-free use-phase has to compensate for the pre- and post-use phase, the product is placed relatively low on the value hill. If the system wants to be improved, the design should be made of less impactful materials, the design should be revised to be easy-to-disassemble, the user should be informed about the maintenance of the GF, there should be possibilities in replacing and repairing the GF and there should be a clear instruction and consideration for the end-of-life, since that is non-existent at this moment.

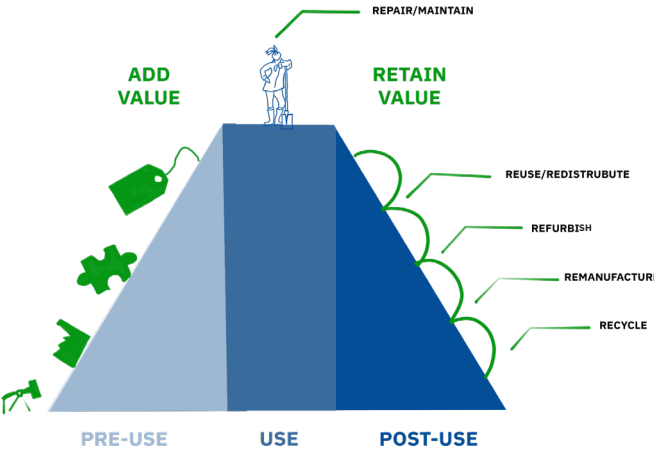


figure 3.10.1: Value hill by Ellen McArthur Foundation. Source: author



3.10.2 Further opportunities

The value hill is a very concrete tool for assessing opportunities to improve a product’s circularity. Beyond this tool, there are interesting other philosophies about increasing circularity. These opportunities align with the lifestyle of the user and the Groundfridge brand vision (section 2.2.3).

Regenerative farming

Floris Schoonderbeek, the designer’s perspective is already based on regenerative farming. Regenerative farming is the practice of restoring ecological systems then solely sustaining them. It is about a holistic approach of food production, gardening and farming that looks at the entire ecosystem, across the function of the soil, the vegetation, the weather, the animals and insects. It reduces exploitation and harm of the earth and promotes a healthy, local ecosystem with long-lasting value.

In terms of the Groundfridge, opportunities include supporting soil process and its microbes, supporting biodiversity, creating a resilient food system and ecological impact on communities. By implementing these ideas, the GF becomes a regenerative tool instead of a static product.

Design with nature

Another approach is designing with nature, rather than separating a product from nature. Specifically this is interesting for the GF, since it is literally embedded in the earth and operates with natural processes as mechanisms. Kennedy et al. (2025) describe biomimicry as an approach that can contribute to sustainable design, with three levels of design with biomimicry. At the form level, natural structures can contribute to improve passive thermal performance. An example in regards to radiative blocking is for example the chitosan shells of sea creatures (Lauster et al. (2023)).

At the level of process, the functioning of organisms are imitated. Evapotranspiration (section 3.6) from plants can be a valuable source of inspiration, drawing heat away from the plants and soil. Lastly, the ecosystem level, focussing on the entire system of relationships, resources and regeneration of nature. Closed loop systems are a prone example, and in the case of the GF this can be done by creating the regenerative concept and creating ecological value.

figure 3.10.2: Design with nature visual. Source: author



3.11 Analysis takeaways

MRO

Improving the thermal performance of the GF.

- 1 Rising environmental and soil temperatures are the primary drivers of temperature.
- 2 The door is the weakest thermal spot, with insufficient resistance against heat transfer.
- 3 The airflow within the GF is uncontrolled.

R02

Increase user value of the GF.

- 8 The product lacks feedback about its internal state.
- 9 The product is a passive system, and lacks interaction
- 10 Users are interested in understanding and learning from the GF and its cycle.

R01

Analysis of the thermal behaviour of the GF.

- 4 The current thermal resistance is not sufficient.
- 5 User behaviour also influences thermal stability.
- 6 Vegetation passively contributes to thermal regulation.
- 7 Temperatures fluctuate due to external and seasonal factors.

R03

Ecological and systemic sustainability

- 11 Passive cooling techniques can offer energy-free opportunities to control temperature.
- 12 Vegetation and soil are underutilised ecological resource.
- 13 The GF has potential to improve sustainable value, by material use, lifecycle improvement and other design implementations.





The thorough analysis that is completed in the previous chapter has established a clear understanding of the Groundfridge in terms of technical behaviour and value for its users. This chapter translates these insights into a coherent design vision, a defined goal with requirements, functioning as a guide to develop the final concept.

# 4 Design Vision

*figure 4.0: The butterfly as a symbol for transformation. Source: author*

## 4 Design Vision

- 4.1 Design vision
- 4.2 Design goal
- 4.3 Design challenge
- 4.4 Design requirements



# 4.1

## Design vision

This design vision translates insights and observations from research into a coherent guideline for design. It defines what the intention of the design should be and gives this project a clear identity.

### 4.1.1 Transition in product interaction

The Groundfridge is designed as a passive product, that is solely placed underground and works without demanding input from its user. This is a strength because of it being a low effort product, but also a limitation since it lacks a deeper integration in the user’s lifestyle. From the analysis, it can be concluded that the product operates as an unknown system, where the user lacks insight in the working of the product. It can also be concluded that the current thermal performance is not matching the desired behaviour, especially during warmer summer periods when the door, the tunnel connection and uncontrolled airflow allow heat exchange to occur and to influence the temperature inside the GF. The transition that the future design proposes is therefore a dual design vision: improving the thermal behaviour of the Groundfridge, and establishing more interaction with the user and its lifestyle. This shift is intended as a transition from a one-directional relationship, where the product simply exists and acts as a functional product, toward a two-directional relationship, where the user understands the product, learns from it and acts upon this. By tackling the thermal weaknesses identified in the analysis and the user’s needs that evolve from user interviews, the new design should add profoundness to the Groundfridge design and the GF can become something that functions better and is better understood. This broader understanding and engagement creates lasting value.

### 4.1.2 Incorporating Mother Nature

In the stakeholder overview (section 2.2), Mother Nature is mentioned, however, she could be taken into account in a more profound way.

The Groundfridge’s working is based on the stable temperature principles of the soil, and is therefore not only its context but the mechanism behind it. It is inevitable to have fluctuations in this soil-, air-, and groundwater temperatures, the vegetation and the seasonal cycles. These factors determine how the GF performs. Rather than having the urge to control and compensate for these unpredictable factors, this project design vision embraces them as design principles.

Designing with nature encapsulates working with the thermal ability of the earth and incorporating passive, nature-based principles into the GF design. In the analysis, some passive strategies are described that the GF could benefit from in a natural way. Using specific vegetation types beyond decoration on top of the GF hill could provide a natural dimension to actively cool the GF by evapotranspiration and passive shadow forming. The GF should be part of an ecological system, and strengthen the products’ relationship with nature rather than just being buried underground. This philosophy also extends to the user. A person that is aware of the fluctuations of nature, how the soil temperature affects their plants, when rain alternates dryness and the effects of this on their garden, is more deeply connected with nature. This connection with nature is a significant desire of the user, and in this way, the GF system can become a means of learning from nature, turning everyday interaction into something meaningful.

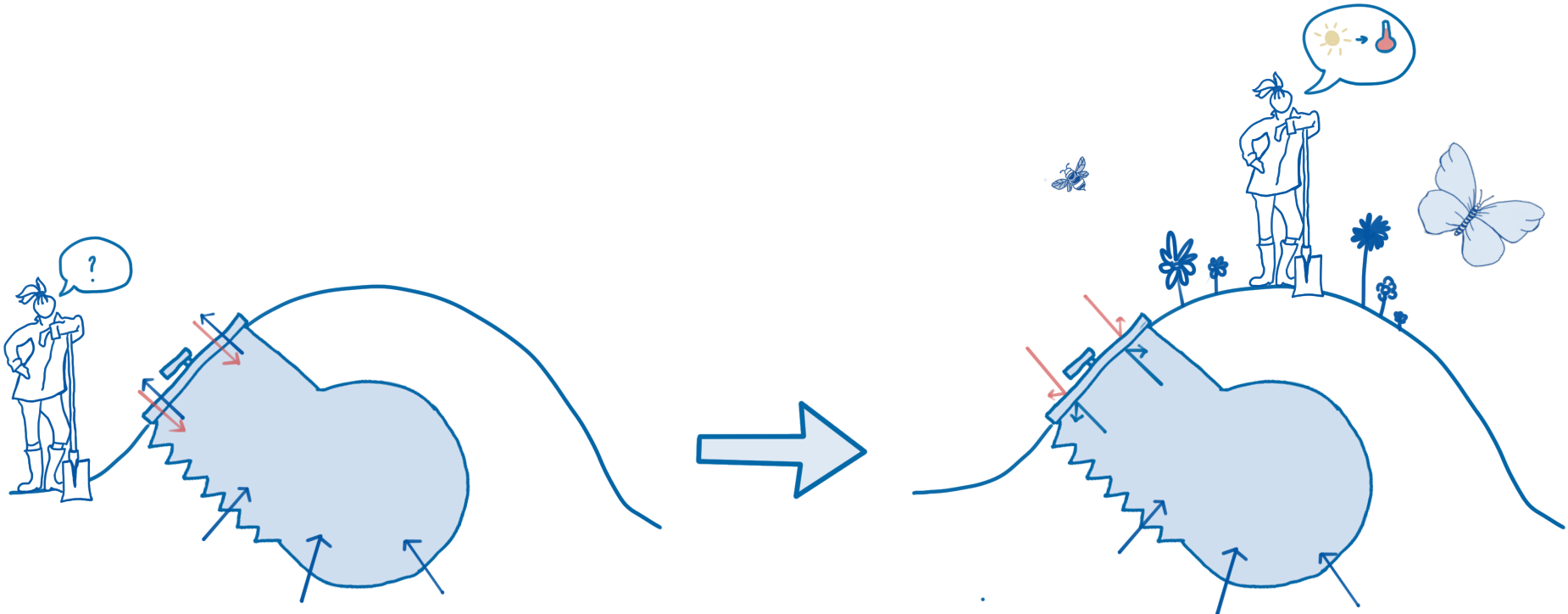


figure 4.1.1: Design Vision Visual. Source: author



## 4.2

# Design goal

From the *resign rationale* a **design goal** was formulated

## Designing and prototype the Groundfridge as a dynamic, ecologically grounded system for passive thermal stability of the off-grid cooling cellar.

A Research-through-Design approach to optimising *conductive*, *convective* and *radiative* heat transfer for a *self-regulating* Groundfridge system.

figure 4.2: Flower fields. Source: author

## 4.3

# Design challenge

The goal is to “*design and prototype the Groundfridge as a dynamic, ecologically grounded system for passive thermal stability of the off-grid cooling cellar*”.

The redesign should control the conductive, convective, and radiative heat transfer to improve internal thermal stability (MRO and RO1). This is achieved by targeting the thermally weak points within the GF, and improving the insulating and radiative blocking properties. The redesign should enable more integration in the lifestyle of the users (RO2) and make the invisible thermal system tangible in an ecologically grounded way that is free of energy dependency (RO3). Together, these directions form a dual design vision that is substantiated by the findings and takeaways from the previous chapters.

## 4.4

# Design requirements

### 1. Thermal resilience

The product must achieve a thermal resistance approaching 3.7 [Rc], so the insulative and radiative heat blocking performance should be improved to achieve more stable internal temperatures.

### 2. Staying off-grid

The product should function independently of the electricity net, aligning with the lifestyle of users. Improvements should be achieved through passive, mechanical and natural means only.

### 3. Weatherproof

The product must be resistant to the weather conditions that the GF encounters.

### 4. Low-maintenance

The product must remain low in maintenance, easy to use and understandable for the user.

### 5. Creating a feedback system

The design implementations should create a feedback system and communicate internal thermal state of the GF.

### 6. Better integrated into lifestyle

The product must be aligned with the lifestyle that the user seeks, and should be an extension of the user’s garden and daily activities. The aesthetics of the implementations should fit into the brand idea.

### 7. Increase human interaction

The product must invite to user engagement, and deepen the user’s relationship and understanding with the product.





With guidance of the design vision that is stated in the brief, the design team translates these goals into concepts and ideas that are evaluated and implemented that fit the design requirements. The core structure of this project: Research-through-design. The design elements are evaluated in order to form a final design.

# 5 RtD

The figure is a collage of various ideation methods. It includes several mind maps with central nodes like 'Brainstorming' and 'Ideenfindung'. There are also lists of ideas, such as 'Ideenfindung' and 'Ideenfindung'. Sticky notes with handwritten text are scattered throughout, providing additional context or examples. The overall theme is creative problem-solving and idea generation.

ted in the previous section, this chapter  
 s ideas, and evaluates what design  
 . Prototyping and testing are part of the  
 gh-Design. By means of this approach,  
 al design.

figure 5.0: Ideation m

figure 5.0: Ideation methods and sketches. Source: author

## 5 RtD

- 5.1 Before the RtD**
- 5.2 Research-through-Design**
  - 5.2.1 RtD explained
  - 5.2.2 Measuring temperatures
  - 5.2.3 Reflection layers
  - 5.2.4 Coatings
  - 5.2.4 Air control
  - 5.2.5 Olla system design
- 5.3 Takeaways**



## Before the RtD

These ideas were placed in an effort versus effect matrix (figure 5.1.1). This matrix functioned as a tool to quickly visualise which interventions would have the most promising effect without high implementation cost, in the form of structural changes and high investments. The ideas that were distinguished by this matrix showed potential and could be tested in the time-frame of this project. The main directions that emerged from this are:

& combining *evapotranspiration* with *user interaction*.

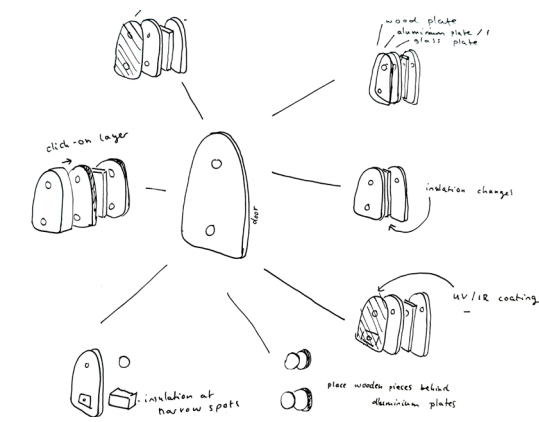
MSc Thesis Iris de Bree



On this page, sketches and brainstorming of ideas are visualised.

Hand-drawn sketches illustrating the design process for a dynamic structure, showing various stages from initial concept to final design.

- Top Left:** "tech design" and "dynamische indeling" (dynamic division) are written above a sketch of a structure with a central column and horizontal bars.
- Top Center:** "beter inspelen op de behoeften" (better response to the needs) is written above a sketch of a structure with a central column and horizontal bars.
- Top Right:** "Design a cellular structure makes it more responsive to environmental change via active controlling them to actively adapt the structure according to the need" is written above a sketch of a structure with a central column and horizontal bars.
- Middle Left:** "beton planken in tunnel met tunnel armatuur" (concrete slabs in tunnel with tunnel reinforcement) is written above a sketch of a structure with a central column and horizontal bars.
- Middle Center:** "met klein kleeplakje zodat het hele ding open kan worden" (with small sticker so that the whole thing can be opened) is written above a sketch of a structure with a central column and horizontal bars.
- Middle Right:** "Kijk naar erfenis van doe extra rook is statische blik" (Look at the inheritance of the extra smoke is a static view) is written above a sketch of a structure with a central column and horizontal bars.
- Bottom Left:** "het idee van de open structuur" (the idea of the open structure) is written above a sketch of a structure with a central column and horizontal bars.
- Bottom Center:** "addition of structural information" is written above a sketch of a structure with a central column and horizontal bars.
- Bottom Right:** "verschillende verslaktheidsgraden" (different degrees of clogging) is written above a sketch of a structure with a central column and horizontal bars.
- Far Right:** "plants as a flow purifier" is written above a sketch of a structure with a central column and horizontal bars.
- Far Bottom Right:** "plants inside CE" is written above a sketch of a structure with a central column and horizontal bars.
- Far Bottom Left:** "bouwte voor de CE" (built for the CE) is written above a sketch of a structure with a central column and horizontal bars.
- Far Bottom Center:** "Design" is written above a sketch of a structure with a central column and horizontal bars.





# Research-through-Design

After ideation and the process of developing the This section is the Re- search-through-Design phase. Since there are multiple challenges in the current Groundfridge product, this approach is used to detect what imple- mentations have great potential to improve the product. These potentials are prototyped and tested in order to gain insights and design directions. This section highlights the most significant tests, other test can be found in the appendix.

## 5.2.1 RtD explained

Research-through-Design (RtD) is an approach in which the process of designing is used as a way to generate knowledge and insights. This meth- od uses theoretical knowledge in combination with creation, prototyping, testing and reflecting of design implementations to better understand the interactions and possible solutions of a design. RtD is an iterative process of making and evaluating implementations, in order to discover new perspec- tives.

In this project, RtD was used to explore and develop design implementations of an improved GF system. The process was based on insights from the literature review, informing the development of prototypes. Through prototyping, testing and evaluation and reflection, this project reviewed how the MRO/RO's could be answered and brought into practice. The insights gained guided the final design.

To understand what type of heat the prototype is trying to test, a visual system is created (figure 5.2.1). This system indicates whether a prototype or test is addressing conductive, convective or radiative heat.



figure 5.2.1: Symbols for conductive, convective, radiative heat. Source: author

## 5.2.2 Measuring temperatures

### Netatmo sensors

In order to get data to analyse what is happening in the GF, a measuring setup was created. Three Netatmo sensors were placed in the GF, at differ- ent spots to get insights in what is happening internally, and compare them with each other. In the first setup (figure 5.2.2.1a), there were two sensors at the door, to compare the in- and out-stream of the air valves located in the door and one further down in the cellar.

Halfway there was a change in setup, as it became evident that the temperature of the ambient environment was important as well. Therefore, the setup was changed (figure 5.2.2.1b), and one of the door sensors was placed outside.

### Evaluation

This became a very important source of insights in this project, as it gave re- al-time data through the entire project. By means of this data, it became ap- parent that the door was indeed the weakest point, and many other insights about the internal temperature and ventilation system were gained from this. Appendix E shows the visualisations that were created by the Netatmo web application.



### Arduino sensors

In order to be able to measure other experiments, an Arduino temperature setup was created (figure 5.2.2.2 & appendix S). This setup had four distinct temperature sensors, that were connected to ThingSpeak, an online graph visualiser. This setup was coded so it logged temperatures every 10 minutes.

### Evaluation

This was a side project of Arduino programming in order to be able to meas- ure and compare multiple surfaces at the same time. It was a very helpful tool as it created a large set of real-time data. The setup was made com- pletely watertight, so test could be done during the day and night. Later, the interval was changed to 30 minutes, so the data was easier to evaluate.

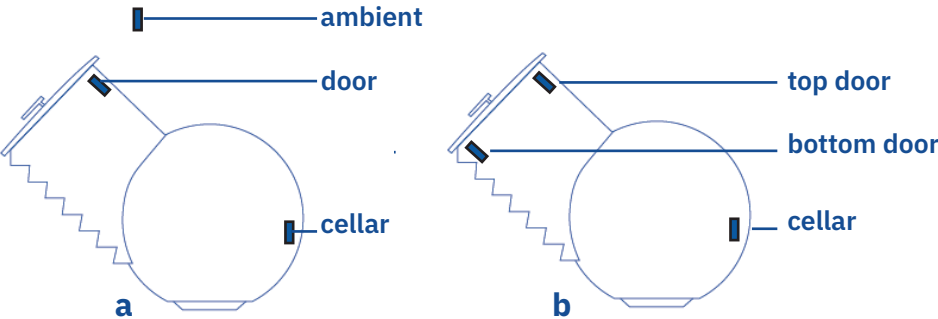


figure 5.2.2.1a&b: Measurement set-ups inside the Groundfridge.



figure 5.2.2.2: Arduino set-up. Source: author



5.2.3 Reflection layers

Aluminium reflection

A plate of aluminium was placed on top of the GF door, in order to test whether making an aluminium door was going to solve the problem. The idea behind this is that aluminium has a high reflectivity, and therefore reflects the solar radiance back into the atmosphere (section 3.7). The test was performed over a timespan of 24 hours, with a comparison test without the plate of 24 hours as well. In appendix J the results are described and visualised.

Evaluation

From this test, it became evident that having an aluminium plate will reflect radiative heat, but the metal will be a good conductor for ambient heat and only increase internal temperatures in the GF.



Reflection layer

To test the combination of a reflective and insulation, a test was done (appendix N). In order to test this, two prototypes were made from acrylic glass, flax insulation and aluminium foil. These boxes are simplified versions of the layered door design, as they have 2 layers of plastic, with insulation on the inside. Two set-ups were created, one with an aluminium foil (setup A, figure 5.2.3.2) and one without (setup B, 5.2.3.3). Both of the boxes have a layer of air between the outer shell and the insulation or reflection foil, since that is necessary for radiative heat to be reflected. The goal was to prototype the current door, and add another reflective layer to test whether the integration of this foil inside of the door made difference.

Evaluation

From this prototype, it became evident that reflection foil has a significant effect on keeping infrared heat outside. However, this combinations of materials should be tested on a larger scale and more in the context of the GF.



figure 5.2.3.1: Aluminium plate on GF door. Source: author

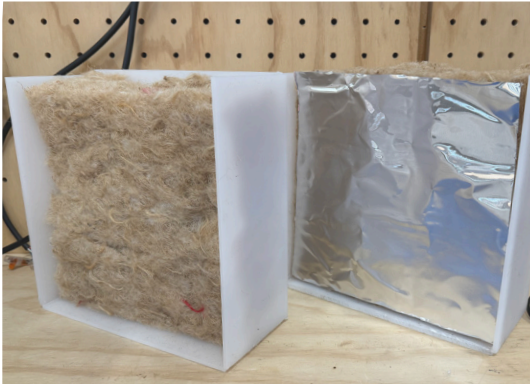


figure 5.2.3.2: Acrylic boxes with materials, set-up A (left) & set-up B (right). Source: author



figure 5.2.3.3: Boxes photographed with a thermal camera. Source: author

5.2.3 Coatings

Different coatings V1

In section 3.5 the theory of passive radiative cooling is explained. This test setup was created with 6 panels with different coatings: control, white paint, CaCO3, TiO2, and a mix of CaCO3 and TiO2 (appendix S). The panels were arranged outside and by means of a thermal camera, the temperature of the panels on the front and backside were measured and compared.

Evaluation

It became evident that white paint and TiO2 had the lowest measured temperatures and CaCO3 together with the control had the highest measured temperatures.

Since the measurements are done only with a thermal camera, this test is not precise enough. The thermal camera calculates the temperature based on reflectivity of the surface and is therefore not the absolute temperature.

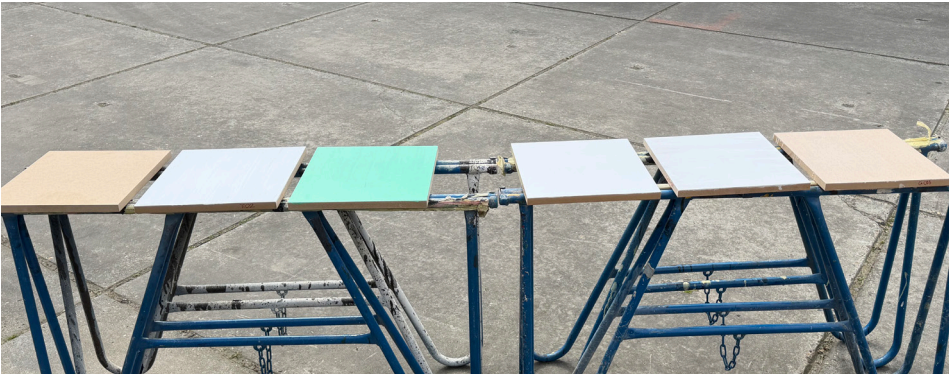
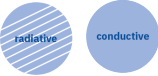


figure 5.2.3.1: Different coatings setup V1. Source: author

Different coatings V2

To build on the evaluation of the test setup, this test was done to evaluate which surface coating most efficiently reduces the absorption of heat, created by solar radiance and ambient heat (appendix S). In this test, the use of the Arduino sensors (section 5.2.1) was added in combination with the thermal camera. The setup was measured over a period of 24 hours, so the radiative cooling properties could be better analysed. Four panels were used: control, TiO2, white paint and CaCO3.

Evaluation

White paint and TiO2 both achieved sub-ambient temperatures on surface level during daytime. CaCO3 again performed worse than all the other panels. White paint, followed by TiO2 is the strongest passive cooler.

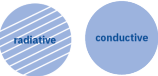


figure 5.2.3.2: Different coatings setup V2. Source: author



Coating ratio

From the test with different types of coatings became clear that TiO2 was the most interesting coating to use as radiative cooling mechanism. Therefore, this test was conducted to explore how different concentrations of TiO2 would effect this cooling effect (appendix T). Four panels were coated with green paint mixed with 0%, 5%, 10% and 20% TiO2 by weight and were set-up outside in the exposure of the sun. The panels consisted out of two layers, with an air gap in between and the temperature sensor placed in the middle of it. The Arduino sensor setup logged the temperature over a period of 24 hours. Ambient temperature was recorded simultaneously to compare the temperatures with.

Evaluation

All the concentrations reduced the heat absorption compared to the 0% panel. The higher the concentration, the better the result. At peak temperature (12:53), the 20% panel was measured 2.0°C cooler than the 0% panel.

During the analysis of this test, it became evident that the particle size of the TiO2 was not optimal for passive radiative cooling. Further research stated that integrating this particle size is a research on its own, and therefore, it was concluded that this would not be appropriate for this project.

The tint of the paint does have a significant effect and therefore, the design should opt for a lighter colour rather than the green colour it currently has.

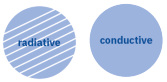


figure 5.2.3.3: Different ratio setup. Source: author

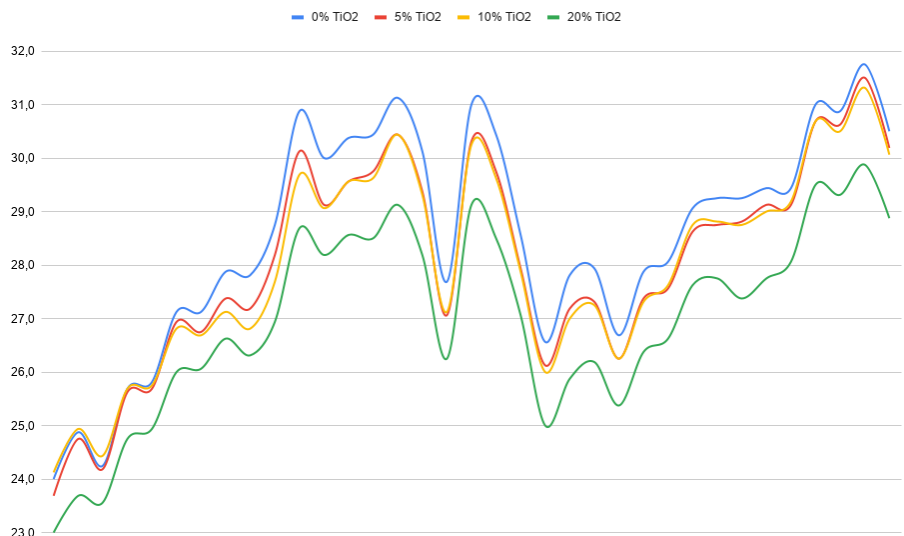


figure 5.2.3.4: Temperature measurements of different ratios.

5.2.4 Air control

Smoke test

At the beginning of the project, it was unclear whether the ventilation system performed as desired. In order to understand how the ventilation system performed, an airflow simulation was done. From this, it became clear that a realistic simulation is quite complex. To analyse the airflow path and whether the air was distributed across the whole GF, a smoke test was performed. With a smoke machine placed outside of the air inlet of the GF door, the ventilator moved the smoke to the other side of the tunnel. By means of a live camera, a recording was created to later analyse this.

Evaluation

From this test, it can be concluded that the ventilation system is sufficient. Additionally, other people already were busy with an improved version of the ventilation system that was easier to understand, monitor and had more power. Therefore, the ventilation system itself falls out of scope of this project.



figure 5.2.4.1: Smoke test setup. Source: author

Air valve cover

Since the air valves are uncovered, the air from outside and inside can mix in order to reach a stable temperature. This test explores what the impact of air valve covers during the day would have on the internal temperature of the GF (appendix P). Two caps were 3D printed and applied on the air valves during the day. As a control, another day with a similar diurnal curve was compared to see the results. In the first test, the caps were removed at 17:00, and this disturbed the airflow significantly, resulting in even higher temperatures than the control day. Hence, a second iteration was done in which the caps were removed after sunset, when the ambient temperatures dropped below internal temperatures.

Evaluation

From the tests, it can be concluded that the addition of the valve covers is not as easy as it seems. The covers do have a slight influence, but they also have a negative influence as the built up heat is also unable to escape. A smart system could be integrated that automatically opens and closes based on the outside and internal temperatures. Additionally, as the insulation in the door is not sufficient, the covers can also not compensate for this. Therefore, this intervention also falls out of scope until the insulation is improved.

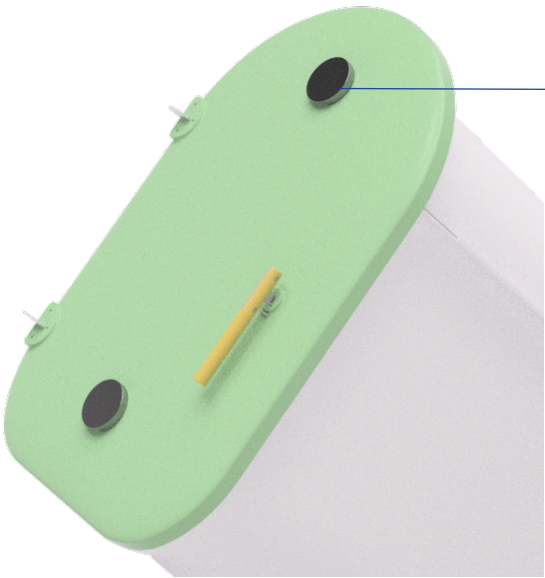


figure 5.2.4.2: Render of valve covers. Source: author



Strip curtain

Another air control test was performed, in the form of a strip curtain (appendix U). This PVC strip curtain was hung at the top of the tunnel, in order to measure whether internal temperatures stayed more stable when opening the door. On the day of the measurement, the door was opened three times for a short period. The temperatures of this were compared to the data of the control day, where there was no curtain and the same amount and time of opening the door.

Evaluation

The results of this test show that the addition of the curtain has great potential. The curtain has a significant stabilizing effect on the cellar temperature, despite the with-curtain day reaching higher temperatures. Cellar temperatures on both days reached 12.5°C max, with the ambient peak temperature on the with-curtain day was 7°C higher than the without-curtain day. However, a direct conclusion can not be drawn, since the days differed significantly in peak temperature. A more controlled test setup should be established, with multiple days of testing. This can confirm the stabilizing effects of the strip curtain.



figure 5.2.4.3: Strip curtain in GF. Source: author

5.2.4 Olla system design

Olla pot

As stated in the design vision (4.1.2), ideas were generated for creating a nature based system that would have cooling effects (appendix H). The idea was generated from the phenomenon of evapotranspiration (section 3.5). The goal of this test was to evaluate whether a combination of an olla system and vegetation would reduce the soil temperature in comparison to the soil alone. To test this, the soil of two terracotta pots were measured during a whole sunrich week. The first setup was a pot with an olla system, a terracotta pot filled with soil, an inflow of water and a moist regulating plant. The other setup was the control setup, the same pot with the same amount of soil. The temperatures were measured during a whole week, with intervals of 30 minutes. The temperature was measured at surface level and approximately 15 cm deep in both setups. Ambient temperature was logged as well in order to compare it with.



figure 5.2.4.1: Olla test set-up. Source: author

Evaluation

The results of the test conclude that the olla prototype is functioning as an active evapotranspiration system and has a cooling mechanism. The data of the temperatures clearly visualises a significant cooling effect at both depths. The data shows promising effects, since the cooling effect increases as ambient temperature rises. On warmer days, the deep sensor at the olla setup logged +/- 3°C cooler than the control setup. Simultaneously, at shallow level, the olla pot read +/- 5-8 °C cooler in comparison to the control setup. This aligns with the theory behind evapotranspiration, as soil surface evaporation and transpiration from vegetation are greater. On days with lower temperatures, the difference between the olla setup and the control setup decreases and sometimes disappears close to entirely. This confirms the cooling effect is driven by latent heat and the energy that raises soil temperature in the control setup is transformed into water vapour. After a whole week, the water level of the basin that was approximately 20L halved down, meaning +/- 10L of water had evaporated through the system.

This test is very promising and interesting due to the self-regulating nature of this system. The olla in combination with the vegetation actively cool down the soil when the temperatures are the highest and plants are under large heat stress. Therefore, this idea has to be further tested in a larger setup and during a longer period. A note to make is the fact that the olla setup also has more shadow created by the vegetation. Therefore, some cooling effect could be assigned to this but it emphasizes the importance of vegetation and plants on top of the GF hill.





Float valve

In order to create a system that works automatically and does not need much effort from the user, a float valve system was tested. The idea is that there is a floating object attached to the water inlet of the olla, that automatically regulates the water level within an olla. In this way, the only requirement for the water flow system to work is a bit of pressure inside of the basin. As the water level drops, the buoyancy of the floating object gets smaller and therefore drops, resulting in a pin to free the way of the water tube and water flows in the olla. When the floating object rises again, the inlet is blocked and water stops running. To test this, a 3D printed version of a float valve was attached inside of an olla and the working mechanism was assessed

Evaluation

This exact system worked in the sense that the floating part of the valve did become more and less buoyant in correlation to the water level. That has promising potential, since it means the olla is automatically filled when the water level decreases. However, this specific float valve did not completely stop the water from flowing, since it was 3D printed. The flow of the water should be more exact in future systems.



figure 5.2.4.2: Float valve test. Source: author

5.3 RtD takeaways

MRO

Improving the thermal performance of the GF.

- 1 A reflection layer in combination with insulation is significant in reducing radiative heat transfer in the door.
- 2 The colour of the surface has measurable effect on heat absorption, and should be a lighter colour.
- 3 Addition of a strip curtain shows promising potential in stabilising internal temperatures when opening the door.

R02

Increase user value of the GF.

- 6 The lack of an understanding was confirmed during testing.
- 7 The olla system can be self-regulating, creating a low-effort system

R01

Analysis of the thermal behaviour of the GF.

- 4 Air valve covers have limited effect, and should not be the priority.
- 5 Passive cooling coatings are too experimental and expensive for this project, a lighter colour is the better alternative.

R03

Ecological and systemic sustainability

- 8 The olla/vegetation system demonstrates a measurable and self-regulating cooling system.
- 9 The olla system becomes more relevant in higher temperatures.
- 10 A float valve can regulate the water level and prevent water waste.



figure 6.0: The Groundfridge on location. Source: Oep Schilling

In this chapter, all insight from previous explorations will be converged into a final design. This design consists of two implementations, focusing on the thermal stability of the Groundfridge: the Climate gate, a redesign of the door and the Groundflow, an evaporative system. The design interventions are presented by visualizing them in their context, their embodiment, the thermal behaviour and lastly, a use case scenario. Each intervention will be validated against their thermal performance, manufacturability, user desirability, economic viability and sustainability, to assess how well the design fulfils the assignment focus.

# 6 Final design

## 6 Final design

### 6.1 The living Groundfridge system

#### 6.2 Climate gate

##### 6.2.1 The design

#### 6.3 Groundflow

##### 6.3.1 Groundflow system

##### 6.3.2 User scenario

##### 6.3.3 Manual

#### 6.4 Validation

##### 6.4.1 Thermal performance

##### 6.4.2 Manufacturability

##### 6.4.3 User validation

##### 6.4.4 Estimated costprice

##### 6.4.5 Sustainability in design



figure 6.1.1: The Living Groundfridge: Climate Gate in context. Source: author



figure 6.1.2: The Living Groundfridge: Groundflow in context. Source: author





figure 6.1.3: The Living Groundfridge in context. Source: Jelle van den Brink



## 6.1

# The Living Groundfridge

The Living Groundfridge system consists of two intertwined design implementations that combine improved thermal performance and deepens relationship between the product and its user. By implementing these two systems as combined, the overall thermal stability improves and the product value increases.

The Climate Gate mitigates the thermal weakness located in the door of the current product. By increasing the insulative and radiative blocking characteristics, the door acts as a thermal barrier guarding the Groundfridge from warmer outside temperatures, protecting the products that are stored inside. The internal conditions will be stable, even during peak temperatures.

The Groundflow system makes the system alive and connected to Mother Nature. A water basin connected to multiple ollas, combined with a vegetation plan, adds an extra layer of thermal performance.

Evapotranspiration is the driving force behind drawing away heat from the Groundfridge hill. The more the sun shines, the more water is evaporating, making it a self-regulating system. This functions as a barrier between the surface soil and the Groundfridge that is buried underneath.

The user's interaction with the Groundfridge system improves as a result. The Groundflow system acts as a feedback system for the user: how hard the system has been working means how hot it was, and how the inside conditions are fluctuating due to this. Maintaining and monitoring become a ritual that is integrated in the sustainably driven lives of the users.

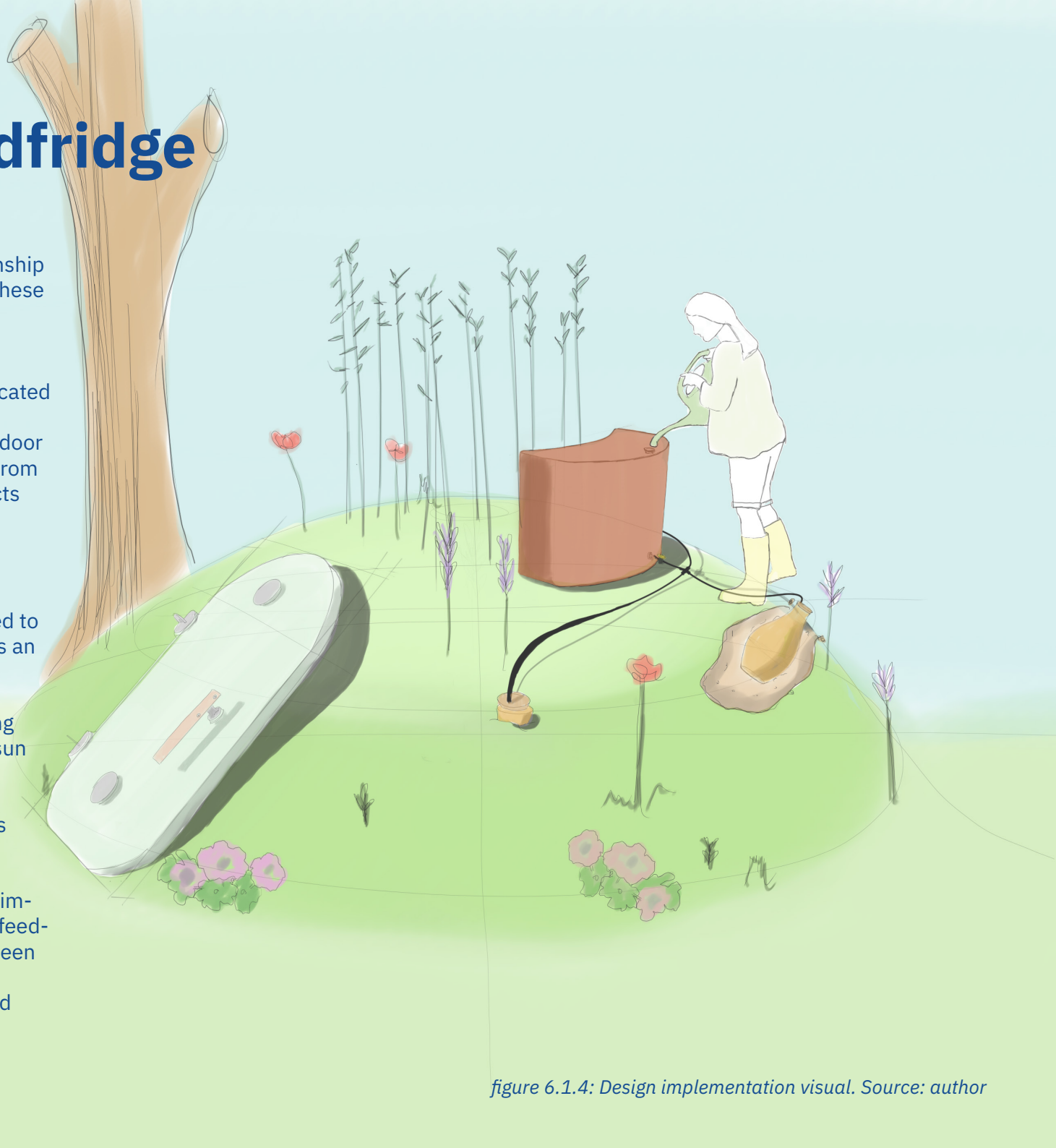


figure 6.1.4: Design implementation visual. Source: author



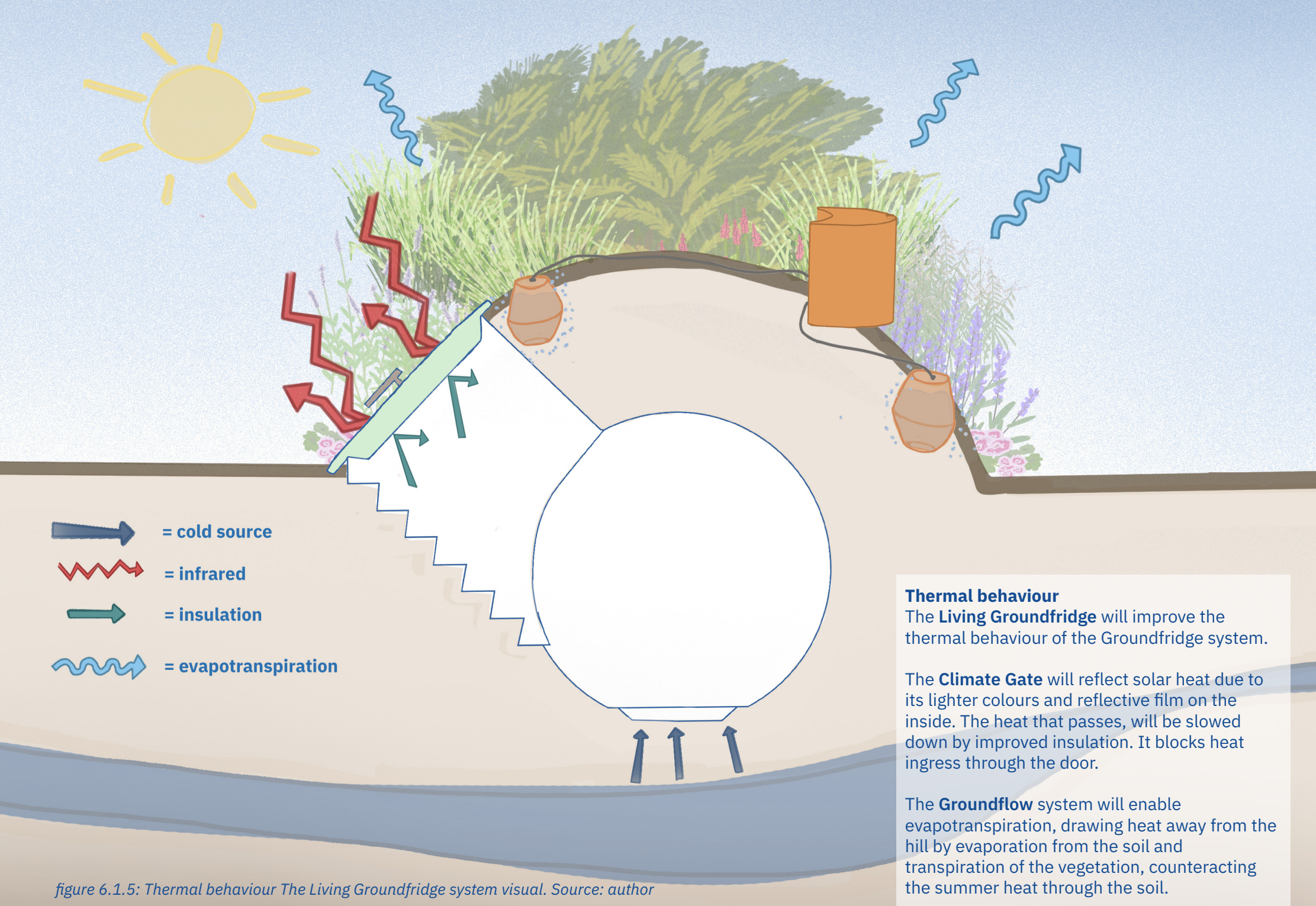


figure 6.1.5: Thermal behaviour The Living Groundfridge system visual. Source: author

## 6.2

# Climate Gate

### 6.2.1 The design

#### Improved design

The Climate Gate is a redesign of the door, transforming the weakest thermal spot of the Groundfridge into a thermal barrier. The surface of the Climate Gate is finished in a lighter green gelcoat, significantly reducing solar heat absorption. Beneath the outside surface of the door, the combination of a reflective foil and an air gap, actively blocks radiative heat, originating from solar radiation and ambient temperatures, reflecting it back to the outside. Heat that still penetrates through these layers is absorbed by the insulation inside. Finally, a thicker layers of insulation increases the thermal resistance and heat will enter the inside of the Groundfridge more slowly. Together, these interventions will increase the overall thermal resistance of the door to the desired 3.7 [Rc].

#### Embodiment

A cross-section of the improved design is visible in figure (6.2.1.2). The geometry of the outer glass composite shell will stay the same, and the inner glass composite shell will be made 48.05 mm thicker. That creates space for the air gap, Mylar reflection layer and thicker insulation slab. The surface of the composite will change to a lighter colour gelcoat, preferably RAL 6019 instead of 6021. This change reduces the absorption of solar heat. The application of this will stay the same as in the previous design. The combination of the Mylar reflection film and the air gap will result in a reflecting layer that blocks radiative heat. The air gap is necessary for radiative heat to exist and to be blocked, before it is converted into conductive heat. The Mylar film is attached onto the Rockwool with some glue at the sides, so it is evenly spread across the insulation. To hold the Mylar reflection film in place, two spanners of 20 mm, exactly the measurements of the air gap, are horizontally placed in the outer shell. This tightens the reflection film and supports the performance of the film. The insulation will be the same material, but made thicker with 28 mm. This is cut so it fits the bulb of the inner shell. The existing rubber will be also implemented in this design to keep the door airtight and decrease convectional heat entering the GF.

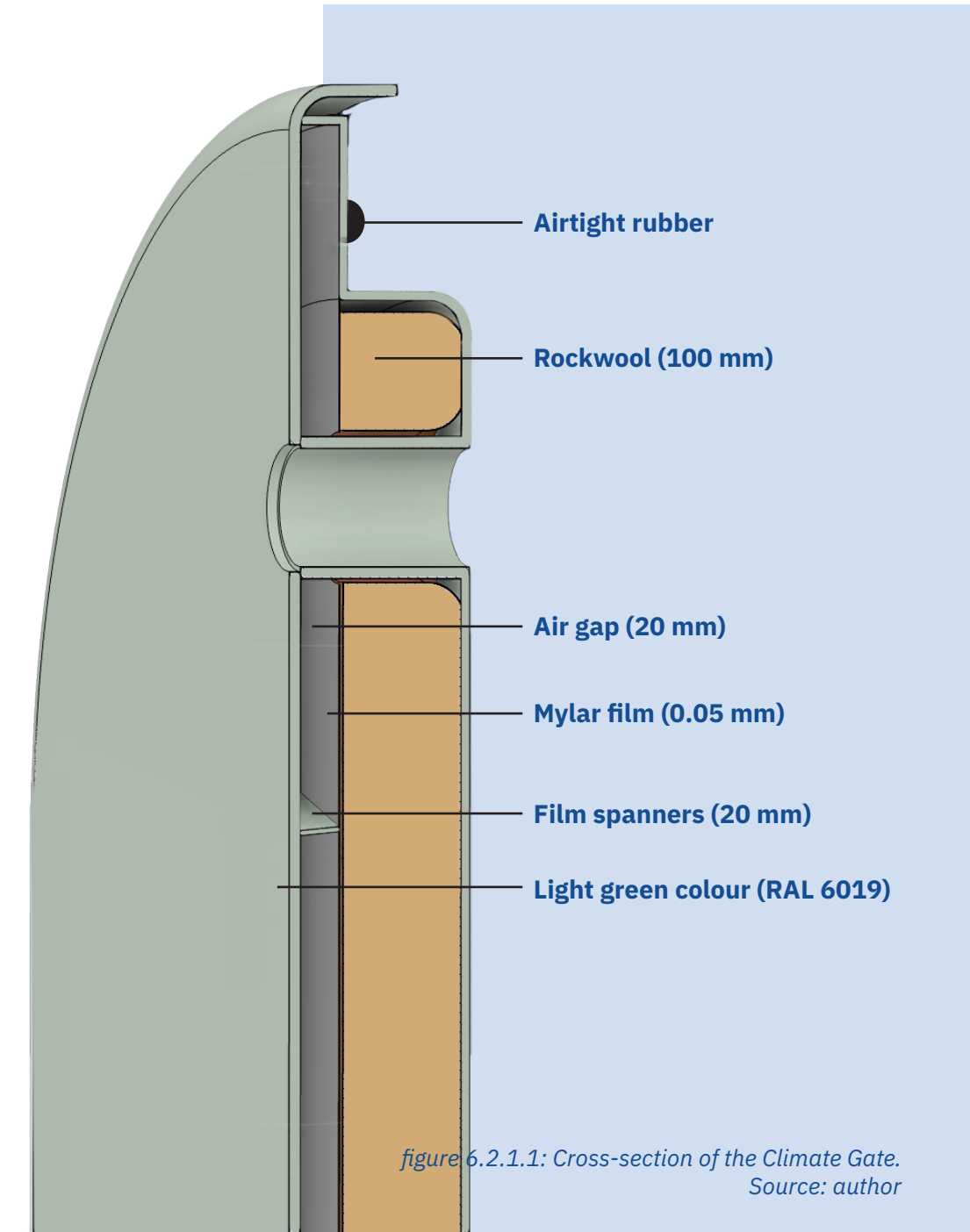


figure 6.2.1.1: Cross-section of the Climate Gate. Source: author





figure 6.2.1.2: Prototype of the Climate Gate. Source: Jelle van den Brink

# Improvements

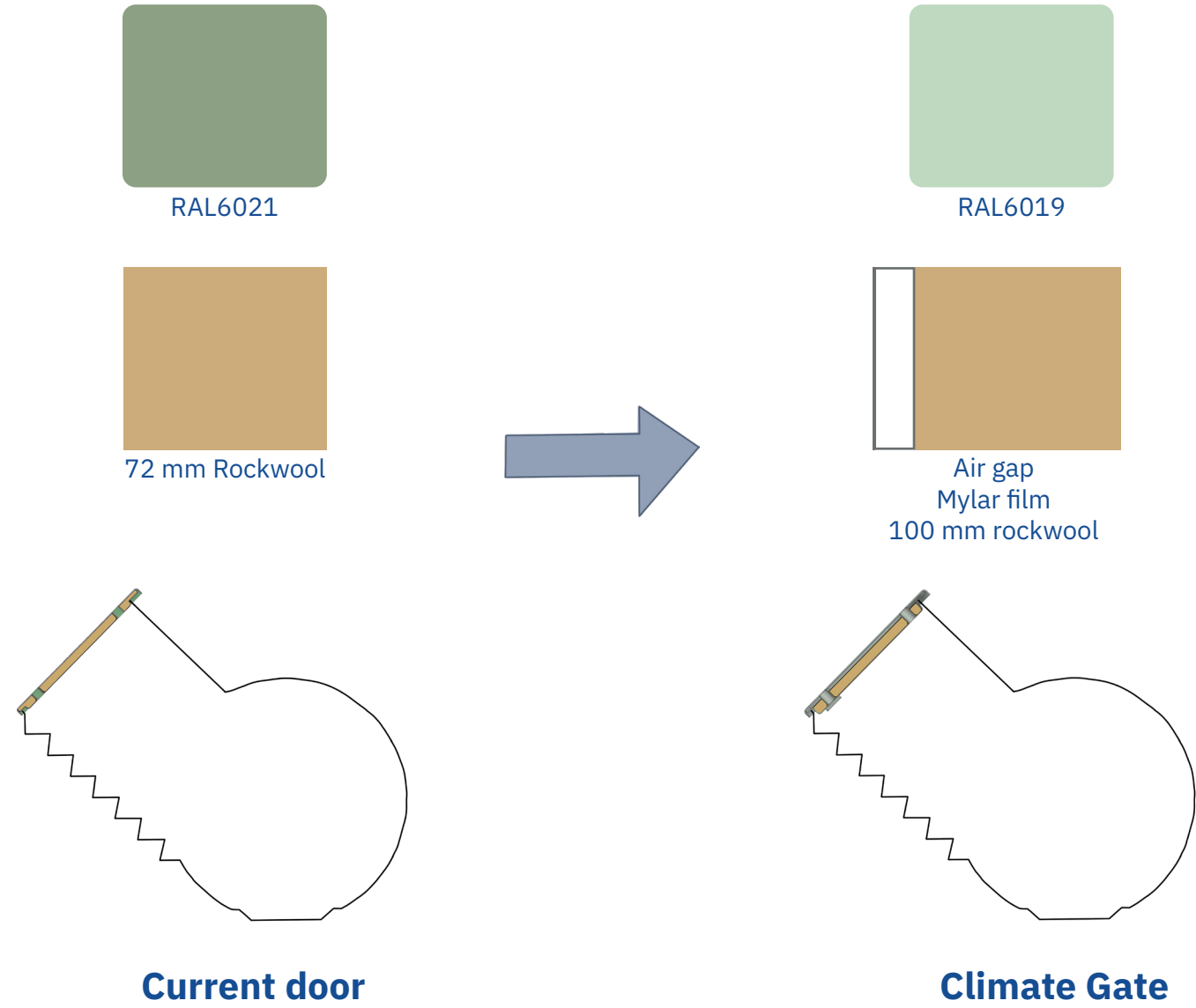


figure 6.2.1.3: Improvements in comparison to current door. Source: author



## 6.3

# Groundflow

### 6.3.1 Groundflow system

#### The concept

The Groundflow system transforms the Groundfridge from a passive product into a living, self-regulating system that actively cools the Groundfridge and the hill around. It is serving as a barrier between the buried Groundfridge and the surface soil, that is warmed during warm days. The water basin is placed higher on the Groundfridge hill, and is connected to an olla network. The ollas are buried underground and transfer the water that is originating from the Groundflow basin to the roots of the plants on top of the hill. Due to the nature of the terracotta material, water is slowly released to the vegetation. As the soil and the plants evaporate the water from the ollas, heat is drawn away to the atmosphere. This heat is in the form of latent heat in water vapour. This system is completely natural and happens in the plants surrounding us. It is a self-regulating system, and the warmer it is outside, the more evapotranspiration takes place.

The vegetation on top of the Groundfridge hill is carefully curated and divided into three layers: a top layer of vegetation with a lot of static air, a middle layer of vegetation with water regulating characteristics and a bottom layer that integrates the hill into the surrounding garden (figure 6.3.1.1).

The user is connected to this system by monitoring and refilling the basin. This establishes a simple, yet meaningful interaction ritual that connects the user to the thermal conditions of the GF and the natural mechanism behind it. The vegetation plan also results in a beautifully flourishing hill that is integrated in the user's garden. The plant types are carefully chosen in order to be green almost all year round, without too much maintenance.



figure 6.3.1.2: User interacting with the Groundflow system. Source: author

figure 6.3.1.1: Prototype of the Groundflow system. Source: author



figure 6.3.1.3: Jinke planting the vegetation. Source: Jelle van den Brink



## Vegetation plan

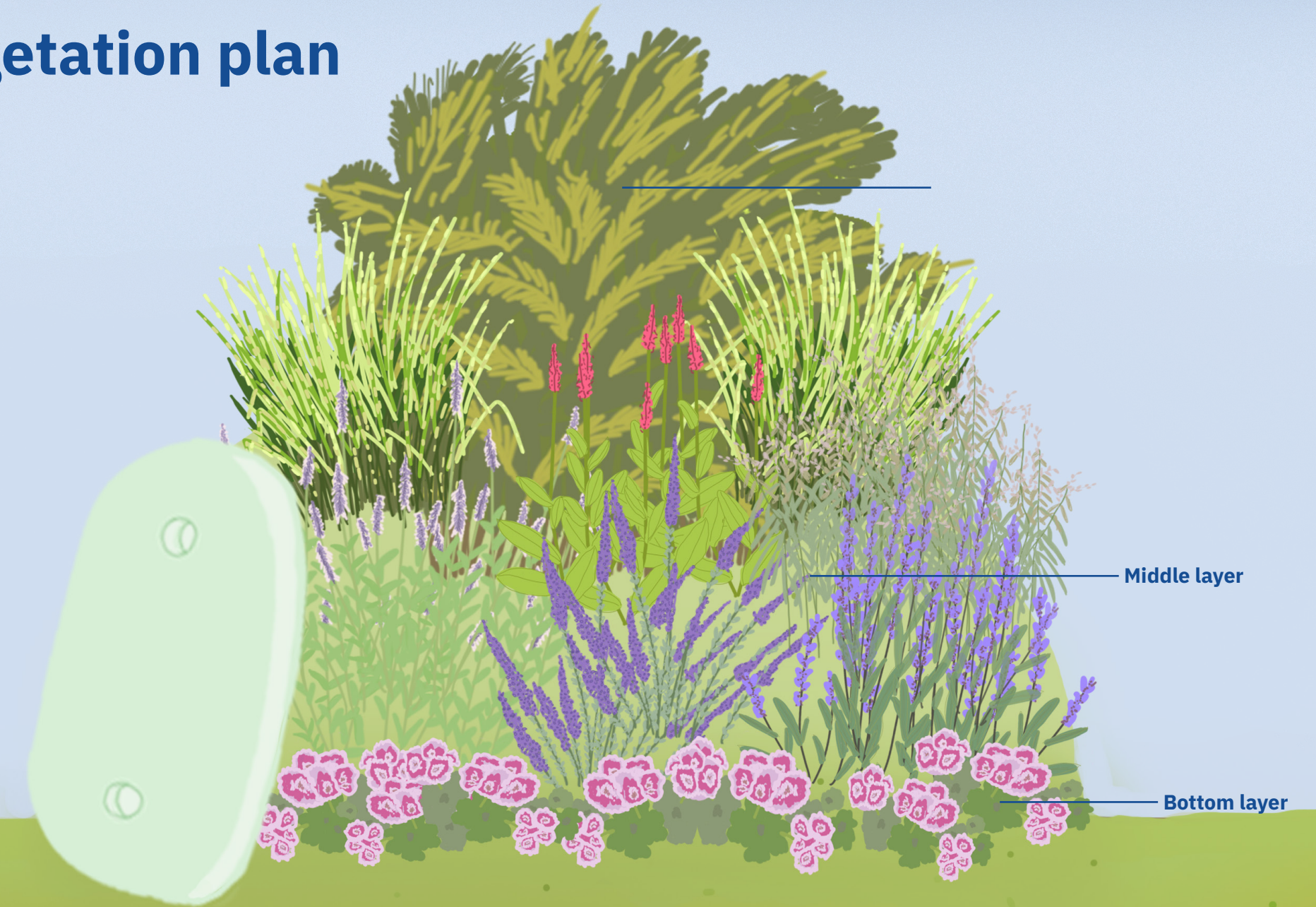


figure 6.3.1.4: Groundflow vegetation plan. Source: author



**Embodiment**

The system is a passive water supply system, that works from the Groundflow basin. The user puts water inside of the basin, that can store up to 250 litres of rainwater. From this basin, the water automatically is divided by micro-hoses and dividers into four ollas, that are located in the middle layer of the Groundfridge hill. To keep the ollas filled at all time, the float valves are integrated in the ollas. These valves drop and rise with the water level, driven by buoyancy, and regulate the inflow of water. The user does not have to constantly monitor the ollas and only the water basin.

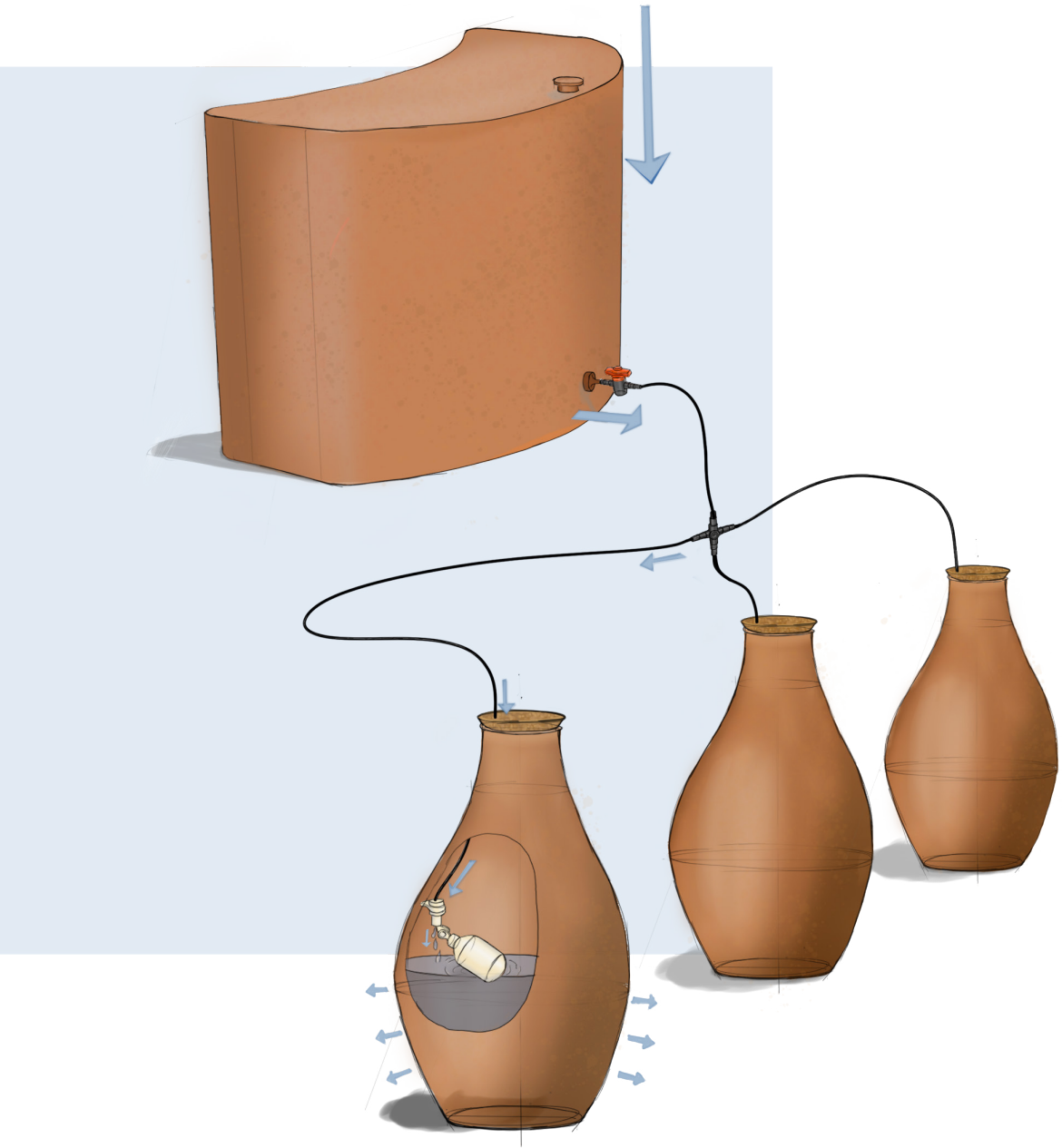


figure 6.3.1.5: Groundflow water supply system drawing. Source: author

**6.3.2 User scenario**

**How does the Groundflow work?**

1. The user installs the Groundfridge in the regular way with a scavenger.
2. Immediately after the installation of the Groundfridge, the Groundflow system is installed by burying the ollas in the ground, and placing the basin on top of the hill, like the topview\* visualises.
3. The user follows the guidelines, which describes how to plant the vegetation types according to the three layers as described in the manual.
4. The user fills the water basin whenever it is empty and the water automatically flows into the ollas.
5. By means of evapotranspiration and breaking of warm air, the heat is drawn away from the Groundfridge hill.
6. The user enjoys their product cold from a cool Ground-

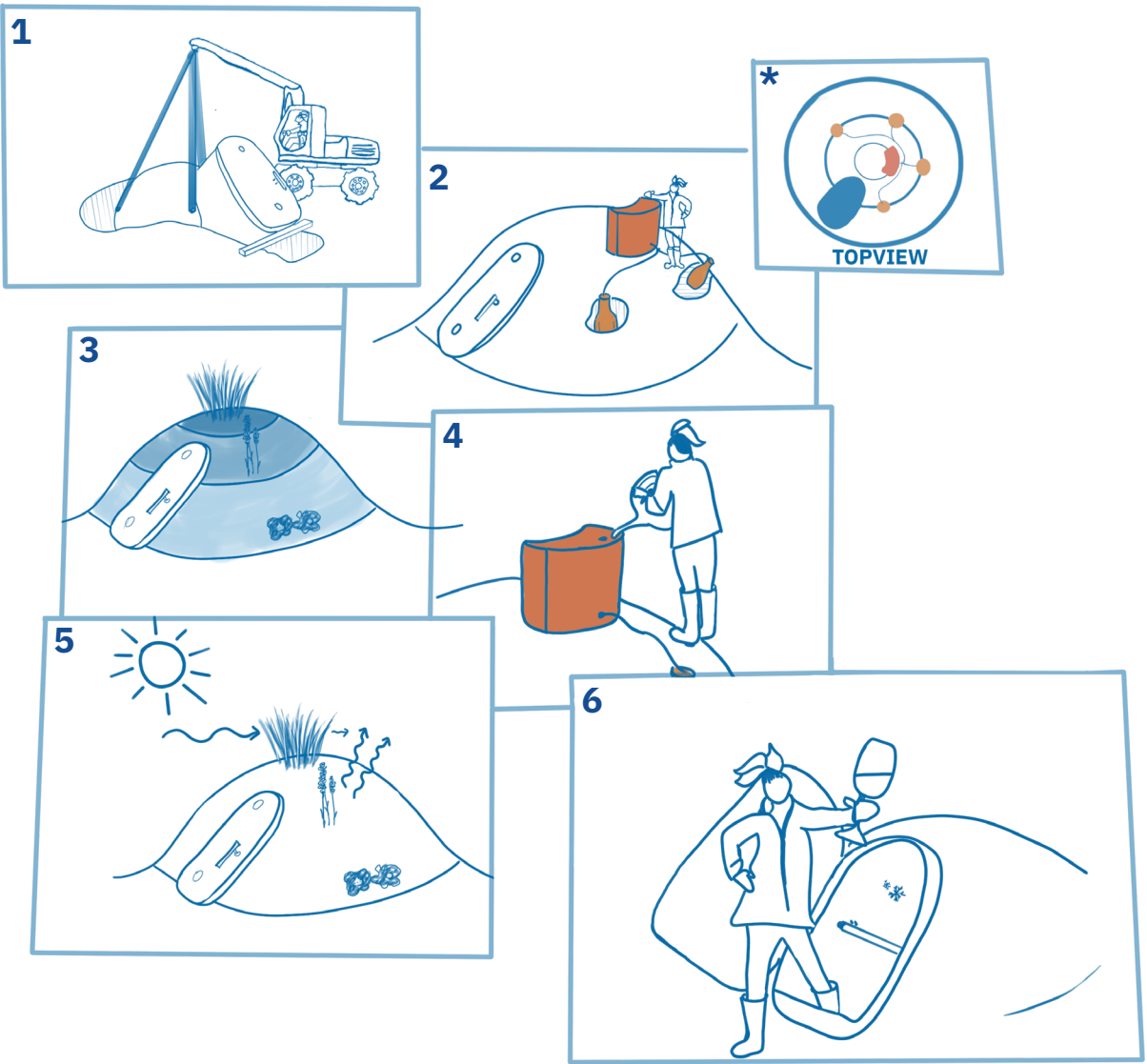


figure 6.3.2.1: User scenario of Groundflow system. Source: author





figure 6.3.3.3: Groundflow manual interaction. Source: author

### 6.3.3 The manual

Next to the system being crucial for its functionality, there is another key element that is necessary to educate the user about the working mechanism behind the Groundflow system, installation and maintenance: the manual.

Interaction value only is relevant when the user understands the product. Therefore, a Groundflow manual is created, to educate the user about the system. This manual functions as an instruction about the Groundflow system, as well as an informative source for the vegetation plan, so that the user has an indication about what plants to put on top of the soil surrounding the Groundfridge.

This manual covers everything from system visualisation and vegetation layers to plant description, the working mechanism, step-by-step usage, and maintenance guidance (appendix Z).

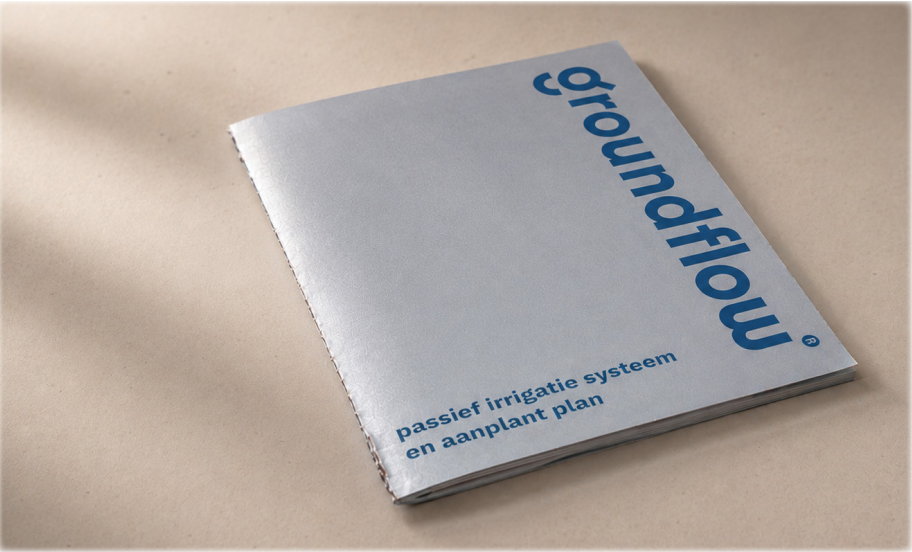


figure 6.3.3.1: Groundflow. Source: author, enhanced with ChatGPT.



figure 6.3.3.2: Groundflow manual. Source: author



6.4  
Concept development

A goal of this project was creating a full-scale prototype, which was made over time with a lot of iteration and testing. At Fiction Factory, it was possible to create all of the prototypes.

Climate Gate

To make the prototype of the Climate Gate, the analysis and RtD section functioned to gain insights about material use and dimensions. After creating this idea, the concept was created in a 3D modelling programme. In order to fit on the CNC, the model was built from 18 mm sheets, with shanks nested in order to prevent waste (image 6.4.2). After milling the wood, the parts were assembled with dowels and glue, integrating the insulation and reflection foil. The final prototype was made with Okoume front piece and the rest in plywood since this functions better in outside environments. The door was finished with a Rubio monocoat, in a lighter colour.

Groundflow

A prototype of the Groundflow system was created by welding 1 and 2 mm steel in the specific shape. Rolling it to create radius and grinding away all the excess steel. This took quite a lot of effort, since the shape was rounded, so it was a two-person job ;). After finishing it and welding it waterproof, the Gardena micro hose system, float valves and ollas were connected and tailored to the dimensions of the Groundfridge hill. The basin self-regulated, keeping the water level consistent.

Manual

The Groundflow manual and all its visualisations were created with Adobe Photoshop, InDesign and Illustrator. Since the visualisations had to be consistent with the brand vision, all the illustrations were created in the same style and manually made.

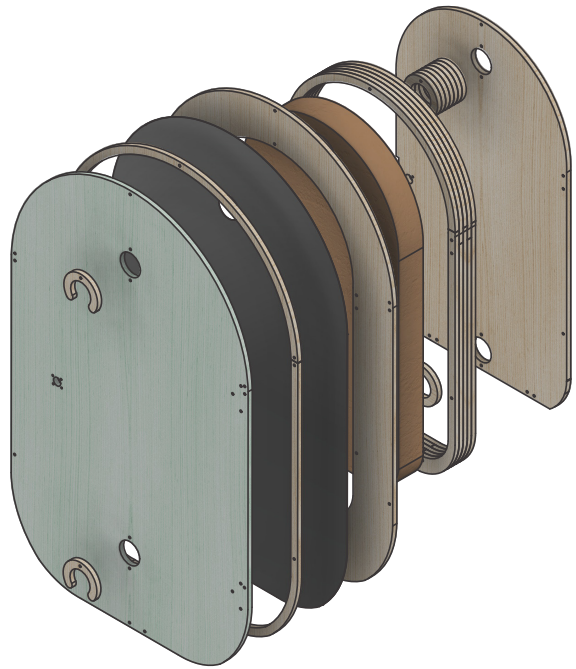


figure 6.4.1: Concept development. Source: author



figure 6.4.2: Prototype fabrication in Fiction Factory. Source: au-





figure 6.4.3: Installing the Groundfridge on site. Source: Jelle van den Brink

## 6.4

# Validation

### 6.4.1 Thermal performance

#### Climate gate thermal performance

The first door prototype (figure 6.2.1.1 and appendix Y) shows that the improvements of this door increase the thermal stability of it. The thermal resistance of the final climate gate will be improved to  $R_c$  3.7. That is an improvement of 1.7 times in comparison to the current door. Based on this  $R_c$ , it is estimated that it blocks about 41% of ingress heat, contributing to an improvement of 10-15% of the total system. This is supported by the measurements done with the first Climate Gate prototype (appendix Y), showing the internal temperature stays more stable and lower in comparison to the current door. On warmer days, the internal temperature of GF stays at least  $1^\circ\text{C}$  closer to the soil temperature, with the estimation of this having a cooling effect up to  $2^\circ\text{C}$ . The final prototype is installed, and will be tested later due to time constraints. This will be valuable data that Groundfridge can use to validate this design, and improve the construction of their product.

#### Groundflow thermal performance

As the olla test (section 5.2.4) showed, the addition of vegetation and an olla system clearly reduced the temperature of the soil measured in two points. At surface levels this reduction of temperature was about  $5 - 8^\circ\text{C}$  cooler and at lower level it reduced temperature  $3^\circ\text{C}$ . Research substantiates this and it is expected that evapotranspiration will reduce the soil temperature between  $2-5^\circ\text{C}$ . In order to compare it concretely, the water basin has a capacity of 250 L, and during a warm summer period it is estimated that one basin per week will be evapotranspired. Given that the latent heat of vaporization of water is approximately  $2.45 \text{ MJ kg}^{-1}$  (Allen et al., 1998), this amount of water corresponds to a latent cooling flux of about 1.0 kW. Compared to the Siemens KG36EALCA refrigerator-freezer combination (Siemens NL, n.d.), which consumes approximately 149 kWh per year and has an estimated cooling output of 43 W, the implementation of the Groundflow can be compared to roughly 24 domestic refrigerators. Similarly to the prototype of the door, a prototype of the olla system is installed in the context of the Groundfridge hill and the thermal analysis can be done in the nearby future.

### 6.4.5 Manufacturability

#### Manufacturing feasibility

While the proposed door improvement strategy shows strong thermal performance, in personal communication from the manufacturer raised important feasibility concerns. In order to fit the thicker insulation, a 20 mm air gap with and fit insert the Mylar film tightly, spanners should be inserted. However, over time, the Rockwool might settle and gradually lose contact with the skins, resulting in a reduction of insulative properties. Reliably creating the air gap would require the internal spanners and other reinforcement that demand trials, testing and production time.

As an alternative, Wentech recommends foam injection, filling the cavity between the laminated shells completely and the insulation would not settle while adding minimal production time. However, this would require new moulds specifically adapted to the injection process with injection and air escape holes. These findings do not invalidate the thermal performance, but indicates that translating the design into a reliable, repeatable production may require a revised design and insulation strategy beyond the scope of this thesis.



6.4.2 User validation

In section 3.8.2, the user needs are described. In order to validate whether the design intervention is desirable, these needs should be satisfied.

Monitor the product

The Groundflow uses the water basin as a feedback system about the ambient conditions of the environment. The higher the ambient temperatures are, the more evapotranspiration takes place, and the faster the water flows through the system. This reflects also on the internal conditions of the GF. The level of the water basin works as a monitoring system and the user becomes aware of fluctuations in temperatures by becoming aware of the changing water level of the system.

Seasonal awareness

The vegetation plan added to the Groundflow system becomes a mechanism for the user to become more aware about seasonal changes in their garden.

Sustainable lifestyle

Integrating an evapotranspirative mechanism in combination with a vegetation plan contributes to more biodiversity and more stable temperatures in the users’ garden. This is contributing to their perception of sustainability.

Connection to garden

The vegetation plan is carefully curated to integrate the GF hill into the garden, and by filling the water basin, the user will be in touch with the plants more often.

Product with pride

As the stability of the GF increases, the user will be likely to be more satisfied with the GF and this leads to pride. The system is a more holistic system, aligning with the desire of the user.

Effortless functioning

The only input that the user has to give is filling and monitoring the water basin and preparing it in winter and summer. The rest of the system is self-regulating and therefore requires little effort.

Organisation of inventory

The users often forgot what was stored inside of their Groundfridge. With a printable inventory list,they can hung inside their house to keep track of what is stored inside. An example of this inventory list can be found in appendix BB.

Validation with user

The Living Groundfridge was installed on Texel, complete with the Climate Gate and the Groundflow system. The Climate Gate was very easy to install and the future users understood immediately how the system would work, based on the manual. The user was very enthusiastic about the look of the Groundfridge hill and the Groundflow system and was very curious to see how the experience was over time. The integration of the system and the vegetation plan fostered a lot of curiosity and

There were some concerns about blockage of the micro hose system, and therefore the system should be revised in order to make more reliable. This is taken up in Additionally, the vegetation plan is based on relatively small plants, and in this context some extra plants were added to create a more cohesive hill.



figure 6.4.2: User needs.Source: author

6.4.3 Estimated costprice

For the company to evaluate what investment should be made, an estimated costprice is calculated. The cost prices are an estimate, since it varies widely as there are a lot of factors to keep into account. The prices vary based on production volume, so to make a realistic estimate, the volume of 20 GFs per year will be used as the baseline.

Climate Gate

The improved door will be made by the same manufacturer as the current door, as this is the most straightforward choice. The manufacturing price of a current door is approximately €500, including all steps. The redesign of the door would require new moulds for the fibreglass composite shells, while the other layer can be used in the future. This new mould is the largest investment for Groundfridge. In the redesign, there would also be an addition of 28 mm insulation and a layer of reflection foil, with spanners keeping this in place.

Based on assumptions, the estimated cost price per door improvement is calculated as following:

€9000 for designing and creating new moulds, that allow the additions within the door. This includes designing the door, creating a mould, and finishing it for usage. If taking 20 GFs per year, this would be an addition of €450 per GF for one year. However, the cost of the mould would decrease over the years.

Price per door:

- €6 for addition of 28 mm of Rockwool (Isolatieoord, n.d.)
- €15 for purchasing and assembling of the Mylar reflection foil (personal communication)
- €55 for purchasing and assembling the spanners to keep the foil and insulation in place (personal communication).

The total addition would be €76 per door, for a significant improvement in thermal stability.

Groundflow system

The Groundflow system is a new system, and determining this cost price is also dependent on multiple factors, such as sourcing the materials, assembling the products. This product will be assembled at FictionFactory, and sold to the user whenever they want to purchase it. If assuming that 50% of users wants the addition of this system, meaning 10 systems per year.

Based on assumptions, the estimated cost price per Groundflow system is calculated as the following:

- €300 for a custom Corten steel water basin
- €60 for a system of four, 4-litre ollas
- €25 for the micro hose system, including tap, dividers and micro hose itself
- €16 for four float valves, that are assembled into the olla
- €40 for assembling the system, and making it ready to ship.

The total materials and manufacturing price would be calculated at €441, and this will be sold for around €1067,22, if the margin is 50% and VAT is 21%.

For a unique, personalised system, this can be validated as successful, as it fits into the premium garden market that Groundfridge positions itself in already. The vegetation plan is a recommendation and therefore it is the users own responsibility. In appendix W, an overview of the estimated costs is given, coming to a cost of €227.

To contextualise the viability of the Groundflow system, it can be compared to an automated Gardena microdrip system (Gardena, n.d.). This is an irrigation system that is connected to sensors to automatically start dripping when it is getting warmer. This system costs usually between €200 and €350. Therefore, the Groundflow is positioned significantly higher, but it works as a thermal regulator and is completely passively, requiring no power source, software and little maintenance. Additionally, the Corten steel basin can be a sculptural garden element.



### 6.4.4 Sustainability in design

#### Design with nature

The Groundflow system actively cools the GF hill through evapotranspiration. This is an example of designing with nature, harnessing a natural occurring mechanism that vegetation have used for eternity to regulate internal temperature. The implementation of vegetation and water-regulating systems into the Groundflow, the system embraces biomimicry and includes natural ecosystems that regulate the temperature of an ecosystem, without relying on external energy. Thus, including evapotranspiration contributes to environmental sustainability as it does not require additional energy supply, tackling urban heat island effects and improving thermal stability. The implementation of this creates a resilient and regenerative system, working hand-in-hand with Mother Nature.

#### Biodiversity

The vegetation plan is created around the idea of plant species that are suitable for Dutch soil and environments. The plants also increase biodiversity since the bamboo and miscanthus in the top layer creates a habitat for birds and insects (Goadart et al., 2010). The flowers of the middle layer attract different insects, like bees, butterflies and other insects and act like a pollinating environment (Erickson et al., 2021). The bottom layer increases the ecological value for organisms in the soil and insects as well (Jędrzejewska-Szmek et al., 2018). Addition of this vegetation plan, that is powered by the Groundflow system, will add beneficial values to a garden, especially in urban environments.

#### Water waste

The Groundflow system is self-regulating, and the combination of ollas and float valves control the flow of water automatically. This prevents water waste between 50 and 70% (Sagouspe, 2025), while maintaining a beautiful garden. The water that supplies the Groundflow system could be sourced from rainwater, or directly connected to the Raintap by Floris Schoonderbeek. By relying on alternative water sources, the need for freshwater is minimized and emphasizes the system’s regenerative and sustainable approach.

#### Materiality

While the Groundflow system embraces regenerative, nature-based sustainability principles, the Climate Gate is more complex in material sustainability. The door assembly remains predominantly polymer-based, using fibreglass composite skins in combination with Rockwool insulation and Mylar film. This assembly is hard to recycle, since it is bonded together with epoxy. This multi-material composite assembly is difficult to separate at the end-of-life and therefore becomes significantly difficult to reuse or recycle. This was a deliberate trade-off, since introducing alternative materials that were more sustainable into a product that is already polymer based would have added complexity without meaningfully improving circularity. The redesign therefore prioritises thermal performance and manufacturability over full circularity. Therefore it is representing a conscious compromise between sustainability, feasibility and viability than a naive pursuit of sustainability.

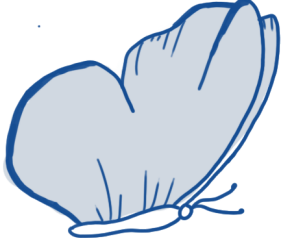
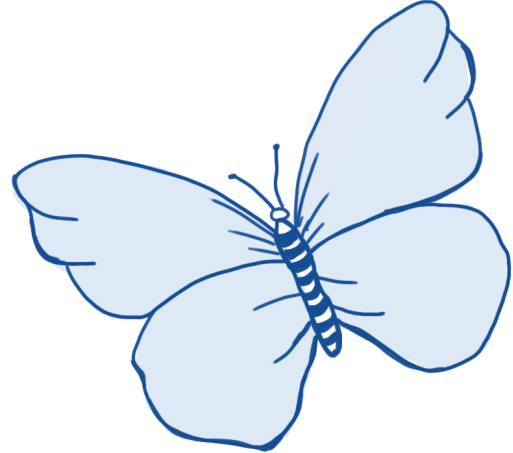


figure 6.4.4: Biodiversity illustration. Source: author





In this chapter, the projects limitations will be discussed , followed up by suitable recommendations for Groundfridge to undertake further steps. A future vision statement will be illustrated to visualise a regenerative future. A conclusion together with a project evaluation will round up this project report.

# 7 Closing

## 7 Closing

- 7.1 Project limitations
- 7.2 Advice for Groundfridge
- 7.3 Future vision statement
- 7.4 Conclusion
- 7.5 Evaluation



# Project limitations

Every project is a product of effort, time and resources available. This design project was carried out with great ambition, but just like any other project, it operates within its boundaries. This section presents an honest review of limitations encountered during the design project, concerning the testing conditions, scale of validation and a number of insights that fell outside the scope.

## Environmental volatility

The door redesign shows an improvement of thermal stability, and the increased thermal resistance contributes to lower internal temperatures. The thermal performance is very likely to improve, but this is not guaranteed. The Groundflow system shows great potential during testing by regulating the temperature of the surface and subsurface of the soil, but its exact effects are difficult to determine due to the complexity of natural systems. Nature is a highly volatile system with a wide range of different factors influencing the temperature. Not all possible locations, soil type, climate contexts and installation factors were tested and analysed.

## Non-simultaneous prototype testing

The testing of the prototype door in comparison to the original was done sequentially, and not side by side. Therefore, the conditions under which was tested were not identical, limiting direct comparison. In order to be able to compare, data with similar environmental conditions were analysed and compared.

## Long-term performance

The measurements conducted in this project aimed to be precise and consistent. Yet the results from these are relatively small-batched due to the time limitation of this project. In order to have a clear interpretation of how the prototypes function over time and in different weather conditions, a longer period of testing should be done. Due to the time constraints, the last prototype has not been tested and analysed, but this will be done after finalisation of this project.

## Prototype fidelity

The Climate Gate prototype is made of different materials than the future door consists of, and therefore can influence the results from the testing. Different base materials, finishes and assembly can have an effect on the thermal performance of the prototype.

## User validation

The user validation in this project was limited to installation of the Ground-flow system and proof of the Groundflow manual. In order to substantiate the desirability, a larger sample of users should be tested.

## Geographically specific vegetation plan

The vegetation plan is creating according to the suitability of the plants in the Netherlands and European countries with a temperate maritime climate. Therefore, in order to implement the functionality of the vegetation plan in other geographical regions, the specific climate should be assessed and the vegetation plan should be adapted to this.

## RtD as methodology

RtD was the central methodology used in the process of generating insights and knowledge. However, these insights are context-bound, interpretation specific and difficult to generalise. The findings are generated from a specific design situation, and therefore the insights should be understood as specific for this project.

## Sustainability compromises

The materials selected in the redesign of the door are mostly polymer based materials, and therefore not biodegradable or circular. The redesign of the door contributes to sustainability by increasing the thermal performance and previously environmental benefits in the sustainability validation (6.4.4). This is deliberately chosen compromise, since implementation of biodegradable insulation and reflection into a product that is already polymer based, will only increase difficulty of recycling. Therefore, in the redesign the insulation will be Rockwool, the radiation film is Mylar, and the coating stays the same. This results in a compromise between sustainability, feasibility and viability, whereby manufacturability is taken into account.

# Advice for Groundfridge

This project aimed to increase the value of the Groundfridge and its user experience. As the Groundfridge is dependent on many interacting factors, there is always room for further development. This section suggests what further developments can be done by Groundfridge from insights in this project.

## Measurement and monitoring

The thermal behaviour of the GF is dependent on seasonal variation, and therefore all the implementations done should be tested across multiple seasons to get proper insights about its behaviour. Additionally, the measurements and data generation of the GF should be done in multiple locations, soil types and climates to get an understanding of its behaviour. In these measurements, it is recommended to insert multiple other temperature measurements, like soil temperatures at different heights and internal temperature at different heights.

## Customer interaction and relationship

Analysis in this project revealed that there is a lack in understanding the product among users. Currently, there are no guidelines about the use of the GF. It is unclear what products can be stored in the GF, and how they have to be stored. To address this lack of clarity, it is recommended to create a user manual that guides the user in how to use, maintain and live with the product. Information is a significant factor to create understanding and long-lasting value. A newsletter or platform sharing the latest developments and insights would help sustain a relationship with both existing users and potential clients, strengthening their connection to the product and the brand.

## Groundwater and soil temperature awareness

Since the groundwater and soil temperature are the main cold sources, it would be recommended to make the user aware of these. This can be done by creating a widget on the Groundfridge.com website or by referring to the KNMI website. In this way, the customer is also connected to the site, and the relationship between the brand and the consumer is strengthened.

## Rethink product positioning

From the user interviews, it became apparent that the GF is often purchased with the motivation that it is a more affordable alternative to a customized or prefab cellar. Moreover, the GF does often not require a permit, making it an attractive option. Including this in the marketing strategy is recommended, so this should be communicated on the website or other channels more pronounced. It is also recommended to create user stories and personas, in order to map the needs of the users and adapt GF’s service and systems accordingly. This would contribute to product and brand positioning.

## Product improvements

Several opportunities for further product development emerged during this project. Firstly, the Groundflow system should be refined and made bullet-proof, to increase reliability and reduce user monitoring. Some ideas are provided in appendix AA. Second, the RtD insights concluded that integrating a curtain into the tunnel could minimise heat gain when opening the door. This idea can be implemented in the form of a simple curtain that the user can close before opening the door. Further research is recommended into the thermal influence of the exposed tunnel section and the air gaps within the Climate Gate to identify additional performance improvements. In addition, a smart ventilation system could be developed to regulate airflow based on temperature differences between the interior and exterior environment. Finally, because high humidity limits the Groundfridge’s suitability for dry storage, a climate-control solution for moisture regulation could expand its functionality and appeal to a broader range of users.

## Sustainability

For future development and to fully align with the sustainable vision of the brand, it would be valuable to research alternative materials for the design. Substituting the fibreglass composite that is almost impossible to recycle, to an alternative construction that is easier to process in recycling streams. Also, in the sustainability analysis it became apparent that there is no information or program regarding the end-of-life, which is something that Groundfridge should provide in order to call itself a sustainable brand. Integrating ease-of-disassembly or a recycling program is recommended, so that the product can be taken care of in the end phase of its life. Lastly, Groundfridge should include traceability in its communication, since that is becoming an important topic, regarding the Digital Product Passport that is now being developed by the ESPR (n.d.).



# Future vision statement

The Groundfridge is not a product. It is a threshold to a sustainable lifestyle.

We have forgotten how to live with the seasons. Everything we want is always available. We store food in machines without knowledge and we throw away the things we do not know and understand. We want more and more, quicker and quicker. Does that make us happy?

The Groundfridge is the beginning of a different story.

From a surface perspective it is a passive, underground root cellar that keeps food cool without use of electricity. Just a product.

Beneath that, the Groundfridge becomes a teacher. Seasonal change. The growth of plants. The stable temperature of the earth. To live with a Groundfridge is to relearn the intelligence of the earth that most of us have forgotten about: knowledge that was once common and now nearly lost.

On an even broader perspective, Groundfridge becomes a connector. The garden and the Groundfridge are one continuous system. Storing what you grow. Understanding the cycle of the seasons that grew it. The garden, the user and the Groundfridge become one.

At its widest reach, the Groundfridge becomes a cycle itself. Preserving. Fermenting. Composting what is left. Return it to the soil in order to grow more food. What nature gives, is also given back. The cycle closes.

The Groundfridge does not ask people to change their lives overnight. It invites the user to take it step by step and rediscover the relationship humans once had with the earth.

figure 7.3.1: Groundfridge Vision Puzzle. Source: author, enhanced with ChatGPT



figure 7.3.2: Laying the puzzle. Source: author

This is the vision behind the puzzle: not a product to own but practices to embed into a lifestyle. All the rings have an extra profoundness.

Groundfridge becomes more than a product, but a platform to connect people with the seasonal cycle. To inspire users into fermenting again, preserving, how to use food waste, what vegetables and fruits are in season and how to grow it.

Groundfridge should create an infrastructure for reconnecting with nature again, a road to a different future.

The ground was always intelligent. We just stopped engaging with it.

The future Groundfridge listens again and teaches us to do the same.



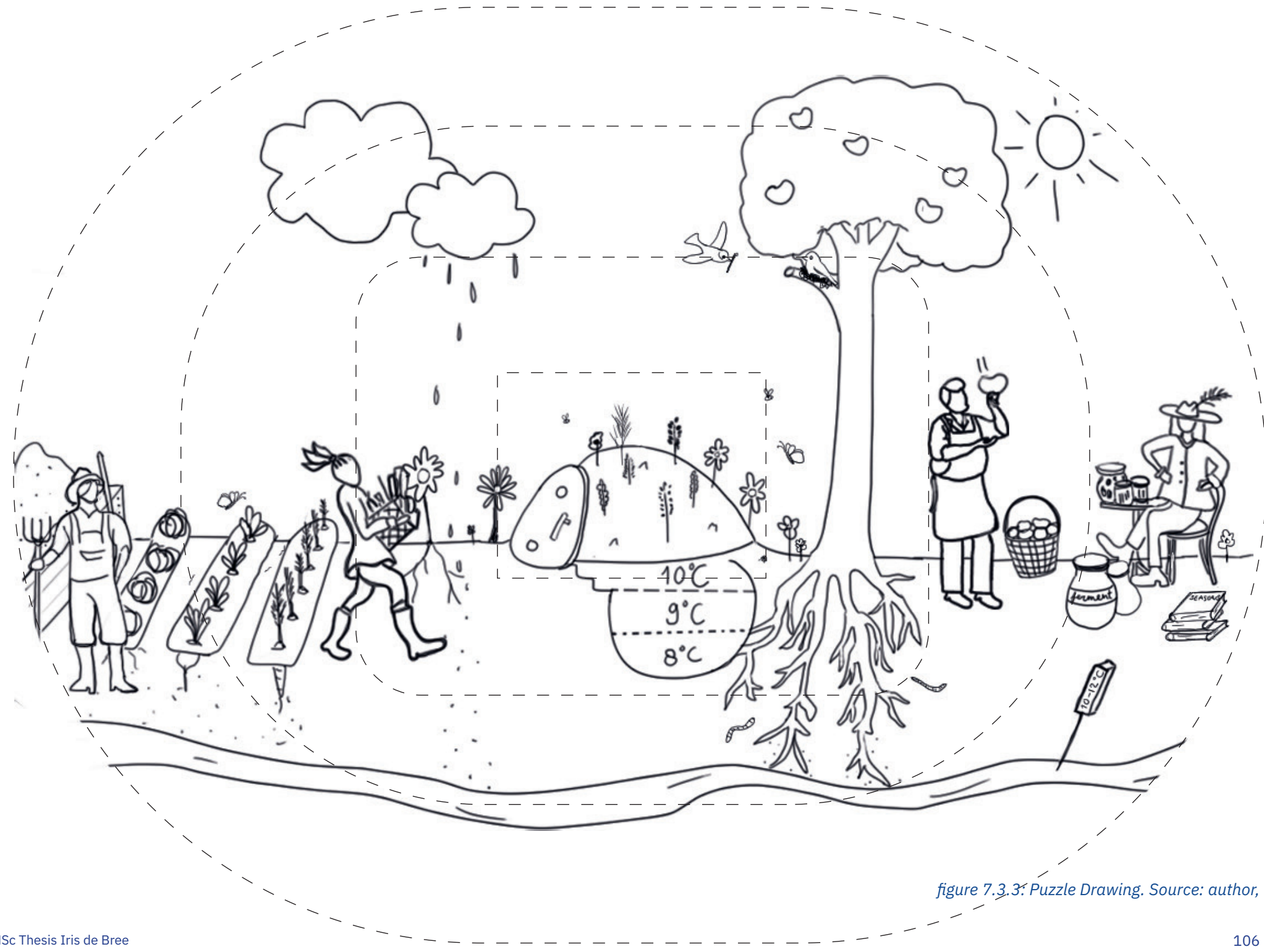
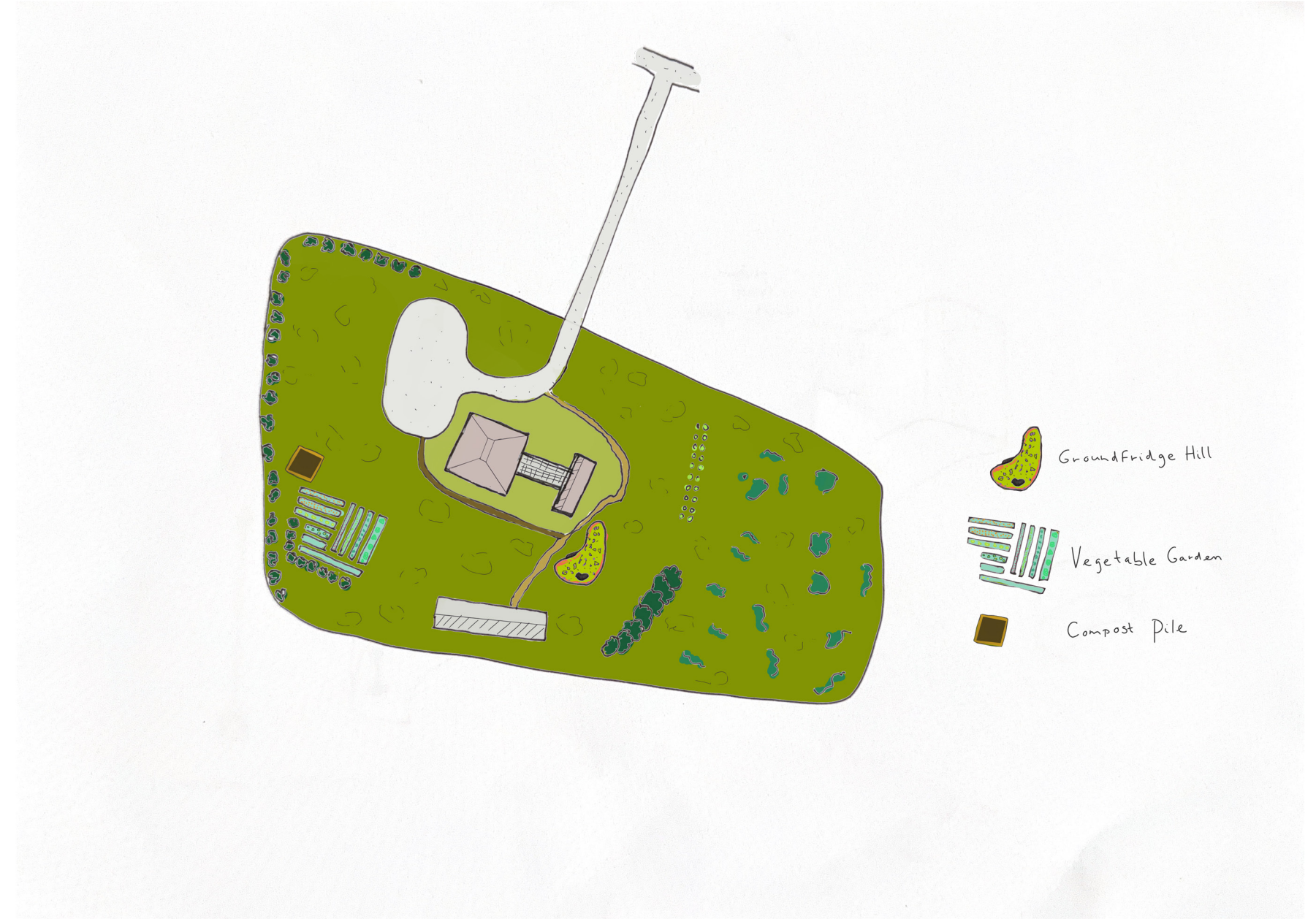


figure 7.3.3: Puzzle Drawing. Source: author,





## Conclusion

This graduation project aimed to explore how the Groundfridge could become cooler. By analysing the thermal behaviour of the existing Groundfridge and investigating opportunities to optimise conductive, convective, and radiative heat transfer, the project identified technical opportunities. In the analysis of the current system context, it became clear that the user asked for a better understanding of the product, and the project focus evolved into one that integrated experience into the design and connected the product back with its user and nature.

The resulting Living Groundfridge combines two cooperative design interventions. The Climate Gate improves thermal stability by means of increasing the thermal resistance in the door. By integrating more insulation, a reflective film in combination with an air gap and changing the gelcoating to a lighter tint, the door reduces heat transfer from the atmosphere into the Groundfridge. Through the integration of these passive design strategies, the Groundfridge becomes more resilient to fluctuating environmental conditions without extra energy supply.

The Groundflow system increases this resilience by introducing nature as an active component in the cooling process. By means of an olla network, a Groundflow water basin and a carefully constructed vegetation plan, the system utilises evapotranspiration to regulate temperature by drawing away heat from the Groundfridge hill. As temperatures rise, the more heat is drawn away naturally, creating a self-regulating system that responds directly to environmental conditions. The Groundflow system makes these processes visible and understandable through the growth of vegetation, the water demand and the Groundflow manual.

Together, these interventions demonstrate that thermal performance and user engagement can support each other. The user is connected with passive cooling and becomes an active stakeholder in monitoring, maintaining and regulating the natural mechanisms that support the Groundfridge. The simple action of filling the basin or caring after the vegetation become meaningful actions that foster a deeper appreciation for food preservation, climate and ecology.

The Living Groundfridge demonstrates the potential of designing with nature rather than merely solving problems for it. The Groundfridge, its vegetation and its user become part of an interconnected system. Fresh food, ecological value and meaningful user interaction are the results of this. In doing so, the project presents a vision for sustainable product design in which natural processes are enfolded in daily practices, creating a more meaningful life.

figure 7.4: Oep and Iris installing the Groundfridge. Source: Jelle van den Brink



## Evaluation

After six months, this project has come to an end. From the beginning of the project, I wanted a project that gave me a lot of opportunities to learn. That is exactly what happened.

The topic of the redesign of the Groundfridge was centred around thermally improving the system. Since the Groundfridge is placed underground and exposed to various environmental factors, the thermal state of the system is capricious, making it a complex yet interesting assignment.

Through analysis and Research through Design, I have tried to encapsulate the behaviour in order to scope the assignment. This required a lot of iteration and the process was at times undefined. Writing the report and formulating takeaways served as a way to order the insights gained during the process.

Much like the Groundfridge itself, this project also had its fluctuations. To maintain structured during the project, I documented my process in a weekly update mail. Each update consisted of all the tasks done in the previous week, plans for the coming week, by using the “*What?, What so?, Now what?*” method, I evaluated the experiences I had and solutions for problems. In combination with advice for myself, I gained a lot of insights about my process and what challenges I came across.

The supervisory team consistently challenged me to create a project with real value and the meetings functioned to reflect on how I was doing. After the mid-term meeting, there was a very valuable reflection moment in which the supervisory team encouraged me to go beyond just the technicalities and explore other opportunities and stick to my own intuition more. This led into the Groundflow system, which covered more of the desirability and interaction aspects of the system. Later, after the Greenlight milestone, I was encouraged again to do something with my own vision of the product and the brand. This brought the project closer to my personal ambitions and created extra depth in the results.

A goal of this project would be to have a full-scaled prototype by the end. Both the prototypes of the Climate gate and the Groundflow, including vegetation plan and manual, have been implemented in a real Groundfridge and are currently being monitored. Since I got the opportunity to go to Fiction Factory, I also had access to the workplace. By asking a lot of questions across multiple facets of the organisations, I gained a great deal of insights into physically making products through, among others, woodworking, metalworking and Arduino programming. This broadened my skillset and deepened my understanding of production and what it means to work in a real project context.

This process of analysis, RtD, reflection and iteration resulted in meaningful implementations. The Climate Gate and the Groundflow in combination with the vegetation plan shows promising results in improving the thermal stability of the Groundfridge system. Beyond the thermal improvements, the addition of the Groundflow system together with the vegetation plan contributes to the brand by integrating interaction and regenerative approaches of sustainability into the system. Those are valuable implementations that go beyond mere functionality.

The implementations developed in this project are a starting point from where Groundfridge can develop its product and brand. The living Groundfridge system suggests a direction for a thermally stronger product that has enhanced interaction. There is more to explore and I am curious to see where it goes. Looking back, this project has taught me that meaningful design lives in the space between technical solutions and human intuition. The project required me to be precise and empirical, as well as to trust my own vision and process. Pushing myself technically, creatively and personally made me a more capable designer.





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**AI Disclosure**  
Artificial Intelligence was in this report used to order scientific reports, improve structure and grammar of text and to enhance some figures.

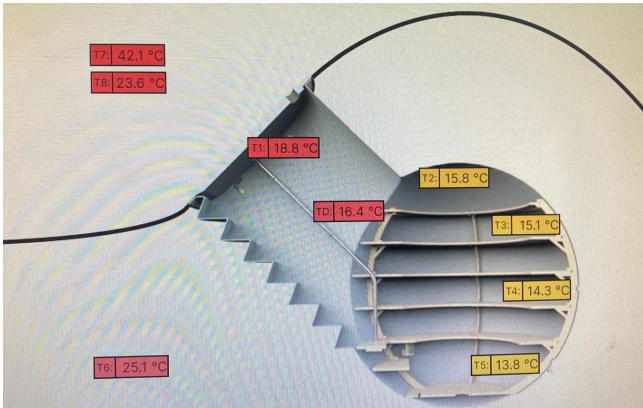
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# 9 Appendices

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## Appendix A - Previous temperature measurements



## Appendix B - Interview vragen en antwoorden

Vragen:

- hoe lang heeft u de Groundfridge al
- waarvoor heeft u een GF aangeschaft, welk doel?
- hoe ervaart u het gebruik van de Groundfridge?
- wat bewaart u het meest in de GF?
- wanneer gebruikt u uw GF, ochtend, middag, avond?
- merkt u een verschil in uw gebruik in de verschillende seizoenen (lente, zomer, herfst & winter)?
- zijn er dingen die u doet om de temperatuur beter te reguleren?

Antwoorden:

**Tom.** Deze mensen hebben de GF in de voortuin geplaatst en gebruiken hem als wijnrijpingskast.

- Hoe lang heeft u de Groundfridge al

Wij hebben de GF al sinds eind juli 2025, dus nu 6 maanden.

- Waarvoor heeft u een GF aangeschaft, welk doel?

We wilden een kelder van 4 x 8 meter in de voortuin onder de grond, alle plannen waren er al tot de tekening van de bar toe. Vergunningen waren er ook, maar toen kregen we de prijsindicatie van de aannemer, en wat eerst 63 000 euro ging worden, werd ineens twee ton. Toen zagen we het voorbij komen in een magazine en zijn we in Olst gaan kijken en wilden we dit gelijk.

De oplossing voor een kelder zonder vergunning. Al helemaal met de locatie aan de Vegt kan het grondwater erg hoog komen, hadden we misschien wel veel problemen gehad met een echte kelder.

Ook fietste ik wel vaak langs de ijskast wat de adel vroeger had bij het slot hier in de buurt en dat is altijd in mijn hoofd blijven hangen.

- Hoe ervaart u het gebruik van de Groundfridge?

Tot nu toe goed, maar we hebben hem nog niet zo lang. Het zou wel handig zijn als er een thermometer bij zou zitten. Daarnaast ventileren we hem tussen 5 en 7 ongeveer twee uur lang. Het koudste wat hij is geweest is 5 graden en het warmste is 27.6 in de zomer bij de installatie.

- wat bewaart u het meest in de GF?

Alleen maar wijn, ik gebruik het als een rijpingskast, en dat is ideaal want we komen er niet zo vaak. Er passen wel meer dan 500 flessen wijn in.

- Wanneer gebruikt u uw GF, ochtend, middag, avond?

1 keer per week, voornamelijk 's avonds als ik een glaasje wijn wil.

- Merkt u een verschil in uw gebruik in de verschillende seizoenen (lente, zomer, herfst & winter)?

Nog niet echt gemerkt want we hebben hem kort. Het is wel zo dat als de kou erin zit, die er niet zo snel meer uitgaat en als de warmte erin zit idem dito.

- Zijn er dingen die u doet om de temperatuur beter te reguleren?

De deur ligt wel in de zon, maar er hangt een blauwe regen die in de zomer als parasol functioneert. Later zullen we misschien een fruitboom planten voor extra schaduw, en er groeit ook een amandelboom voor.

Aanvullingen:

ze hadden er wel een beter slot op gewild, zeker met de wijn erin.  
ze vinden het een super leuk concept, en hadden hem zelfs nog wel in een maatje groter gewild.  
ze hebben het gevoel alsof de GF een beetje scheef staat (ik heb zelf erin gestaan en ik voelde dit ook wel een beetje)  
de GF is waanzinnig snel geïnstalleerd  
hij merkt wel heel veel slakken, misschien kan daar nog een extra rubberen rand gemaakt worden om dit echt buiten te houden



ze gaan nog het onkruid eruit halen, wat eerder tot wel een meter hoog groeide. er zijn planten die overwaaien vanaf de dijk aan de Vegt en daardoor hun zaadjes in de bult verspreiden vlierbessen en veldbloemen willen ze planten voor bijen en insecten ze gaan een trappetje aanleggen, zodat ze op de bult ook goed planten kunnen planten en onderhouden ze hadden een vergunning voor een kelder in de voortuin, maar de wetgeving zegt dat dit max 1 meter boven de grond mag. Richtlijnen en communicatie hierover zouden ze ook handig vinden.

Quote:

“het belangrijkste is dat je hem lekker groen moet laten zijn”

**Gerben en Claudia.** *Deze mensen hebben de GF achter de carport gelegd. Ze wonen in een baars, dus een veld tussen het bos.*

- Hoe lang heeft u de Groundfridge al

bijna een jaar, maar in de zomer kregen we hem niet koud

- Waarvoor heeft u een GF aangeschaft, welk doel?

Als opslag voor koelere producten. We hadden alles overal liggen, aardappelen en andere dingen, en wilden 1 plek om alles op te bergen. We waren op zoek naar alternatieve koelmogelijkheden, en het past bij het leven hier. Een airco-achtig systeem wilden we niet. En een kelder kost een ton extra.

- Hoe ervaart u het gebruik van de Groundfridge?

Goed. Aan het begin was de GF lek en werkte de ventilator niet, maar dat is nu wel opgelost. We vinden het wel onhandig om het niet aan huis te hebben, en soms missen we een overzicht van wat we in huis hebben. Maar kelders komen met veel toeters en bellen, hebben funderingen nodig, ventilatie. Tov een kelder is de GF niet duur, en bij een kelder moet je ook nog maar afwachten hoe het gaat zijn.

- Wat bewaart u het meest in de GF?

wijn, jam, eten en groenten. Het werkt als voorraad en opslag. Sommige dingen komen uit de tuin en andere dingen komen uit de supermarkt

- Merkt u een verschil in uw gebruik in de verschillende seizoenen (lente, zomer, herfst & winter)?

In de zomer wordt het wel een beetje te warm. Het zou ook fijn zijn als we meer inzicht hadden in hoe de temperatuur is, en ook hoe de ventilatie werkt. We hebben daar geen inzicht op. De ventilatie kan beter want op een gegeven moment gaan de groenten schimmelen. Ik heb ook weleens de groenten buiten moeten zetten om goed te ventileren.

- Zijn er dingen die u doet om de temperatuur beter te reguleren?

We hebben hem op een heel natte plek gelegd, waar het grondwater erg hoog is. Hier is het ook koud. De deur zit ook in de schaduw van de carport, wat super goed werkt.

Aanvullingen:  
we missen een simpele thermometer erin, het liefst met een vochtmeter. het zou wel super fijn zijn als we de temperatuur zouden kunnen reguleren. Het is logisch dat als het te warm is, je de GF niet kouder krijgt, maar een streef temperatuur zou wel echt fijn zijn, dat hij het automatisch aanpast. Er is ook niet echt een minimale temperatuur. Er is nu gewoon geen temperatuur sturing vanuit de gebruiker we vonden de ventilatie door de leuning door erg leuk, en misschien ook wel handiger dat de koude lucht van onder komt, en misschien ook wel beter voor de luchtstroom. we zouden ook wel wat meer weten over welke producten goed gaan op welke temperatuur. daarnaast zou je ook het Tesla model kunnen aannemen, dat je een product verkoopt wat ook nog verbeterd wordt en dat je contact houdt met de gebruiker en daar dus ook feedback van krijgt. Mensen accepteren het ook als auto's kapot zijn, als je zegt dat je constant verbetert, maar niet als je zegt dat het een compleet product is. Ik hou me ook zeker aanbevolen als jullie

met iets nieuws komen, zelf als ik ervoor moet betalen. we vinden het leuk dat het een europees product is, en dat mag je ook best promoten als het niet goed wordt geïnstalleerd kan het breken, dus je moet wel weten wat je doet. esthetiek vinden we mooi. De vorm is gaaf en de kleur is mooi. Het hout aan de binnenkant is ook heel leuk maar snel vies. RVS zou kunnen, maar dat is wel wat te koud. Is berken wel geschikt voor buitenklimaat?

Quote:

“we hadden alles overal liggen, nu ligt het op één plek!”

*Walter Bouwman (Vorst). Zij hebben de GF achter in de tuin in een schaduwrijke plek. Ze groeien een voedselbos aan.*

- Hoe lang heeft u de Groundfridge al

We hebben de GF nu een klein jaar.

- Waarvoor heeft u een GF aangeschaft, welk doel?

Voor eigen consumptie, en later voor de producten van het voedselbos, maar niet alles zal erin passen. We hebben geen kelder in huis, en ook niet echt een koude ruimte. Vandaar dat wij de GF hebben aangeschaft.

- Hoe ervaart u het gebruik van de Groundfridge?

Het werkt eigenlijk heel goed, hij blijft goed koud. Bij aankoop was de GF lek, en de ventilator was kapot, maar nu is dat beide gemaakt en werkt het heel goed.

- Wat bewaart u het meest in de GF?

Kombucha, voorraad en wijn. Er staat veel havermelk in. De directe voorraad hebben we in huis, en de rest ligt hier. We houden een lijstje bij wat in de GF ligt.

- Merkt u een verschil in uw gebruik in de verschillende seizoenen (lente, zomer, herfst & winter)?

De GF doet het goed. Hij draait al een klein jaar mee en in de zomer doet hij het eigenlijk ook goed. Het is veel koeler en drank en wijn blijft op goede temperatuur en dan is het binnen no time koud genoeg.

- Zijn er dingen die u doet om de temperatuur beter te reguleren?

Niet echt. Ze hebben ook een thermometer aangeschaft.

Aanvullingen:  
Het slot kan er wel op maar als mensen binnen willen komen kunnen ze toch wel binnenkomen. Ik ben ook benieuwd naar het Circlefarming evenement, dus als dat plaatsvindt dan ben ik er graag bij. plannen voor voedselbos: noten, fruit, struiken, besjes

**Take-Aways:**

temperatuur blijft redelijk goed, zelfs in zomer, beter dan verwacht. Maar de mensen hebben het ook nog maar max een jaar. mensen die ik heb gesproken begrijpen de fluctuatie in de zomer en zijn daar ook op ingesteld mensen vinden het leuk om mee te doen en betrokken te blijven thermometer bij aanschaf is een heel goede regeling van de temperatuur (min & max) is erg interessant gebruikers willen graag weten welke producten geschikt zijn, en op welke temperatuur deze moeten blijven.



Appendix C - Airflow simulation

I measured the airflow of the current ventilation system, which is the BeQuiet Wings 2 system, with a diameter of 9 cm. I placed the Kimo measurement tool in front of the ventilation system, to measure the air flow (volume flow).

The bequiet! pure wings 2, with a diameter of 92mm, is a version of a fan for computing, gaming and multimedia systems (PURE WINGS 2 120mm PWM High-speed, n.d.). According to the specifications, this fan is appropriate for gaming and multimedia systems, specially made to be a fan with a low level of noise of 18.6dB(A) at maximum speed. The airflow (m^3/h) should be between 33.15 - 56.02 at 100% Pulse Width Modulation (PWM). The static pressure at 100% is 2.23 (mm/H2O).

To ensure the actual airflow, I set up a test with a Kimo airflow measurement tool, and the separated ventilation system, inside the building. I simply put the Kimo airflow-meter in front of the ventilation system, and read the values of the displays. Within a minute the airflow had an average value of 41 m^3/h.

I also measured the airflow when the ventilation is attached to the door, instead of in a building. Then the measured airflow had a value of 22 m^3/h. Additionally, I measured the airflow at the bottom of the tunnel, which is approximately 0 m^3/h. It can be that the airflow at the bottom of the tunnel is lower than the threshold of the airflow meter, resulting in an airflow of zero. Additionally, there is a low air flow & velocity due to the large area (A) of the sphere. The sphere has a diameter of 2.3 meters, in comparison to the diameter of the tunnel that is 1.08 meters.

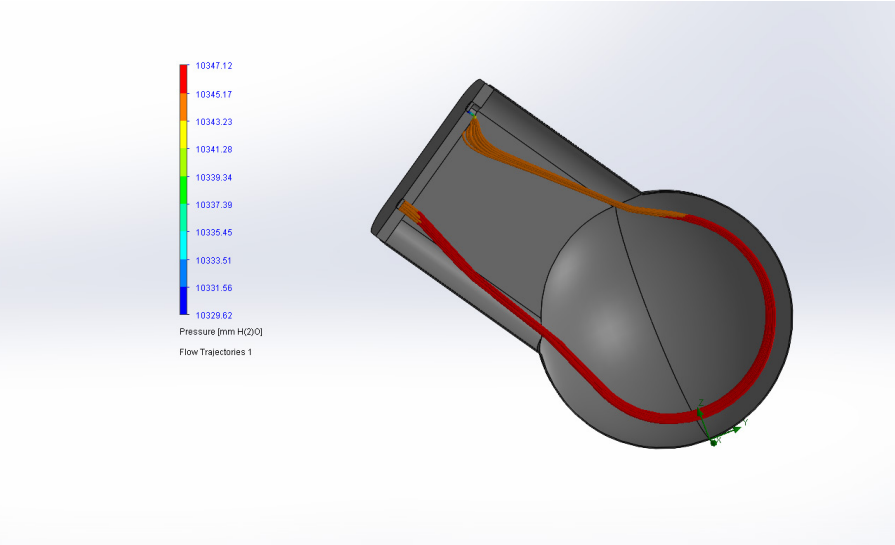


figure C1:Solidworks Simulation

To get a better understanding of the airflow within the GF, I have simulated the airflow in Solidworks. I created a simplified version of the GF, and created a flow simulation. I used the measured airflow (22 m^3/h) from the inlet of the ventilator, and transferred this to another velocity unit, which is 0,00611 (m/s).

I created a simulation, and used boundary conditions of the ventilator inlet and the ventilation hole at the top of the door.

- inlet volume flow is  $22\text{m}^3/\text{h} = 0,00611111\text{ m}^3/\text{s}$
- turbulent flow

As is visible in the pictures, the air follows a path from the inlet to the outlet of the door. It is visible that the air has a preferred pathway, and from this it can be concluded that there are possibly stagnant zones, in which the air is not flowing.

Appendix D - Smoke test

It is very complicated to simulate a geometry, with all the factors, especially with different temperatures. Therefore, I conducted a smoke test, to visualize the airflow within the globe. In this test, I put a smoke machine at the inlet of the ventilation hole to test how the air from the outside environment would behave at the inflow of the ventilation. I set up a camera in the GF to record the behaviour of the smoke, and later analyse this.

At 14:37:15 the smoke entered the GF for the first time. The smoke was not uniformly, but created clouds of smoke with different densities.  
At 14:37:24 the smoke was already at the end of the tunnel. It stayed at the bottom half of the tunnel.  
At 14:37:35 the smoke was halfway through the globe. At that point the height of the smoke increased to half of the tunnel and half of the globe.  
At 14:37:45 the smoke was at the end of the globe too, and the height kept increasing.  
At 14:38:04 the smoke was throughout the whole height of the GF, both the tunnel and the globe.  
At 14:39:17 the smoke was uniformly spread across the screen, and there was no big difference in smoke density.

Conclusion:  
The system is sufficient

The system provides moderate ventilation (~2.8 ACH), sufficient for basic air renewal but not for rapid flushing or high-demand ventilation applications. Installation losses significantly affect fan performance, highlighting the importance of system-level evaluation.



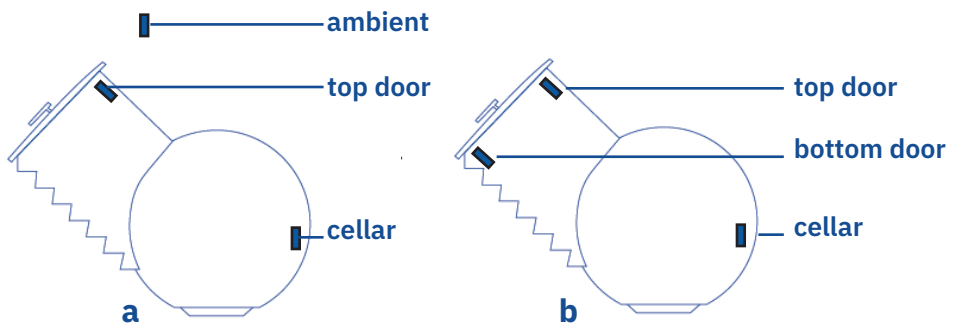
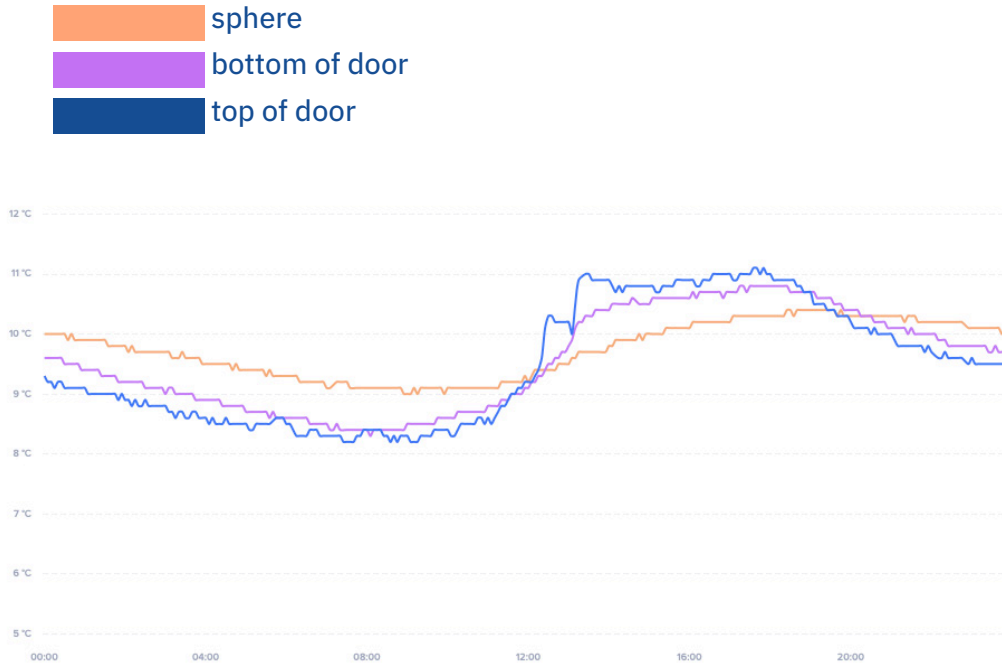


Appendix E - Current temperature measurement

In order to measure the temperatures within the GF, three sensors were placed. One is placed at the top of the door, one is placed at the bottom of the door and one inside of the dome. Throughout the project, the sensors were switched, in order to measure the ambient temperature. The set up changed from b to a, so one ambient, one top door and one located in the cellar.

These sensors are from Netatmo, and therefore connected to the Netatmo-app, which makes graphs out of the temperature. Throughout the whole of the project, I have monitored the Groundfridge that is located at FF. An overview of the dashboard is visible in the right bottom picture.

The graph underneath is made on 19 march, and it is clear that around 13:15 there is a peak. That is when Mark entered the GF and opened the door for approximately 2,5 minutes.



Appendix F - SWOT analysis of the current door

Strengths

- Thermal**
  - Insulation present
  - Fibreglass has a little reflectivity
  - North-facing orientation reduces direct solar heat gain
- Durability**
  - Effectively keeps rodents and insects out
  - Durable, weather-resistant coating
  - Easy to clean and maintain
- Installation**
  - Simple integration and installation during manufacturing
  - Centralizes technical components (ventilation, covers, insulation)

Weaknesses

- Thermal Performance**
  - Low thermal resistance ( $R_c \approx 2.2$ )
  - Compressed insulation reduces effectiveness (less trapped air)
  - Thermal bridges present in ventilation openings and hinges
  - Solar radiation still penetrates the door
- Airtightness & Moisture**
  - Limited sealing, not fully airtight
  - Minimal rubber sealing band
  - Risk of moisture ingress and condensation
- Usability & Ergonomics**
  - Heavy to operate
  - Handle material (wood) degrades over time
- Robustness & Longevity**
  - Seal degradation over time (wear, hardening)
  - Hinge misalignment possible with long-term use
  - Performance sensitive to installation accuracy (tolerances)

Opportunities

- Thermal & Technical Improvement**
  - Increase insulation value (higher  $R_c$ , better materials)
  - Reduce or eliminate thermal bridges
  - Improve sealing (multi-layer gaskets, better airtightness)
  - Develop controlled ventilation (reduce heat loss while maintaining airflow)
- Usability & Design**
  - Lighter door or assisted opening (e.g., counterbalance)
  - Improved handle (durable, weather-resistant materials)
  - Enhanced user experience (smooth opening/closing, better “feel”)
- Sustainability & Lifecycle**
  - Use sustainable or bio-based materials
  - Design for disassembly and repairability
  - Modular components for easy replacement/upgrades
- Safety & Reliability**
  - Integrate safety features (e.g., soft-close)
  - Improve water management (drainage, sealing against rain)

Threats

- Threats**
  - Weather extremes (rain, frost, heat)
  - Algae growth and surface degradation
  - Water accumulation, leakage, or freezing
- Performance Risks**
  - Thermal inefficiency affecting overall system performance
  - Long-term degradation of seals, insulation, and hinges
- User Behavior**
  - Improper closing or frequent misuse
  - Lack of maintenance (e.g., dirty or damaged seals)
- Product Positioning**
  - Upgrades may significantly increase cost
  - Risk of over-engineering (e.g., adding electricity to an off-grid concept)
  - Mismatch with user expectations (simplicity vs high-tech features)
- Safety Risks**
  - Potential injury from heavy door (fingers, handling)
  - Slip hazard due to wet or algae-covered surface



## Appendix G - Existing thermal systems review

### Active systems

#### Refrigerator

According to Koelet (1992), a refrigerator operates through four processes: evaporation, compression, condensation, and expansion. The cycle starts at the evaporator, where the refrigerant, a liquid with a low boiling point, is allowed to boil at a relatively low temperature, absorbing heat from inside the refrigerator in the process. The resulting vapour is drawn into the compressor, which maintains a low-pressure environment in the evaporator while simultaneously pressurizing the vapour. The pressurized vapour then travels to the condenser, where it releases heat to the surrounding environment and condenses back into a liquid. Finally, the liquid passes through an expansion valve, where its temperature and pressure drop rapidly before it re-enters the evaporator, beginning the cycle again. Additionally, the refrigerating system is insulated to make the internal processes more efficient, causing the compressor to run less frequently and use less energy. The insulation often consists of three layers: a polystyrene inner liner, a polyurethane foam insulating core, and a metal sheet as outer protective layer (Laguerre et al., 2003). This multilayer approach offers a useful reference when considering how the Groundfridge could be further optimized for thermal stability.

#### Hydrocooling

The process of the refrigerator is based on the principle of the ability of water to function as a thermal mass. Therefore, an alternative of cooling the GF would be by means of hydrocooling, the circulation of cold water in order to draw away heat from an object (Britannica, n.d.). In the context of the GF, water could be extracted from the ground and could be recirculated on top of the GF, where the temperatures are higher, and the water would naturally flow back to the groundwater that is located deeper in the soil.

#### Recuperator

A recuperator is a heat exchanger that uses waste heat from one liquid to preheat another fluid (ScienceDirect, n.d.). It could also work as a cooling system as the heat exchange between fluids could also draw heat away from a fluid in order to lower its temperature. A recuperator could enhance the ventilation system of the GF by recovering cool energy from the air that is pushed out of the GF, and use it to cool incoming fresh air.

#### Thermoelectric coolers

In thermoelectric coolers electrical currents are applied to a thermoelectric module, heat from one side of a semiconductor is transferred to the other side. This creates one cold side where heat is absorbed and one hot side where heat is released (ATS, 2024). Thermoelectric coolers do not require coolants or refrigerants and have a low energy demand and therefore could be interesting to couple with the already existing solar panel without significant change in the system.

#### Geothermal pumps

Geothermal heat pumps use the stable temperatures of the soil to exchange its heat with. In a closed system, water or another fluid circulated through pipes buried beneath the surface and redirected to a building or object, creating a heat exchange between the ground and the object (Department of Energy, n.d.). Water has a higher thermal conductivity and allows heat to flow between these objects. In summer it will function as a cooler, while in winter the ground temperature will be higher than the outside temperature.

This could be applied to the GF, and pipes filled with fluid connected to the earth could be built around the GF in order to stabilize the temperature within the GF.

### Passive systems

#### Earth to air heat exchange

Just like the geothermal pump, an earth-to-air heat exchange (EAHE) system is a heat exchange set-up in which the temperature of the air is changed with the use of the captured heat or cold of the soil (Peretti et al., 2013). It is an interesting method, as it makes use of renewable and natural energy sources. It is used to regulate the temperature of buildings. Peretti et al. (2013), concludes that an EAHE is often combined with another system like ventilation.

At the inlet, the air is sucked into a ventilation system and travels through an underground tube. The temperature captured in the soil, will alter the initial temperature of the air, by means of convection. In the case of the Groundfridge, the temperature of the soil for the heat exchange should be lower, in order to cool down the air that will be put into the GF.

#### Strategic air vents

Gravity ventilation is a passive ventilation strategy that relies on the natural tendency of warm air to rise (Khanal & Lei, 2011). Therefore, strategic placements of air lower and higher vents can improve this ventilation flow, as well as for the GF.

#### Solar chimney

A solar chimney (Maghrabie et al., 2022) is a hollow vertical structure that connects the interior of a building to the outside, using convection of air heated by solar energy to improve natural ventilation. When the air inside the chimney heats up and its density decreases, the air will naturally flow up and draws cooler, fresh air to the bottom of the chimney. This could be implemented in addition to the already existing ventilation system of the GF and could increase the rate of air exchange. This is particularly interesting for warm days where there is little wind.

#### Addition of thermal mass

According to Verbeke & Audenaert (2018), addition of thermal mass could help stabilize temperatures within buildings. If materials with high thermal mass are added in a building, they can function as temperature buffers. When connected to the earth, stored temperature is gradually conducted away into the surrounding soil, due to their characteristics.

#### Phase changing materials

Phase changing materials (PCM's) are materials that can absorb and release large amounts of heat during the change of their physical state (Ghamarie et al. 2024). When their phase changes from solid to liquid or liquid to gas, they can draw away a lot of heat from an environment. Vice versa, when they change from gas to liquid and liquid to solid, they can release a lot of energy to that environment. In that way they can passively regulate the temperature in the GF. A PCM is directly added into the mortar or concrete mix, but can also be used in the form of PCM capsules, and then integrated into the soil.

#### Wax actuator

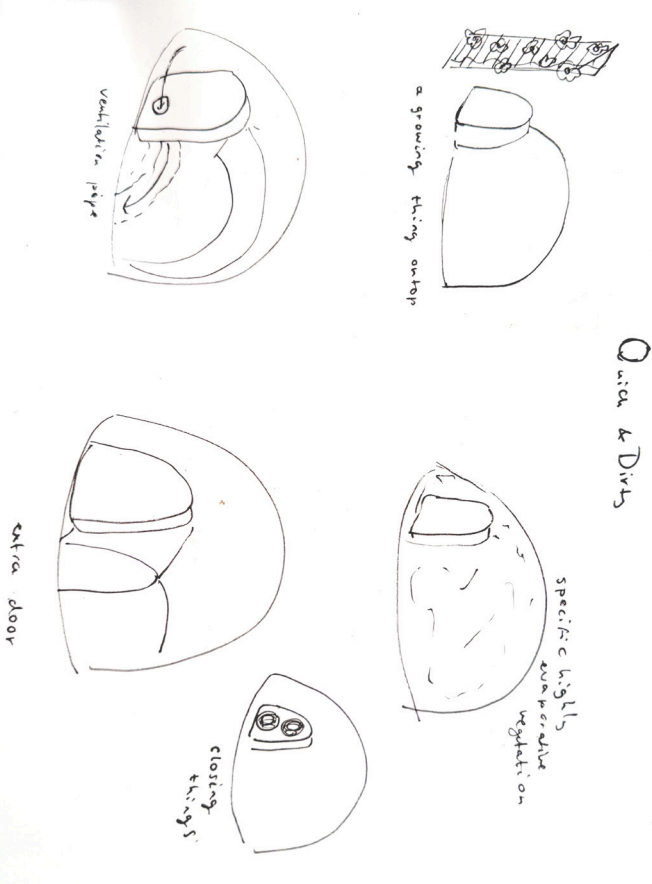
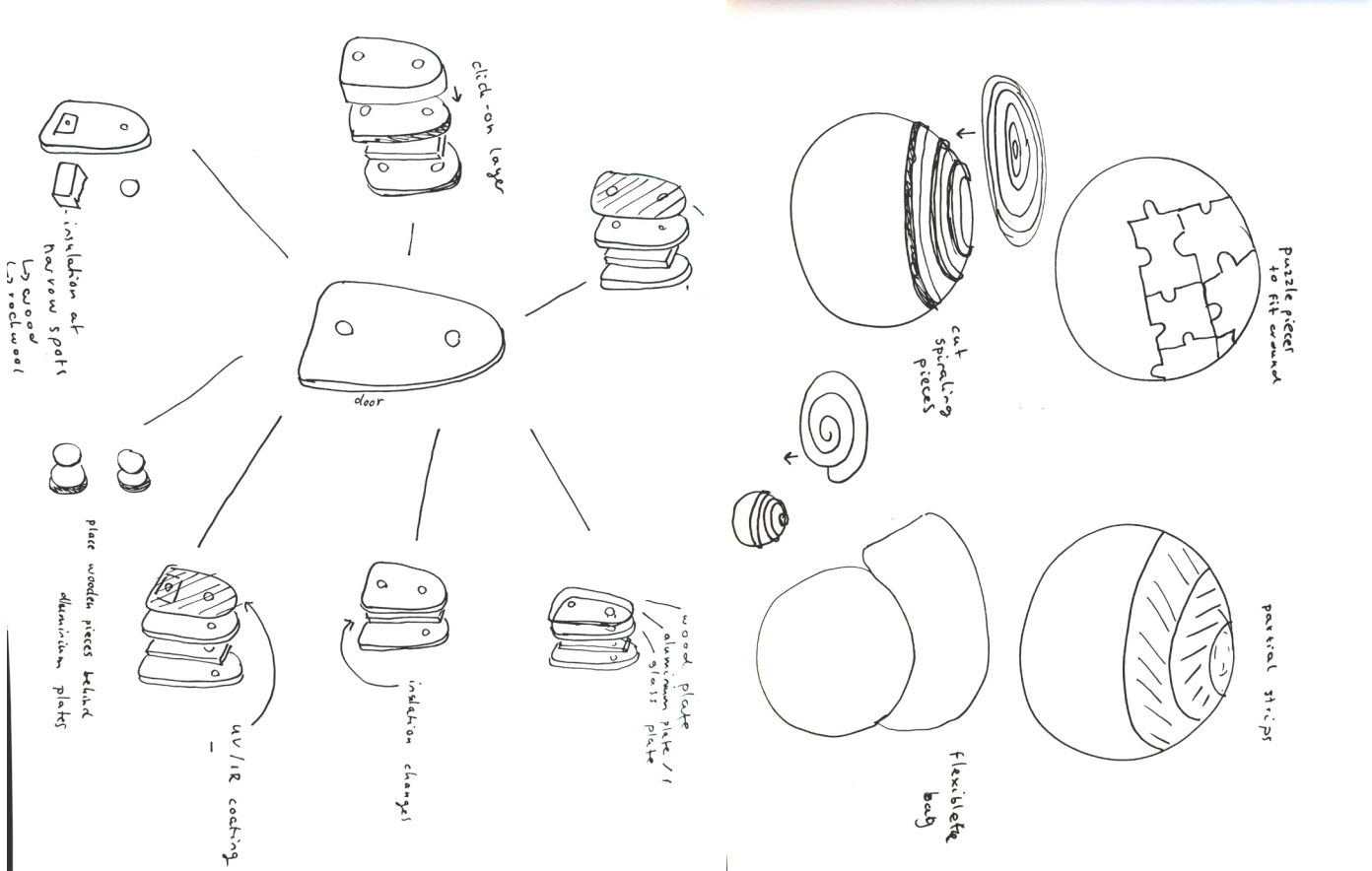
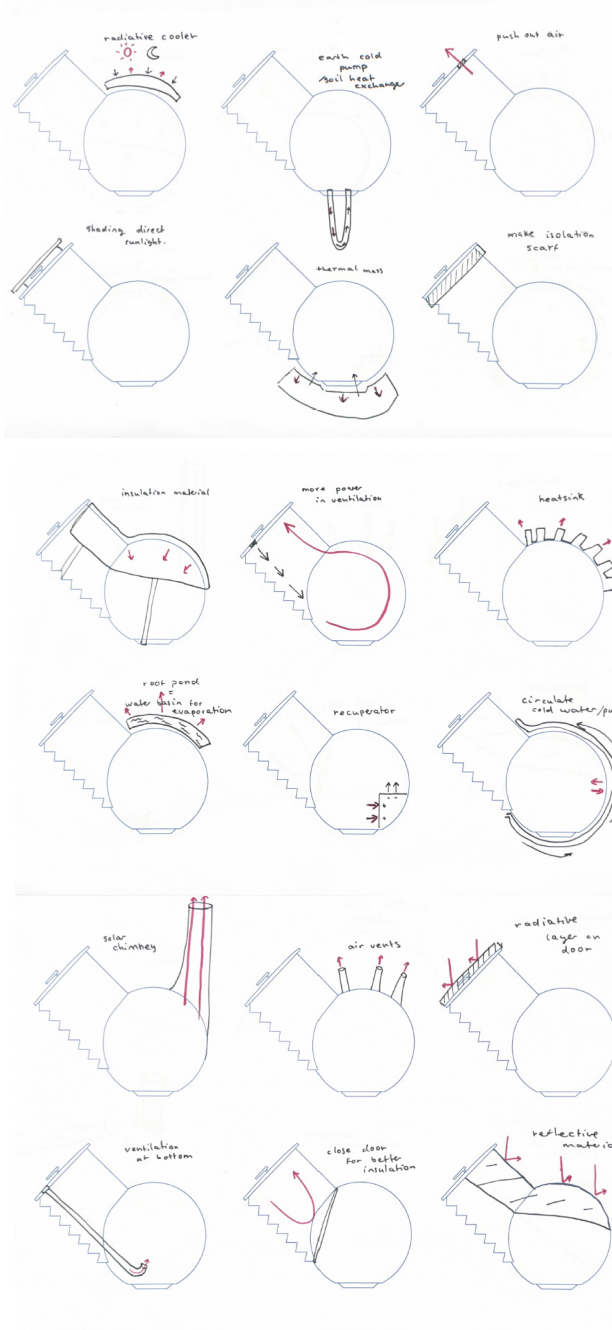
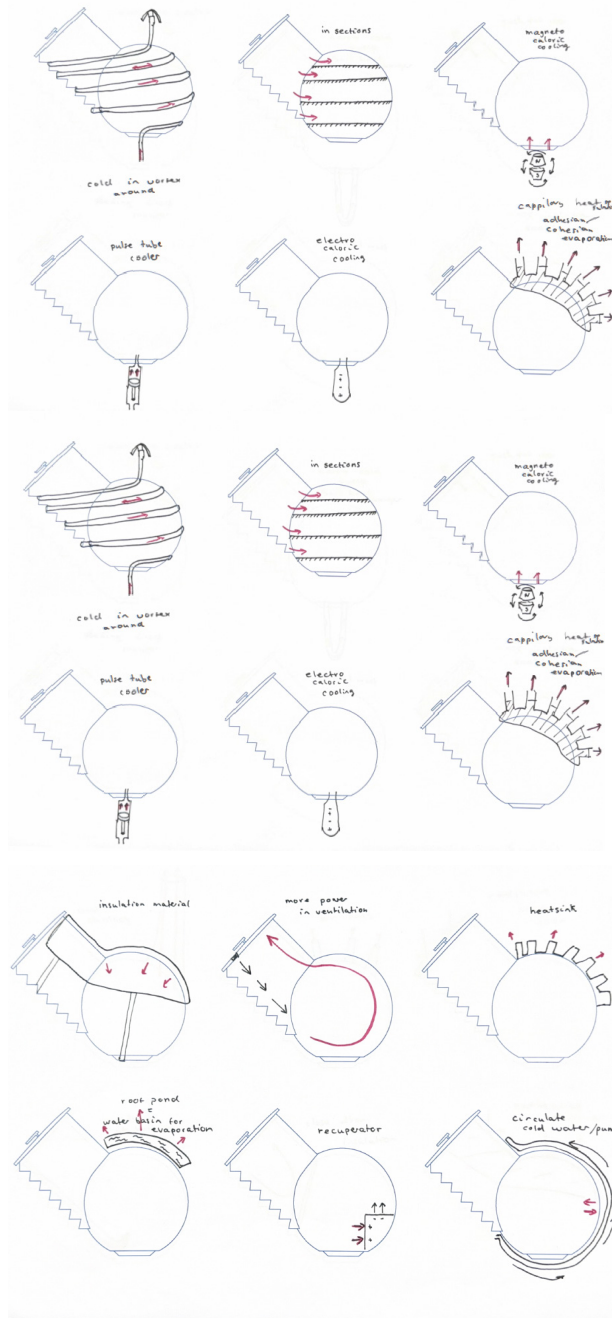
This mechanism is based on the principle that wax expands when it is heated, and therefore the crank is opening the vent (Mann et al., 2020). It is also a mechanism that uses phase changing materials. When the temperature decreases, the wax shrinks and the vent closes again. This makes it an automatic, passive system. Integration of these vents within the GF could passively

#### Underground umbrella as insulation

The underground thermal umbrella is a concept in which a layer of insulation is placed underneath Earth's surface. Roots & Hagentoft (2004), write about this in their research about underground insulation to protect the house from permafrost. The umbrella creates a division between the top layer of the Earth and the soil underneath, thereby reducing the amount of conduction between those layers. This can be applied to the GF, and therefore the heat generated by the warming of the soil and warmer rainwater is kept from the GF and the frost in winter as well.



Appendix H - Ideation of solution





Appendix I - Harris Profile

This Harris profile was used to choose the design direction in an early state of the project. From this, it was concluded that a redesign of the door would be more beneficial in comparison to a teacosy.

**Thermal stability**  
The climate gate will help with fluctuations of direct sunlight and atmospheric temperature changes. A redesign will counteract these fluctuations. = +1

The tea cosy will improve the temperature differences that come from the warming of the top layer of the soil, and therefore will regulate the inflow of heat from the soil. = +2

**Technical certainty**  
The redesign of the climate gate will be based on research about radiative coatings and insulation materials. These topics are well covered and therefore have a high technical certainty. = +2

The tea cosy is about materials that have to perform insulation behaviour in underground contexts. There is uncertainty about degradability, moisture and the actual performance of the thermal regulation. = -1

**Implementation ease**  
The climate gate will be quite modular, since the door is installed separately and is therefore easier to implement. A challenge lies in the integration of the insulation material in the door itself. = +1

For the tea cosy, there should be an additional product installed, which changes the process of installation. Also, there will be an additional product that should be transported to the customer. = -1

**Implementation risk**  
At the climate gate, challenges will lie in the durability and sustainability of the coating and insulation materials, as well as insulation of hinges and sealing. Since the door is modular and easily accessible, there will be relatively low risk once the door is implemented. = +1

The tea cosy will be a high risk implementation, since there is a lot of factors that can influence this implementation. Underground, there will be a lot of factors influencing the performance of the design, such as moisture trapping, degradability and mould. = -2

**Cost**  
For the climate gate, there will probably be high initial costs, like moulding costs for the door and a redesign. After, the costs will be lower and there are minimal risk costs. = -1

For the tea cosy, the material cost can be relatively low depending on the material. There will be high costs in testing and designing the geometry of the product. Risk costs may be high. = -1

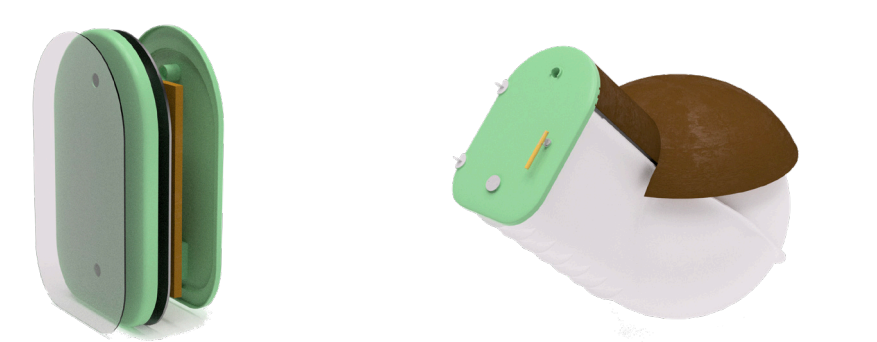
|                              | Door Redesign |    |    |    | Top Insulation |    |    |    |
|------------------------------|---------------|----|----|----|----------------|----|----|----|
|                              | -2            | -1 | +1 | +2 | -2             | -1 | +1 | +2 |
| Thermal stability            |               |    |    |    |                |    |    |    |
| Technical certainty          |               |    |    |    |                |    |    |    |
| Implementation ease          |               |    |    |    |                |    |    |    |
| Implementation risk          |               |    |    |    |                |    |    |    |
| Cost                         |               |    |    |    |                |    |    |    |
| Complexity of sustainability |               |    |    |    |                |    |    |    |
| Customer perception          |               |    |    |    |                |    |    |    |

**Complexity of sustainability**  
The climate gate is made of reinforced composite, and therefore it is not made of a renewable material. It will be a challenge to implement an environmentally friendly coating and insulation material. However, compared to the tea cosy, there will be less material used and probably this solution is a more durable design. = -1

The tea cosy can be easily made from sustainable materials, but it will be complex to create a durable design. Trade-offs between function and sustainability should be made. = +1

**Customer perception**  
The climate gate will be a visible feature, and therefore will be easier to understand in terms of customer perception. It is easy to understand what this design will do and therefore easier to market this high-tech door. = +1

The tea cosy will be underground, and therefore people will not actually interact with it. However, it will be easy to understand that it will insulate the GF. = +1



Appendix J - Aluminium plate test

Wednesday 5th march 16:30 - Monday 9th march 9:30

Results were not valid due to much opening of the GF.

**Second try**  
On Tuesday 17th March at 16:45, after the strongest period of the sun the aluminium covered wooden plate was placed on the door. It was left there until Wednesday 18th March 16:45. The 24 hours after were as a reference, since temperatures were similar on those two days.

**Results**  
The temperatures measured without the aluminium plate are generally lower, contradicting the expectations. However, this could have happened due to the conductive characteristic of aluminium, and that a ventilation gap between the door and the aluminium should have prevented this conduction to the inside of the door.

With aluminium plate

| Factor                  | 16:45 | 20:00 | 24:00 | 04:00 | 08:00 | 12:00 | 16:00 | 20:00 |
|-------------------------|-------|-------|-------|-------|-------|-------|-------|-------|
| Grondtemperatuur 100 cm | 8.9   | 8.9   | 8.9   | 8.9   | 8.9   | 8.9   | 8.9   | 8.9   |
| Buitemtemperatuur       |       |       | 6.5   |       |       |       | 15.1  |       |
| Deur boven              | 11.4  | 10.6  | 10.5  | 10.1  | 9.9   | 10.3  | 10.7  | 10.5  |
| Deur onder              | 10.9  | 10.6  | 10.5  | 10.1  | 9.9   | 10.3  | 10.7  | 10.5  |
| Koepel                  | 10.3  | 10.2  | 10.4  | 10.3  | 10.1  | 10.1  | 10.3  | 10.4  |

Without aluminium plate

| Factor            | 16:45 | 20:00 | 24:00 | 04:00 | 08:00 | 12:00 | 16:00 | 20:00 |
|-------------------|-------|-------|-------|-------|-------|-------|-------|-------|
| Grondtemperatuur  | 8.5   | 8.5   | 8.5   | 8.5   | 8.5   | 8.5   | 8.5   | 8.5   |
| Buitemtemperatuur |       |       |       | 6.0   |       |       | 17.1  |       |
| Deur boven        | 11.0  | 10.3  | 9.5   | 9.2   | 9.0   | 9.6   | 10.2  | 9.7   |
| Deur onder        | 10.7  | 10.4  | 9.7   | 9.4   | 9.2   | 9.6   | 10.3  | 10.0  |
| Koepel            | 10.3  | 10.3  | 10.0  | 9.8   | 9.6   | 9.7   | 10.2  | 10.1  |





Appendix K -Wooden Plate Test

On a day with direct sunlight, the door was placed outside in the sun. I placed the door of the GF outside in the sun, and created a wooden plate of Multiplex 18 mm behind the gap where the ventilation is placed. The half of the gap is covered with the wooden plate and the other half is not, to look at the difference of when wood insulation is applied and when not.

Results

| Time  | Without Wood | With Wood |
|-------|--------------|-----------|
| 11:57 | 15.2         | 15.2      |
| 12:13 | 17.2         | 15.4      |
| 13:03 | 22.9         | 18.6      |
| 14:01 | 21.8         | 18.3      |

Conclusion

The measurements demonstrate a clear and consistent insulating effect of the concrete plywood plate. As solar radiation increased during the morning, the two conditions were significantly different, reaching a maximum difference of 4.3°C at 13:03, that was at peak solar intensity.

The condition without wood peaked at 22.9°C, while the condition with wood peaked at only 18.6°C. By 14:01 both conditions show a slight cooling, likely due to a shift in sun angle but the difference remains stable at 3.5°C.

It is visible how “easy” the sun passes through the door and how an addition of insulation can help this, especially in thinly insulated parts of the door.

Discussion

- The measurement should have been measured over a longer period of time, with more measurements.
- The camera can only measure surface temperature, and not the temperature within the material
- It is unsure how the plywood reduces the temperature, whether it is because of insulation, emissivity or shading.



Appendix L -Solar simulation

Direct sun path simulation

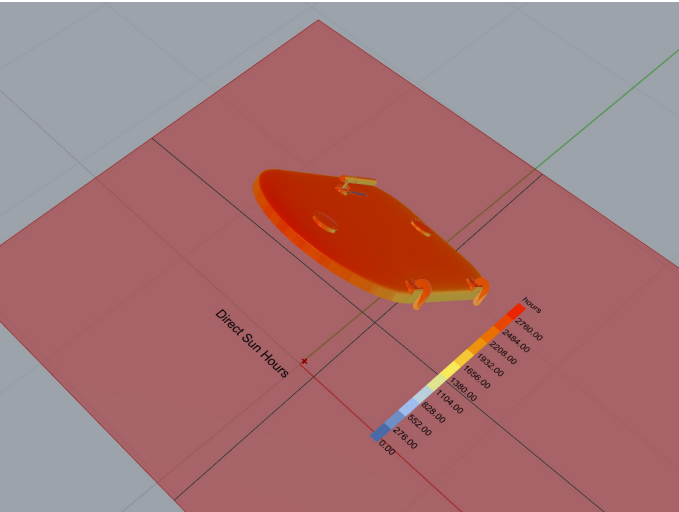
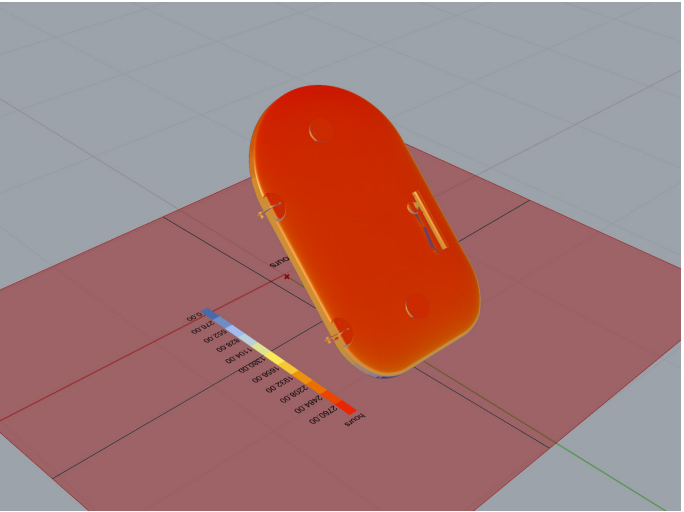
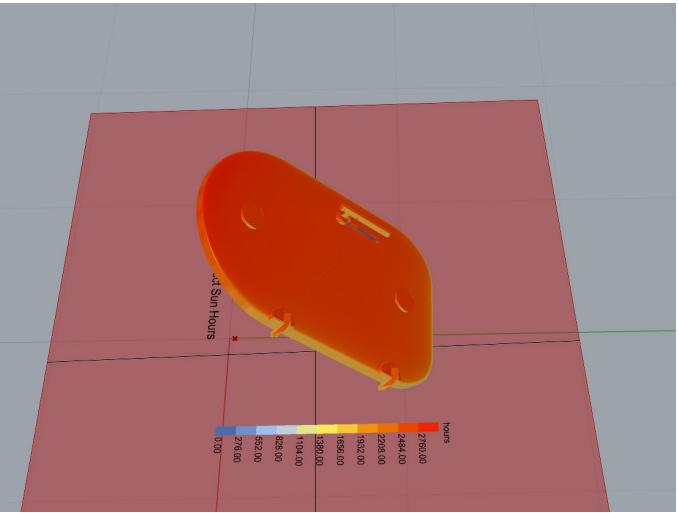
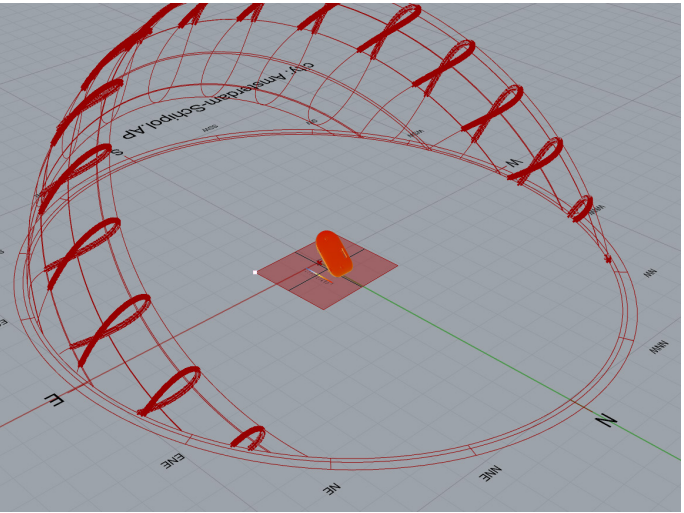
These simulation shows the sun path for Amsterdam-Schiphol over the full year. The door is modelled as if it is placed towards the North. The loops represent the sun’s position at different times of year.

By the use of Rhino-Grasshopper and the LadyBug plug-in, this analysis is visualised.

The period in which the analysis was set is March 21st - September 21st (spring and summer, in which there is the most sun).

Radiation Analysis

The front of the door is almost entirely orange/red, meaning it receives high radiation across most of the surfaces. There is a lot of direct sun on top of the door as well. This is explainable a the door is tilted, and therefore in the range of the path of the sun.





Appendix M - Materials

| Material                        | Lambda (W/mK) | Thickness (m) | Rc = 5 | Reflectivity | Emissivity | Costs (m²) ES'     | Biodegradability | Source                                                                                                                                                                                                                                                                                                                                                                                                                | Lambda | Source emissivity                                                                                                                                                                                                       | Site |
|---------------------------------|---------------|---------------|--------|--------------|------------|--------------------|------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| <b>Insulation</b>               |               |               |        |              |            |                    |                  |                                                                                                                                                                                                                                                                                                                                                                                                                       |        |                                                                                                                                                                                                                         |      |
| Soil                            | 2,0000        | 10            |        | 5            |            |                    |                  |                                                                                                                                                                                                                                                                                                                                                                                                                       |        |                                                                                                                                                                                                                         |      |
| Sheeps wool                     | 0,0400        | 0,2           |        | 5            | 0,80-0,95  | €17-40             |                  | <a href="https://edepot.wur.nl/461687">https://edepot.wur.nl/461687</a>                                                                                                                                                                                                                                                                                                                                               |        |                                                                                                                                                                                                                         |      |
| Glass                           | 0,0400        | 0,2           |        | 5            | 0,85-0,90  |                    |                  | <a href="https://eurocave.nl/en/insulation-value-of-different-materials/">https://eurocave.nl/en/insulation-value-of-different-materials/</a>                                                                                                                                                                                                                                                                         |        |                                                                                                                                                                                                                         |      |
| Sand                            | 2,0000        | 10            |        | 5            |            |                    |                  |                                                                                                                                                                                                                                                                                                                                                                                                                       |        |                                                                                                                                                                                                                         |      |
| Cork                            | 0,1500        | 0,75          |        | 5            |            |                    |                  |                                                                                                                                                                                                                                                                                                                                                                                                                       |        | <a href="https://www.google.com/search?client=safari&amp;rls=en&amp;q=granorte+cork&amp;ie=UTF-8&amp;oe=UTF-8">https://www.google.com/search?client=safari&amp;rls=en&amp;q=granorte+cork&amp;ie=UTF-8&amp;oe=UTF-8</a> |      |
| Cellulose                       | 0,0390        | 0,195         |        | 5            |            |                    |                  |                                                                                                                                                                                                                                                                                                                                                                                                                       |        |                                                                                                                                                                                                                         |      |
| Wood fiberboard                 | 0,0380        | 0,19          |        | 5            | 0,90-0,95  |                    |                  | <a href="https://www.samaterials.com/blog/emissivity-basics-and-examples.html">https://www.samaterials.com/blog/emissivity-basics-and-examples.html</a>                                                                                                                                                                                                                                                               |        |                                                                                                                                                                                                                         |      |
| Wood wool                       | 0,0500        | 0,25          |        | 5            |            |                    |                  |                                                                                                                                                                                                                                                                                                                                                                                                                       |        |                                                                                                                                                                                                                         |      |
| Shells                          | 0,1550        | 0,775         |        | 5            |            |                    |                  |                                                                                                                                                                                                                                                                                                                                                                                                                       |        |                                                                                                                                                                                                                         |      |
| Air                             | 0,0250        | 0,125         |        | 5            |            |                    |                  |                                                                                                                                                                                                                                                                                                                                                                                                                       |        |                                                                                                                                                                                                                         |      |
| Hempcrete                       | 0,0710        | 0,355         |        | 5            |            |                    |                  | <a href="https://www.iso hemp.com/sites/default/files/2025-09/ISH_technical_datasheet_Hempblock_EN_2025.pdf">https://www.iso hemp.com/sites/default/files/2025-09/ISH_technical_datasheet_Hempblock_EN_2025.pdf</a>                                                                                                                                                                                                   |        |                                                                                                                                                                                                                         |      |
| hemp-lime                       | 0,0600        | 0,3           |        | 5            |            |                    |                  | <a href="https://www.exie.be/en/products/canadry">https://www.exie.be/en/products/canadry</a>                                                                                                                                                                                                                                                                                                                         |        |                                                                                                                                                                                                                         |      |
| Hempwool                        | 0,0388        | 0,194         |        | 5            |            |                    |                  |                                                                                                                                                                                                                                                                                                                                                                                                                       |        |                                                                                                                                                                                                                         |      |
| Extruded glass b                | 0,1580        | 0,79          |        | 5            |            |                    |                  |                                                                                                                                                                                                                                                                                                                                                                                                                       |        |                                                                                                                                                                                                                         |      |
| Glass foam                      | 0,4000        | 2             |        | 5            |            |                    |                  |                                                                                                                                                                                                                                                                                                                                                                                                                       |        |                                                                                                                                                                                                                         |      |
| Flax wool                       | 0,0280        | 0,14          |        | 5            |            | €8-18              |                  | <a href="https://www.rvo.nl/meldcodes-isolatie/ka18311-isovlas-vlaswol-pl140-en-hoger-dakisolatie">https://www.rvo.nl/meldcodes-isolatie/ka18311-isovlas-vlaswol-pl140-en-hoger-dakisolatie</a>                                                                                                                                                                                                                       |        |                                                                                                                                                                                                                         |      |
| Glass mineral wc                | 0,0400        | 0,2           |        | 5            |            |                    |                  |                                                                                                                                                                                                                                                                                                                                                                                                                       |        |                                                                                                                                                                                                                         |      |
| Rock wool                       | 0,0330        | 0,165         |        | 5            |            | €5-11              |                  |                                                                                                                                                                                                                                                                                                                                                                                                                       |        |                                                                                                                                                                                                                         |      |
| Regular pearls                  | 0,1200        | 0,6           |        | 5            |            |                    |                  |                                                                                                                                                                                                                                                                                                                                                                                                                       |        |                                                                                                                                                                                                                         |      |
| Bio Pearls                      | 0,1200        | 0,6           |        | 5            |            |                    |                  | <a href="https://www.termokomfort.nl/isolatieparels/biofoampearls">https://www.termokomfort.nl/isolatieparels/biofoampearls</a>                                                                                                                                                                                                                                                                                       |        |                                                                                                                                                                                                                         |      |
| PUR/PIR                         | 0,0250        | 0,125         |        | 5            |            |                    |                  |                                                                                                                                                                                                                                                                                                                                                                                                                       |        |                                                                                                                                                                                                                         |      |
| Styrofoam/XPS                   | 0,0200        | 0,1           |        | 5            |            | €5-12              |                  | <a href="https://www.rvo.nl/subsidies-financiering/isde/meldcode/lijsten/isolatiematerialen?sortBy=relevance&amp;sortOrder=DESC&amp;page=0&amp;query=xps">https://www.rvo.nl/subsidies-financiering/isde/meldcode/lijsten/isolatiematerialen?sortBy=relevance&amp;sortOrder=DESC&amp;page=0&amp;query=xps</a>                                                                                                         |        |                                                                                                                                                                                                                         |      |
| Bluedec                         | 0,0135        | 0,0027        |        | 5            |            |                    |                  | <a href="https://bluedec.nl/lambda waarde/">https://bluedec.nl/lambda waarde/</a>                                                                                                                                                                                                                                                                                                                                     |        |                                                                                                                                                                                                                         |      |
| Bluedec                         | 0,0100        | 0,05          |        | 5            |            |                    |                  | <a href="https://www.rvo.nl/meldcodes-isolatie/ka18415-bluedec-bluedec-dakisolatie">https://www.rvo.nl/meldcodes-isolatie/ka18415-bluedec-bluedec-dakisolatie</a>                                                                                                                                                                                                                                                     |        |                                                                                                                                                                                                                         |      |
| XPS (extruded p                 | 0,0380        | 0,19          |        | 5            |            |                    |                  | <a href="https://eurocave.nl/en/insulation-value-of-different-materials/">https://eurocave.nl/en/insulation-value-of-different-materials/</a>                                                                                                                                                                                                                                                                         |        |                                                                                                                                                                                                                         |      |
| Miscanthus                      |               |               |        | 5            |            |                    |                  |                                                                                                                                                                                                                                                                                                                                                                                                                       |        |                                                                                                                                                                                                                         |      |
| Argex                           | 0,1160        | 0,58          |        | 5            |            |                    |                  | <a href="https://argex.eu/wp-content/uploads/Technical/NL/AR_8_16_340_DOP_2_TF_NL.pdf">https://argex.eu/wp-content/uploads/Technical/NL/AR_8_16_340_DOP_2_TF_NL.pdf</a>                                                                                                                                                                                                                                               |        |                                                                                                                                                                                                                         |      |
| Expanded Perlite                | 0,0500        |               |        | 5            |            |                    |                  | <a href="https://duofoor.eu/en/products/perlite-vermiculite/brikmat-afstandshouders#:~:text=Characteristics%20of%20Perlite%3A&amp;text=Lambda%3A%200,04%20to%200,06%20W/m%20water%20and%20organic%20solvents">https://duofoor.eu/en/products/perlite-vermiculite/brikmat-afstandshouders#:~:text=Characteristics%20of%20Perlite%3A&amp;text=Lambda%3A%200,04%20to%200,06%20W/m%20water%20and%20organic%20solvents</a> |        |                                                                                                                                                                                                                         |      |
| Pumice                          | 0,1200        |               |        |              |            |                    |                  |                                                                                                                                                                                                                                                                                                                                                                                                                       |        |                                                                                                                                                                                                                         |      |
| Resol                           | 0,0210        | 0,105         |        | 5            |            |                    |                  |                                                                                                                                                                                                                                                                                                                                                                                                                       |        |                                                                                                                                                                                                                         |      |
| Metisse                         |               |               |        |              |            |                    |                  |                                                                                                                                                                                                                                                                                                                                                                                                                       |        |                                                                                                                                                                                                                         |      |
| Spray cork                      | 0,0450        | 0,225         |        | 5            |            | €15-35             |                  |                                                                                                                                                                                                                                                                                                                                                                                                                       |        |                                                                                                                                                                                                                         |      |
| Nanocoating                     |               |               |        |              |            |                    |                  |                                                                                                                                                                                                                                                                                                                                                                                                                       |        |                                                                                                                                                                                                                         |      |
| Polycaprolacton                 |               |               |        |              |            |                    |                  |                                                                                                                                                                                                                                                                                                                                                                                                                       |        |                                                                                                                                                                                                                         |      |
| Aerogels                        | 0,0340        | 0,17          |        | 5            |            | €20-60             |                  |                                                                                                                                                                                                                                                                                                                                                                                                                       |        |                                                                                                                                                                                                                         |      |
| <b>Reflective</b>               |               |               |        |              |            |                    |                  |                                                                                                                                                                                                                                                                                                                                                                                                                       |        |                                                                                                                                                                                                                         |      |
| Aluminium                       |               |               |        |              | 0,97       | 0,03 €1-5          |                  |                                                                                                                                                                                                                                                                                                                                                                                                                       |        |                                                                                                                                                                                                                         |      |
| Mylar                           |               |               |        |              | 0,95       | 0,05 €0,5 -2       |                  |                                                                                                                                                                                                                                                                                                                                                                                                                       |        |                                                                                                                                                                                                                         |      |
| Metallised polypropylene        |               |               |        |              | 0,95       | 0,05 €0,5 -2       |                  |                                                                                                                                                                                                                                                                                                                                                                                                                       |        |                                                                                                                                                                                                                         |      |
| Low-e coating                   |               |               |        |              | 0,97       | 0,22 €5-15         |                  | <a href="https://www.sciencedirect.com/science/article/abs/pii/S0257897297000340">https://www.sciencedirect.com/science/article/abs/pii/S0257897297000340</a>                                                                                                                                                                                                                                                         |        |                                                                                                                                                                                                                         |      |
| <b>Ratiative cooling</b>        |               |               |        |              |            |                    |                  |                                                                                                                                                                                                                                                                                                                                                                                                                       |        |                                                                                                                                                                                                                         |      |
| Lignin                          |               |               |        |              |            | €/kg               |                  |                                                                                                                                                                                                                                                                                                                                                                                                                       |        |                                                                                                                                                                                                                         |      |
| ATO (Antimony Tin Oxide) powder |               |               |        |              | 0,9 ?      | 0,97               |                  | <a href="https://www.sciencedirect.com/science/article/abs/pii/S0926669023000067">https://www.sciencedirect.com/science/article/abs/pii/S0926669023000067</a>                                                                                                                                                                                                                                                         |        |                                                                                                                                                                                                                         |      |
| TiO2 (in composite film)        |               |               |        |              | 0,91       | 0,92 €2-3,5        |                  | <a href="https://www.sciencedirect.com/science/article/abs/pii/S2352492824018701?via%3Dihub">https://www.sciencedirect.com/science/article/abs/pii/S2352492824018701?via%3Dihub</a>                                                                                                                                                                                                                                   |        |                                                                                                                                                                                                                         |      |
| SiO2 (in composite film)        |               |               |        |              | 0,91       | 0,83 €0,85-1       |                  | <a href="https://www.sciencedirect.com/science/article/abs/pii/S0927024822002562?via%3Dihub">https://www.sciencedirect.com/science/article/abs/pii/S0927024822002562?via%3Dihub</a>                                                                                                                                                                                                                                   |        |                                                                                                                                                                                                                         |      |
| zinc oxide                      |               |               |        |              |            |                    |                  |                                                                                                                                                                                                                                                                                                                                                                                                                       |        |                                                                                                                                                                                                                         |      |
| Chitin film                     |               |               |        |              | 93,1       | 0,9 €8-50          |                  | <a href="https://advanced.onlinelibrary.wiley.com/doi/10.1002/advs.202206616">https://advanced.onlinelibrary.wiley.com/doi/10.1002/advs.202206616</a>                                                                                                                                                                                                                                                                 |        |                                                                                                                                                                                                                         |      |
| Chitosan film                   |               |               |        |              | 96         | suitable in mid-IR |                  | <a href="https://advanced.onlinelibrary.wiley.com/doi/10.1002/advs.202206616">https://advanced.onlinelibrary.wiley.com/doi/10.1002/advs.202206616</a>                                                                                                                                                                                                                                                                 |        |                                                                                                                                                                                                                         |      |
| XPS (extruded polystyreen)      |               |               |        |              | 79         | low                |                  |                                                                                                                                                                                                                                                                                                                                                                                                                       |        |                                                                                                                                                                                                                         |      |
| ACA                             |               |               |        |              | 97 ?       |                    |                  |                                                                                                                                                                                                                                                                                                                                                                                                                       |        |                                                                                                                                                                                                                         |      |
| Glassfiber composite            |               |               |        | 0,9          |            |                    |                  |                                                                                                                                                                                                                                                                                                                                                                                                                       |        |                                                                                                                                                                                                                         |      |
| Ceramic aerogel                 |               |               |        |              | 95         | 0,93 €50-300/m²    |                  | <a href="https://www.sciencedirect.com/science/article/abs/pii/S138589472204997X">https://www.sciencedirect.com/science/article/abs/pii/S138589472204997X</a>                                                                                                                                                                                                                                                         |        |                                                                                                                                                                                                                         |      |
| CaCO3 -acrylic paint            |               |               |        |              | 96         | 0,94 €0,10-0,30    |                  | <a href="https://www.sciencedirect.com/science/article/pii/S2666386420302368">https://www.sciencedirect.com/science/article/pii/S2666386420302368</a>                                                                                                                                                                                                                                                                 |        |                                                                                                                                                                                                                         |      |
| White pigment                   |               |               |        |              | 94         | 0,92               |                  |                                                                                                                                                                                                                                                                                                                                                                                                                       |        |                                                                                                                                                                                                                         |      |

Highlighted materials

In order to create a layered door design that has the desired characteristics, a material studies is done in order to compare materials with each other. Materials that could be suitable are described here, although there are many more materials listed in the sheet during the project (appendix L).

Insulation materials

Insulation materials have characteristics of slowing down conductive heat transfer. They have low lambda (λ) values, increasing the thermal resistance. Materials that are insulating are:

- Rockwool (λ = 0.028)
- flax wool (λ = 0.038)
- sheeps wool (λ = 0.040)
- aerogel (λ = 0.034)
- spray cork (λ = 0.045)
- XPS (λ = 0.020)
- Bluedec (λ = 0.014)

Reflective materials

Reflective materials are substances that reflect radiative heat, because of their high reflectivity (r) values. Materials with high reflectivity are:

- Aluminium (r = 0.97)
- Mylar film (r = 0.95)
- Metallised polypropylene (r = 0.95)
- Low-e coating (r = 0.97)

Passive radiative materials

Passive radiative materials reflect incoming radiation during daytime and simultaneously emit long wave infrared radiation accumulated over time. This could be integrated in the design of the door with the aim that the infrared will not pass through the door. These materials require high reflectivity (r) and high emissivity (ε )properties to function in this way. Materials are:

- TiO2 (r = 0.91 , ε = 0.92)
- SiO2 (r = 0.91 , ε = 0.83)
- Chitin (r = 0.93 , ε = 0,90)
- CaCO3 acrylic (r = 0.96 , ε = 0.94)
- Ceramic aerogel (r = 0.95, ε = 0.93)



Appendix N - Aluminium foil reflectivity test

**Goal**  
The goal of this test is to measure what the difference is when you put a layer of reflective foil inside of the insulation.

**Set-up:**  
A: set-up with two plastic shells with insulation in between, with a layer of air in between.  
B: set-up with two plastic shells with insulation and foil, with a layer of air in between.

- Materials**
- acrylic glass 4 mm box (self made)
  - insulation (60 mm), isovlas
  - aluminium foil (0.1 mm)

- Method**
1. create both set-ups
  2. put an IR-panel in front
  3. let it stand for 2-3 hours
  4. log temperature of back panel every 30 minutes

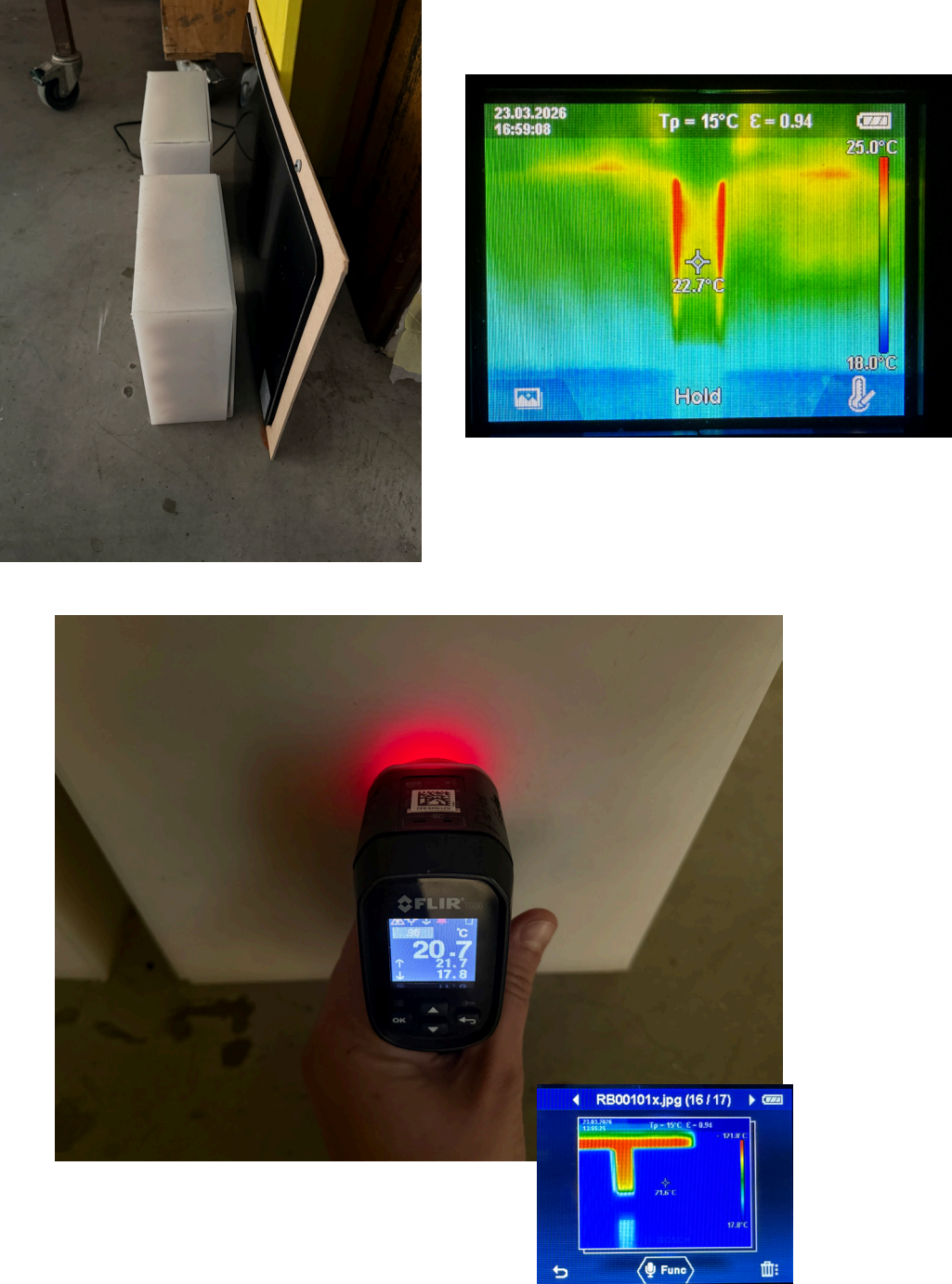
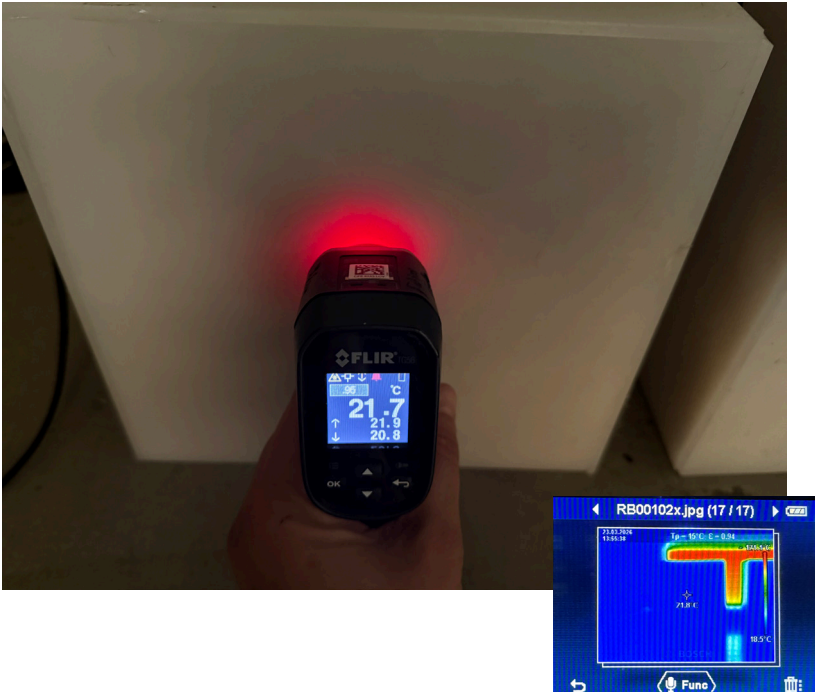
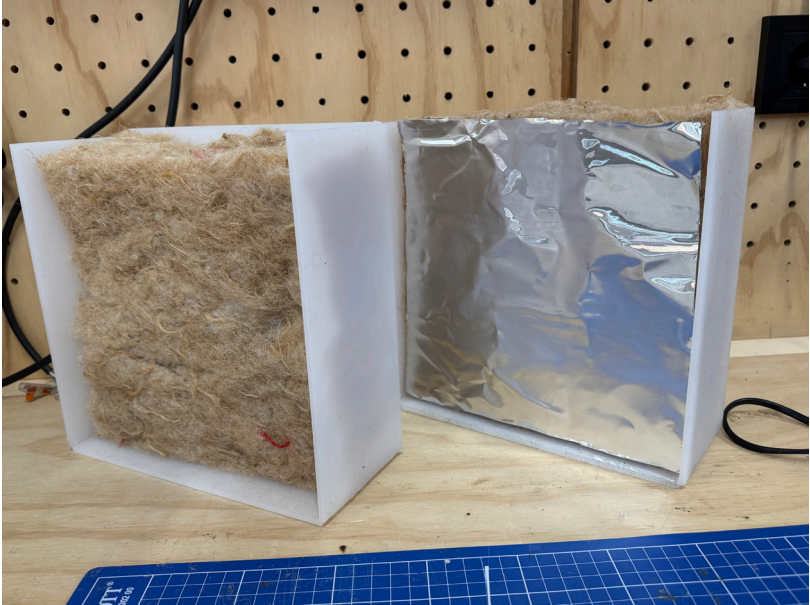
The two boxes with different set up will be placed in front of an IR panel, with the same distance from the panel. Every half hour the temperature will be measured in order to test whether there is a difference in IR that will pass through the material combination. This will be measured with a thermometer with laser point and a thermal camera with an emissivity of 0.94 set, as this is the emissivity of plastic. Both the backside and frontside were measured. The ambient room temperature was around 20°C throughout.

| Time  | A_back | A_front | B_back | B_front |
|-------|--------|---------|--------|---------|
| 14:10 | 21.8   | 21.8    | 21.6   | 21.6    |
| 14:40 | 20.4   | 52.5    | 20.0   | 58.8    |
| 15:10 | 20.7   | 54.1    | 20.2   | 64.2    |
| 15:40 | 21.6   | 69.7    | 20.5   | 73.1    |
| 16:10 | 21.7   | 60.1    | 20.6   | 70.6    |
| 16:40 | 21.6   | 60.2    | 20.6   | 72.2    |
| 17:10 | 21.9   | 58.1    | 20.5   | 62.3    |

- Observations**
- Set-up B (back) was consistently measured with a lower cold face than set-up A (back). The difference grows over time and stabilizes approximately 1.0 - 1.4°C after 90 minutes.
  - Set-up B (front) was consistently 8 - 13°C hotter than set-up A (front), confirming that the foil was reflecting infrared radiation back toward the heat source rather than allowing it to pass through the set-up
  - When photographing both set-ups, a colour difference is clear.

- Limitation**
- The experiment was conducted at an ambient temperature of 20°C, resulting in a relatively small temperature difference between the back faces of the set-up and the room temperature, limiting the sensitivity
  - The back temperatures were harder to measure, as there was a too small area to put the temperature tool.

**Conclusion**  
There is a significant difference between the set-ups, concluding that the foil does reflect radiation back to the source.





## Appendix O - Gesprekken met experts

**Ik had een gesprek met Martin Tenpierik, hij is bezig met klimaat responsive en adaptieve bouwsystemen oftewel CRABS (Climate responsive and adaptive building systems).**

### Take-aways:

- Lichte coating is beter dan donkere coating
- Reflectieve laag is goed, cachering zorgt namelijk voor reflectie (mits een laag lucht ertussen). Dus dat is sowieso goed
- De reflectie gebeurt in de zichtbare range, en de emissie in de niet zichtbare range, dus IR en zo.
- Passieve straling coating kan ook zeker werken, dat is wel prijzig en nieuw, maar voor een oppervlakte zoals de deur ziet het er wel geschikt uit. Je moet wel zorgen dat de deur dan op de hemelkoepel gericht is, anders werkt het niet
- Double face 2.0, dat gaat over een paneel dat draaibaar is, gemaakt van een zouthydraat en een aerogel aan de andere kant.. Dus aan één kant een PCM, dat warmte opneemt, en dan kan je hem omdraaien om de warmte weer vrij te laten door de passieve werking van de aerogel.
- Een PCM bij de ventilator zou ook nog goed zijn, zo kun je de warmte reguleren.
- Of een peltier systeem wat dus deze warmtewisseling teweegbrengt. Dit werkt juist op dagen dat de zon schijnt, want dan is er meer warmte dus werkt het systeem beter
- Een tunnel, maar dan geen passieve koeling op de deur.
- Zouten of silicium om het vocht te onttrekken
- Planten werken verdampend (evaporative) maar ook de aarde icm deze planten. Dus als je alleen de planten hebt, heb je alleen die verdampende mogelijkheid.
- Eigenlijk moet je op een warme dag de deur volledig luchtdicht maken, want zo stop je de warmtewisseling.
- Je zou een simulatie kunnen doen met deze factoren en daaruit kunnen kijken welke onderdelen wat doen, en hoeveel je nog nodig hebt voor een stabiele temperatuur

**Ik had ook een gesprek met Tiemen Kos, hij heeft een afstudeerproject gedaan bij Foamlab, een bedrijf dat foam maakt van bacteriele cellulose.**

### Take-aways:

- Het schuim van Foamlab is een biomateriaal, dus het zal daarmee concurreren.
- Als je het schuim droogt aan de lucht, krijg je een krokant chipje. Als je het vriesdroogt, krijg je een super lichte foam. En als je andere materialen toevoegt kan je dit reguleren, en zelfs combineren.
- Als isolatiemateriaal is het niet waterafstotend en het neemt juist heel erg goed foam op.
- Lambda waarde is 0,033.
- Foamlab is ook bezig met een vacuum insulation panel, een VIP.
- Een interessante overtuiging van het gebruik van Foamlab is dat het concurreert met oliederivaten,

## Appendix P(a) - Caps testing

### Test

Two 3D printed caps were placed on top of the GF air in- and outlet. The goal was to see whether limiting the airflow through these holes would affect the internal temperatures of the GF. Two days were measured: 6th of April, without caps, and 7th of April, with caps. Temperatures were compared by the data collected in the Netatmo web application.

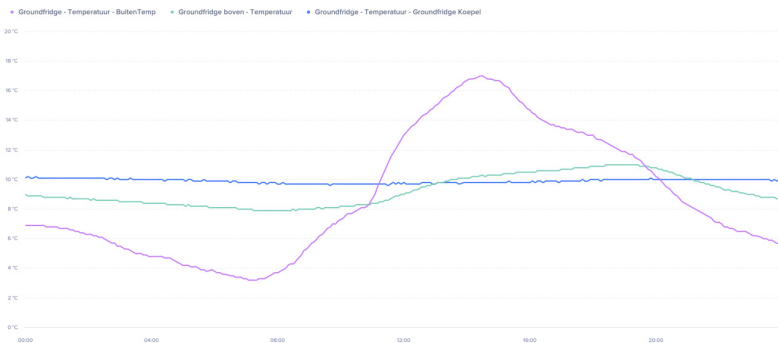
### Observations

- On both days, outside temperature followed a similar pattern: starting around 3.7°C, weakening at 16.7/16.8 at 15:00, then falling back to 5-8°C at midnight.
- On April 6th (without caps), the dome temperature stayed quite flat at 9.7-10.0°C all day. The temperature in the top slowly rose from 7.9°C to a maximum of 10.8°C.
- On April 7th (with caps), the dome temperature remained stable at 9.5 - 9.7°C during the capped period. However, the top temperature spiked sharply to 17.7°C at 17:50, rising above the outside temperature.
- After the cap removal at 16:55, this spike was formed, suggesting a heat pulse as the outside air mixed with the interior.
- Humidity in the top section dropped noticeably on April 7th after cap removal. It dropped from 79% at 16:00 to 71% at 20:00, compared to a stable 78-79% on April 6th. This suggests drier outside air entered when the caps were removed.
- The dome humidity remained very stable on both days (73%).

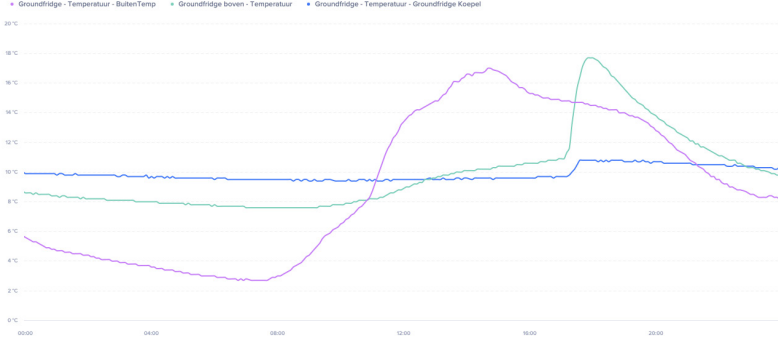
### Conclusion

- The removal of the caps caused a significant heat accumulation in the upper section. The dome remained largely unaffected, protected by the ground mass.
- Removing the caps in the late afternoon is probably worse than having no caps at all
- If caps are used, they should be removed after sunset, to avoid importing heat, opening up at the same time as ventilation could be optimal.
- Humidity data suggests that sealed ventilation also slightly reduces moisture exchange, which could be beneficial or detrimental depending on storage goals.

### April 6th without caps



### April 7th with caps



### Limitations

- Only one day per condition was measured. More repetitions are needed to confirm the pattern.
- No sensor was placed inside the ventilation shaft itself, so shaft temperature at the moment of cap removal is unknown



## Appendix P(b) - Caps testing 2

### Test

A second test was conducted, in which the same caps were removed after sunset, when the ambient temperature drop below the internal temperatures of the GF.

### Observations

- The GF dome remained stable under both conditions, staying in a 0.6°C range.

### Conclusion

There are no decisive results that align with the expectation of the caps slowing down heat.

### Limitation

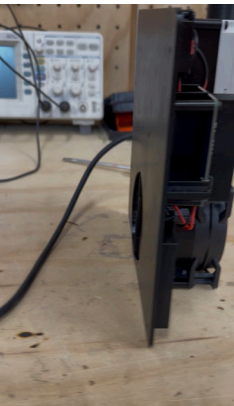
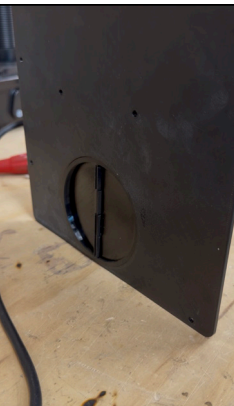
- Only a single day was measured per condition
- The two days were not identical in the ambient environment
- No sensor was placed close to the valve to see the direct effects of this.

## Appendix P(c) - Check valve

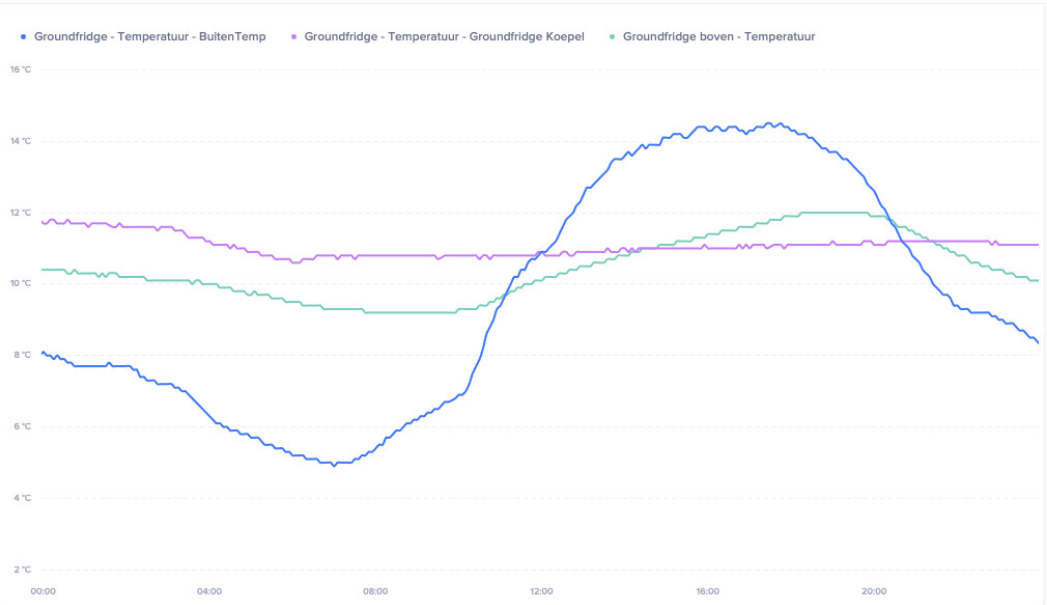
### Goal

The goal is to create system that opens the ventilation shaft in the GF door when the ventilation is working and encloses the ventilation shaft when the ventilation is turned of. The ventilation is already regulated that it can be set according to a desired time and length.

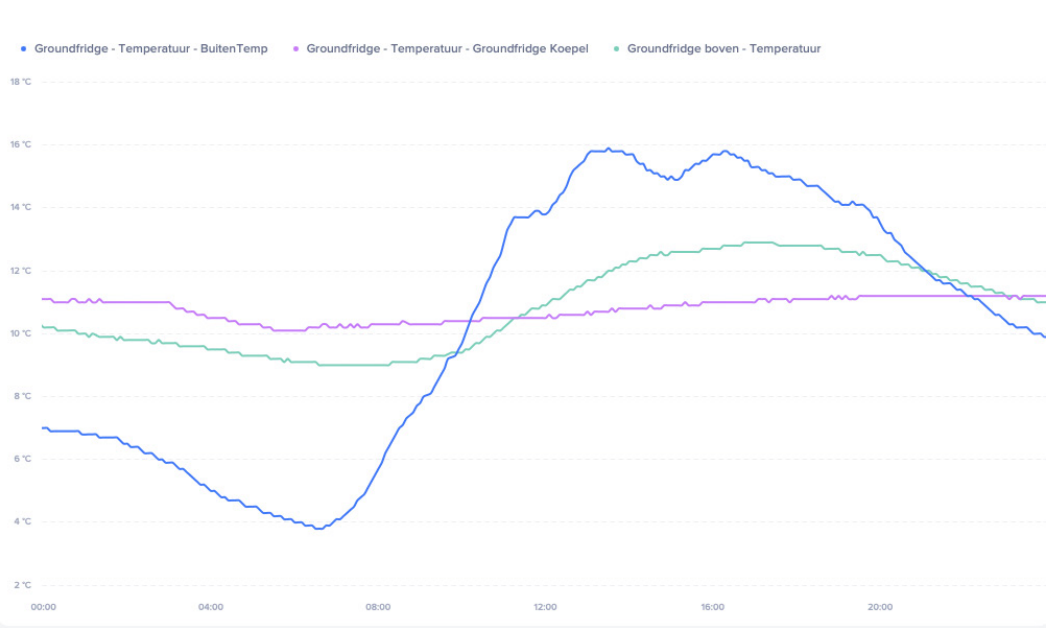
I prototyped a check valve, however, since the door is tilted, the check valve automatically opens up, and does not close anymore. This can be solved with a spring but then the power of the ventilation decreases.



April 21st



April 27th



## Appendix R - Co-creation session

To generate ideas, and come up with out-of-the-box directions, I hosted two co-creation/brainstorm sessions.

### First session

The first one was together with 3 co-workers at Fiction Factory. I generated 3 questions that I wanted to think about, being:

- How can you integrate natures cycle into the GF?
- How can the GF grow old in a better way?
- How to make the GF colder?

Ideation about this gave some meaningful ideas, and also a good insight how to host a session.

### Takeaways

- generate more value, like a fermentation cabinet,
- collect rainwater and use this
- connect it with (regenerative) gardening
- add an extra door or corridor

### Second session

The second session was together with a friend that also studies industrial design engineering. Together we wandered through some methods of co-creation. The aim was to connect nature with the GF, and improve the relationship with the user, the product and Mother Nature.

First we formulated a question and performed the ladder of abstraction, after which we did a flower of association, after which we connected this to absurd questioning, after which we came up with concrete directions and ideas. It was very insightful, and her experience with co-creation contributed largely to insights and creativity.

### Takeaways

- give the nature a stage
- measure the nature around
- generate an image of the nature
- make it bigger than yourself





## Appendix S - Radiative cooling paint test

### Goal

The goal of this experiment is to evaluate the radiative cooling performance of five different coatings applied to MDF panels under real outdoor conditions. The experiment aims to determine which coating most effectively reduces surface temperature through solar reflectance and thermal emittance, and whether any coating achieves sub-ambient surface temperatures, which are the defining characteristic of a functional radiative cooling material.

### Set-Up

Four 30×30 cm MDF panels of 18mm thickness were prepared, each with a different surface coating:  
Control (uncoated MDF)  
TiO2 mixed into varnish  
White paint  
CaCO3 mixed into varnish

Panels were placed horizontally and face-up on metal painting scaffolds outdoors in Amsterdam, elevated off the ground to allow airflow underneath. Testing was conducted on April 14–15, 2026 under partly cloudy conditions.



### Method

Two measurement methods were used in parallel: Thermal camera measurements were taken at four timepoints (10:00, 13:00, 15:00, 17:00) using an infrared thermal camera with emissivity set to 0.93. Both the front (sky-facing) and back (scaffold-facing) surfaces of each panel were measured at each timepoint. Ambient air temperature was recorded manually alongside each measurement round. Continuous temperature logging was performed using DS18B20 digital temperature sensors ( $\pm 0.5^{\circ}\text{C}$  accuracy), connected with an ESP32 module, attached to the back surface of four selected panels:

1. Control
2. TiO2
3. White paint
4. CaCO3

Sensors were connected to an Arduino micro-controller and logged to ThingSpeak at 10-minute intervals over a full 24-hour period from 10:00 on April 14 to 10:00 on April 15, 2026, capturing both daytime and night time thermal behaviour.

### Observations - Front & Back Thermal Camera Test

- White paint and TiO2 varnish consistently measured below ambient air temperature on the front surface during daytime testing, with White paint reaching  $-1.4^{\circ}\text{C}$  and TiO2 reaching  $-0.3^{\circ}\text{C}$  below ambient at noon (13:00), confirming a sub-ambient cooling effect under partial sun conditions.
- The front/back delta of White paint and TiO2 was consistently negative throughout the daytime measurements ( $-1.0^{\circ}\text{C}$  and  $-0.7^{\circ}\text{C}$  respectively at 13:00), indicating that the coating surface was cooler than the MDF substrate underneath, confirming that heat was being rejected upward toward the sky rather than absorbed.
- The control and CaCO3 panels showed a consistently positive front/back delta ( $+2.9^{\circ}\text{C}$  and  $+2.7^{\circ}\text{C}$  at 13:00), indicating net solar heat absorption at the surface.
- CaCO3 varnish performed worse than the uncoated control panel across all thermal camera measurements, with front surface temperatures up to  $0.2^{\circ}\text{C}$  higher than the control at solar noon, attributed to the visually translucent coating layer allowing solar radiation to pass through to the

MDF substrate.

- 

### Limitations - Front & Back Thermal Camera Test

- Ambient air temperature was only recorded manually at four discrete timepoints (10:00, 13:00, 15:00, 17:00)
- Thermal camera measurements were taken at only four timepoints, rather than continuously, limiting temporal resolution of front and back surface temperatures due to manual measurement.
- The test was conducted under partly cloudy conditions, introducing variability in solar irradiance between measurement rounds, reducing the comparability of readings taken at different times.
- The 30×30 cm panel size introduces edge effects that may influence temperature readings if the thermal camera was not consistently centered on each panel.
- Wind speed was not quantitatively logged, introducing an uncontrolled convective cooling variable.

### Conclusion - Thermal Camera Test

White paint and TiO2 varnish both demonstrated sub-ambient front surface temperatures under partial solar irradiance, with white paint achieving the strongest cooling effect of  $-1.4^{\circ}\text{C}$  below ambient at solar noon. The negative front/back temperature delta of these coatings confirms that heat is being rejected at the coating surface rather than absorbed. CaCO3 varnish in its current formulation performed worse than the uncoated control, attributed to insufficient particle loading resulting in a translucent coating with poor solar reflectance.

### Observations - 24-Hour DS18B20 Sensor Test

- All four panels followed a consistent temperature curve over 24 hours, rising during daytime and falling after sunset, confirming stable and reliable sensor operation throughout the full test period.
- During daytime, CaCO3 consistently recorded the highest back temperatures of all four panels, with the largest temperature fluctuations corresponding to cloud passages, confirming it has the poorest solar reflectance of the coatings tested.
- White paint and TiO2 ran slightly cooler than the control during daytime hours, consistent with the thermal camera front surface results.
- Synchronized temperature oscillations across all four temperature sensors during daytime corresponded with cloud passages, confirming

consistent sensor response and validating the reliability of the measurement setup across all panels.

- All four panels converged to within  $1^{\circ}\text{C}$  of each other during the night-time period (21:00–06:00), with temperatures ranging between  $5\text{--}7^{\circ}\text{C}$  across all panels.

### Limitations — 24-Hour DS18B20 Sensor Test

- The DS18B20 temperature sensors were mounted on the back of 18mm MDF panels, introducing significant thermal buffering that dampened surface temperature signals. This is particularly limiting during nighttime when panel-to-panel differences are small ( $1\text{--}2^{\circ}\text{C}$ ), making nighttime radiative cooling performance inconclusive from the sensor data alone.
- Ambient air temperature was not continuously logged alongside the sensor data, making it impossible to calculate panel-to-ambient temperature differences across the full 24-hour curve.
- The partly cloudy conditions introduced repeated variability in solar irradiance throughout the day, reducing the magnitude of temperature differences between panels compared to what would be observed under fully clear sky conditions.
- Wind speed was not quantitatively logged, introducing an uncontrolled convective cooling variable across the full 24-hour period.

### Conclusion — 24-Hour DS18B20 Sensor Test

The 24-hour sensor test confirmed the relative ranking of coatings established by the thermal camera measurements, with CaCO3 consistently the worst performer and White paint and TiO2 the coolest panels during daytime. Nighttime performance remains inconclusive due to the thermal buffering effect of the 18mm MDF substrate and the absence of continuous ambient temperature logging. Further testing with thinner panels and continuous ambient temperature measurement is recommended to fully characterize nighttime radiative cooling performance.



The Arduino code that was used:

```
#include <WiFi.h>
#include <OneWire.h>
#include <DallasTemperature.h>
#include <ThingSpeak.h>

// ===== WIFI =====
const char* ssid = "ff21guest";
const char* password = "ff21guest";

// ===== THINGSPEAK =====
unsigned long channelID = 3339334;
const char* writeAPIKey = "XGDL9IPV2MTE9C63";

WiFiClient client;

// ===== SENSOR =====
#define ONE_WIRE_BUS 5
OneWire oneWire(ONE_WIRE_BUS);
DallasTemperature sensors(&oneWire);

// ===== CONFIG =====
const int NUM_SENSORS = 4;
const char* sensorNames[NUM_SENSORS] = {
  "Sensor 1",
  "Sensor 2",
  "Sensor 3",
  "Sensor 4"
};

// ===== TIMING =====
unsigned long lastTime = 0;
unsigned long interval = 600000;

void setup() {
  Serial.begin(115200);

  sensors.begin();

  WiFi.begin(ssid, password);
  Serial.print("Connecting to WiFi");

  while (WiFi.status() != WL_CONNECTED) {
    delay(500);
    Serial.print(".");
  }

  Serial.println("\nWiFi connected");

  ThingSpeak.begin(client);
}

void loop() {
  if (millis() - lastTime > interval) {
    lastTime = millis();

    sensors.requestTemperatures();

    float t[NUM_SENSORS];

    Serial.println("Temperatures:");

    for (int i = 0; i < NUM_SENSORS; i++) {
      t[i] = sensors.getTempCByIndex(i);

      Serial.print(sensorNames[i]);
      Serial.print(": ");
      Serial.println(t[i]);
    }

    // Send to ThingSpeak (4 fields only)
    ThingSpeak.setField(1, t[0]);
    ThingSpeak.setField(2, t[1]);
    ThingSpeak.setField(3, t[2]);
    ThingSpeak.setField(4, t[3]);

    int response = ThingSpeak.writeFields(channelID, writeAPIKey);

    if (response == 200) {
      Serial.println("Upload OK");
    } else {
      Serial.print("Error: ");
      Serial.println(response);
    }
  }
}
```

## Appendix T - Strip curtain test

### Goal

The goal of this test was to measure the difference in temperature when a strip curtain was placed inside of the tunnel, with the aim of reducing convective heat.

### Set-Up

MDF bow (fitting curve of tunnel top)  
PVC strips  
Hook

The PVC strips were attached on the MDF bow, with the length as long as the tunnel height. A hook was attached to the bow, and it was hung from the ceiling of the GF tunnel with the strips reaching the bottom of the stairs.

### Observations

*Without curtain (29th of April, ambient temperature max 18°C)*

- The cellar (koepel) temperature remained stable between 11-12°C throughout the day.
- The temperate at the door rose to a peak of 16°C around 16:00.
- The gap between the outside temperature and the cellar temperature reached +/- 7°C at peak afternoon.
- There are visible spikes after the opening of the door.

*With curtain (1th of May, ambient temperature max 26°C)*

- The temperature of the cellar remained largely stable, drifting to 12.5°C across the day.
- The temperature at the door rose substantially higher than the 29th of April, reaching 18°C in the afternoon, due to a higher outside/ambient temperature
- Despite the temperature at the door being significantly higher than on the day without a curtain, the temperature within the cellar was similarly muted
- No sharp spike in the cellar temperature was visible during door openings, despite outside temperatures being ~8°C higher than on the comparison day

### Conclusions

- The curtain appears to protect the cellar efficiently, even when the ambient temperatures during the days were significantly different. The with-curtain day was around 8°C hotter outside then the without-curtain day. Yet the temperature in the cellar behaved almost identically in both charts. The curtain compensated for a much more demanding thermal environment.
- The door temperature on the witouth-curtain day peaked at 16°C. With the curtain, it peaked at 18°C, which is higher but far below the outside temperature. The curtain is clearly limiting how much outside heat penetrates into the tunnel zone, which in turn protects the cellar.

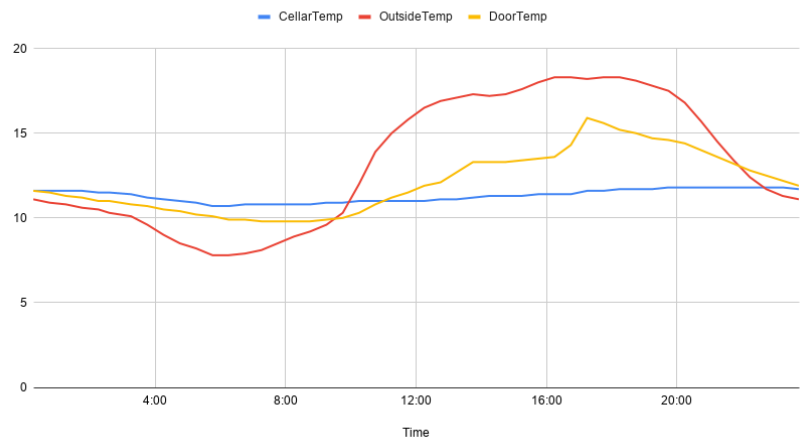
### Limitations

- The days had very different outside temperatures, and therefore a direct comparison is not possible.
- It is only tested with one day per condition, and therefore has a small sample size.
- The door opening schedule was the same on both days, but the impact depends on how warm the inside of the GF had already become
- There was no sensor between the curtain and the cellar entrance, and therefore there is a lack of measurement of the effect of the curtain.

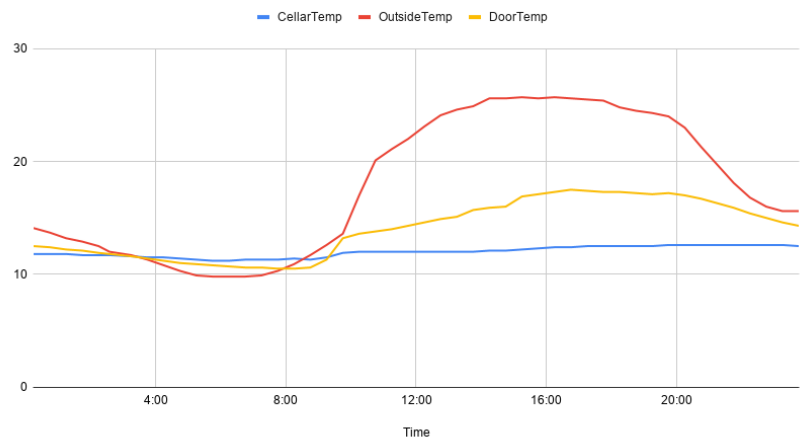




Temperature with Strokecurtain



Temperatures without Strokecurtain



## Appendix U - TiO2 ratio test

### Goal

The goal of this experiment is to evaluate the radiative cooling performance of four different ratios of TiO2 in a coating under real outdoor conditions. The test aims to determine which ratio of TiO2 mixed into a varnish/coating is the most effective in cooling surface temperatures

### Set-Up

Four 30×30 cm okume double panels, with an air gap in between. All the panels have a different amount of TiO2 powder mixed into green paint:

0% (control)

5%

10%

20%

Arduino temperature logger connected to ThingSpeak with 4 DSB temperature sensors

Thermal camera

Panels were placed horizontally and face-up on metal painting scaffolds outdoors in Amsterdam, elevated off the ground to allow airflow underneath. Testing was conducted on April 29th, 2026 under partly sunny/partly cloudy conditions.



### Method

Four panels of 0%, 5%, 10% and 20% TiO2 mixed into green paint, measured by weight, were tested. The panels were placed outdoors under direct sun on 29th of April 2029 were tested, with continuous Arduino temperature logging and logging of ambient temperatures across the day.

### Observations

At peak (around 12:30-13:30), the panels ranged from 29.5°C (0%) to 27.5°C (20%). In comparison with the ambient temperature, that was 17.1°C at its peak. The difference in surface temperature and ambient temperature for the control panel was 14.0°C and 12.0°C for the 20% panel, a difference of approximately 1.8°C. The difference of 5% panel was 12.5°C and the difference for 10% was 12.1°C. The cooling effects increased with the concentration of TiO2, and there was a bigger improvement in 0-5% and smaller in the 5-10-20%. The 20% panel also cools down faster in a decrease in ambient temperature.

### Limitations

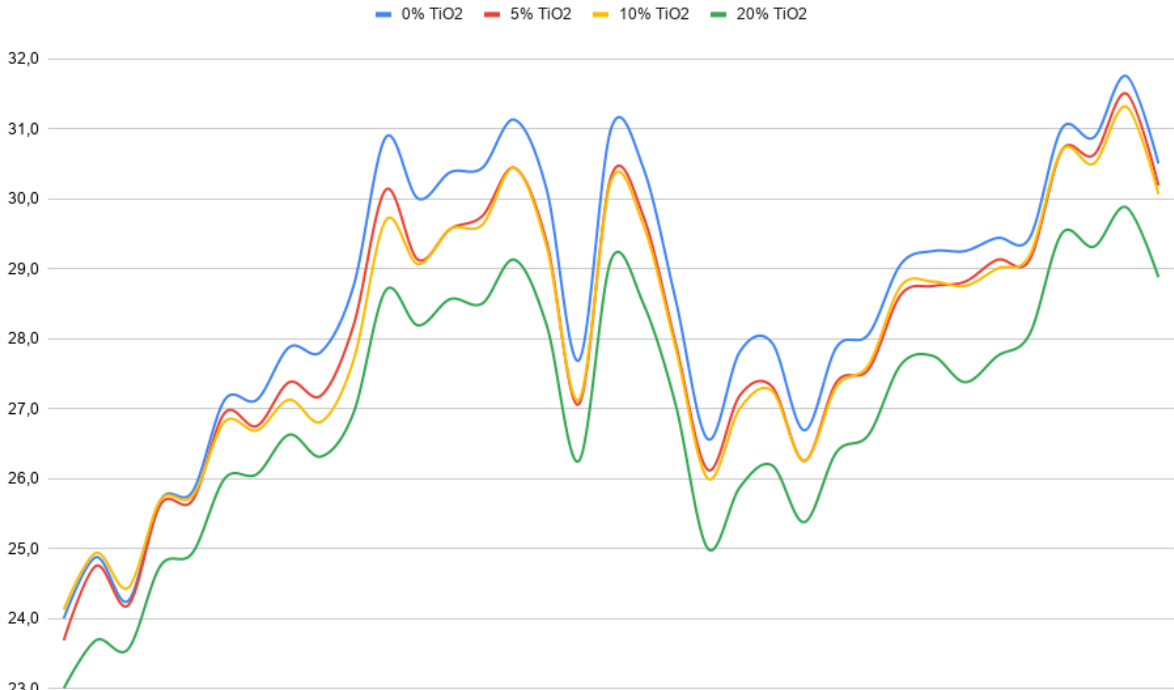
- The Arduino measured the air gap in between the sandwich panels, and not directly the surface temperature. In all panels this was similar, however, the air gap has created a buffer for the measuring.
- The test was conducted during a single day, and therefore is a small batch test
- The variables of wind, humidity and partial cloud cover were uncertain, and so the test was done in an uncontrolled setting
- The TiO2 that was used was a standard pigment-grade size, and therefore not optimised for radiative cooling. That particle size should be 200nm.
- Only 4 concentration levels were tested, and no replication of panels were tested.
- Generally, green colours absorb solar radiation

### Conclusions

Adding TiO2 particles into green paint produces a measurable effect in heat absorption under direct solar exposure. The effect is consistent during the whole period of testing. The maximum reduction of the temperature difference is 2.0°C. Probably this effect is a result of colour lightness, and therefore it can be concluded that a lighter colour will have a positive effect on temperature reduction. Additionally, the lighter colour has a faster decrease in temperature, which confirms the goal of radiative cooling.



|                | 0% TiO2 | 5% TiO2 | 10% TiO2 | 20% TiO2 | ambient |
|----------------|---------|---------|----------|----------|---------|
| 10:33:51+02:00 | 24,0    | 23,7    | 24,1     | 23,0     | 12,8    |
| 10:43:50+02:00 | 24,9    | 24,8    | 24,9     | 23,7     | 14,1    |
| 10:53:50+02:00 | 24,3    | 24,2    | 24,4     | 23,6     | 14,4    |
| 11:03:50+02:00 | 25,7    | 25,6    | 25,7     | 24,8     | 14,8    |
| 11:13:51+02:00 | 25,8    | 25,7    | 25,8     | 24,9     | 15,0    |
| 11:23:51+02:00 | 27,1    | 26,9    | 26,8     | 26,0     | 15,4    |
| 11:33:51+02:00 | 27,1    | 26,8    | 26,7     | 26,1     | 15,6    |
| 11:43:51+02:00 | 27,9    | 27,4    | 27,1     | 26,6     | 15,9    |
| 11:53:51+02:00 | 27,8    | 27,2    | 26,8     | 26,3     | 16,0    |
| 12:03:51+02:00 | 28,8    | 28,2    | 27,7     | 26,9     | 16,2    |
| 12:13:51+02:00 | 30,9    | 30,1    | 29,7     | 28,7     | 16,6    |
| 12:23:51+02:00 | 30,0    | 29,1    | 29,1     | 28,2     | 16,7    |
| 12:33:51+02:00 | 30,4    | 29,6    | 29,6     | 28,6     | 16,8    |
| 12:43:51+02:00 | 30,4    | 29,8    | 29,6     | 28,5     | 16,9    |
| 12:53:51+02:00 | 31,1    | 30,4    | 30,4     | 29,1     | 17,1    |
| 13:03:51+02:00 | 30,1    | 29,4    | 29,3     | 28,2     | 17,1    |
| 13:13:51+02:00 | 27,7    | 27,1    | 27,1     | 26,3     | 17,0    |
| 13:23:51+02:00 | 31,0    | 30,3    | 30,3     | 29,1     | 17,3    |
| 13:33:51+02:00 | 30,4    | 29,8    | 29,6     | 28,5     | 17,4    |
| 13:43:51+02:00 | 28,6    | 27,9    | 27,9     | 27,1     | 17,3    |
| 13:53:51+02:00 | 26,6    | 26,1    | 26,0     | 25,0     | 17,1    |
| 14:03:51+02:00 | 27,8    | 27,2    | 27,0     | 25,9     | 17,1    |
| 14:13:51+02:00 | 27,9    | 27,3    | 27,3     | 26,2     | 17,2    |
| 14:23:51+02:00 | 26,7    | 26,3    | 26,3     | 25,4     | 17,2    |
| 14:33:51+02:00 | 27,9    | 27,4    | 27,3     | 26,4     | 17,3    |
| 14:43:51+02:00 | 28,1    | 27,6    | 27,6     | 26,6     | 17,3    |
| 14:53:51+02:00 | 29,1    | 28,6    | 28,8     | 27,6     | 17,5    |
| 15:03:51+02:00 | 29,3    | 28,8    | 28,8     | 27,8     | 17,6    |
| 15:13:51+02:00 | 29,3    | 28,8    | 28,8     | 27,4     | 17,7    |
| 15:23:51+02:00 | 29,4    | 29,1    | 29,0     | 27,8     | 17,7    |
| 15:33:51+02:00 | 29,4    | 29,1    | 29,2     | 28,1     | 17,9    |
| 15:43:51+02:00 | 31,0    | 30,7    | 30,7     | 29,5     | 18,0    |
| 15:53:51+02:00 | 30,9    | 30,6    | 30,5     | 29,3     | 18,2    |
| 16:03:51+02:00 | 31,8    | 31,5    | 31,3     | 29,9     | 18,3    |
| 16:13:51+02:00 | 30,5    | 30,2    | 30,1     | 28,9     | 18,3    |



## Appendix V - Olla test

### Goal

The goal of this test was to measure the difference in temperature of the soil when an olla and vegetation is placed inside a container.

### Set-Up

Two terracotta pots of 40 cm diameter  
One small terracotta pot of 8 cm with lid  
Water container  
Micro-hose (Gardena)  
Tap (to stop the water)  
Soil  
Plant (nepeta)  
Arduino set-up with temperature sensors

### Method

Two terracotta pots were filled with soil. In one of the pots, a plant and a smaller terracotta pot with a lid was placed. The water basin was filled with water, and a micro hose with micro tap was attached to the water basin. The micro hose end was placed inside the smaller pot, and the lid was put on top.

Two temperature sensors were placed in each big pot. One on surface level and one deeper at a depth of approximately 15 cm deep.

A shed was placed over the pots to prevent rainwater from interfering with the tests.

Temperatures were logged over a period of 7 days.

### Observations

- At depth, there is a clear temperature difference at warmer days, meaning it is heat-dependant. On warmer days, the deep olla sensor reads measurably cooler than the deep control sensor. The gap is most pronounced at daily peak temperatures: on May 5 for instance, when the control deep reaches ~26°C, the olla deep sits around 23°C, a difference of roughly 3°C. At night the temperatures drop, as the evaporative demand falls. The two deep temperatures converge back towards the same values. This pattern repeats across every warm day in the dataset and is the clearest evidence of an active cooling mechanism.
- The shallow olla sensor shows an even larger cooling difference: During peak daytime heat (May 4–5, May 9–10), the control shallow hits 32–36°C while the olla shallow stays in the 23–27°C range, a sustained difference of 5–8°C. The shallow zone is where evaporation from the soil surface and transpiration through plant roots are most intense, so the greater cooling there is consistent with the evapotranspiration mechanism being strongest closest to the olla. Additionally, here there is a shadow formed by the plant.
- The cooling effect scales directly with heat load: on cooler or overcast days (May 3, May 6–7, the final days of the dataset), the gap between olla and control narrows at both depths and sometimes disappears almost entirely. The more heat energy available to drive evaporation, the greater the cooling effect. This is the signature of latent heat cooling: the energy that would raise soil temperature is instead consumed by vaporising water.
- The water consistently flows out of the basin into the ollas. During the week, the amount of water reduced into half of the tank at the end of the week. This means that the olla actively gives of water to the soil and takes water from the basin.



Conclusions

The olla prototype is functioning as an active evaporative cooling system. The temperature data at both sensor depths is consistent with peaking ambient temperatures. The cooling effect is real, repeatable across multiple days, detectable at both depth and shallow location, and is proportional to the available heat load.

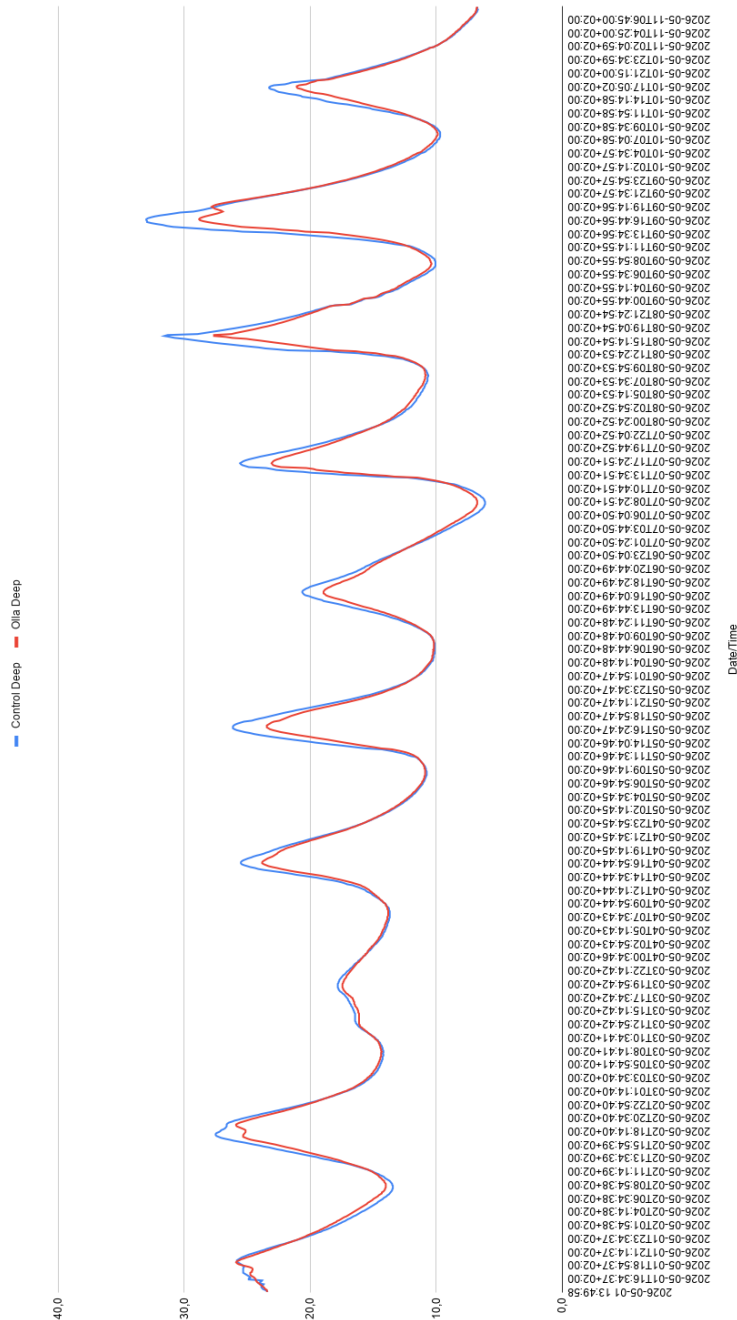
The heat dependence of the effect is particularly significant: the olla delivers the most cooling precisely when the plants need it most. It is self-regulating in the right direction.

Takeaways

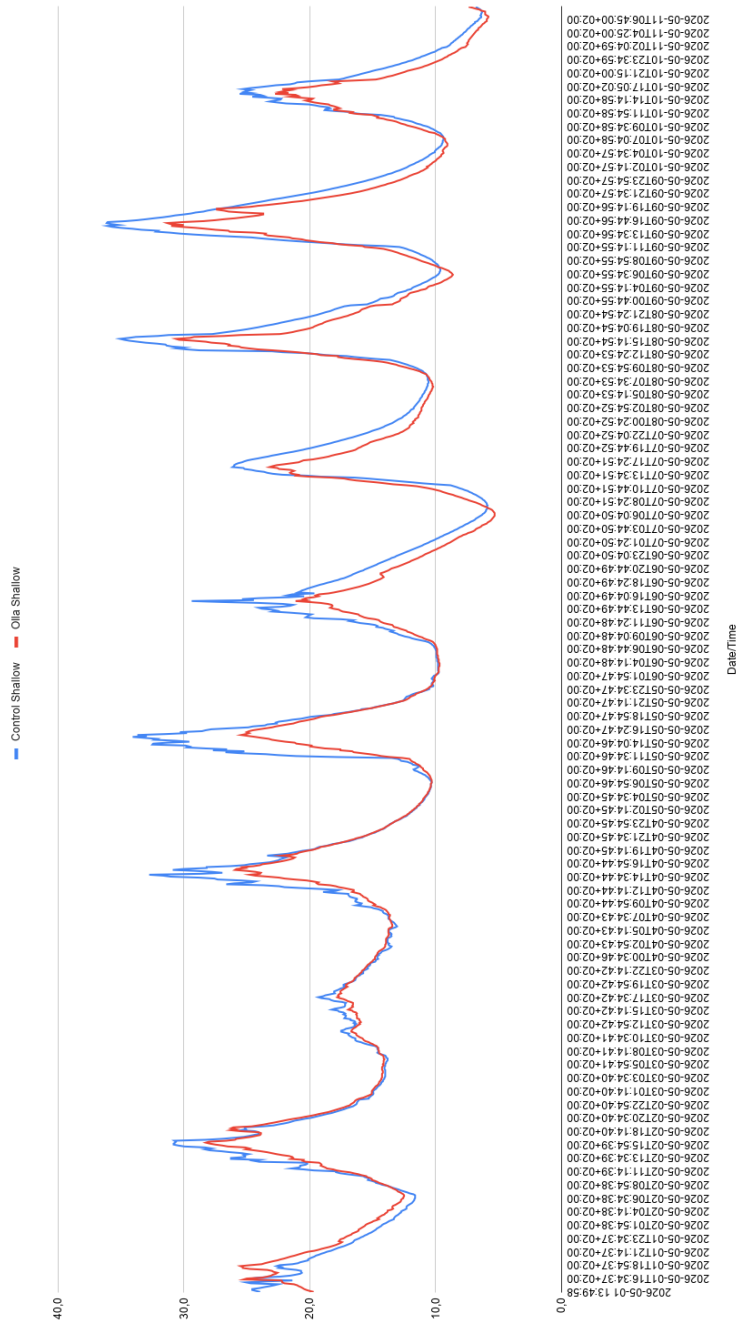
- The core concept is validated: water evaporation from the olla is measurably cooling the surrounding soil at both depths.
- The effect is the strongest at peak heat, which is desirable.
- The self-regulating nature is a key design strength.
- The test is performed during moderate spring temperatures, but to full discover the potential, the set-up should be tested during warmer days.
- The evaporation rate should be measured in order to fully characterise the system.



Deep Temperature - Olla vs Control



Shallow Temperature - Olla vs Control





## Appendix W- Vegetation plan

| Plant              | Latijnse naam                  | Grootte                      | Functie                                                                             | Bloeiperiode                                                  | Zorg                                                                      | Hoeveelheid |
|--------------------|--------------------------------|------------------------------|-------------------------------------------------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------------------|-------------|
| <i>Boven</i>       |                                |                              |                                                                                     |                                                               |                                                                           |             |
| Paraplu bamboe     | Arundinaria murielae           | H: 2- 2,5<br>D: 1,5 - 2      | Windscherm,<br>stilstaande lucht,<br>verminderde<br>warmte uitwisseling<br>via wind | hele jaar<br>groenblijvend                                    | Dode stengels<br>in voorjaar                                              | 1           |
| Chinees prachtriet | Miscanthus sinensis 'zebrinus' | H: 1,5 - 2<br>D: 0,8 - 1,2   | Windscherm,<br>stilstaande lucht,<br>verminderde<br>warmte uitwisseling<br>via wind | Groen in lente -<br>herfst<br>sept-okt<br>pluimen             | In lente<br>terugknippen<br>tot 10 - 20 cm<br>boven grond                 | 2 - 3       |
| <i>Midden</i>      |                                |                              |                                                                                     |                                                               |                                                                           |             |
| Dropplant          | Agastache rugosa               | H: 0,6 - 0,8<br>D: 0,4       | Hoge verdamping,<br>dus actieve koeling<br>Trekt bestuivers<br>aan                  | Groen vanaf<br>maart/april<br><br>Bloei in juli -<br>augustus | In maart<br>terugknippen<br>Weinig zorg                                   | 5 - 8       |
| Kattenkruid        | Nepeta                         | H: 0,6<br>D: 0,35            | Hoge verdamping<br>Erosiewerend                                                     | Groen vanaf<br>maart<br><br>Bloei in mei -<br>september       | Na eerste<br>bloei<br>terugknippen                                        | 4 - 6       |
| Duizendknoop       | Persicaria amplexicaulis       | H: 1 - 1,2<br>D: 0,5 - 1     | Vochtvasthoudend,<br>dus actieve koeling                                            | Groen vanaf<br>maart/april<br><br>juli - september            | In maart<br>terugknippen<br>Sterft in de<br>winter af                     | 2 - 4       |
| Salie              | Indigo spires                  | H: 1 - 1,5<br>D: 0,7         | Vochtverdamping<br>Zonreflecterend                                                  | Groen vanaf<br>maart/april<br><br>juli - september            | In maart/april<br>terugknippen<br>tot +/- 10 cm<br>boven<br>verhoute deel | 4 - 6       |
| Plataargras        | Chasmanthum latifolium         | H: 0,8 - 1<br>D: 0,6 - 0,8   | Structuur en<br>beweging<br>Insecten<br>Schuilplaats                                | Groen vanaf<br>maart/april<br><br>juli - september<br>bloemen | In voorjaar to<br>5 cm<br>terugknippen                                    | 3 - 4       |
| <i>Onder</i>       |                                |                              |                                                                                     |                                                               |                                                                           |             |
| Ooievaarsbek       | Geranium                       | H: 0,2 - 0,4<br>D: 0,4 - 0,6 | Bodembedekker<br>Erosiebestrijding                                                  | Halfwintergroen<br>mei -<br>september<br>bloemen              | Na bloei<br>terugknippen<br>voor herbloei                                 | 4 - 6       |

## Vegetation plan

In the visual on the right, an overview of the plants that should be planted on top of the GF hill is visualised. These specific types are insights of a conversation with my grandmother, who has a lot of knowledge about plant types, researched online and validated with a gardener.

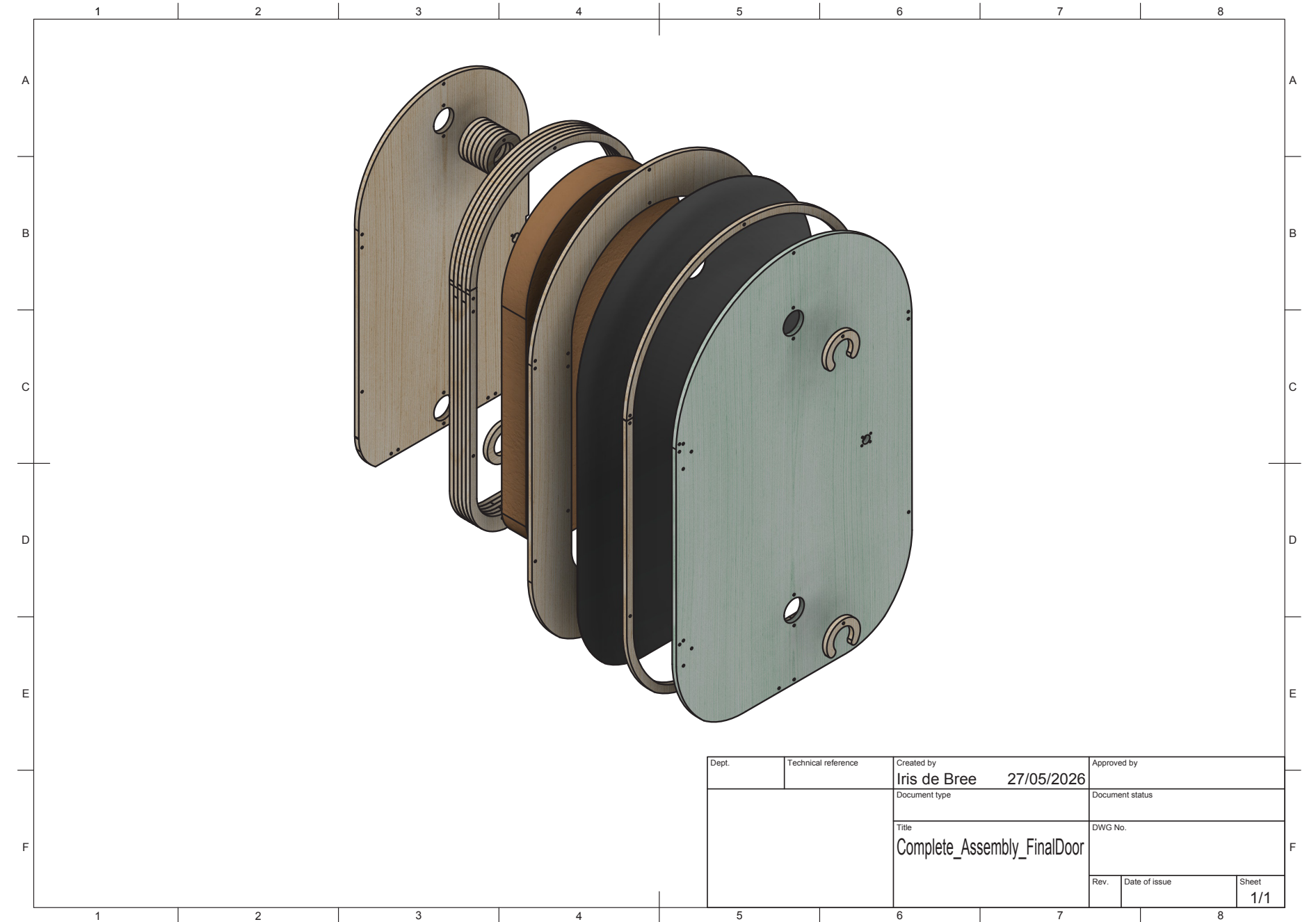
The table visualises the plant types per layer, the Latin name, the height, function, period of blossoming, care advice and quantity to be planted.

## Cost estimate

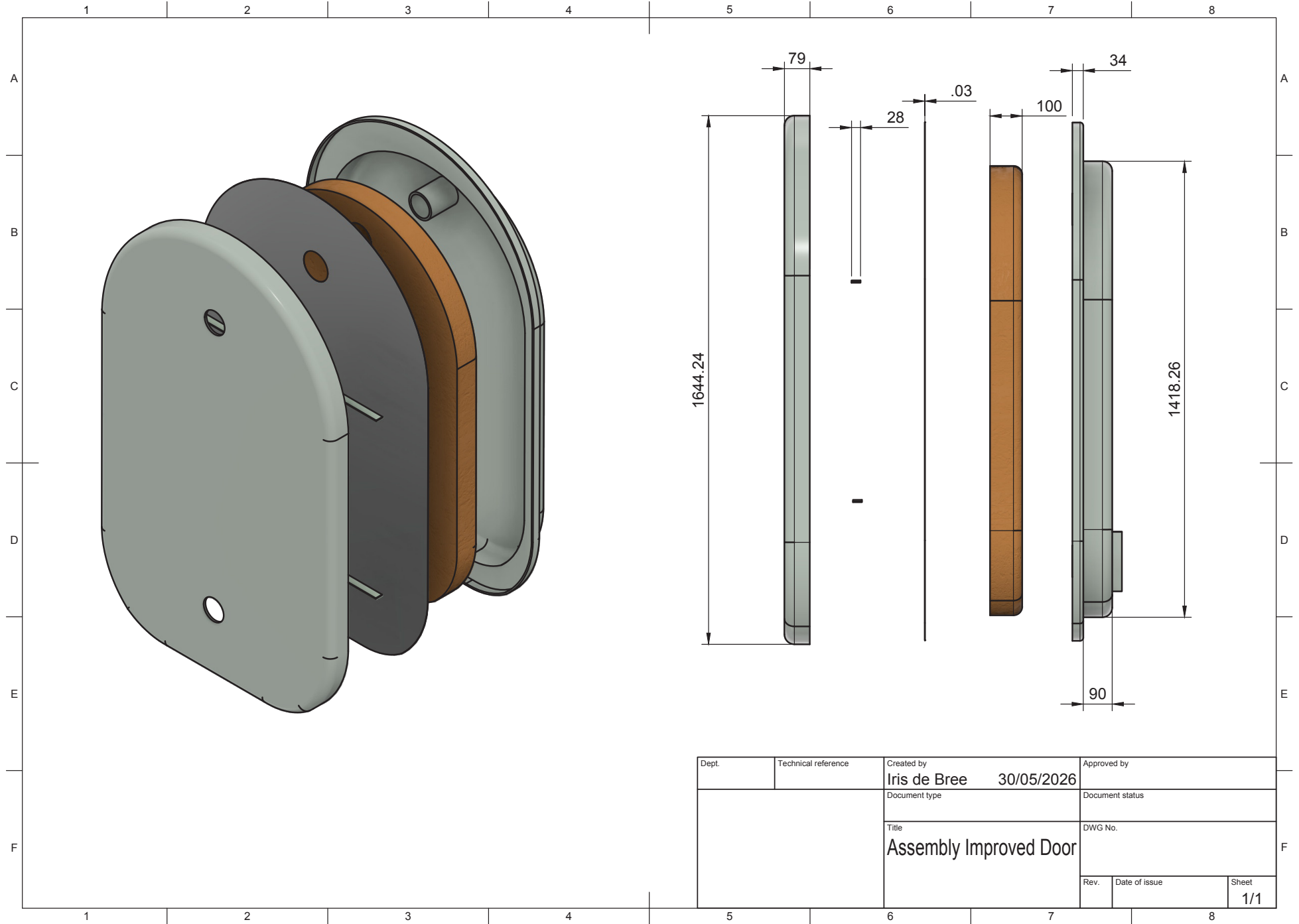
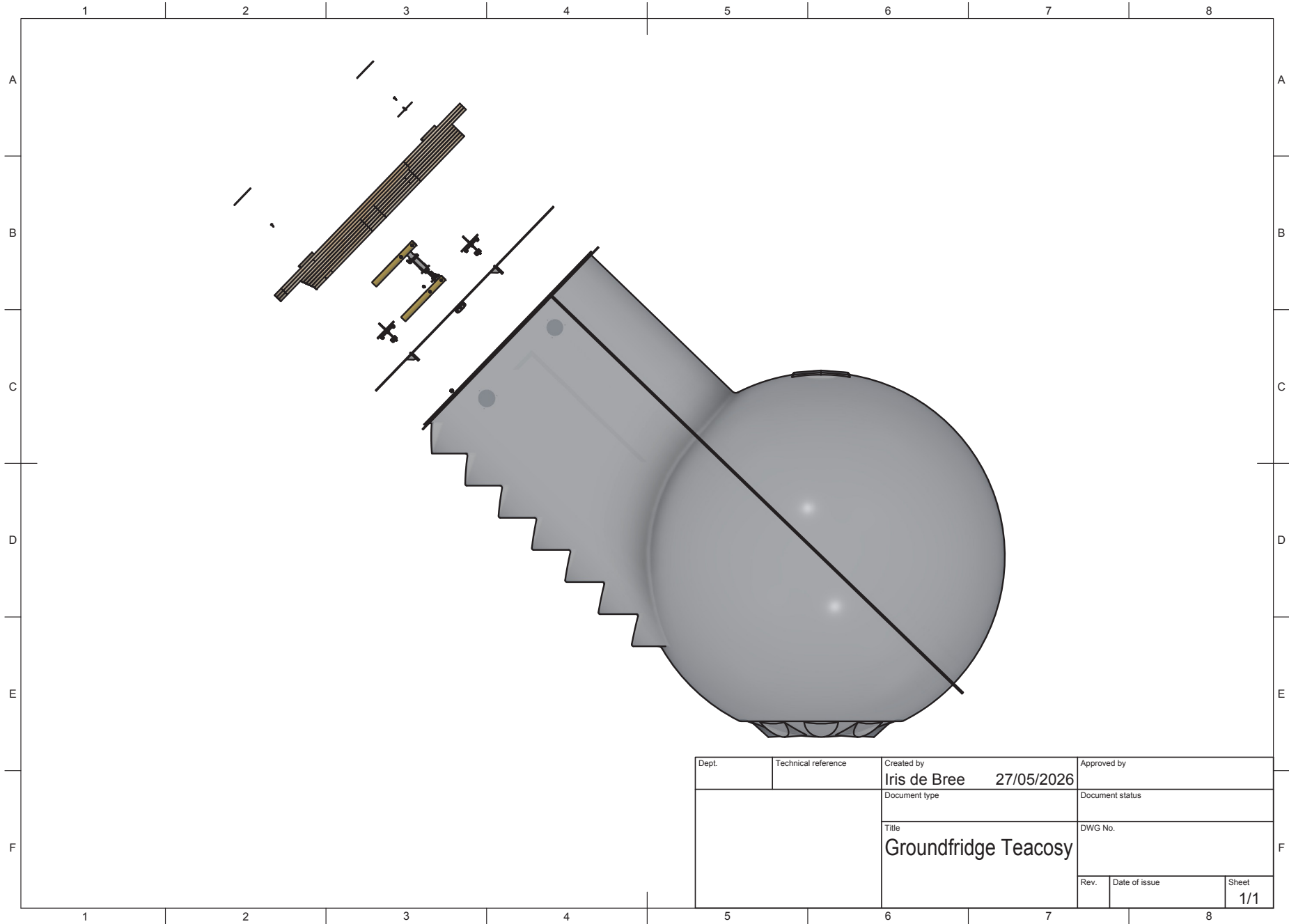
The table underneath visualised the costs that are estimated to plant the full range of plants.

| Cost estimate: €227 |             |       |          |        |                                                                                                                                                                                                                                                                                                                                                                                     |
|---------------------|-------------|-------|----------|--------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Plant               | Size        | Price | Quantity | Total  | Source (NL)                                                                                                                                                                                                                                                                                                                                                                         |
| Paraplu bamboe      | 80 - 100 cm | €25   | 1        | €25    | <a href="https://www.fleur.nl/fargesia-murielae-bamboe?specifications_buitemplanten_plantaize=8">https://www.fleur.nl/fargesia-murielae-bamboe?specifications_buitemplanten_plantaize=8</a>                                                                                                                                                                                         |
| Chinees prachtriet  | 10 - 30 cm  | €9    | 3        | €27    | <a href="https://groeneparadijs.nl/miscantibus-sinensis-chinees-prachtriet.html">https://groeneparadijs.nl/miscantibus-sinensis-chinees-prachtriet.html</a>                                                                                                                                                                                                                         |
| Droplant            | 5 - 25 cm   | €3,5  | 7        | €24,50 | <a href="https://www.fleur.nl/vagastache-blauw-fortune-37724?_q=1*gaep7o*up*MQ*ga*MTYaNDU2MjMwNkxNzc3Mk1NzY1*ga_YTJQc0Y0dHl*vcE3NzcyOTU3NjU3bzE3ZkZlZDdE3NzcyOTU3NzAsAaU3JGawJG5hNjQxMDY4Mw">https://www.fleur.nl/vagastache-blauw-fortune-37724?_q=1*gaep7o*up*MQ*ga*MTYaNDU2MjMwNkxNzc3Mk1NzY1*ga_YTJQc0Y0dHl*vcE3NzcyOTU3NjU3bzE3ZkZlZDdE3NzcyOTU3NzAsAaU3JGawJG5hNjQxMDY4Mw</a> |
| Kattenkruid         | 0 - 30 cm   | €8    | 5        | €45    | <a href="https://groeneparadijs.nl/nepeta-l-aaseni-kattenkruid.html">https://groeneparadijs.nl/nepeta-l-aaseni-kattenkruid.html</a>                                                                                                                                                                                                                                                 |
| Duizendknoop        | 0 - 30 cm   | €11   | 3        | €33    | <a href="https://groeneparadijs.nl/sericaria-amplexicaulis-duizendknoop.html">https://groeneparadijs.nl/sericaria-amplexicaulis-duizendknoop.html</a>                                                                                                                                                                                                                               |
| Salie               | 9 cm        | €2,5  | 5        | €12,50 | <a href="https://border.nl/product/salvia-in-digo-spires/">https://border.nl/product/salvia-in-digo-spires/</a>                                                                                                                                                                                                                                                                     |
| Plataargras         | 10 cm       | €6    | 4        | €24    | <a href="https://groeneparadijs.nl/chaenactis-lutulum.html">https://groeneparadijs.nl/chaenactis-lutulum.html</a>                                                                                                                                                                                                                                                                   |
| Ooievaarsbek        | 10 cm       | €6    | 6        | €36    | <a href="https://groeneparadijs.nl/geranium-dalmaticum-oovevaarsbek.html">https://groeneparadijs.nl/geranium-dalmaticum-oovevaarsbek.html</a>                                                                                                                                                                                                                                       |

## Appendix X - Prototype and final design drawings









# Appendix Y - Door prototype V1

## Goal

This test was conducted in order to analyse whether the redesigned door (PrototypeDoor) reduces heat in comparison to the original door (RegularDoor). The goal is to see whether the internal Groundfridge temperatures stay closer to the ground temperature.

## Set-Up

Both doors were monitored in the field, and had to be installed on the Groundfridge. This meant that the measurements were in situ.

- Regular door: the regular door of Groundfridge, with Rc = 2.2. Logged between 29/05/2026 and 31/05/2026
- PrototypeDoor: the improved door, with Rc = 3.7. Logged between 14/05/2026 and 20/05/2026

For both set-ups the three sensors were compared, being ambient temperature, door temperature (on the inside of the door) and cellar temperature (deeper in the storage space). Ground temperature data of KNMI was used as a stable reference.

## Method

- Ambient, door and cellar temperatures were logged automatically by Netatmo sensors and similar intervals were compared.
- The temperatures were analysed and compared to decide whether one door would be more efficient in keeping heat outside.
- Temperature data were compared in multiple combinations:
  - $\Delta(\text{ambient} - \text{cellar})$  to quantify external heat influence
  - $\Delta(\text{door} - \text{cellar})$  to assess heat transfer across the door
  - $\Delta(\text{cellar} - \text{ground})$  to evaluate how closely the cellar tracks the stable ground temperature

## Results

In the graphs, the results are visible.

## Observations

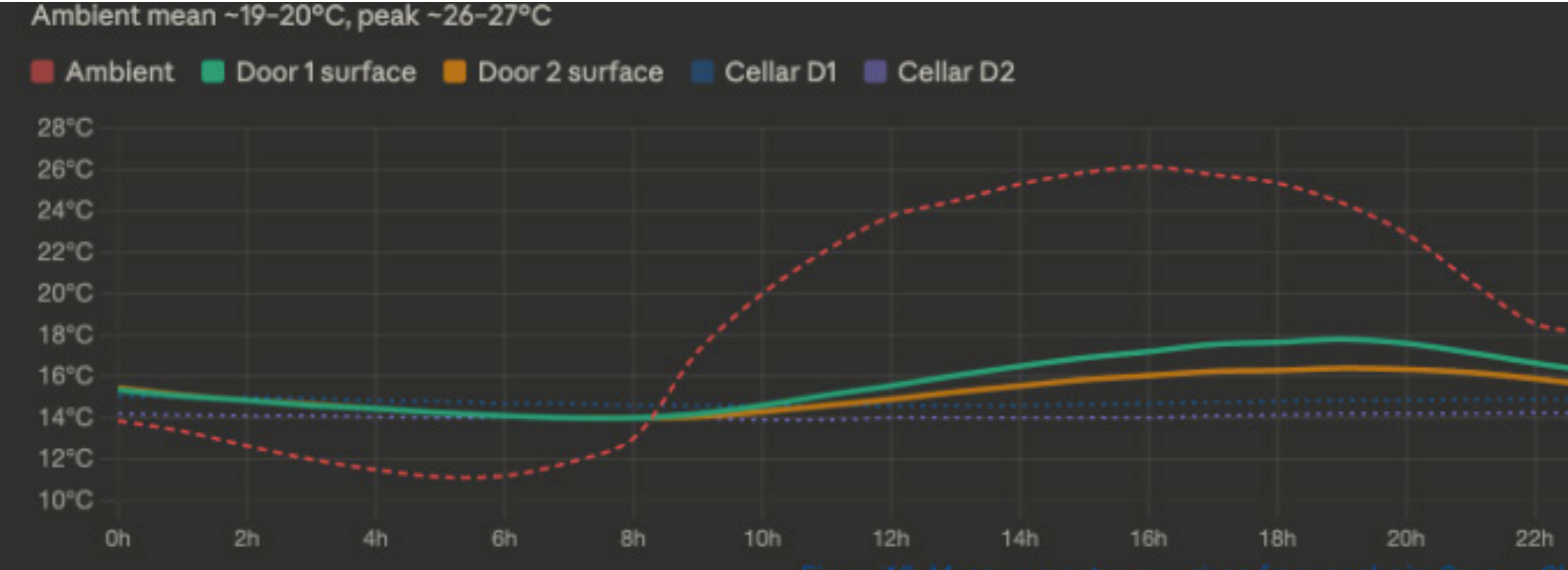
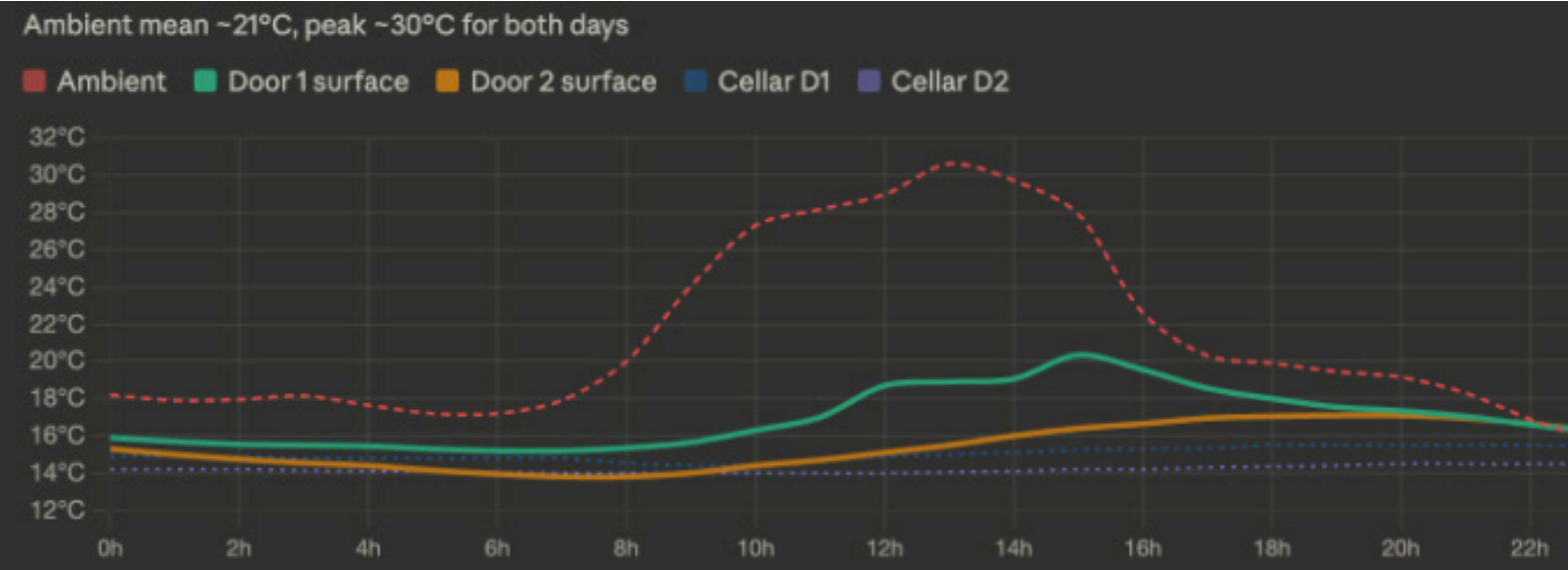
- Regular door: the door temperature reflected the ambient temperature closely, and rose significantly above the cellar temperature (e.g. ambient 30.6 °C , door 18.8 °C and cellar 15.0 °C ). The cellar temperature responded by gradually increasing, reaching 17.1 °C The cellar temperature was 2-3 °C above ground temperature in warmer periods.
- PrototypeDoor: door temperature stayed closer to cellar temperature even as ambient rose (e.g. ambient 30.6 °C , door 18.8 °C and cellar 15.0 °C ). The cellar stayed within roughly 1 to 1.5 °C to the ground temperature throughout the monitored period.
- At comparable ambient conditions, the PrototypeDoor was several degrees cooler than the RegularDoor, and the door temperature was throughout significantly cooler.
- The differences between the doors became the largest during high ambient temperatures, with RegularDoor showing noticeably higher heat transfer

## Limitations

- The doors were not monitored over the same time period. Ambient temperatures were not identical at the measurements. Therefore, the data can not be treated as directly comparable measurements, however with use of AI, it was possible to create indirect comparisons.
- Groundtemperature was stable, but not identical. This introduced a baseline offset
- Only temperature was compared, however humidity, wind speed and solar irradiance data were not logged.

## Conclusions

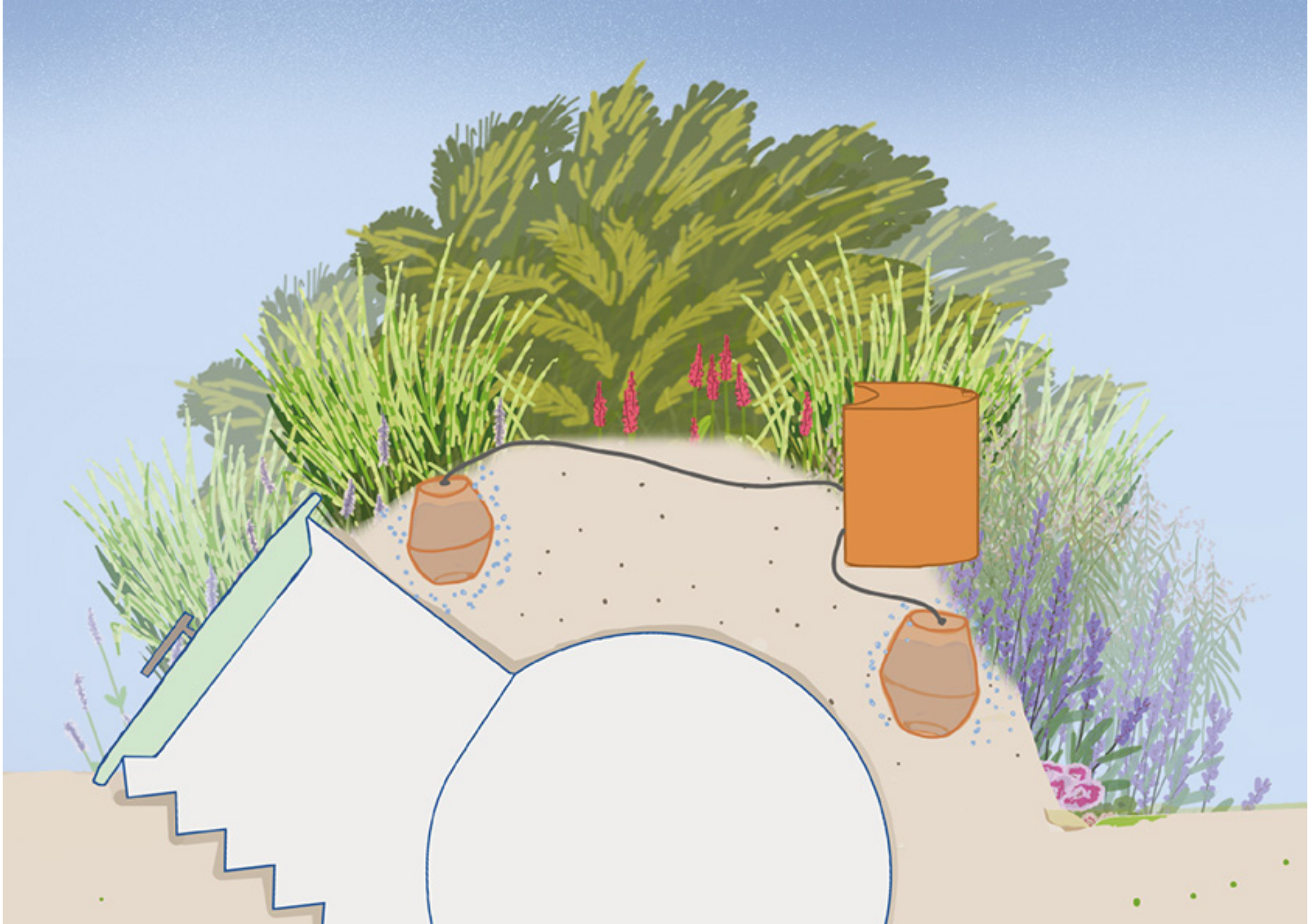
The PrototypeDoor demonstrated significantly better insulation performance compared to the RegularDoor across all relevant comparison metrics. Cellar temperature stayed closer to the groundtemperature, differed more from ambient temperature and the door temperature stayed closer to cellar temperature. These results indicate that the PrototypeDoor design is more effective against ambient heat rises and provides a more thermally stable cellar environment.





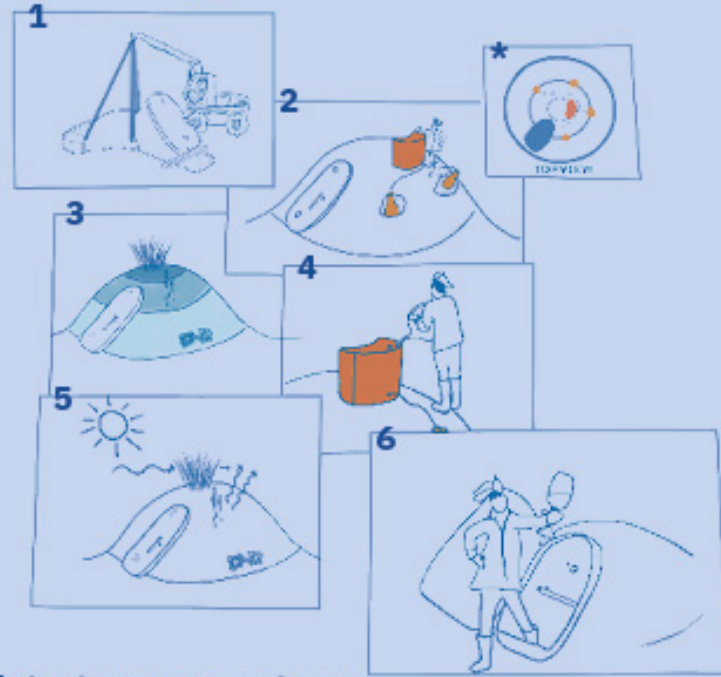
**Appendix Z - Groundflow manual**

A manual for the user to understand and install the Groundflow system is created. This passive irrigation system and vegetation plan manual is visualised in this appendix.





## Werking

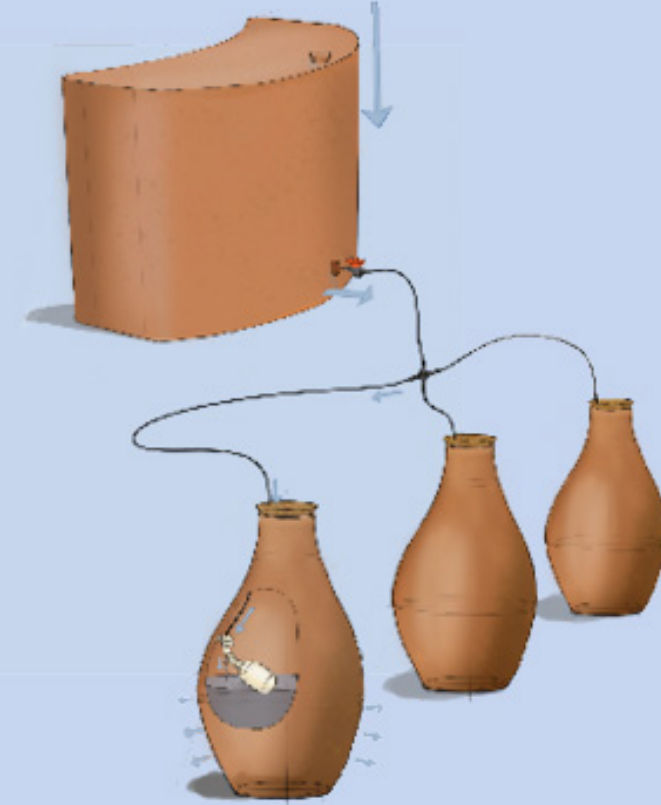


### Watertoevoer systeem

De gebruiker installeert de Groundfridge op de gebruikelijke manier met een graafmachine. Direct na de installatie van de Groundfridge wordt het Groundflow-systeem geïnstalleerd door de ollas in de grond te begraven en het waterbassin bovenop de heuvel te plaatsen, zoals de topview\* laat zien.

De gebruiker volgt de richtlijnen uit de Groundflow-handleiding over het planten van de vegetatietypen in de drie lagen zoals het vegetatieplan op de achterkant van de handleiding. De gebruiker vult het water bassin wanneer het leeg is, waarna het water automatisch de ollas instroomt. Door middel van verdamping van de grond en via de planten in de middelste laag, en het breken van warme lucht door de bovenste laag wordt de warmte van de Groundfridge-heuvel afgevoerd. De gebruiker geniet van een goed gekoelde Groundfridge.

## Systeem

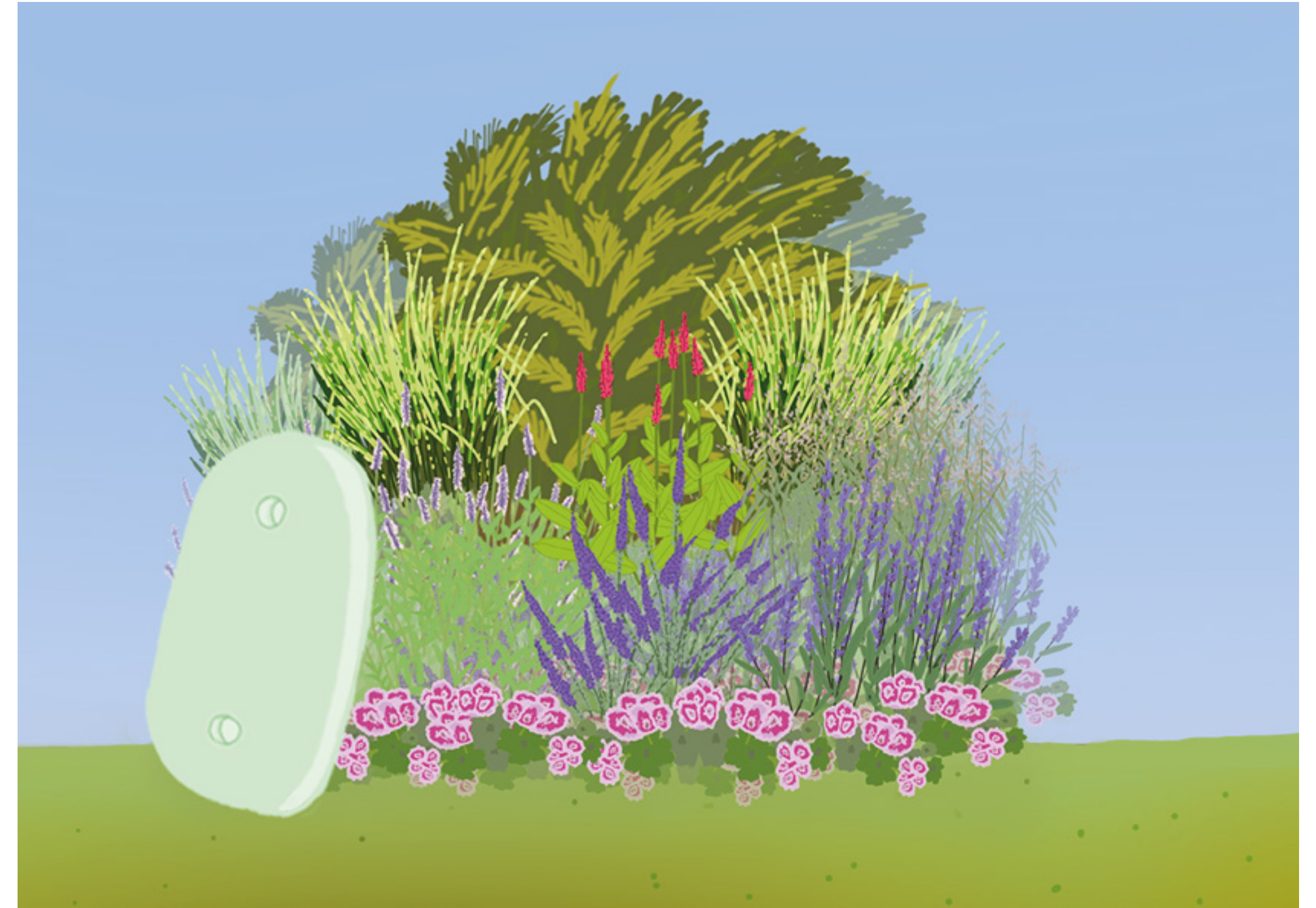


### Watertoevoer systeem

Vanuit het bassin stroomt het water naar de verschillende olla's. Dit gebeurt geheel automatisch via de verdeler door de microslang. In de ollas zitten vlotterventielen, die ervoor zorgen dat het waterpeil altijd correct blijft.

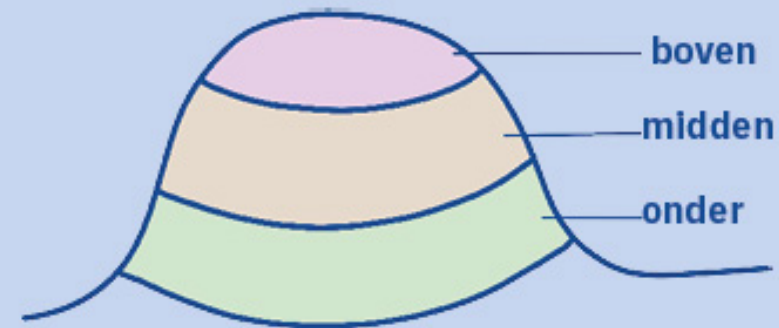
Als het water eenmaal in de olla zit, sijpelt het door de terracotta wand heen naar buiten, richting de wortels van de planten.

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## Vegetatie lagen



### Bovenste laag

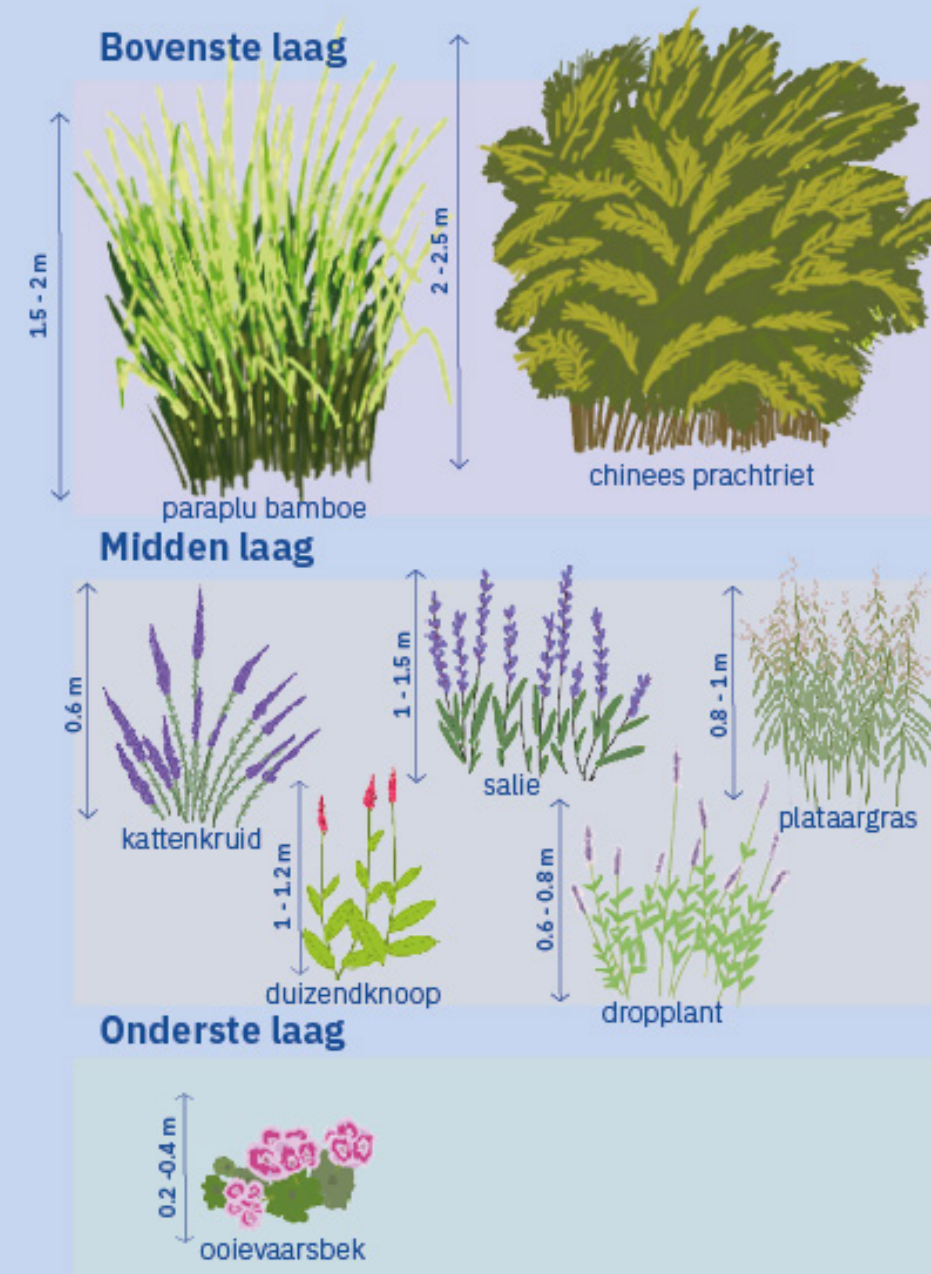
Deze planten fungeren als windbreker en voorkomen daardoor dat de heuvel opwarmt. Daarnaast zorgt deze laag, door zijn weelderige structuur, voor stilstaande lucht en werkt zo als isolatie. Deze laag werkt daarnaast ook als habitat voor vogels en insecten.

### Middelste laag

Deze laag fungeert als verdamer: de laag die water vanuit de ollas opneemt en het, onder invloed van warmte, laat verdampen in de atmosfeer. Deze laag trekt insecten zoals bijen en vlinders aan, en draagt bij aan de biodiversiteit.

### Onderste laag

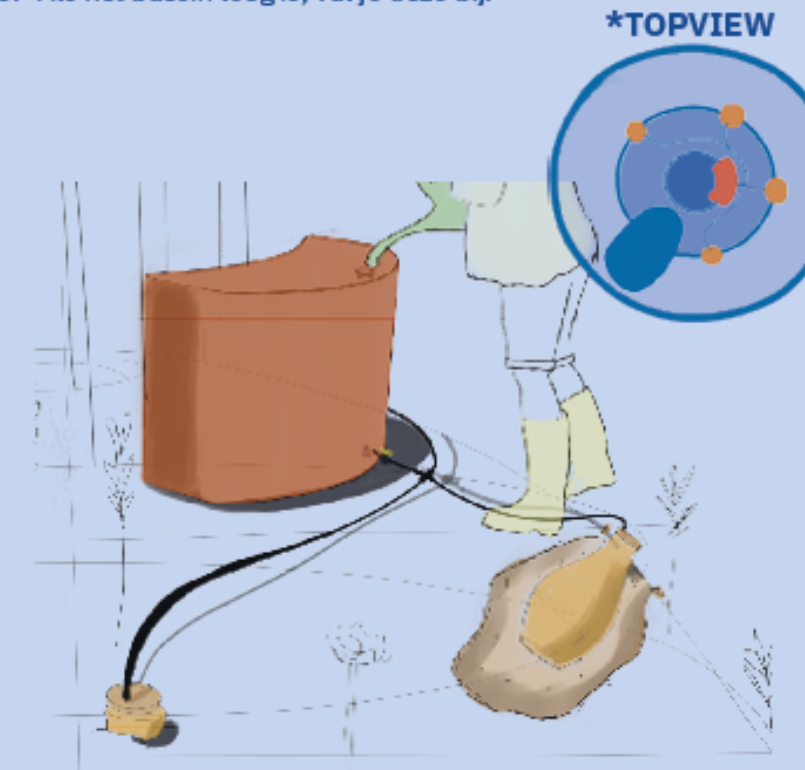
De planten in deze onderste laag zijn verantwoordelijk voor het creëren van een kleurrijke overgang tussen de functionele lagen en het vlakke maaiveld, terwijl ze tegelijkertijd bodemerosie van de heuvel voorkomen. Daarnaast is deze laag wederom positief voor de biodiversiteit van insecten.



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## Installatie

1. Koppel de uiteindes van microslangen aan de bevestigingsstukjes van de deksels van de ollas
2. Graaf de ollas in, zo diep dat alleen de dop boven de aarde uitkomt. Plaats ze in de middelste laag van de berg, en plaats ze zoals de topview\*.
3. Plaats het waterbassin hoger op de heuvel, zodat er druk ontstaat.
4. Koppel de slangen, verdelers en het kraantje zodat alles met elkaar is verbonden.
5. Vul het bassin met water, en zet het kraantje open.
6. Als het bassin leeg is, vul je deze bij.



## Onderhoud

In principe is het systeem passief, wat betekent dat je, behalve het waterreservoir aanvullen, er niet veel aan hoeft te doen.

Er zijn wel een paar aandachtspunten, zodat het systeem beter werkt.

Voor de eerste vorst intreedt moet het systeem leeg zijn, daarom zijn er een paar stappen die moeten worden volbracht voordat de eerste vorst intreedt:

1. Leeg het bassin
2. Draai de kraan dicht, en ontkoppel de slangen van het bassin
3. Graaf de ollas uit, en leeg deze ook. Bewaar ze in de winter op een droge plek, dan zullen ze niet breken.

Om de planten goed te laten functioneren zijn er ook een aantal punten waar op moet worden gelet:

1. Behandel de planten zoals je normaal ook zou doen, dus knip ze terug wanneer dat nodig is.
2. Geef de planten de eerste weken paar weken dat ze zijn aangeplant genoeg extra water, zodat de wortels kunnen groeien.
3. Bij de aanleg van de planten, is een laagje compost van belang zodat de planten genoeg nutriënten hebben. In het tweede jaar kan wat extra compost de groei stimuleren.

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Plantenlijst

| Plant              | Latijnse naam                  | Grootte                      | Functie                                                                 | Bloelperiode                                        | Zorg                                                           | Hoeveelheid |
|--------------------|--------------------------------|------------------------------|-------------------------------------------------------------------------|-----------------------------------------------------|----------------------------------------------------------------|-------------|
| Boven              |                                |                              |                                                                         |                                                     |                                                                |             |
| Paraplu bamboe     | Arundinaria muricellae         | H: 2- 2,5<br>D: 1,5 - 2      | Windscherm, stilstaande lucht, verminderde warmte uitwisseling via wind | hele jaar groen-blijvend                            | Dode stengels in voorjaar weghalen                             | 1           |
| Chinees prachtriet | Miscanthus sinensis 'zebrinus' | H: 1,5 - 2<br>D: 0,8 - 1,2   | Windscherm, stilstaande lucht, verminderde warmte uitwisseling via wind | Groen in lente - herfst<br>sept-okt pluimen         | In lente terugknippen tot 10 - 20 cm boven grond               | 2-3         |
| Midden             |                                |                              |                                                                         |                                                     |                                                                |             |
| Droplant           | Agastache rugosa               | H: 0,6 - 0,8<br>D: 0,4       | Hoge verdamping, dus actieve koeling<br>Trekt bestuivers aan            | Groen vanaf maart/april<br>Bloei in juli - augustus | In maart terugknippen                                          | 5-8         |
| Kattenkruid        | Nepeta                         | H: 0,6<br>D: 0,35            | Hoge verdamping<br>Erosiewerend                                         | Groen vanaf maart<br>Bloei in mei - sept            | Na eerste bloei terugknippen                                   | 4-6         |
| Dulzend-knoop      | Persicaria amplexicaulis       | H: 1 - 1,2<br>D: 0,5 - 1     | Vochtvasthoudend, dus actieve koeling                                   | Groen vanaf maart/april<br>Bloei in juli - sept     | In maart terugknippen<br>Sterft in de winter af                | 2-4         |
| Salie              | Indigo spires                  | H: 1 - 1,5<br>D: 0,7         | Vochtverdamping<br>Zonreflecterend                                      | Groen vanaf maart/april<br>Bloei in juli - sept     | In maart/april terugknippen tot +/- 10 cm boven verhoutte deel | 4-6         |
| Plataargras        | Chasmanthium latifolium        | H: 0,8 - 1<br>D: 0,6 - 0,8   | Structuur en beweging<br>Insecten<br>Schuilplaats                       | Groen vanaf maart/april<br>juli - september bloemen | In voorjaar to 10 cm terugknippen                              | 3-4         |
| Onder              |                                |                              |                                                                         |                                                     |                                                                |             |
| Oolevaars-bek      | Geranium                       | H: 0,2 - 0,4<br>D: 0,4 - 0,6 | Bodembedekker<br>Erosiebestrijding                                      | Halfwintergroen<br>mei - september bloemen          | Na bloei terugknippen voor herbloei                            | 4-6         |

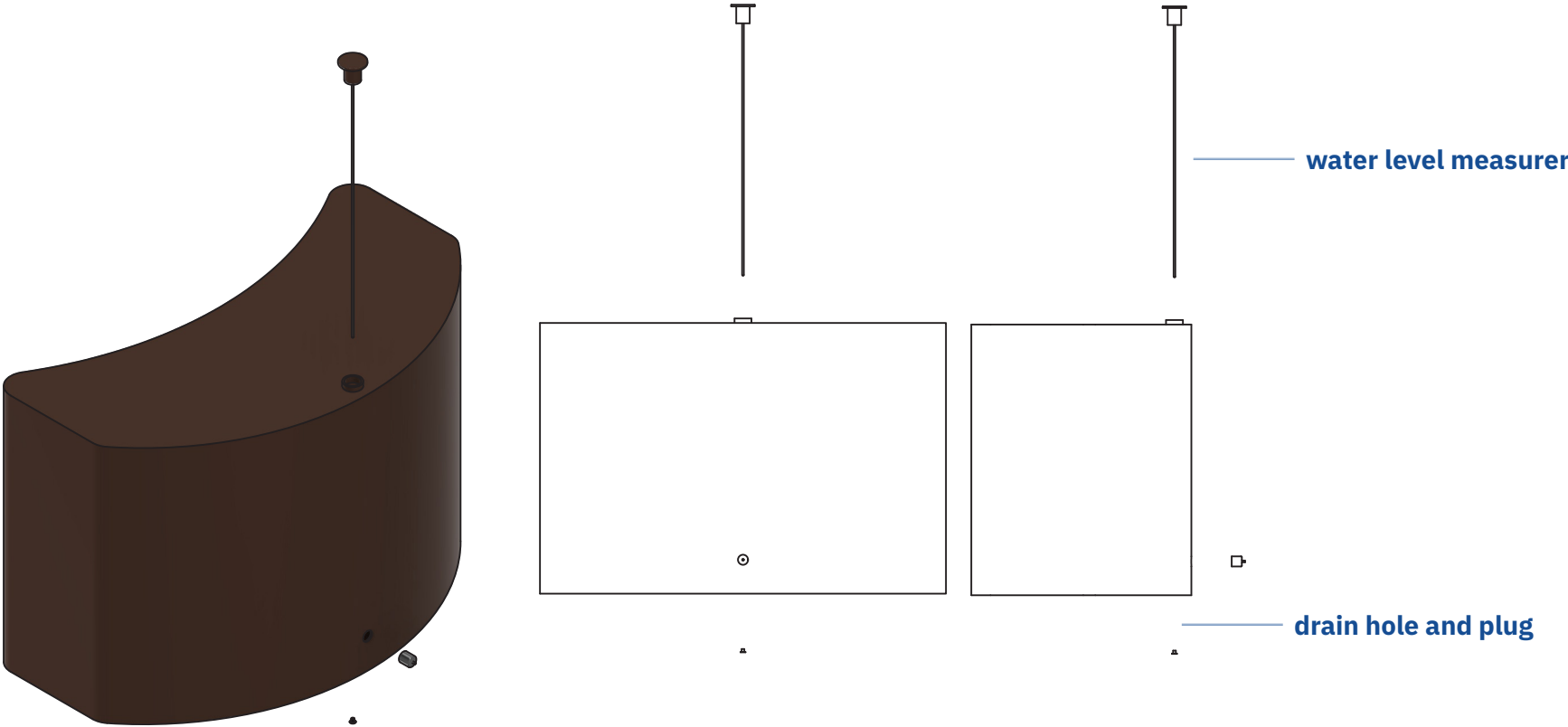
\* Het aantal planten per soort kan naar wens worden aangepast. Wordt er meer van één soort gekozen, dan vermindert het aantal van de andere soort in dezelfde laag

groundflow

Appendix AA - Redesign Groundflow Basin

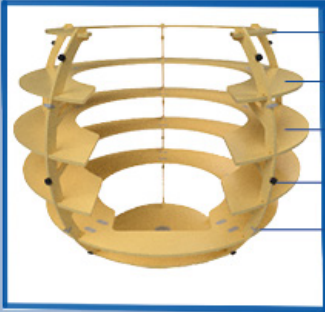
After installing the Groundflow system, some insights emerged from this. Due to the time constraints, it was not possible to incorporate these into the final design. However, the following visuals represent a final brainstorm session exploring how the system could be further developed and refined.

- There should be a method to know the water level, for example something like this water level measurer. A drain hole and plug should be added to be able to empty the basin before winter and whenever something is up.





Appendix BB -Groundfridge Inventory list



Plank 5 - warmste

Plank 4

Plank 3

Plank 2

Plank 1 - koudste

Inventarisatie  
Groundfridge

Plank 1

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.....

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Plank 2

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Plank 3

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Plank 4

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Plank 5

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Thanks for reading,  
hope you enjoyed!

