DEVELOPMENT OF A RAINWATER HARVESTING SYSTEM FOR ORGANIC GARDENING DRIENERLO (BTD)

Bachelor Thesis Creative Technology

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Abstract

During long periods of drought, members of Organic Gardening Drienerlo (BTD) have to irrigate their gardens by using tap water. This paper examines how a rainwater harvesting system (RHS) without a fixed catchment area can be developed for BTD with the main goal to reduce tap water usage. The research question that is answered is *"How to develop a rainwater harvesting system without a fixed catchment area for Organic Gardening Drienerlo?"*.

The final RHS is an Arduino controlled system that includes a catchment surface and a shadow surface that work automatically based on sensor values. The catchment surface can be rolled out to harvest rainwater into a buffer. Alternatively, the shadow surface can be rolled out to protect the garden from the sun.

The results of the user evaluation are based on the answers and opinions provided by the participants in the interview after seeing the prototype demonstration. 11 out of 14 system requirements were met and based on the results of the interviews it can be concluded that most of the participants were interested in the RHS prototype.

Future development is needed, however as a proof of concept the realized rainwater harvesting system for BTD can be considered successful.

Acknowledgement

There are a number of people I would like to thank for their help and support during my graduation project. First of all, I would like to thank my supervisors Richard Bults and Katarzyna Zalewska for their help during the project. They supported me by sharing feedback and offering help with challenging elements of the project. Furthermore, I would like to thank Alfred de Vries who provided useful input, tools and equipment and 3D prints. I would also like to thank Cornelis van Elzakker, my contact person of my client Organic Gardening Drienerlo, for sharing his feedback and thoughts on the project and the process. In addition, I would like to thank Edwin Dertien, who gave me valuable tips for working with stepper motors and Novizon Zonwering for tips on realizing a low budget sunscreen system. I would like to thank all the people who participated during the system evaluation sessions. Finally, I would thank family and friends for their support during the project.

Contents

List of Abbreviations

BTD	Organic Gardening Drienerlo
IoT	Internet of Things
KNMI	Royal Netherlands Meteorological Institute
RC	Runoff coefficient
RHS	Rainwater harvesting system
POC	Proof of Concept
BED	Big Easy Driver

List of Figures

List of Tables and Formulas

1 Introduction

Climate change has caused more droughts. [1] In the Netherlands these effects are also visible. Rapports of the Royal Netherlands Meteorological Institute (KNMI) indicate that past few years, the Netherlands has faced a precipitation deficit [2] (Figure 1). Especially in the eastern regions of the country, including Enschede, high precipitation deficits have been measured [2] (Figure 2).

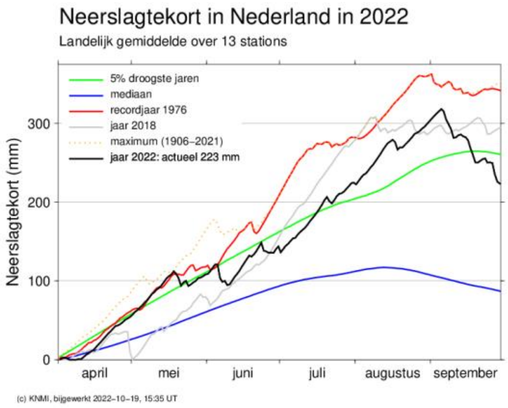

Figure 1: Precipitation deficit (mm) in the Netherlands in 2022 from April to September. Source: KNMI

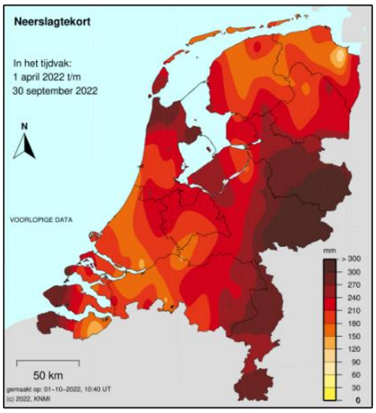

Figure 2: Precipitation deficit (mm) map of the Netherlands in 2022 from April to September. Source: KNMI

The lack of rainfall makes it hard for plants or crops to grow during prolonged periods of drought, without the use of fresh water sources to water them. However, especially during these droughts, fresh water becomes scarce which makes tap water a very unsustainable alternative.

Organic Gardening Drienerlo (BTD) is a community garden located at the campus of the University of Twente facing the problem of freshwater scarcity. The community garden consists of 132 gardens of 22.5 m^2 each. At this moment, BTD uses a small water pump to pump up groundwater. However, this does not provide the community with enough water to irrigate all gardens, so they occasionally switch to tap water. In addition, during long periods of drought this BTD practice is forbidden as water becomes scarce.
A sustainable fresh water source should be used. A common way of collecting fresh water is with a rainwater harvesting system (RHS). A RHS is a system that uses a catchment area to direct rainwater into a buffer, which can be used later for non-potable purposes such as irrigation [3]. Since BTD has little to no access to roofs as a rainwater catchment area, another catchment solution needs to be developed. This solution should be built such, that collection does not prevent natural irrigation of the BTD gardens.

The aim of the project is to develop a prototype of a rainwater harvesting system that can be used by BTD. Based on the presented situation and the aim of the project this thesis will try to answer the following research question:

"How to develop a rainwater harvesting system without a fixed catchment area for Organic Gardening Drienerlo?"

To give an answer to this question, the report is built up as follows. In Chapter 2, background research will be performed. Chapter 3 will address the methods and techniques used during the project. Chapter 4 covers the ideation phase of the project. After the ideation phase an idea will be chosen to set up its specifications in Chapter 5. The realisation of the prototype will be addressed in Chapter 6 after which Chapter 7 evaluates on the prototype. Chapter 8 includes the discussion and recommendations for future work and finally, Chapter 9 concludes the project.

2 Background Research

In this chapter, relevant topics of the background research will be addressed. The topics that are included in the background research are related to the situation of Organic Gardening Drienerlo (BTD) that is described in the introduction. In addition, this chapter includes a state of the art on rainwater harvesting systems.

The first topic to be addressed is how rainwater can be harvested effectively and factors that influence efficiency. This includes what is needed to harvest rainwater. Then the distribution of the water is be discussed and ways for efficient irrigation.

2.1 Harvesting

BTD needs a lot of water to irrigate their gardens. Therefore, it is important that effectivity of the design is taken into account. Efficiency, the quality of doing something well with no waste of time or money, can differ for every situation. An efficient water harvesting system should harvest as much water as possible when a rainfall event occurs.
One of the components that influences the total amount of water being collected by a rainwater harvesting system is the catchment quantity of rainwater. Catchment can be calculated using three parameters [4]:

1) R is the rainfall or precipitation in millimetres per year (mm/y),
2) A is the catchment area in meters squared (m^2), and
3) RC is the runoff coefficient.

With these parameters the following formula can be constructed with Q being the quantity of the collected water:

$$Q = R * A * RC$$

Formula 1: Quantity of the collected water. source: [4]

2.1.1 Precipitation

The R parameter of the formula, is the parameter for the precipitation. The precipitation is not an influenceable parameter and is differs per region. BTD is located in Twente, one of the eastern regions of the Netherlands. Therefore, the average annual precipitation of Twente gives an indication of the value of R that should be used. Based on the datasheet of precipitation in Twente from Royal Netherlands Meteorological Institute (KMNI) [5], the following bar chart can be made:

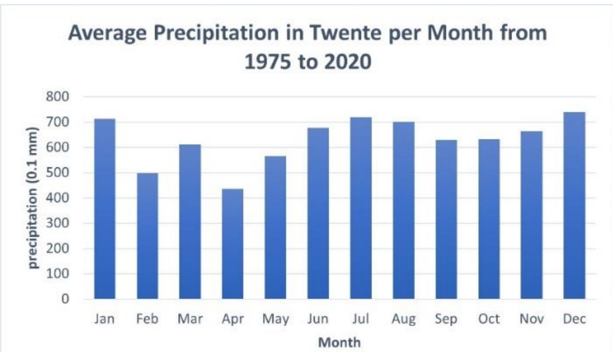

Figure 3: Average precipitation in Twente per month from 1975 to 2020.

Figure 3 shows the average precipitation in Enschede per month from 1975 to 2020. The data presented shows that on average December is the month in Twente with the highest precipitation of 74 mm. Alternatively, April is the month with the lowest precipitation of 436 mm. The average annual precipitation in the region of Twente is 758 mm. This is the value used for the R parameter.

2.1.2 Runoff Coefficient

The runoff coefficient (RC) is a factor that is related to the water that is collected and the volume of the precipitation. [6] Considering a water harvesting system, RC should be as large as possible. The runoff coefficient can be calculated using the following formula:

$$RC = \frac{V_r}{V_p}$$

Formula 2: Runoff coefficient. source: [6]

In this formula, V_r is the runoff volume and V_p is the volume of the precipitation. When V_r is high in relation to V_p, this indicates that RC is closer to 1 and thus a lot of water will be collected. V_r depends on multiple things such as soil, gradient, permeability and land use [6]. Also, there is potential evaporation which will be discussed later. [7] Finally the size and slope of the catchment area play a big role in how much rainwater can be harvested.

2.1.3 Catchment Area

The catchment area is an important parameter for a rainwater harvesting system. The larger the size of the catchment area the larger the amount of water that is being collected. [4] A catchment area the size of a garden of Organic Gardening Drienerlo would be 22.5 m^2. Also the slope of the catchment area is relevant, since it has influence on the RC value. A catchment area with a larger slope usually has a higher runoff. A slope value of 6.98 degrees has a RC value of 0.47 and a slope value of 15.47 degrees has a RC value of 0.59. [8] Furthermore, the material of the runoff area has an effect on the RC value and thus the total amount of collected rain. A roof with a galvanized iron sheet as surface area results in a RC value of 0.9, where a concrete roof has a RC value of 0.7. [9]

2.1.4 BTD water usage

Summer 2022 BTD used tap water 5 days in the week for three weeks straight. They used a 4 sprinkler systems that distributed water over their gardens. The operating hours of the sprinklers were from 9.00 to 17.00, meaning 8 hours a day. A sprinkler distributes about 1000 litres of water per hour.

This information is needed to calculate the amount of tap water that is used to irrigate the community garden during the summer of 2022. The amount of tap water used is equal to 480.000 litres of water. In order to fully switch to harvested rainwater, the following formula can be used where the size of the catchment area is being determined:

$$A = \frac{water\ usage}{R * RC}$$

Formula 3: Area for water usage

By filling in the formula presented with the researched values for water usage, rainfall R and the runoff coefficient RC, it results in the following outcome:

$$A = \frac{480.000}{758 * 0.7} = 905\ m^2$$

In order to fully switch to harvested rainwater BTD needs a catchment area of $905m^2$.

2.2 Distribution

After rainwater has been harvested, the water has to be distributed for irrigation. The goal of efficient irrigation is to irrigate crops properly using the least amount of water. Smart systems can help achieving this goal. There are also several ways to store the water and ensure water quality which will be discussed.

2.2.1 Existing Distribution Techniques

Different irrigation techniques have different efficiencies. Sprinkle irrigation for example, replaced furrow irrigation and is now commonly used. [10] Sprinkle irrigation is an efficient irrigation technique, since the water distribution amount and duration are easily controllable. It is an automated system. Another advantage of the system is that it is less labour intensive than manual irrigation. [11]
Another technique is mist irrigation. One of the advantages of this technique is that the mist lowers the temperature of the leaf which results in a lower vapor pressure so there is less evaporation. [10]

2.2.2 Water Volume

The volume of water needed for irrigation depends on a three factors. Firstly, temperature and humidity, which influences the evaporation. Secondly, irrigation depends on the crops that are being grown and the stage of growth it is in since not every plant uses the same amount of water. [12] [13] The time of the day also affects the quantity. The best time to irrigate the garden is in the morning when it is still cool. The hotter it gets, the quicker water evaporates and therefore irrigation will be less effective. [13] Finally, the size of the area that needs irrigation influences the amount of water needed. A vegetable garden of $10m^2$ needs approximately 60 litres of water per day. [14] This means that a vegetable garden of $22.5m^2$ uses approximately 135 litres of water per day.

2.2.3 Evaporation

Evaporation of water in shade is slower, as the sun's heat increases the energy of water molecules, and they start moving faster, eventually leading to evaporation when the energy is enough to convert into a vapour [15]. Besides shading, another way to avoid evaporation is mulching. Mulching is a practice where the soil is covered with a layer. This can be done with leaves, compost or straw or hay [16].

2.2.4 Smart Systems

Another way to achieve a higher distribution efficiency is by using smart systems. A smart system uses smart technology such as sensors and actuators to analyse situations. For example, for distribution purposes a soil moisture sensor could improve efficiency. The sensor uses soil between its probes as resistance. The resistance depends on the moisture content in the soil. The sensor gives an infinite resistance for dry soil and a very low resistance for 100% moisture in soil. [17] This way, the system can detect when the soil is dry and when distribution is needed.

Such sensors can also be used for weather predictions. Weather has an effect on water needs and by using sensors for weather predictions distribution can be done more efficiently. [18] Another way of smart distribution is Internet of Things (IoT) based distribution. [19] This way online data can be used by the system so it can make more considered decisions.

2.3 Storing

There are several techniques to store rainwater. One of them is a rain barrel. Rain barrels available in different shapes and sizes. These storages are easily accessible, however BTD would need a lot of barrel to have a sufficient capacity. Another way to store rainwater is by using natural or artificial reservoirs such as lakes or ditches [20]. For BTD this would probably be more useful since they would need to store a large amount of water. However, the disadvantage is that the water is exposed to a lot of sunlight so evaporation is higher.

2.4 State of the Art

There are many different kinds of water harvesting systems and designs. Some of the existing systems and designs are addressed.

2.4.1 Rooftop Catchment

One of the most common ways to harvest water is via rooftop catchment. Rainwater falls on the catchment surface. A delivery system, such as gutters and downpipes, is connected to the catchment surface. Finally, via the delivery system, the water is guided to reservoirs where the water is stored. Often a filtration system is included to ensure water quality. There are many companies that built such systems. Examples of companies are Mijn Waterfabriek [21] and Wildkamp [22]. Figure 4 shows a system by Mijn Waterfabriek. Figure 5 shows a system by Wildkamp.

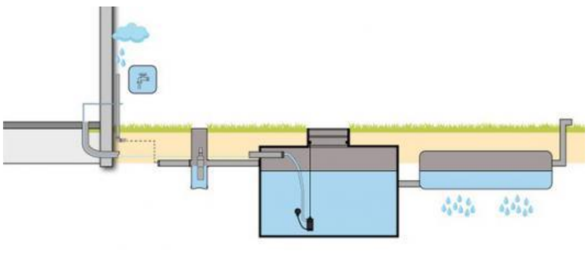

Figure 4: STORMMAX rainwater harvesting system [21].

Figure 5: Slim Rain rainwater harvesting system [22].

2.4.2 Inverted Umbrella Design

Another way to harvest rainwater is with the inverted umbrella design. The concept is based on an umbrella turned inside out. This way a bowl is created and the water collected by the surface is lead to the middle of the catchment area, where the water is led to the storage [23]. The figures below show different approaches on how the design can be interpreted. Figure 6 [24] shows a basic design with the stem leading the water from the catchment area to the storage. The design in figure 7 [25] uses a frame of sticks with a tarp in between to catch the water, which has a whole in the middle to collect the water in the bucket. Finally, figure 8 [26] is an artistic design, which intends to harvest multiple renewable energies under which rainwater.

Figure 6: Stand-Alone Rainwater Collector [24].

Figure 7: Tarp Rainwater Catcher [25].

Figure 8: Sculptural Tree-Like Canopies [26].

2.4.3 Butterfly Structure

The butterfly structure (Figure 9) is a combination between rooftop catchment and the inverted umbrella design. The structure is made such, that the water is harvested by two planes angled towards each other. Via a gutter the water is guided towards the barrel where the water is stored. This design also leaves usable space below the structure. This space could be used for gardening purposes.

Figure 9: Butterfly Structure [25].

2.4.4 Rain garden

A rain garden is a garden that soaks up runoff water. It is designed such, that it holds the water temporarily, whereafter the water slowly seeps back into the ground. Also, the garden works as a filter. [27] The rain garden is not designed to collect water, but it allows for irrigation and after a certain dept it is drained. Instead of the water being drained it might also be collected. Figure 10 shows the cross section of a rain garden.

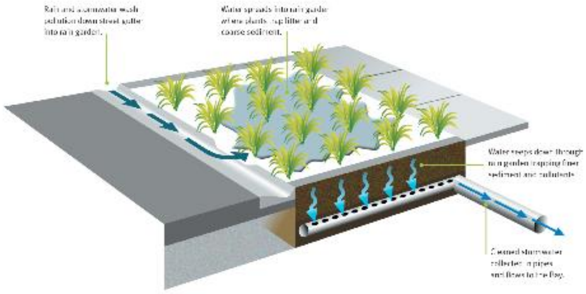

Figure 10: Rain Garden [28].

2.4.5 FogCollector

The final water harvesting system focusses on fog instead of rain. The wind blows fog against the 3D mesh surface of the FogCollector, causing the fog to accumulate into water drops. The water drops eventually fall down into a reservoir. The system is made of UV resistant and food-safe materials. Also the system has flexible troughs that follow the movement of the net in the wind. The FogCollector is presented in Figure 11 [29].

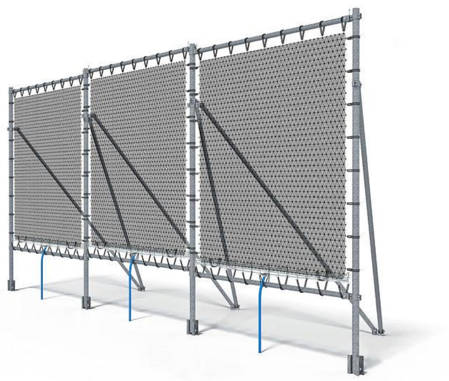

Figure 11: FogCollector [29].

2.5 Conclusion

There are various things to keep in mind when designing a rainwater harvesting system. The three parameters affecting the total amount of water that is being collected are precipitation, the catchment area and the runoff coefficient. The catchment area and the runoff coefficient are influenceable parameters.

A high distribution efficiency can also reduce the water needed. Automated systems are used to control the distributed amount efficiently. Also the time of the day for water distribution is relevant. During the day the sun will cause water to evaporate. Less sun prevents this. Finally sensors can help to decide on and control the water that needs to be distributed.

Two ways to store rainwater are discussed, by using a rain barrel or a natural or artificial reservoir. Since BTD needs a lot of water this is more easy to achieve with a natural reservoir.

Several water harvesting systems are already in use such as rooftop catchment, the inverted umbrella design and fog collectors. These designs all have in common that they use large catchment areas to collect the rainwater and a system that guides the water to a storage.

3 Methods and Techniques

The chosen design process is the Creative Technology design process. The process consists of four phases. The ideation phase, in which creative designs will be generated. The specification phase, in which system requirements and a system architecture is specified along with a use scenario. During the realisation phase, the design will be realised based on the specifications set during the specification phase. Finally, the system will be evaluated.

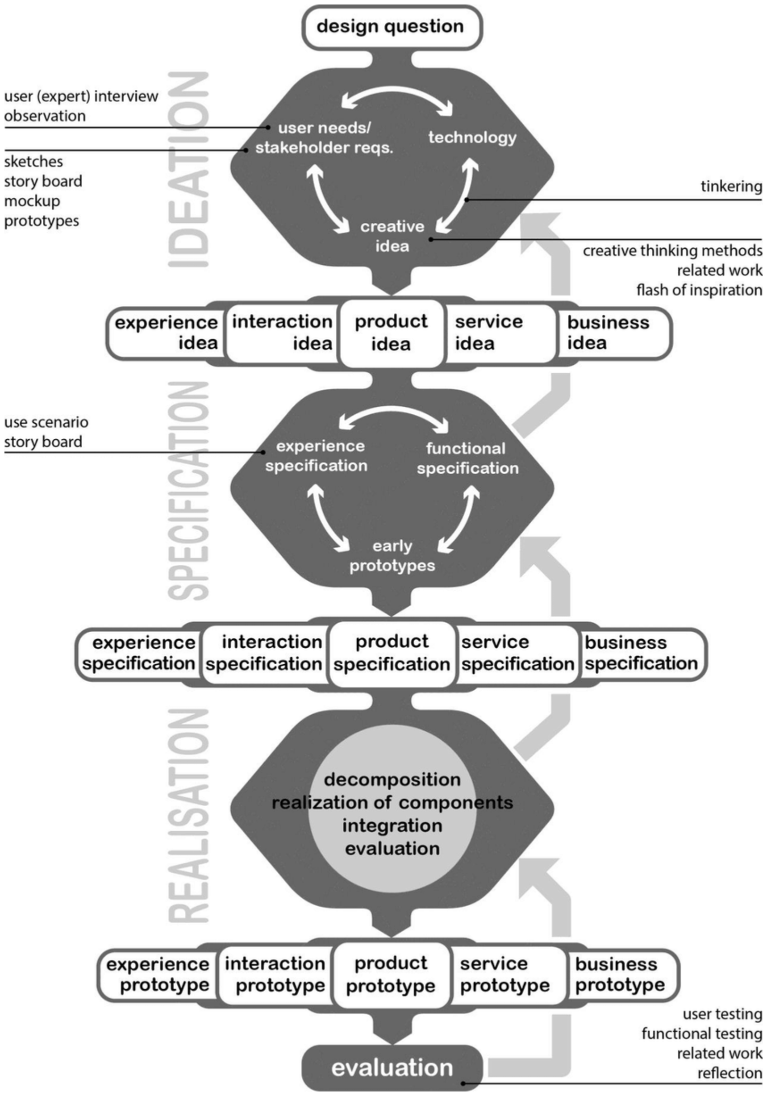

Figure 12: Creative Technology Design Process. [30]

Stakeholder analysis/needs
To make a good system it is important to know the stakeholders of the project. Every stakeholders has its own needs. The stakeholder analysis will be done using the Interest/Power grid. Stakeholders can be categorized using this grid by their power and interest. Depending on the power and interest of the stakeholder, the grid shows how the stakeholder should be managed.

Figure 13: Interest/Power Grid. [31]

The stakeholder needs will be categorized using the MoSCoW technique. [32] This technique can be used to categorize stakeholder needs based on their level of importance. This is an important step to continue to the ideation phase where the stakeholder needs will be taken into account.

Ideation
During the Ideation phase concepts will be generated by sketching. Multiple sketches will be made during a creative sketching brainstorm. Feasibility of the designs are neglectable. In the sketching session it is important that as much sketches as possible are created with a high variety of designs while keeping in mind the stakeholder needs.

Specification
The specification phase will consists of three parts. First a use scenario of the system will be made to give an indication how the system will be used. Next, functional and non-functional system requirements are set up based on the stakeholder needs and the chosen design. Finally the specification phase will be finalized with a system architecture. The system architecture consists of a level 0: System Overview where the rainwater harvesting system (RHS) is drawn as a black box. Also a Level 1: System Decomposition and a Level 2: RHS Decomposition will be made.

Realization
During the realisation phase a scaled down proof of concept prototype will be realised meaning the system will be scaled down for feasibility purposes and should proof that the concept works. The system architecture and requirements are taken as a reference point to build the RHS.

User Evaluation
The user evaluation consists of a system demonstration where different scenarios are simulated, whereafter a set of open questions is being asked to the participants in a semi-structured interview. The chosen interview type is a semi-structured interview since it allows for the possibility of asking follow up questions to explore further their response.

4 Ideation

The Ideation consists of three main topics. Firstly the stakeholder needs and requirements definition are described. Furthermore the preliminary concepts are shown. At last the final concept is presented.

4.1 Stakeholder Needs and Requirements Definition

4.1.1 Stakeholder Identification

Three stakeholders have been identified for this project.

- Stefan Kooy (Me)
- Richard Bults & Katarzyna Zalewska
- Organic Gardening Drienerlo (BTD)

The stakeholders consist of the people that have an interest in the project. As for me, I am interested in the project, because it is my graduation project. Richard and Kasia are the project supervisors. They give feedback on the project and grade the final product. They expect the final product to be a system that fits the Creative Technology program. Finally, Organic Gardening Drienerlo is the client for this project. The community garden requested a system to harvest water to become more sustainable.

4.1.2 Stakeholder Analysis

Each stakeholder has their priority within the project. The priority of the stakeholders will be based on the power they have within the project and the interest they have in the project. Figure 14 shows the classification of the stakeholders based on the power/interest model.

Figure 14: Stakeholder Interest/Power Grid.

The power/interest model in figure 14 shows that Stefan Kooy (me) has a high level of interest. The reason for this is that the project is of great importance of the graduation. Also, the Power of influence is relatively high because I am the designer of the system. As supervisors of the project R. Bults and K. Zalewska have a very high power of influence, since they are responsible for grading the project. Also, they have to give permission to the project based on the relationship to Creative Technology of project. Alternatively, the final product will not affect them, so level of interest in the project is a lot lower. The final stakeholder, Organic Gardening Drienerlo (BTD), has both a very high level of interest and has a high power of influence. BTD is the client who has requested the water harvesting system. The level of interest is very high since the water harvesting system is contributing to their goal to become sustainable. Also, they have a high power influence on the design of the prototype, since they have certain expectations and requirements for the system.

4.1.3 Stakeholder Needs

To identify the stakeholder needs the MoSCoW method was used. The needs of the stakeholder are the requirements for the system based on the stakeholders interest. Together with the client, BTD, several system needs were identified. Based on their priority the needs were categorized into must, should and could. The stakeholder needs are presented in Table 1 below.

MUST
The system must catch enough water to reduce tap water usage to a minimum
The system must at least use the three storage tanks provided by BTD (1000 litres each)
The system must be as cheap as possible
SHOULD
The system should be close to the gardens for accessibility purposes
The system should be manually adjustable
COULD
The system could automated distribution

Table 1: stakeholder needs based on the MoSCoW technique.

4.2 Preliminary Concepts

4.2.1 Concept 1

The first concept is a dynamic system that is using wind direction to position itself. The catchment area can change both its slope and rotate 360 degrees. This way the catchment surface can be put in an ideal position depending on wind direction to catch the highest amount of rain. This concept has as downside that the catchment area cannot be too large because the system has a high wind sensitivity so the system would become instable. This means the system might not be able to harvest enough water for BTD. Figure 15 presents a sketch of Concept 1.

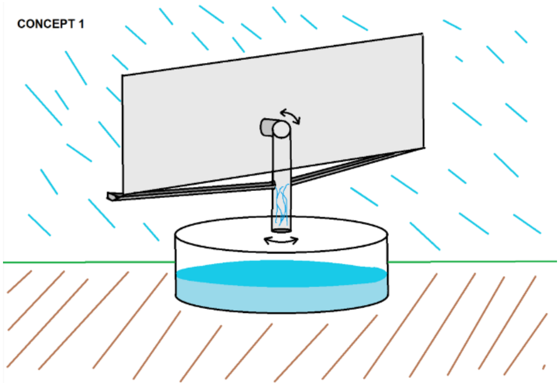

Figure 15: Concept 1.

4.2.2 Concept 2

The second concept is inspired on the rain gardens. The rainwater falls into the garden, irrigating the plants. Normally, the water would slowly seep into the ground. However, this design would include a storage tank underneath the garden to collect the water below the surface. A pro of the design is that the system does not take up any space as soon as it is installed. Also, the system does not block the rainwater from falling into the garden, but it uses it as catchment area instead. Unfortunately, this design is not very suitable for Organic Gardening Drienerlo, since it would mean that the gardens would be removed to install the system. Besides the cost of this system, the installation might also be expensive. For this reason it could also be less suitable for BTD. Figure 16 shows a sketch of Concept 2.

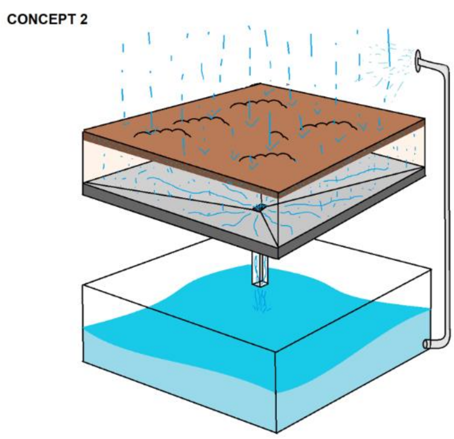

Figure 16: Concept 2.

4.2.3 Concept 3

For the third concept, a transparent roof is built above the garden. When it rains the water can either be collected by the roof or the roof can be opened so the water falls into the garden. This way the system does not block the water from falling into the garden. Based on soil moisture values the roof can be open or closed. The roof is transparent so sunlight can still reach the garden. Figure 17 shows a sketch of Concept 3.1.

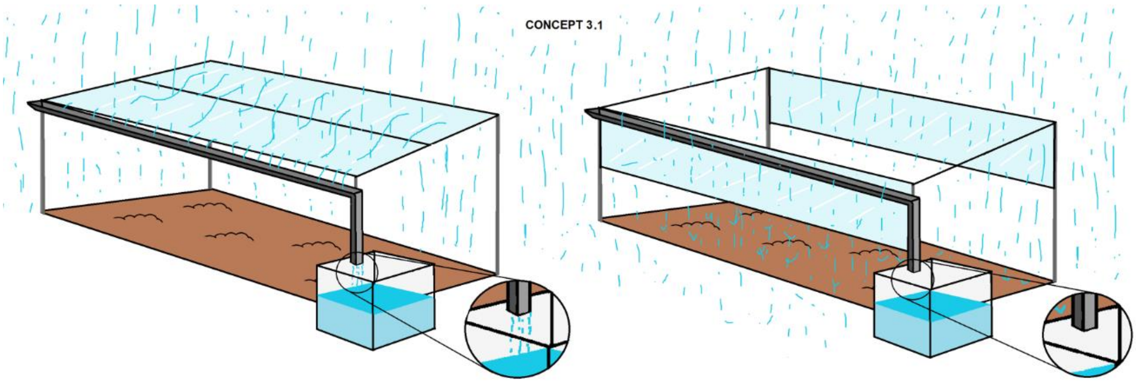

Figure 17: Concept 3.1.

This design could also include wind adaptability. The four legs of the frame would be adjustable in height. This way the catchment area could be angled in the desired direction facing the wind. Weather forecast could be used to position the system beforehand. This way the catchment area is used more efficiently. Figure 18 shows a sketch of Concept 3.2.

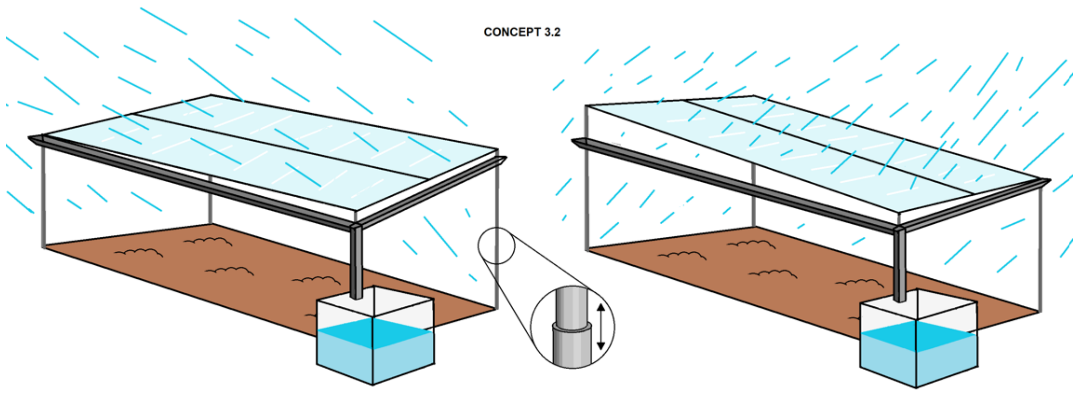

Figure 18: Concept 3.2.

4.2.4 Concept 4

Concept 4 is based on the inverted umbrella design. In case of the catchment area being like the inverted umbrella the system would be able to collect rainwater. The stem is used as storage. Alternatively, the catchment area could go down to create a greenhouse around the garden. The design offers a greenhouse functions along with rainwater harvesting which could be interesting for BTD. However, the design is wind sensitive and could therefore be unstable. Also the design might be harder to realise. Figure 19 shows a sketch of Concept 4.

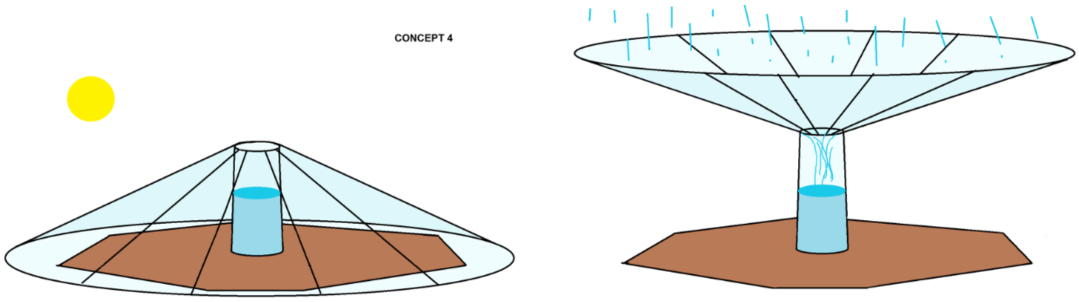

Figure 19: Concept 4.

4.2.5 Concept 5

The last concept resembles Concept 3 a lot. However, this concept includes a movable plane that creates shadow above the garden. The plane can be positioned depending on the light intensity in the garden or the position of the sun. The goal of the plane is to create a shadow to cool the garden below the system. This way evaporation can be slightly prevented and thus less water is needed to water the garden. Figure 20 shows a sketch of Concept 5.

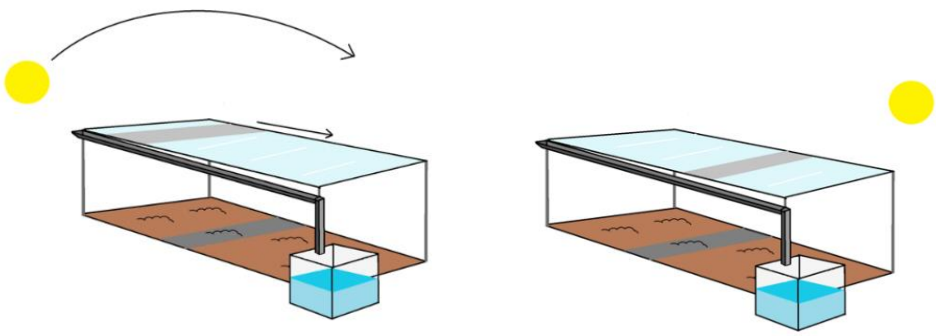

Figure 20: Concept 5.

4.3 Final Concept

The final concept is a more detailed version of Concept 5. It is chosen as the final concept, because the design offers two ways to tackle the water scarcity issue BTD faces. In addition, it is a feasible design for this graduation project considering the time and budget.

The system will be made out of four key parts. Firstly, a frame is needed. The frame must have an option for an angled roof. The second part is the roof. The roof that will be used will consist of two roller systems. One roof will be transparent to be able to let through sunlight. The other roof will be used for creating the shadow above the garden when needed. Either both roofs can be out, one of them or none. In the last case water can fall into the garden. The roof creating the shadow can also be partly out. Also, a delivery system is needed to guide the water into the storage. Finally the system includes sensors to make the system smart and autonomous.

Figure 21: Frame [33].

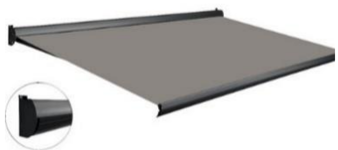

Figure 22: Catchment / Shadow Area [34].

Figure 23: Storage [35].

5 Specification

The specification consists of a persona, an interaction scenario of the envisioned RHS, system requirements and a functional system architecture.

5.1 Persona and Interaction Scenario

5.1.1 Persona

Persona	BTD community member
Name	Rose-Mary Blossom
Job	Retired
Demographics	- 69 years old - 160cm tall - Female - Married - Has a bachelor in Creative Technology
Challenges	- Dry soil during long periods of drought - Wants to use a minimal amount of tap water - Has difficulty walking far with a watering can to her garden
Goals	- Harvest rainwater to reduce tap water usage - Store rainwater - Decrease distance to water storages

Table 3: Persona information

5.1.2 Interaction Scenario

This interaction scenario is based on the persona. The garden owned by **Rose-Mary** is the only garden which with the RHS above it. Everyone can use the rainwater collected by the system.

How will the RHS be used by Organic Gardening Drienerlo?

1. Rose-Mary is about to use the system for the first time. Therefore, she first needs to turn on the system. She pushes the button to turn on the system and an indication light shows the system is turned on.
2. Even though Rose-Mary could adjust the system manually there is no need to do so. The system is automatic so Rose-Mary does not have to do anything more. After a quick talk to some fellow gardeners she leaves and goes home.
3. Overnight it starts raining. The next day is a very hot and the sun shines intensely.
4. In the morning Rose-Mary checks up on her garden. She notices a few things. Firstly, the soil is still wet and in a good condition. Using sensor data the system handled the rain in such a way that the humidity percentage is above the threshold value. Secondly, the storage is filled up a bit too. Apparently the system deployed its catchment area after the soil was wet enough to still catch some rainwater. The final thing he noticed is that the system created a shadow above her garden to reduce evaporation.
5. Rose-Marys fellow gardeners do not have the installation above their garden so the sun caused the soil to dry quicker. However, they can use the rainwater collected by the system above Rose-Marys garden too.
6. A few hours it has become a more cloudy. The system's sun blocking function is activated. However, when Rose-Mary checks the soil she notices that it has become a little dry. Luckily the water storage filled up a bit during last night's rainfall event.
7. Rose-Mary grabs her watering can. She is not very good on her feet but fortunately the storage is not too far away. She places it underneath the storage's valve. He fills up his watering can and distributes the water over his garden himself.
8. A few weeks go by and the storage tanks are filling up more and more. Rose-Mary does not have to worry about overflowing water, because the system will drain the water whenever the maximum capacity is reached.
9. The maximum capacity is reached and during periods of drought Rose-Mary her fellow gardeners have a buffer that they can use to reduce the amount of tap water and be more sustainable.

5.2 System Requirements

System requirements are set up by determining functional requirements and non-functional requirements using the MoSCoW method to categorize all requirements (Table 2). The system requirements are based on the stakeholder needs (SN) that are discussed in Chapter 4.1.3.

Functional Requirements	Non-Functional Requirements
Must	
The system must harvest rainwater **(SN)**	The system must be placed above a garden
The system must have screens that can open and close	The system's storage must be made such that the garden is still reachable
The system must allow water to reach the garden	The system must have waterproof components
The system must adjust depending on the environmental aspects soil moisture and sunlight	The system must be as cheap as possible **(SN)**
The system's sensor data must be checked every 10 minutes	
The system must use precipitation prediction data	
The system must be automatic	
The system must be able to create shadow	
The system must collect water into the storage tanks provided by BTD **(SN)**	
The system must drain water excessive rainwater	
Should	
The system should be manually adjustable **(SN)**	The system should be placed in a close proximity of the garden for accessibility. **(SN)**
The system should have a stand-by mode	The system should have a roof surface slope of approximately 15 degrees
Precipitation prediction data should be updated every 10 minutes	The system's storages should be connected to each other
The system should measure the storage water level for user feedback	The storage should be darkened to avoid bacteria growth.
	The system should be power efficient
Could	
The system could distribute water automatically **(SN)**	
The system could work overcapacity of solar panels near BTD	

Table 2: Functional and Non-Functional System Requirements based on MoSCoW.

5.3 Functional System Architecture

The functional system architecture is meant to identify and give a better understanding of system functions and interactions and how these functions cooperate. The functional system architecture is split up in different levels starting with level 0: System Overview. Then level 1: RHS Decomposition is explained and finally the level 2: RHS Function Description. Each level describes the system in more detail.

5.3.1 Level 0: System Overview

Figure 24 shows Level 0 which is the rainwater harvesting system (RHS), a black box representation of the RHS and the external behaviour of the system. The RHS frequently requests the local precipitation prediction. If rain is predicted, the RHS will collect fresh rainwater in its internal tank if the measured soil moisture is above a threshold value for dry soil. If the internal tank is full, excessive rainwater is disposed to the RHS environment. Sunlight measurements are used to determine when the RHS must activate its sun blocking function. However, this sun blocking function is only activated when the soil moisture is below the threshold value for too wet soil.

It includes all the factors that have influence on the system from the outside. These factors are rainwater, soil moisture and sunlight. Rainwater should be collected by the system. Soil moisture and sunlight are used to determine the status the system should be in. The RHS is a black box.

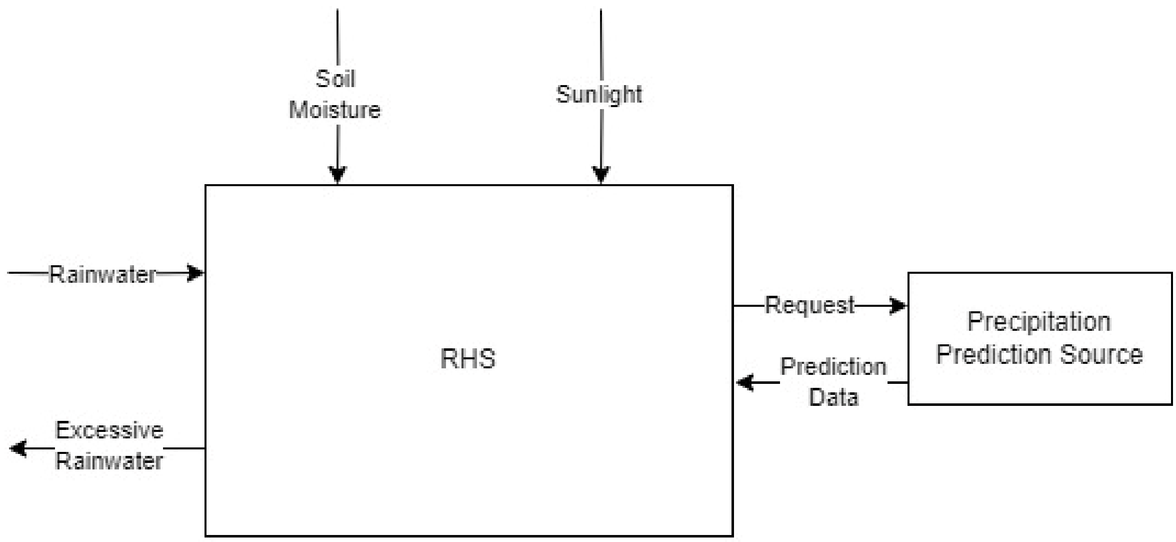

Figure 24: Level 0: System Overview

5.3.2 Level 1: RHS Decomposition

By filling in the black box of Level 0, a Level 1 architecture is created by disclosing the main functions of the RHS. The influences from outside rainwater, soil moisture and sunlight are going into the system. The rainwater enters the system via the catchment function whereafter it is either transferred to the storage or via the storage back to the outside world if the storage function status is “FULL”. The outside variables rainwater, soil moisture and sunlight that enter the system are converted into values for volume, humidity and intensity which are send to the Control Logic. The Control Logic requests precipitation prediction data to control the catchment and shadow functions. Rainwater is collected by the Catchment Function if it is closed, and forwarded to the Storage Function. The storage water level is determined by the Water Level Measure Function. The storage water level decreases when water is tapped from the storage. The Sun Blocking Function is controlled by the Control Logic to block sunlight if needed. Figure 25 shows the Level 1: RHS Decomposition.

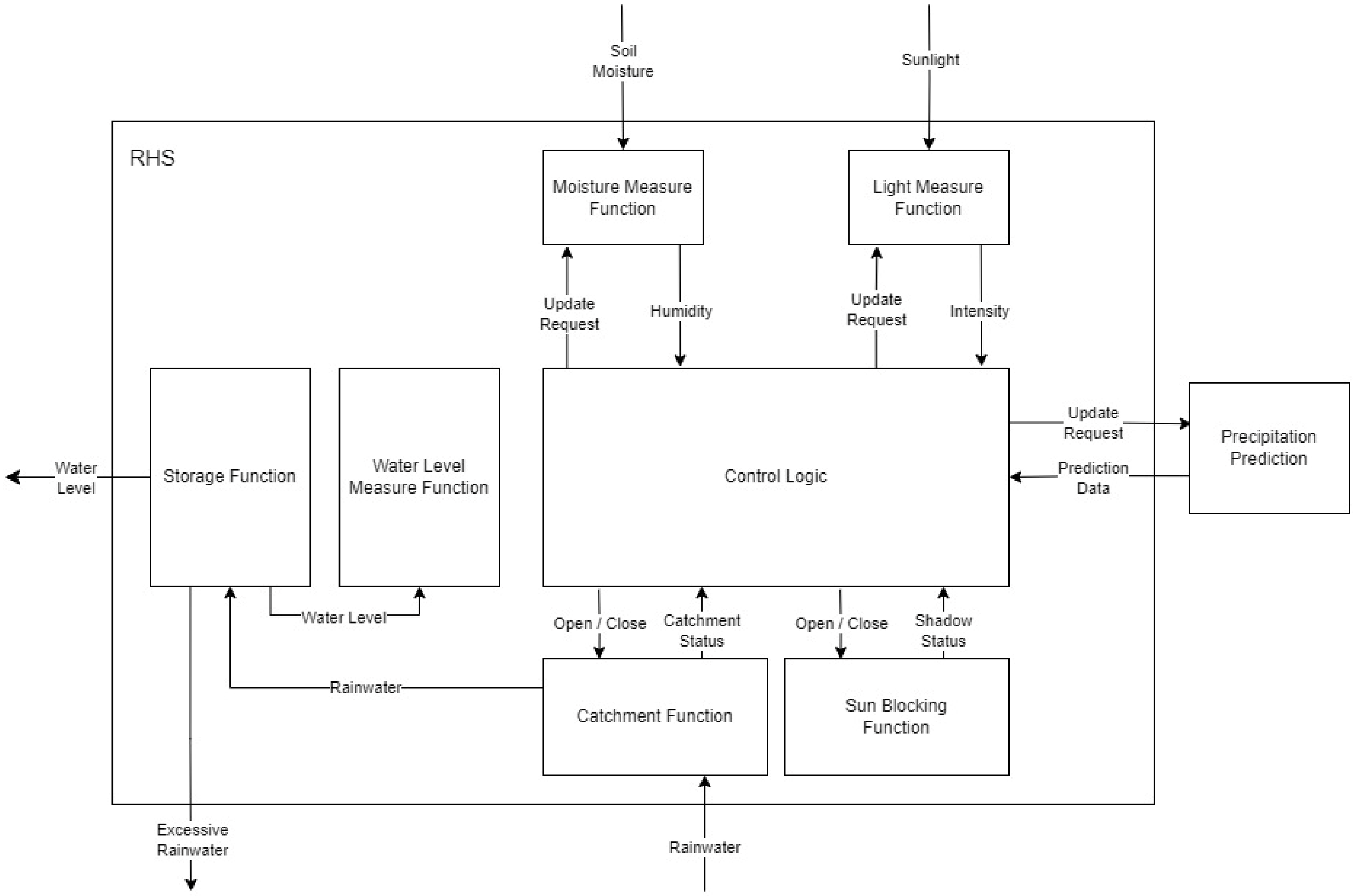

Figure 25: Level 1: RHS Decomposition

5.3.3 Level 2: RHS Decomposition

To go further into detail a Level 2 architecture is made for the control logic and the measure functions. In Figure 26 the control logic architecture is presented. The control logic uses prediction data to determine the precipitation status. It also uses a humidity percentage and a light intensity percentage achieved from the sensor data. The control logic functions as follows:

The catchment control open when:
Prediction status = False
OR
Prediction status = True **AND** humidity < lower threshold value

The catchment control close when:
Prediction status = True **AND** humidity > upper threshold value **AND** sun blocking control = Open

The sun blocking control open when:
Prediction status = True
OR
Prediction status = False **AND** intensity < threshold value
OR
Prediction status = False **AND** humidity > upper threshold value

The sun blocking control close when:
Prediction status = False **AND** humidity < upper threshold value **AND** intensity > threshold value **AND** catchment control = Open

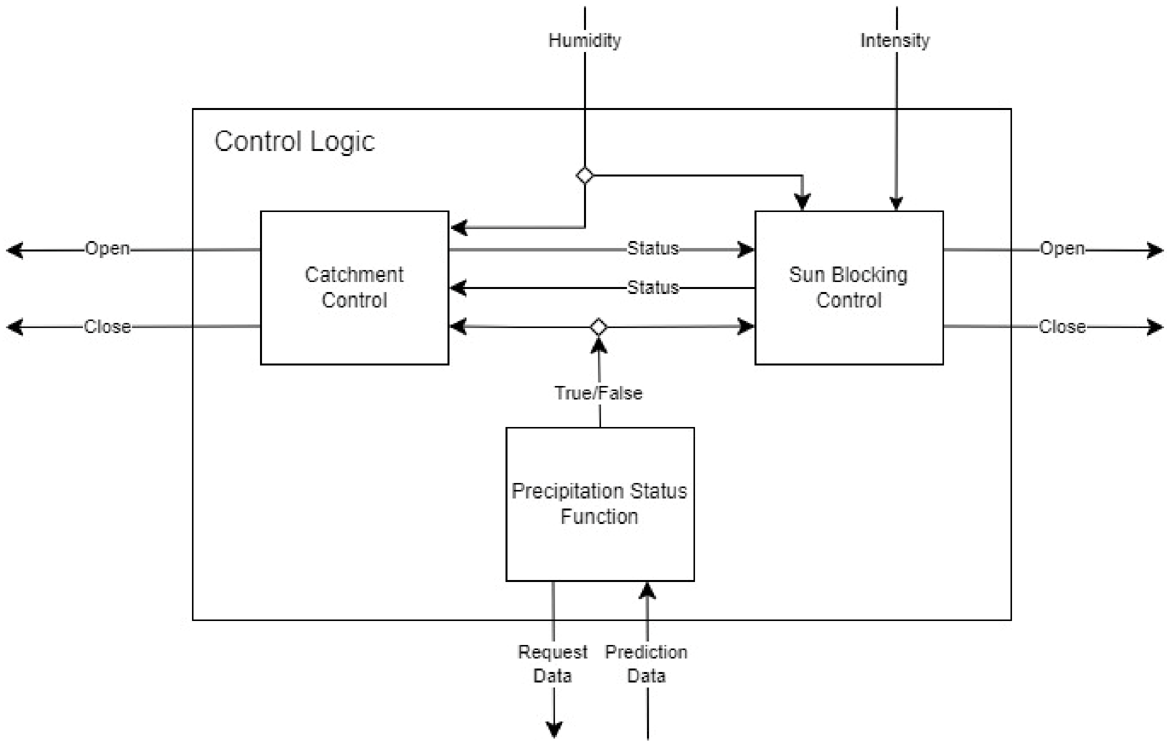

Figure 26: Level 2: Control Logic Architecture

Figure 27 shows the three measure functions that are used. The three measure functions are very similar. They only differ in input and output. The inputs of the measure functions are water level, sunlight and soil moisture. The sensor picks up raw data which is converted into relevant usable data (water level in used storage capacity percentage, sunlight intensity percentage and soil moisture in percentage).

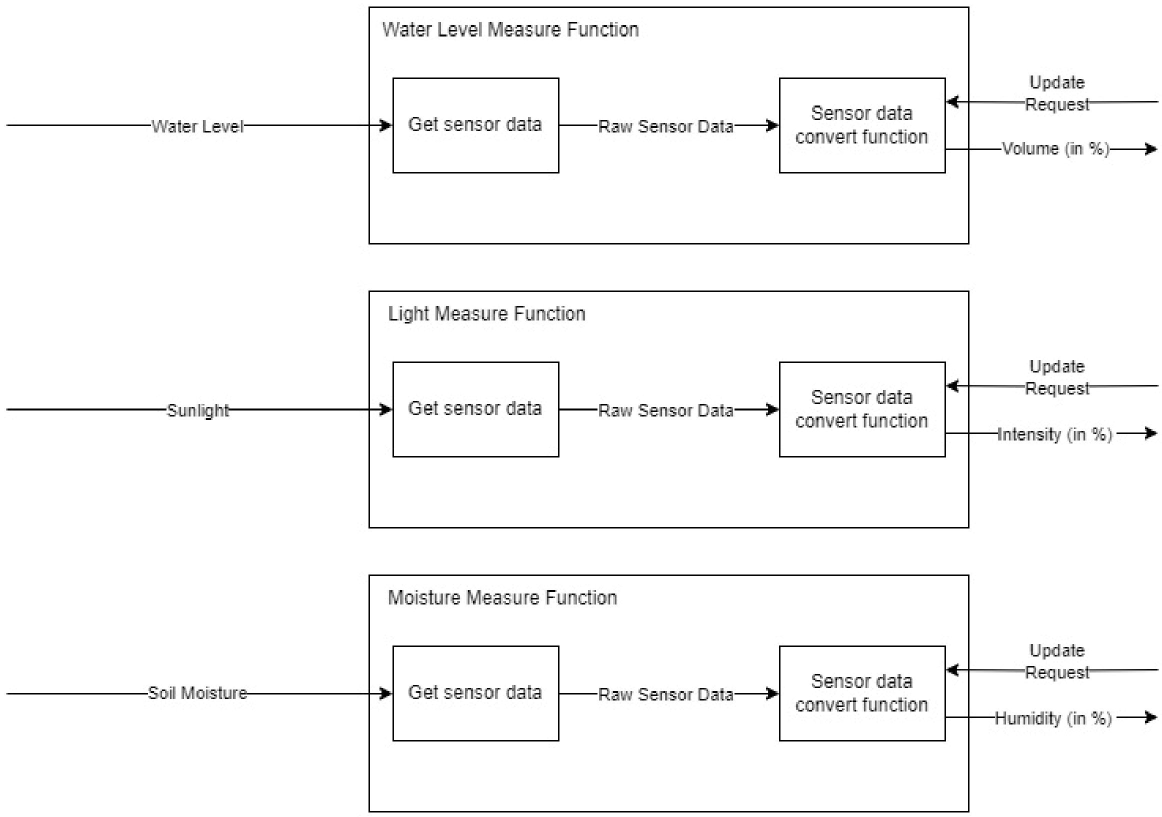

Figure 27: Water Level / Light / Moisture Measure Function Architecture.

5.3.4 Level 2: RHS Function Description

Figure 28 shows an Activity Diagram which gives insight in the flow control of the system including the RHS interaction with the user and the precipitation prediction source.

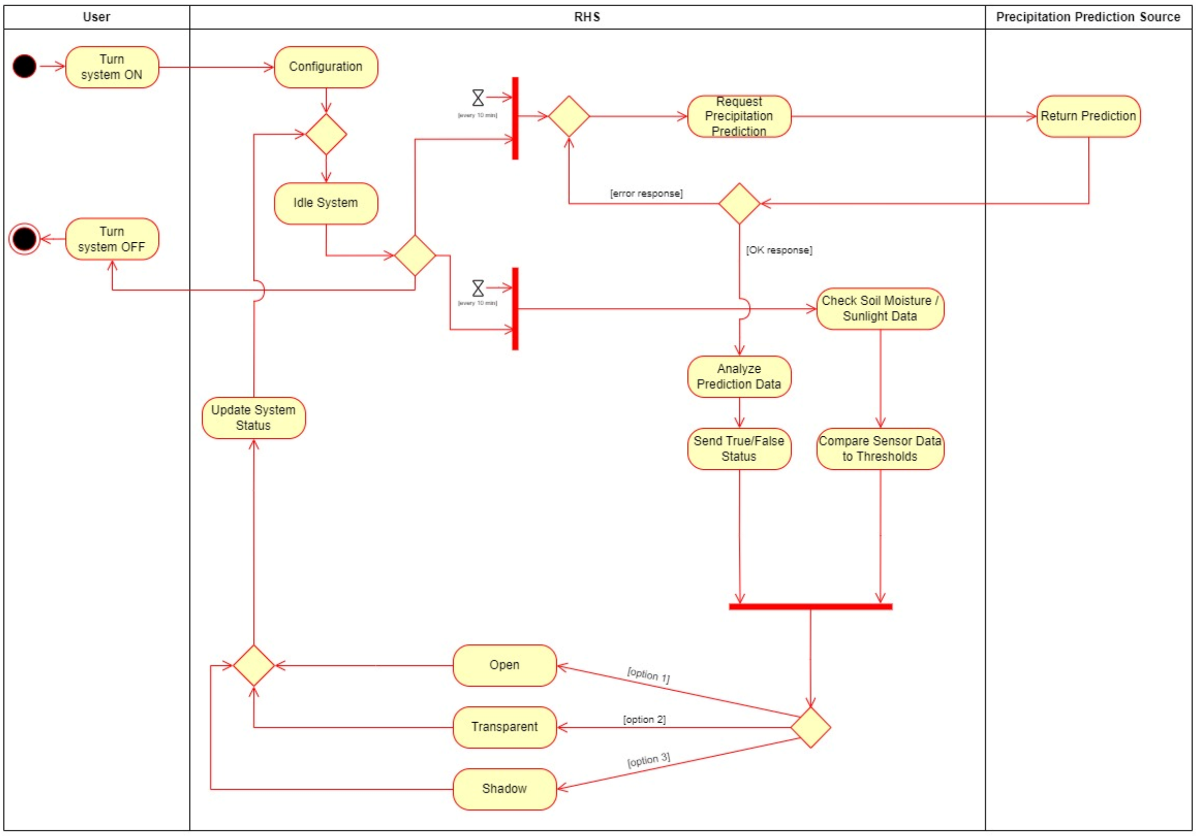

Figure 28: Activity Diagram.

6 Realisation

During the realisation phase a prototype of the system is built. In Chapter 2 it was found that a catchment area of 905m^2. is needed to completely switch from tap water to rainwater. The scale of this system is unrealistic considering the time and resources for this project. Therefore, it is decided to build a low budget scaled down prototype. The prototype is built with limited resources. Considering the catchment area of 905m^2, a scale of 1:450 was made. Additionally, the system is a proof of concept (POC). The system has several functionalities that can be useful for BTD. The POC system needs to show that these functionalities work.

The prototype will be built according to the functional system architecture presented in Chapter 5. Also the system requirements should be implemented according to their MoSCoW based priority with the main focus on must haves. The RHS is built up out of four main parts: the frame, a transparent and shadow surface, two motors and sensors. In this chapter each of them will be described in detail.

6.1 Frame

The frame of the RHS consists of galvanized scaffolding pipes. Two pipes of 1 meter and six pipes of 2 meters were used. Four pipe pedestals were connected to the legs of the frame, since the legs could not be put into the ground at the building location. Four pipe coupling pieces connect the pipes together. Finally, the frame is completed by attaching a gutter.

6.1.1 3D Printed Angle Pieces

To connect the pipes together, four pipe coupling pieces were ordered (Figure 29). However, by using these coupling pieces the required roof angle of 15 degrees was not met. Therefore, four 3D angle pieces were modelled such that they have an angle of 15 degrees and fit both inside the coupling piece and the connecting 1m pipe. The 3D part that was printed can be seen in Figure 30.

Figure 29: Coupling piece

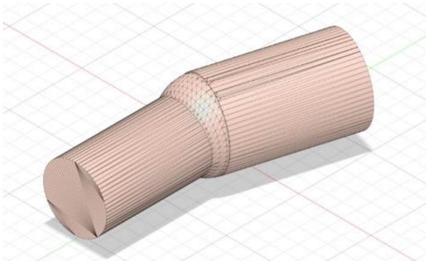

Figure 30: Angle piece

6.1.2 Pipe sizing

After modelling the angle piece, the front legs of the system should be lowered. To calculate the difference in cm between the back legs and the front legs the Pythagorean theorem together with Formula 4 were used as follows:

$$a = c * sin\ (\beta)$$

Formula 4: front and back pipe length difference.

The system should be in an angle of 15 degrees, so β is 15. Furthermore, the hypotenuse “c” can be calculated by adding the length of the tube (100cm) with two times the length of the coupling piece (9cm), which results in 118cm. The values needed to calculate the perpendicular “a” are:

$\beta = 15°$
$c = 118$cm

Substituting the two values into Formula 4 gives:

$$a = 118 * sin\ (15) = \ 30.5$$

The leg pipes of 2m each were then shortened using a steel saw. To make the system more stable first all four legs were shortened by 50cm. Finally, as calculated, the front legs were shortened an additional 30.5cm to achieve the desired height difference between the front and the back of the system.

6.1.3 Gutter

An important system part which is integrated with the frame is the gutter. The goal of the gutter is to guide the rainwater from the system to the rainwater buffer via drainpipes. With wires the gutter was attached to the end of the two side bars of the frame. It has a slight angle to direct the water to the right end of the gutter, where the water is dropped down towards the water buffer. Figure 31 shows the gutter attached to the frame.

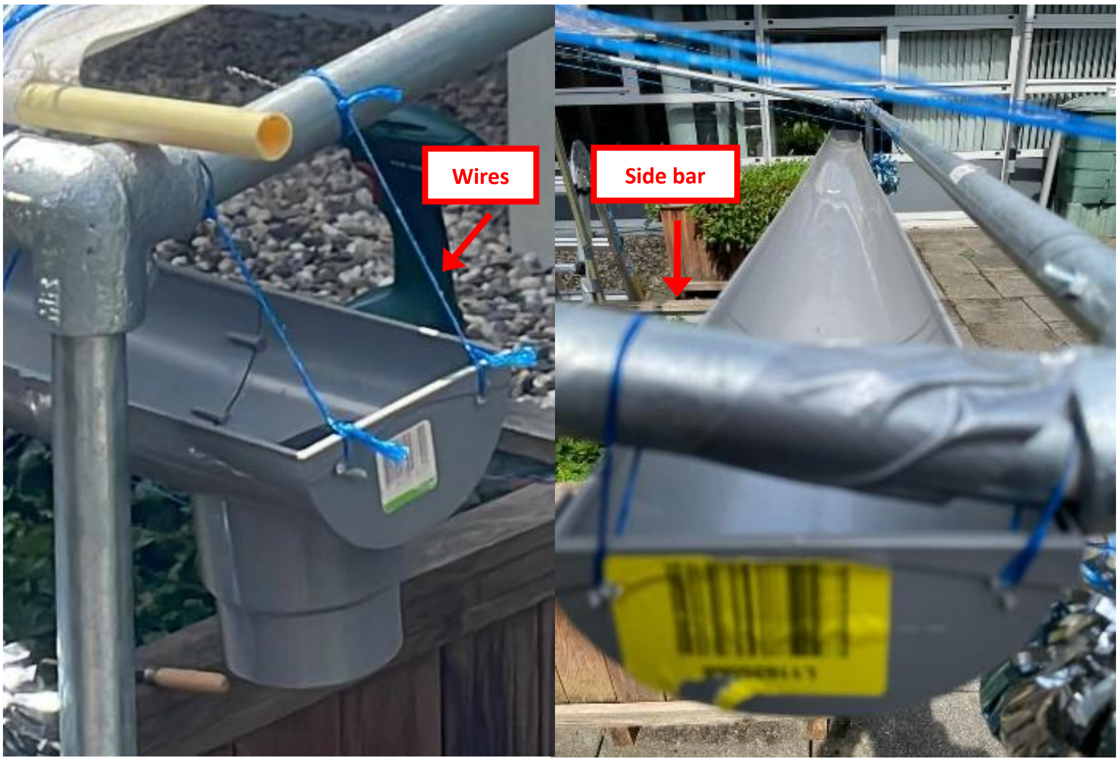

Figure 31: Gutter attachment

6.2 Surfaces

The system is designed such that the “roof” that is attached to the frame is dynamic. This means that the roof can change its status. There are three possible roof statuses: transparent, shadow or open. The system uses a transparent surface and the shadow surface which can be both activated and deactivated. Both surfaces will be explained in further detail, whereafter the control logic is being explained and some technical solutions to make the system work properly.

6.2.1 Transparent Surface & Shadow Surface

The transparent surface is used to catch rainwater and the shadow surface is used to protect the garden from the sun and reduce evaporation. For the shadow surface a fabric was chosen that is able to block the sun from reaching the garden. For the transparent surface it was important that the fabric allows for rainwater harvesting. The rainwater should easily run off the fabric to achieve the highest RC value and therefore the highest rainwater harvesting potential. Therefore, a plastic transparent oilcloth was chosen for the transparent surface. Although the functions of both surfaces are very different, the building process of the two in the system are almost identical.

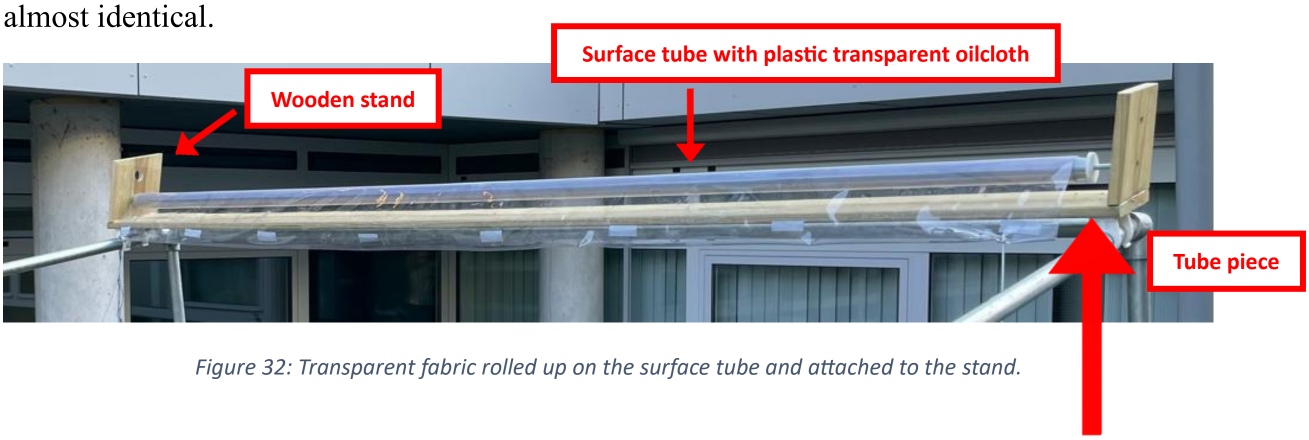

Figure 32: Transparent fabric rolled up on the surface tube and attached to the stand.

First the fabric was attached to the surface tube of 2 meters long with dual sided adhesive tape. This makes it possible to roll up the fabric easily. Next a stand was made to be able to place the surface tubes on top of the frame (Figure 32). The stand consists of a wooden plank with end plates on both sides. The end plates have holes where the surface tubes will be attached to. With a bolt and a nut, a 3D printed parts (Figure 33) were connected to the surface tubes that fit the holes in the end plate. This way the surface tubes are able to freely rotate between the end plates. At the bottom of the plank clamping brackets were screwed to attach the stand to the top, backside of the frame. Finally, attached to the end of both fabrics a PVC tube was attached for extra support while rolling up and down and to keep the fabrics tight (Figure 34).

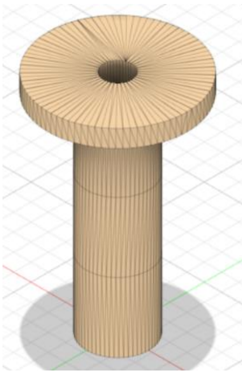

Figure 33: Tube piece model

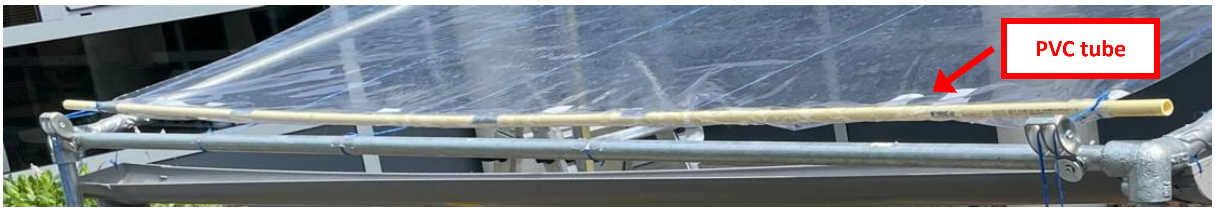

Figure 34: PVC tube attached to the transparent surface.

6.2.2 Control Logic

To explain what decisions the controlLogic() method in the Arduino code of the system makes in various situations a decision tree is presented in Figure 35. The decision tree shows the behaviour of controlLogic(), which is based on the in 5.3.3 specified Control Logic Architecture. The decision tree is based on buffer capacity and the environmental system inputs rainfall, soil moisture and sunlight intensity. Also, as an addition to sunlight intensity, temperature was added.

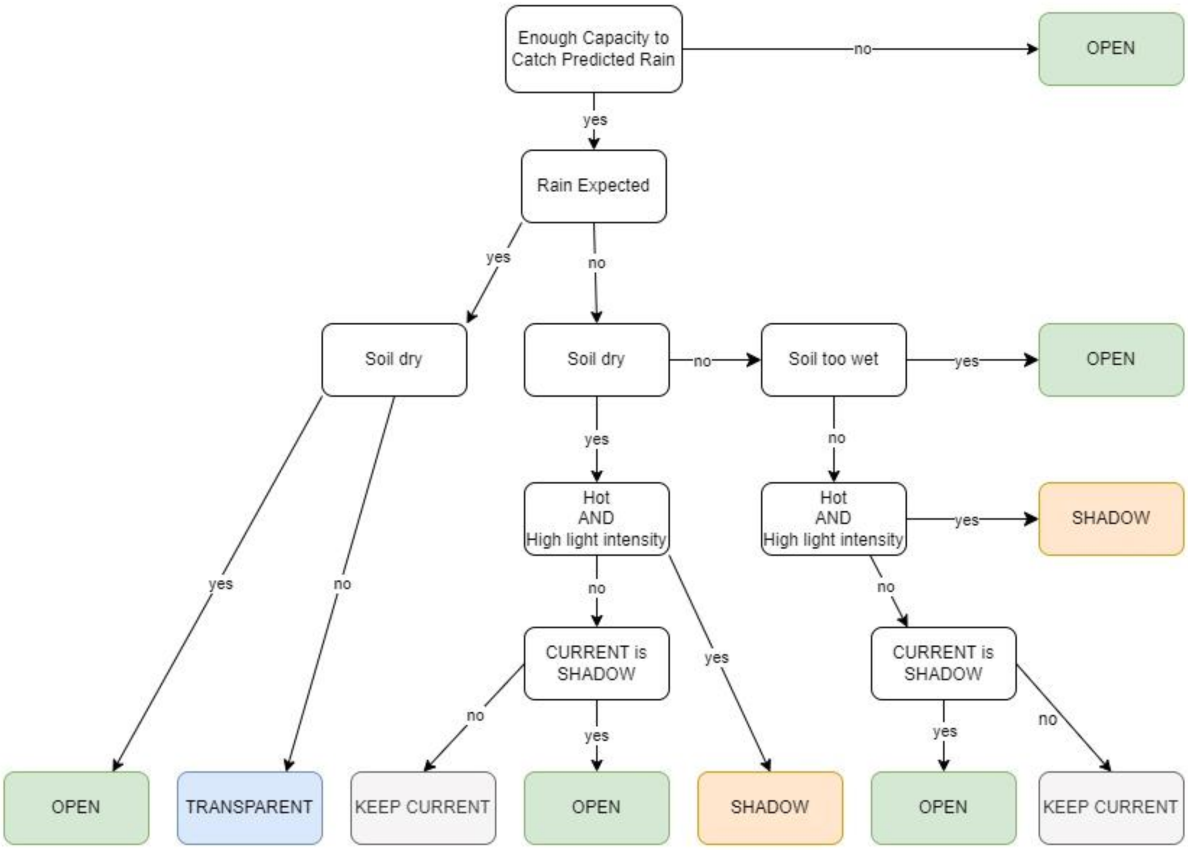

Figure 35: Decision tree for transparent and shadow surface behaviour.

There are four possible outcomes. First the system status can be *open* meaning both the transparent surface and the shadow surface are being rolled up. This can happen when the soil is dry and the rain can irrigate the soil directly instead of catch the rain for later use. Also, when there is no rain expected and the soil is too wet the system status will be open so that evaporation can happen to reduce the moisture level. The system status can also be open when the threshold value of sun intensity or temperature are not exceeded.

The second system status is *transparent*. This only happens when there is enough buffer capacity, rain is expected and the soil is either in good condition or too wet.

The third system status is *shadow*. This only happens when there is no rain expected, the soil is dry or in good condition and both the sun intensity and temperature threshold are exceeded.

The final possible outcome implies that the system will keep its current status which is either open or transparent.

The controlLogic() method of the Arduino code can be found in Appendix A, Figure III.

6.2.3 Pulleys

To the frontside crossbar of the frame two dual pulleys are connected. One to the left and the other to the right side. With a steel drill a hole was made in the frontside crossbar. With a bolt and a nut and two body rings the pulleys were fitted on the frame. The pulleys are guiding wires from the transparent and shadow surfaces to the weights. Figure 36 shows the left pulley with the a wire connected to the transparent surface and a wire connected to the shadow surface.

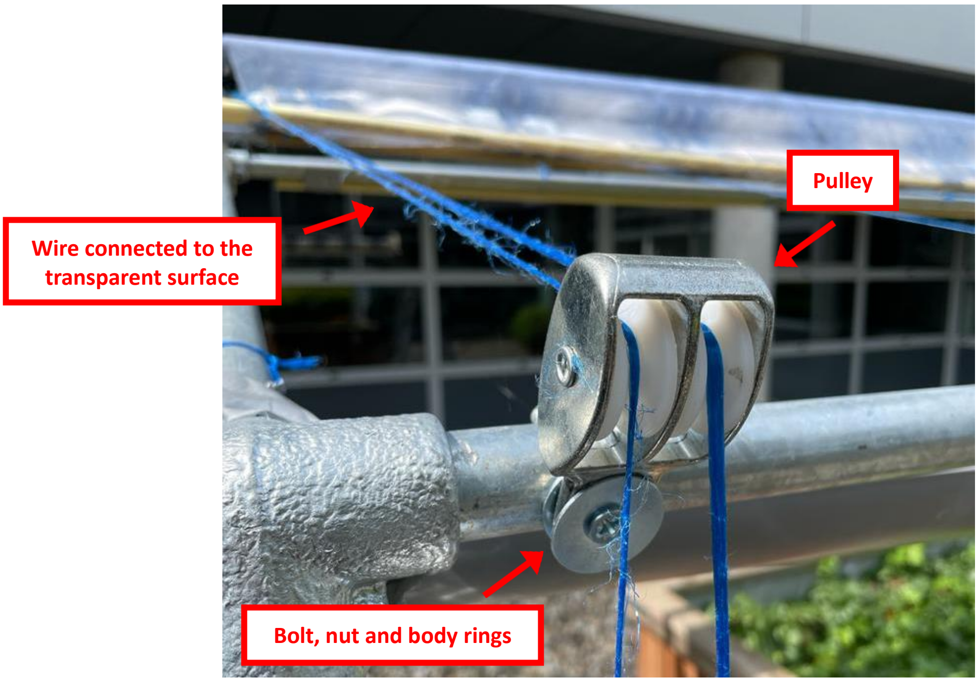

Figure 36: Pulley attached to the frontside crossbar of the frame with two wires attached to the transparent surface and the shadow surface.

6.2.3 Weights

Weights are used to pull down and pull tight the transparent and shadow surface. Especially for the transparent surface it is of importance that the fabric is very tight so the water can run off easily. Attaching a greater weight will result in a tighter fabric. However greater weights also mean that the system needs a very strong motor to pull up the fabric. A balance between these two needed to be found. After doing trial and error a weight of 720g was divided over the two pulleys for each surface.

6.3 Motors

The transparent and shadow surface both have their own motor. The motors are used to roll up and roll down the surfaces automatically. The motors are controlled by the Big Easy Driver. Furthermore, gears were connected to the motor shaft and the surface tubes and system friction was reduced.

6.3.1 Stepper Motor

For this project a Wantai NEMA17 Stepper Motor 42BYGHW811 [36] was used. A datasheet for the specifications of stepper motor was acquired. Some important specifications are listed in Table 4 below.

Model No.	Holding Torque	Step Angle	Rated Voltage	Rated Current
	g-cm	°	V	A
42BYGHW811	4800	1.8	3.1	2.5

Table 4: specifications stepper motor. Source [36]

The specifications in Table 4 shows that the motor has a step angle of 1.8 degrees. This means that in order to do a full rotation, the motor shaft should do 200 steps. Another important specification is the holding torque. The holding torque is a parameter that is needed to calculate how much weight the motor can lift. The other parameter is the radius of the shaft attached to the motor. Since the surface tube is connected to the motor on one side, the radius of the surface tube is used for the calculation. The formula to calculate power *P*, how much weight the stepper motor can lift, is the following [37]:

$$P = \frac{\left(\frac{Holding\ Torque\ (Nm)}{Shaft\ Radius\ (m)}\right)}{9.81}$$

Formula 5: Motor lifting power

The parameters that are being used are:

Holding torque : 4800 g-cm = 0,4707192 Nm
Shaft radius : 28mm = 0.028 m

$$P = \frac{\left(\frac{0.4707192}{0.028}\right)}{9.81} = 1.7\ kg$$

This calculation proofs that theoretically the stepper motor should be able to lift 1.7 kg at its full potential.

6.3.2 Big Easy Driver

The motor is controlled with a motor controller. Each motor has its own motor controller. The motor controller that has been connected to the motor is the Big Easy Driver (BED) [38] [39] (Figure 37). Since two motors were used, two BEDs were needed to control each motor separately. The BED is a stepper motor driver board made to control a bi-polar stepper motor up to a max 2A per phase. The current limiter on the BED was turned all the way up to 2A. For loads approaching 2A the BED must have a heatsink on top to avoid overheating of the chip. To avoid components to overheat and safe power the BED is put in sleep mode when no signals are sent to the driver.

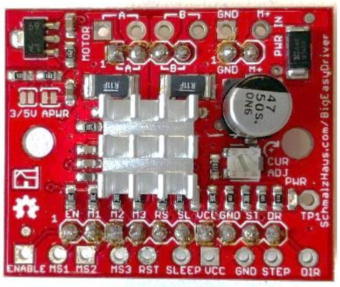

Figure 37: Big Easy Driver

For DC motors, the output torque is directly proportional to the current through the windings [40]. This means that the stepper motor, to which 2.5A can be applied, can only work at 80% of its full potential when 2A is applied. This also means that the in 6.3.1 calculated 1.7kg that can be lifted by the motor decreases to 80%, which is 1.36kg.

The BED is connected to the Arduino. The Arduino code controls the stepper motor behaviour for example whether it should turn clockwise or anti-clockwise, how many steps it should turn and if sleep mode is activated or not. To the other side of the BED, the wires corresponding to each phase are connected to the A and B pins. Finally, 5V was connected to the driver on the Arduino side and 15V was connected to the driver on the motor side. Figure 38 shows the sketch of the circuit.

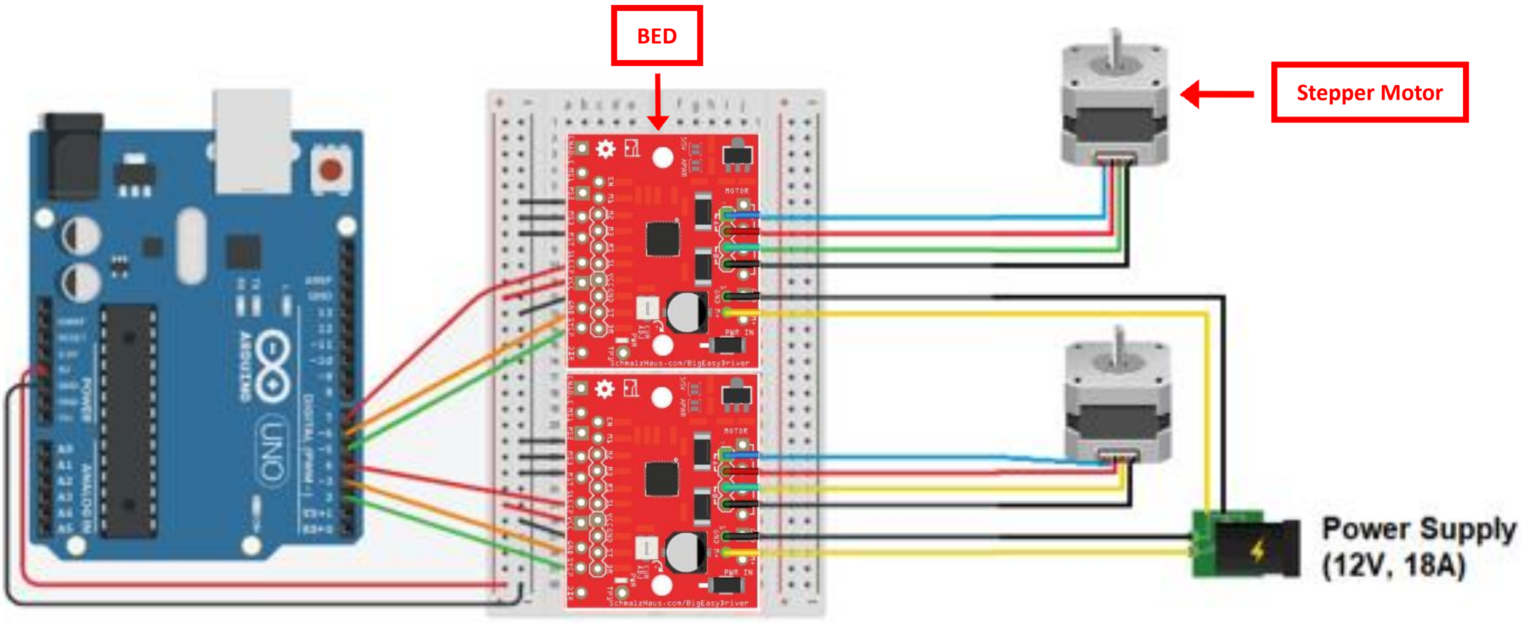

Figure 38: Stepper motor circuit sketch: stepper motors connected to two Big Easy Drivers which are connected to 12V and an Arduino. Arduino digitalPin connections of the BED are as follows: RED wire → SLEEP, ORANGE wire → STEP, GREEN wire → DIRECTION.

6.3.3 Gears

The weights connected to both fabrics were 720g. In theory this means that the 1.36kg lifting power of the motor should be enough to pull up the weights. Furthermore, the fabric itself is an additional weight the motors need to pull up and the system has several friction points which will be described in more detail later.

All these aspects combined caused the motor to be too weak to lift up the fabric with the weights. For this reason, to both of the motors a small gear with 16 teeth was pressure fitted on the motor shaft using a cooling spray. First the shaft shrinks when it is cooled. Then the gear is fitted onto the shaft. When the shaft warms up again the gear is tightly attached to the shaft. To the surface tube, a large gear with 80 teeth was attached. The large gear is five times larger than the small gear, meaning the motor can lift five times 1.36kg which is 6.8kg. Figure 39 shows the small gear attached to the motor shaft and the large gear.

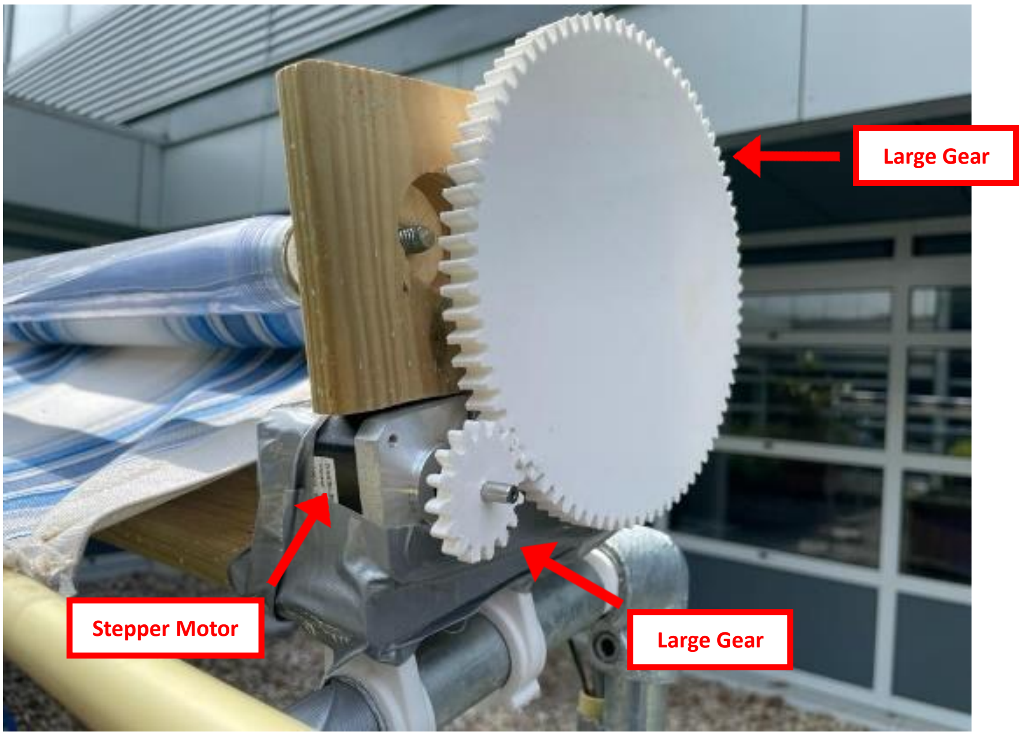

Figure 39: Small and large gear.

6.3.4 System Friction

There are several friction points in the system. The first friction points are the holes in the end plates of the stand that serve the function to rotate the surface tubes. Secondly, the fabric becomes more heavy when it is rolled down causing additional friction. The third friction point are the pulleys. For the motor to be able to roll up the surfaces more easily, each friction point needed to be adjusted in such a way that there is as less friction as possible.

To reduce friction during surface tube rotation, 3D printed bearings were designed (Figure 40). The bearings are made out of plastic. Since plastic is smoother than wood it reduces friction. Another reason why friction is reduced by placing bearings is that the bearings leave no room for the large gear to move meaning a smoother connection between the small and the large gear. Finally, a lubricant was sprayed on the inside of the bearing.

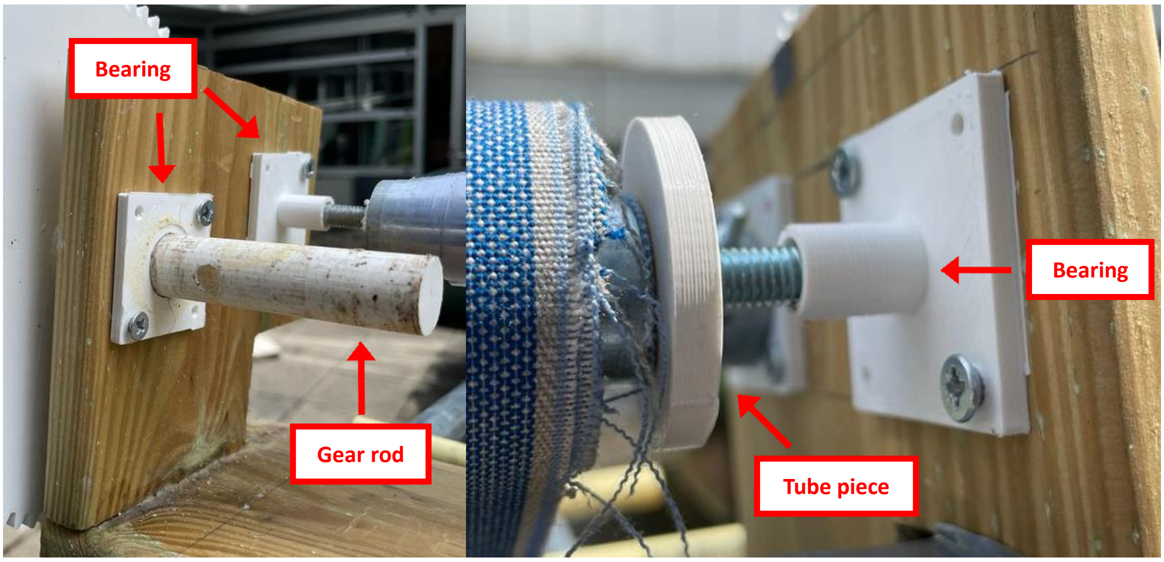

Figure 40: Bearings

The second friction point is the fabric. When it is rolled down the friction increases when it is pulled tight by the weights. To reduce this friction two measures were taken. First, the PVC tube was attached to the end of both fabrics. This keeps the fabric tight. Also the PVC tube supports the fabric on the side bars of the frame. Furthermore, wires were stretched from the back to the front crossbar of the system. These support the fabrics two when they roll down.

The final friction point for which the friction was reduced were the pulleys. Initially, the angle of the pulleys caused them to be located higher. By adjusting the angle of the pulleys, they were slightly lowered. The wire runs more smoothly through them and thus friction is reduced.

The PVC tube, support wires and the left pulley can be seen in Figure 42.

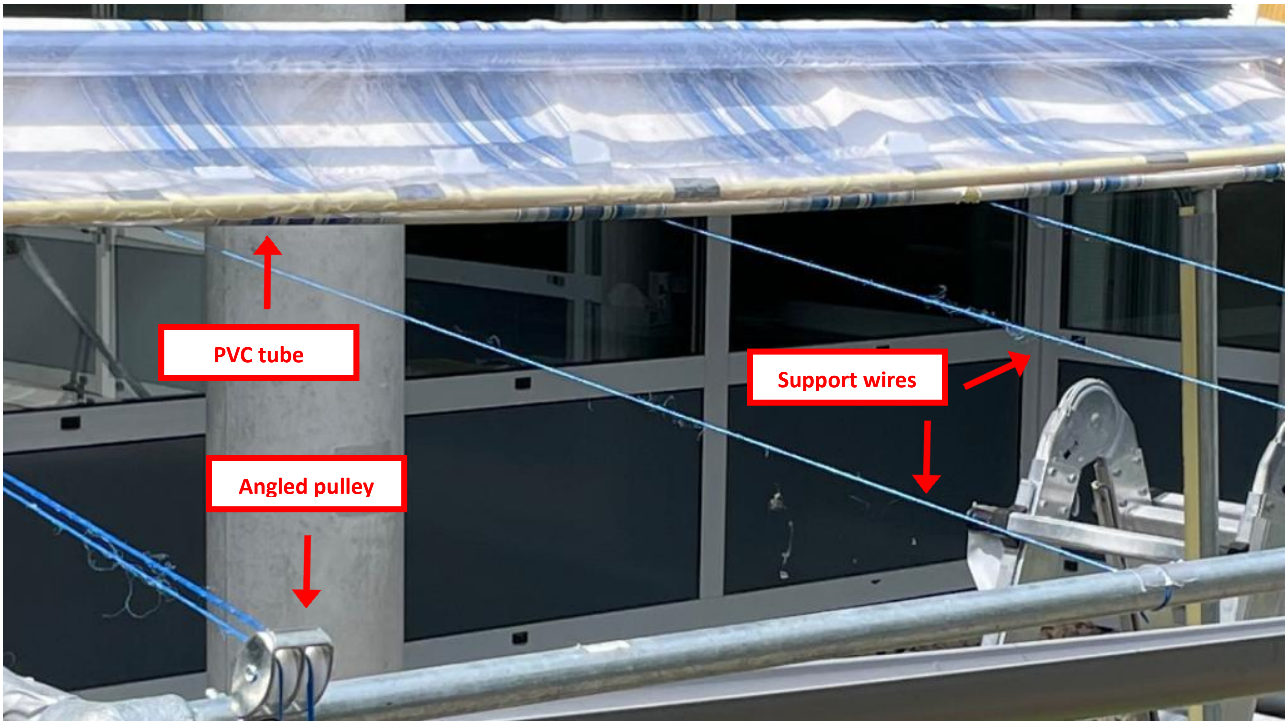

Figure 42: PVC tube and support wires.

6.4 Sensors & Electronics

The system works autonomously based on the environmental aspects soil moisture and sunlight intensity. Additionally, the capacity of the water buffer is measured. To measure these values the system uses sensors. Besides sensors the system also needs a precipitation prediction to function properly.

6.4.1 Soil moisture

There are two types of soil moisture sensors, resistive and capacitive. To measure the soil moisture a capacitive soil moisture sensor [41] was used since it has a higher reliability. By connecting the sensor to 5V, ground and an analog pin on the Arduino [42], the soil moisture can be measured. To calibrate the sensor a calibration setup was made. The test setup consisted of the soil moisture sensor, a pot of soil and water (Figure 43). First, the analog value was measured when the soil moisture sensor was in dry air. The retrieved value was 577. Alternatively, the analog value was measured when the soil moisture sensor was put inside a glass of water meaning very wet conditions (Figure 44). The retrieved value was 273. Mapping these values to 577 being 0 and 273 being 100, the humidity percentage was acquired. Threshold values were programmed in the Arduino code. For vegetables, a soil moisture value below 41% means the soil is too dry, between 41% and 80% the soil is in good condition, above 80% the soil is too wet [43]. Finally, the soil moisture sensor was put in a pot of soil for testing (Figure 45).

Figure 43: Calibration setup

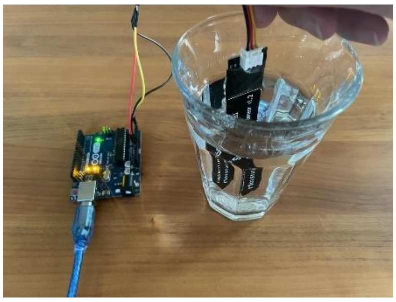

Figure 45: Soil moisture sensor calibration

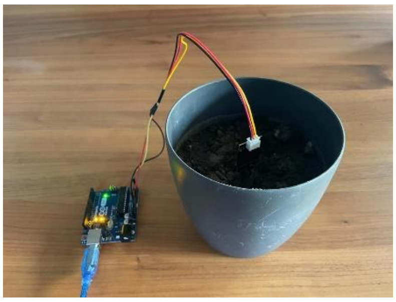

Figure 45: Soil moisture sensor testing

6.4.2 Sunlight intensity & Temperature

For the sunlight intensity an LDR can be used such as the Grove light sensor [44]. The placement of the sensor on the system is important. The sun should always be able to reach the sensor. For this project only one light sensor was used. However, by placing multiple light sensors at different locations on the system and taking the average, the accuracy would increase.

To calibrate the sensor the analog values were captured for three scenarios, the first one being very sunny, the second one being cloudy and the third one being completely dark. The last scenario was mapped to be a sunlight intensity percentage of 0%, where the highest measured value was set to be 100% sunlight intensity. Since the sensor is very sensitive the value for cloudy weather appeared to be 90%. This is the threshold value used in the Arduino code.

Finally, a temperature sensor [45] was also added to the system. The temperature sensor is an addition to the sunlight intensity sensor to make a more specific weather indication. This means that instead of only the sunlight intensity sensor to exceed the threshold value, also temperature should be above a certain threshold before the shadow surface is deployed.

6.4.3 Water level

The water level is measured with an ultrasonic sensor by measuring the distance from the sensor to the water. Depending on the precipitation prediction buffer can either have enough capacity or not. The higher the precipitation prediction, the longer the distance between the water and the ultrasonic sensor should be to have enough capacity.

6.4.4 Rainwater prediction function

Ideally the system would be connected to an online precipitation prediction source. However, since the Arduino does not have internet connection the rainExpected() method was written for the precipitation prediction (Appendix A, Figure II). The function randomly gives a precipitation value. The probability of the precipitation being 0mm is 60%. The probability for rainfall is 40% divided into three categories. 1mm precipitation has a probability of 20%, 2mm is 12% chance and 3mm is 8% chance.

6.4.5 Combined Circuit Sketch

By expanding the sketch in Figure 38 of the stepper motors with the ultrasonic sensor, the soil moisture sensor and the light sensor, the sketch in Figure 46 can be made. The sketch shows the full system circuit.

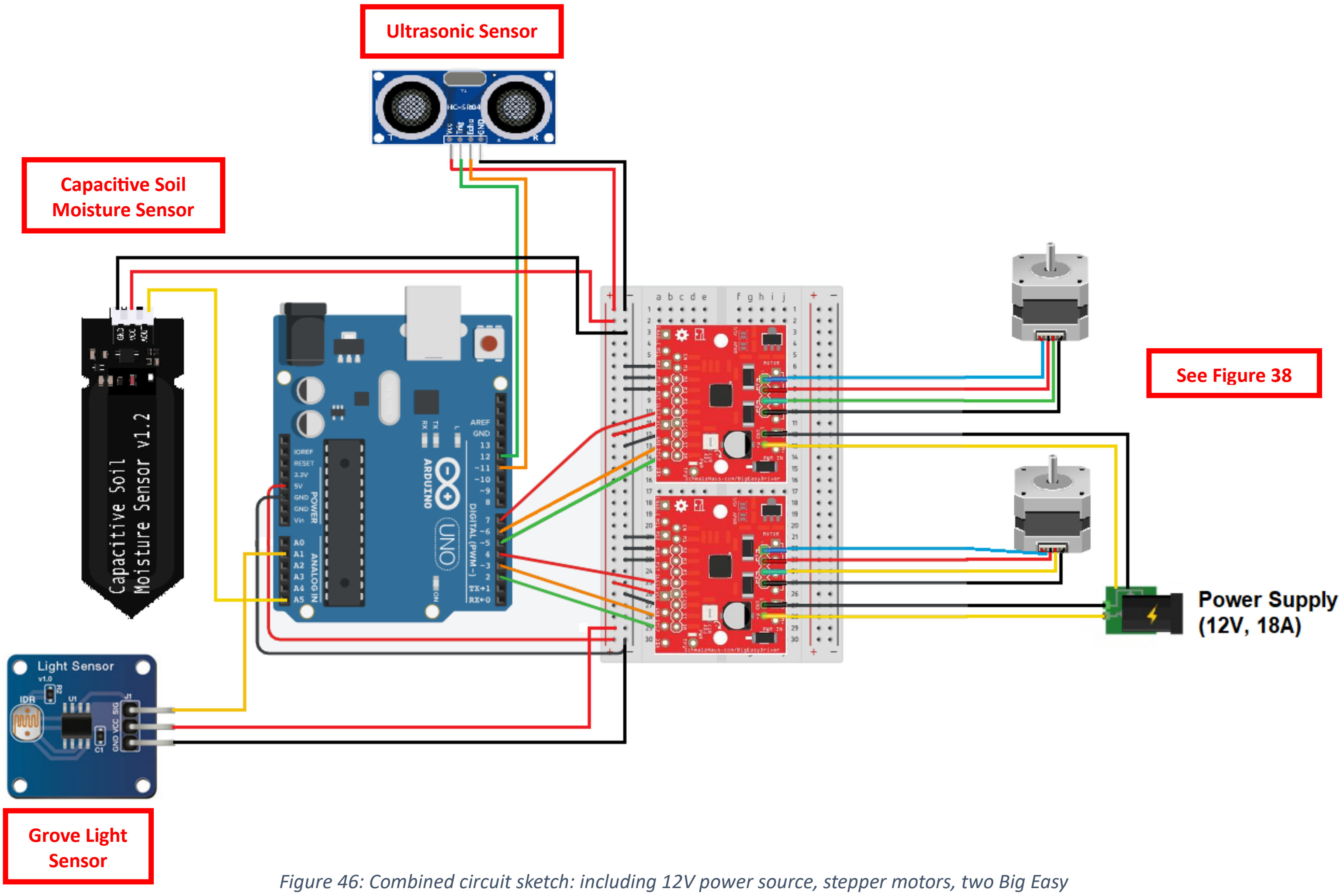

Figure 46: Combined circuit sketch: including 12V power source, stepper motors, two Big Easy Drivers, ultrasonic sensor, soil moisture sensor and light sensor with Arduino connections.

6.5 Prototype evaluation

The RHS prototype will be evaluated based on the functional system requirements that were set out in Chapter 5.2. Table 5 shows which requirements were met and which not.

Functional Requirements	
Must	**Requirement met?**
The system must harvest rainwater **(SN)**	YES
The system must have screens that can open and close	YES
The system must allow water to reach the garden	YES
The system must adjust depending on the environmental aspects soil moisture and sunlight	YES
The system's sensor data must be checked every 10 minutes	YES
The system must use precipitation prediction data	NO
The system must be automatic	YES
The system must be able to create shadow	YES
The system must collect water into the storage tanks provided by BTD **(SN)**	NO
The system must drain excessive rainwater	NO
Should	
The system should be manually adjustable **(SN)**	YES
The system should have a stand-by mode	YES
Precipitation prediction data should be updated every 10 minutes	YES
The system should measure the storage water level for user feedback	YES

Table 5: Functional requirements evaluation

Table 5 shows that most of the functional requirements were realised into the prototype. However, a few requirements were not met. The first requirement that was not met is "The system must use precipitation prediction data". Since the Arduino was not connected to the internet the prediction data could not be retrieved from an online source. However, to simulate rain prediction a method was coded for the system. Another requirement that was not met is "The system must collect water into the storage tanks provided by BTD". Initially, this was a stakeholder requirement. However, since the work place for the prototype was not at BTD, it was decided to use the storage tanks for another purpose. The last requirement that was not met is "The system must drain excessive rainwater", since the storage tank was not connected to the system yet due to a lack of time. Figure 47 shows the realised RHS prototype (See Appendix C for the Component List).

Figure 47: Realized Rainwater Harvesting System: with catchment, open and shadow status

7 User Evaluation

Chapter 7 presents the user evaluation phase. To evaluate the prototype a user evaluation was set up. The aim of the user evaluation is to test the usability and acceptance of the RHS prototype with the target audience, (BTD) community garden members. Finally, a conclusion will be given.

7.1 User Evaluation Setup

The user evaluation sessions consist of two parts, a demonstration and an interview. Each evaluation session takes approximately 30 minutes. During the first part of the session the prototype is demonstrated using simulated sensor values for light intensity and temperature and using the real time data of the soil moisture sensor. The prototype demonstration was done as follows:

A short introduction about the graduation project is given to the participant. Key components such as the transparent and shadow surface and the sensors of the system are explained along with the functionalities of the system. After the short introduction to the graduation project and the RHS prototype the scenarios were played out.

Scenario 1:

- *Rain is expected.*
- *The soil is in good condition.*
- *There is enough capacity in the buffer to catch the predicted rain.*

Scenario 2:

- *No rain is expected.*
- *The soil is in good condition.*
- *The weather is sunny and hot.*

Water was added to the soil moisture sensor to make the soil too wet.

Scenario 3:

- *No rain is expected.*
- *The soil is too wet.*
- *The weather is sunny and hot.*

The system is turned off and manual transparent and shadow surface handling is demonstrated to the participants.

During the demonstration the scenarios were explained to the participants. The system update summary that is outputted in the Arduino serial output monitor is being shown and the reasoning behind a certain decision the system makes is explained to the participants. Figure 48, 49 and 50 show examples of system update summaries of each scenario that were outputted during user testing.

```
* SYSTEM UPDATE SUMMARY *

Predicted Precipitation : 3mm

Capacity          :  50%
Soil Moisture     :  76%
Light Intensity   :  90%
Temperature       :  25°C

CONTROL LOGIC CHECKLIST:
- RAIN EXPECTED
- CAPACITY OK
- SOIL OK

STATUS: SHADOW SURFACE ALREADY IN
STATUS: TRANSPARENT SURFACE OUT
```

Figure 48: System Update Summary example (Scenario 1)

```
* SYSTEM UPDATE SUMMARY *

Predicted Precipitation : 0mm

Capacity          :  50%
Soil Moisture     :  76%
Light Intensity   :  90%
Temperature       :  25°C

CONTROL LOGIC CHECKLIST:
- NO RAIN EXPECTED
- SOIL NOT TOO WET
- SUNNY AND HOT

STATUS: TRANSPARENT SURFACE IN
STATUS: SHADOW SURFACE OUT
```

Figure 49: System Update Summary example (Scenario 2)

```
* SYSTEM UPDATE SUMMARY *

Predicted Precipitation : 0mm

Capacity          :  50%
Soil Moisture     :  97%
Light Intensity   :  90%
Temperature       :  25°C

CONTROL LOGIC CHECKLIST:
- NO RAIN EXPECTED
- SOIL TOO WET
- SUNNY AND HOT

STATUS: TRANSPARENT SURFACE ALREADY IN
STATUS: SHADOW SURFACE IN
```

Figure 50: System Update Summary example (Scenario 3)

During the second part of the evaluation session the participants were interviewed. The chosen interview type is a semi-structured interview. A set of open questions (Appendix B) were asked to the participant with the possibility of asking follow up questions to explore further their response. With consent of the participants, each interview was recorded.

7.2 User Evaluation Results

The results of the user evaluation are based on the answers and opinions provided by the participants in the interview after seeing the prototype demonstration. There were 8 participants in total. 7 of which are members of BTD. The number of participants that gave a certain answer is indicated around every pie chart.

7.2.1 Usefulness

Figure 51 shows why the participants think the community garden could use a system like this. Some participants gave multiple reasons. However, the figure shows that the two most important reasons are rainwater harvesting and shadow creation.

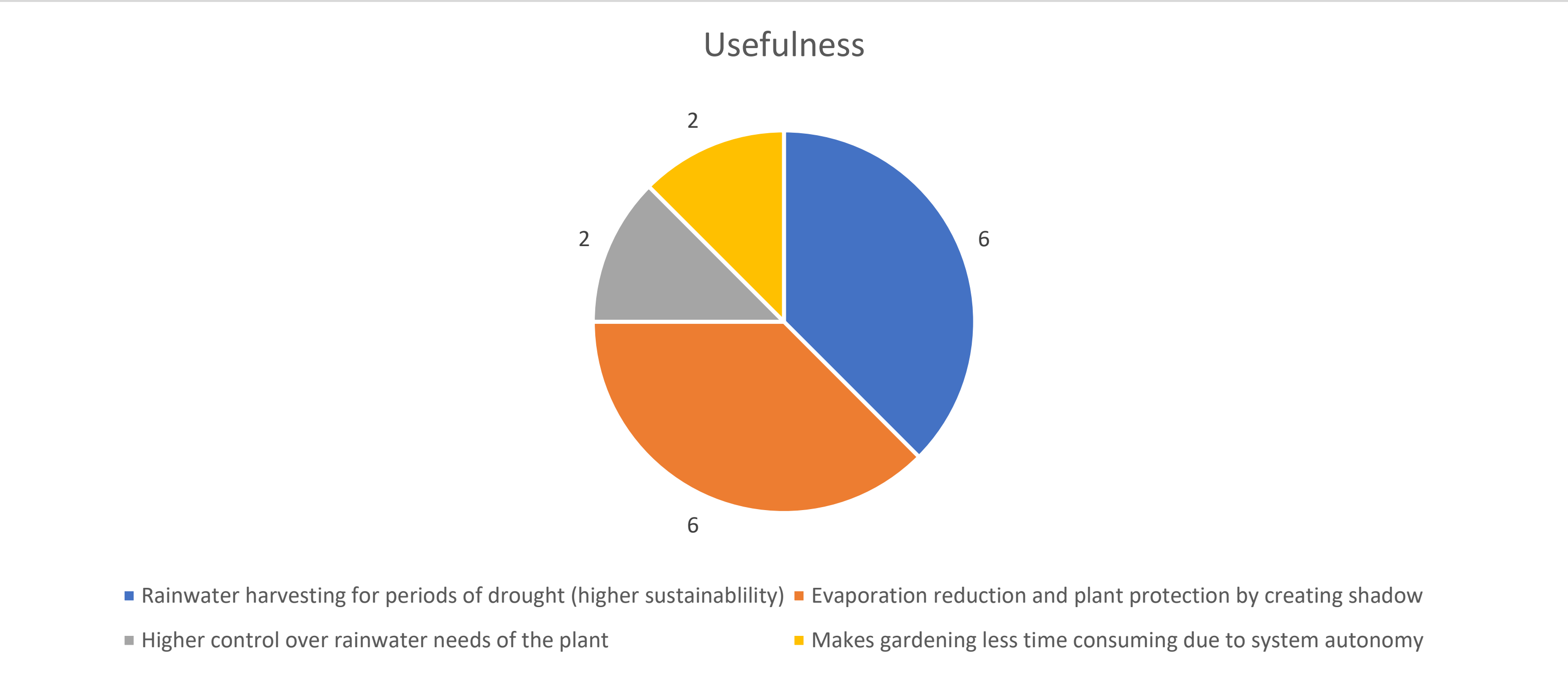

Figure 51: Results on usefulness of the RHS

Multiple participants shared the opinion that the shadow function of the system is especially very useful for younger plants or plants that are very sensitive to hot weather. However, protecting them should not have an effect on the root development of the plants. When plants are exposed to drought and sunlight their roots grow deeper to find more water which increases the strength of the plant.

7.2.2 Scale

Figure 52 shows that 7 out of 8 participants prefer multiple smaller systems over one large system. The 7 participants who prefer multiple smaller systems are the BTD members and the participant who prefers one large system is gardener at a different community garden.

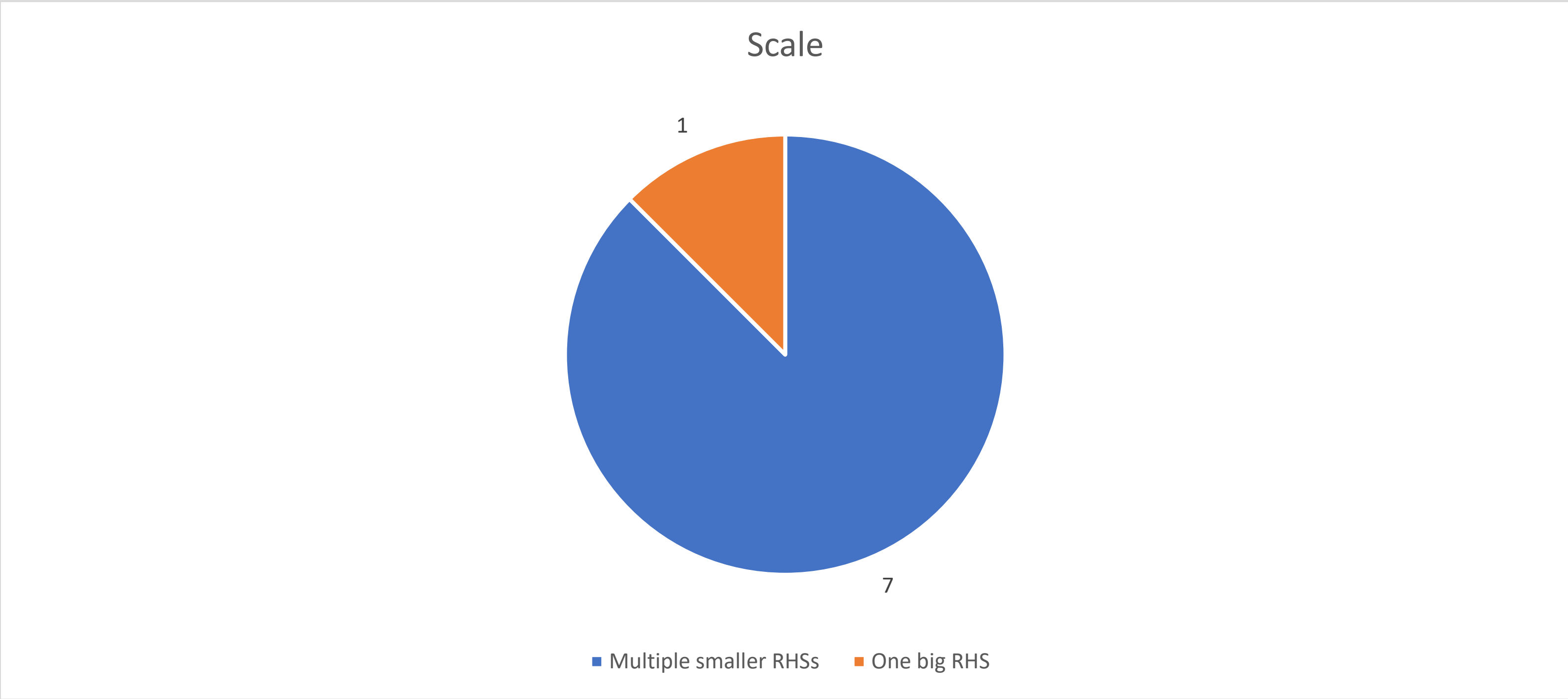

Figure 52: Results on size of the RHS

The most important reason why multiple smaller systems were preferred over one large system by the BTD members is, because a lot of gardens contain a lot of different plants with different needs. A smaller system could be placed above a specific part of the garden. The system settings could be adjusted to the needs of the plants that are planted in that specific part. The participant who preferred one large system over multiple smaller ones faces the opposite situation. Gardens have the same plants so one larger system would target plants with the same needs.

7.2.3 Height

The height of the system is important for the reachability and accessibility of the garden. Figure 53 shows how many participants think the system has a good height, how many participants think the system should be higher and how many participants think the system should be lower. 2 out of 8 people said the height of the current height is good. 5 out of 8 participants think the system should be higher and 2 out of 8 participants think the system should be lower. A total of 9 answers were given since one of the participants shared the advantages and disadvantages of both a higher and a lower system.

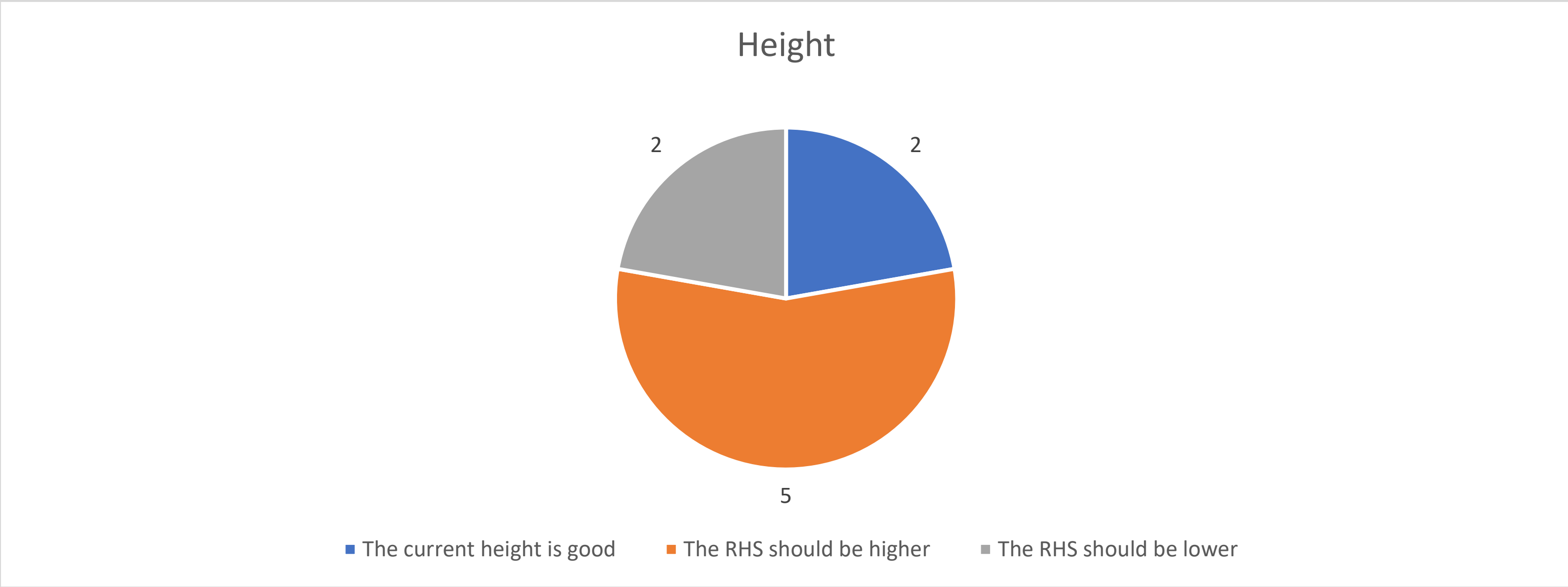

Figure 53: Results on height of the RHS

Most participants thought that a higher system would be better for the reachability of the garden. Especially for the older members it is important that they can walk underneath the system. Besides that, the system should be higher for plants that grow taller.

Reasons for a lower system are based on stability and effectiveness off the system. The closer to the ground the more stable it is during heavy weather. Furthermore, less unwanted rainwater can fall into the garden when the system is lower.

Two persons were happy with the current hight of the system. Especially for plants in containers the height is considered to be good.

7.2.4 Humidity Control

The humidity control of the system was a feature most of the participants liked. 7 out of 8 participants were interested in the feature (Figure 54). Multiple participants indicated that humidity control is based on guessing at this moment with no insight in the actual soil conditions. However, the sensor values should be adjustable by the user.

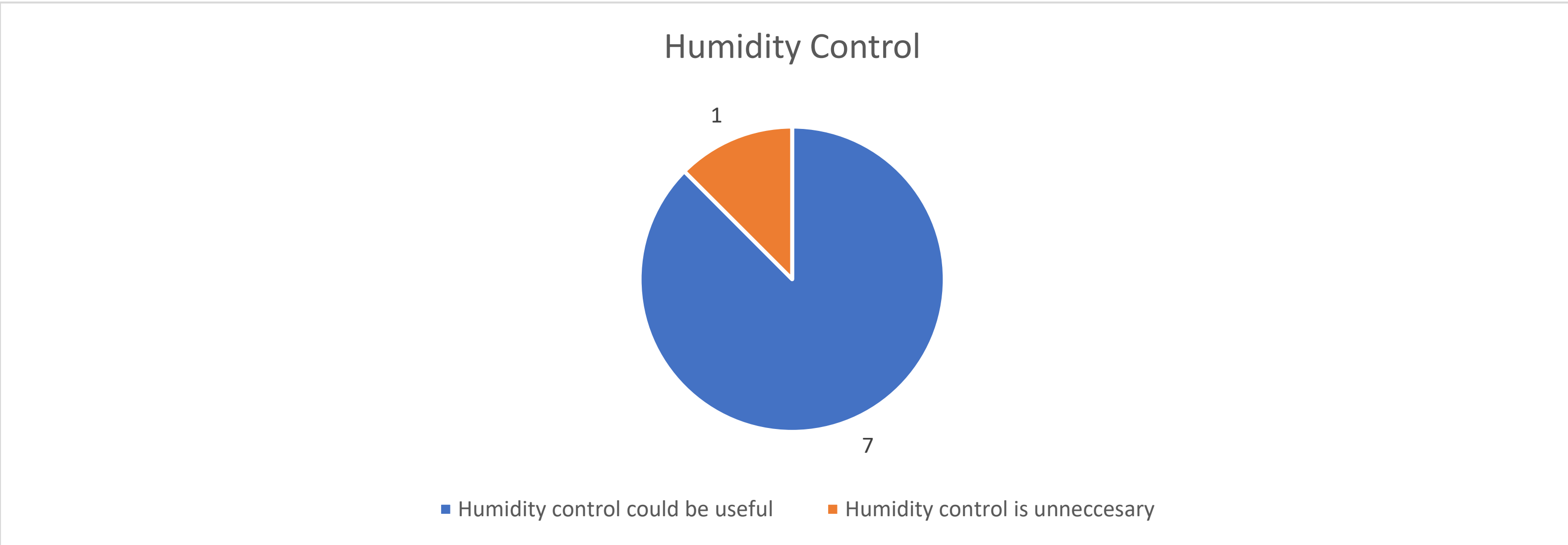

Figure 54: Results on humidity control of the RHS

7.2.5 Manual System Adjustment

Every participant liked the fact that the two surfaces of the system are manually adjustable. This is visualised in Figure 55.

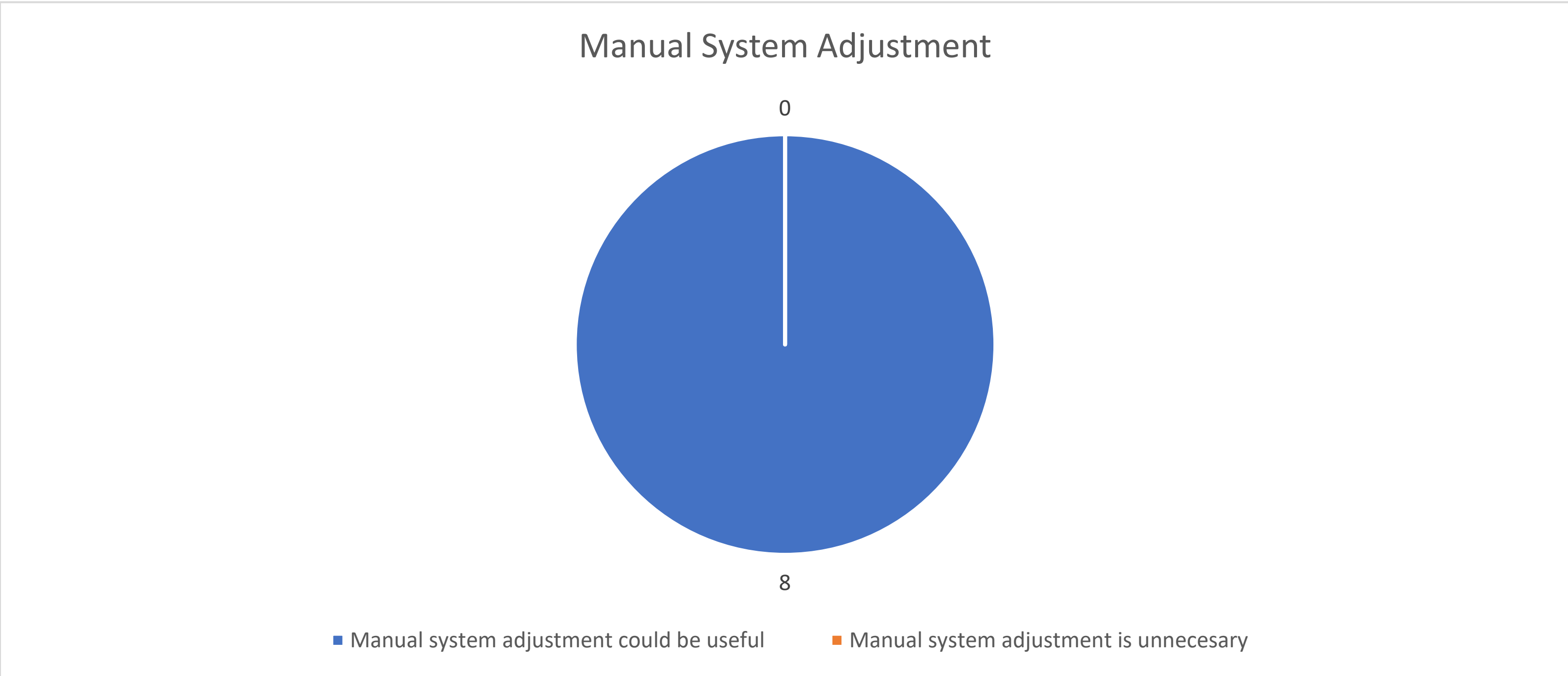

Figure 55: Results on manual system adjustment of the RHS

Several reasons were given why manual adjustment is important. The main reason is that it is important to be able to override technology. For example when the gardener wants to decide for themselves what the system status should be or when system errors occur. Furthermore, the transparent and shadow surface can provide comfort for the gardener, for example when it is raining or it is very hot and sunny they can comfortably work underneath the system by manually adjusting the transparent or shadow surface. Finally, it offers the opportunity for the gardener to experiment with different system setting and setups for different plants.

7.2.6 Personal Use

Finally the participants were asked if they would want such a system above their own garden. Figure 56 shows that 6 out of 8 participants would like to have the system above their garden. The other two said they visit the garden frequently enough and would not need the system. However, they would encourage other gardeners to use it. Also, for all the participants the price of the system is an important factor. Finally, several participants mentioned that they would be interested in seeing an addition such as an irrigation system.

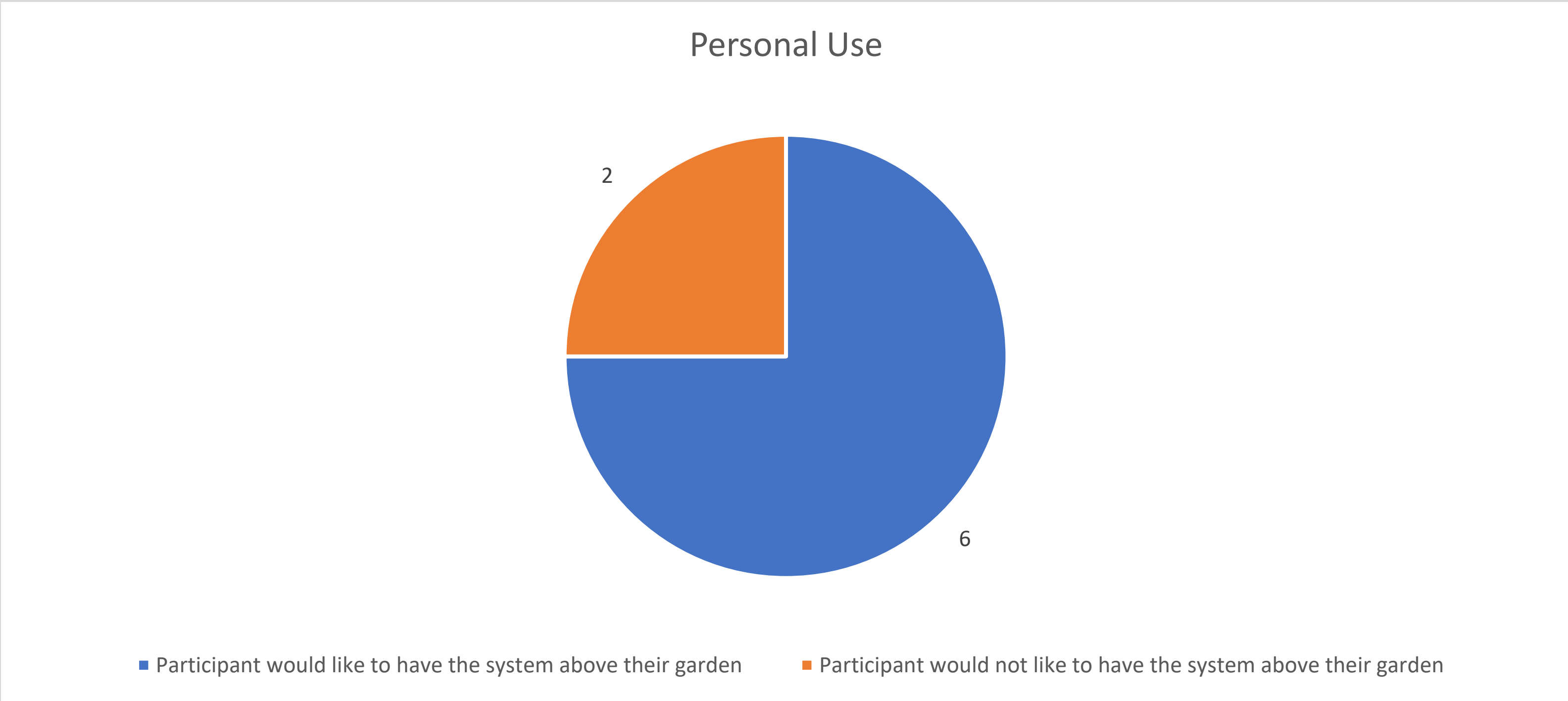

Figure 56: Results on personal use of the RHS

7.3 User Evaluation Conclusion

Based on the results of the evaluation it can be concluded that most of the participants were interested in the RHS. Rainwater harvesting is important for the community garden and most participants like the idea of shadow creation to protect their plants. BTD would benefit more from multiple smaller systems than one large system. The height of the system is currently too low. It should be higher to improve reachability of the garden. Ideally the height would be adjustable to also benefit from the advantages of a low RHS. Most gardeners were also pleased with the humidity control under the conditions that the sensor thresholds and system values could be adjusted. All participants liked that the system is manually adjustable. Finally, most participants would like to use the RHS above a garden. Adding an irrigation system would make it more interesting.

8 Discussion & Future Work

This chapter presents a discussion with limitations of this graduation project and recommendations for future work

8.1 Discussion

For this graduation project a RHS was built for BTD and the functionalities of the prototype were evaluated by members of the community garden. However, there were also some limitations to the project.

Firstly, the RHS is specifically designed for BTD. Although the system could also be useful to other community gardens, the needs of BTD were taken into consideration during the ideation phase. Other gardens might have different needs.

Secondly, BTD needs to be able to store a lot of rainwater. It has not been tested how much storage is needed precisely and how the water can be stored efficiently to occupy as less space as possible.

Thirdly, it is a low budget prototype. This means that the prototype is built using a limited amount of money and resources. For this reason, the current prototype has motors which have a low performance and it would be hard to scale up the prototype. The system does not have waterproof components, which is a hard requirement for a usable product. Also the stability of the system is negatively affected by this. When developing this system further, the stability and with that the durability should be improved. Hereby is wind an important factor, since the current system is very wind sensitive. No research was done on what a full-fledged RHS would cost.

8.2 Future Work

Although a lot of progress has been made concerning the functionalities of the system, to further develop this prototype into a usable product more work still has to be done.

First of all, a key requirement of the system was that the RHS should have waterproof components. Due to the low budget and limited resources, this condition is not yet met with the current prototype. It is important to realise this to so that the effectiveness of the system can be tested, which is the second point of attention.

As for now the effectiveness of the design was not tested yet. Research should be done on the effectiveness of both the rainwater harvesting and evaporation reduction / plant protection function of the system. Data could be gathered for different weather scenarios.

Furthermore, the stability of the current system is low. For future versions of the system it is recommended to either use different materials to build the system or find another solution to make the system more stable. Especially the environmental aspect wind might need extra attention. For example an anemometer could be added to the system. If the wind speed is too high, the system status can be set to open to increase stability by avoiding catching to much wind.

Members of the community garden were interested in several additions to the system. The system should be connected to an app in which sensor values and system settings could be adjusted easily by the user. In addition, the system should also be adjustable in height and it should be portable so it can easily be placed above another garden if needed. Lastly, an irrigation system could be added to the system.

Finally, it is important to do research on what a full-fledged RHS would cost and how much money BTD members are willing to pay for the RHS. This is needed to determine whether it is feasible to develop the RHS into a production-worthy product. The BTD members were interested in placing the system above their garden. However, it is important that they are still interested after knowing the price of the RHS.

9 Conclusion

Climate change has caused more droughts. Organic Gardening Drienero (BTD) is a community garden located at the University of Twente. Currently they are using 480.000 litres of tap water to irrigate their garden during periods of drought. They want to reduce this amount and become more sustainable. This goal can be achieved with the help of rainwater harvesting systems.

The goal of this graduation project was to develop a prototype of a rainwater harvesting system that can be used by BTD. To achieve this goal the following research question was set up:

"How to develop a rainwater harvesting system without a fixed catchment area for Organic Gardening Drienerlo?"

During the research it was found that in order to reduce tap water to a minimum BTD needs a catchment area of 905m^2. In addition, evaporation could reduce the total amount of water needed to irrigate the gardens.

A scaled down (1:450), proof of concept rainwater harvesting system was developed that can catch both rainwater and create shadow above the garden to avoid evaporation with dynamic surfaces. These functions both contribute to the goal of reducing tap water usage. Furthermore, the user evaluation results show that the client BTD is interested in the product. Therefore, the RHS prototype could be considered successful as a proof of concept. Nevertheless, work is still needed to further develop the system into a full-fledged RHS.

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Appendix A: Arduino Code

The full code can be found in a separate document:
"Rainwater_Harvesting_System_Arduino_Code_.ino".
Some referenced snippets of the code can be seen in Figure I, II and III below.

Loop

```
void loop() {
  delay(10000);

  Serial.println("         * SYSTEM UPDATE SUMMARY *");
  Serial.println();
  Serial.println();

  rainExpected();
  Serial.println();
  bufferCapacityUsed();
  soilStatus();
  lightStatus();
  temperatureMeasureFunction();
  Serial.println();
  Serial.println();

  controlLogic();

  Serial.println();
  Serial.println();
  Serial.println();
  Serial.println("System waiting for update...");
  Serial.println();
  Serial.println();
  Serial.println();


  delay(10000);
}
```

Figure I: Loop

Random precipitation method

```
int rainExpected() {
  int precipitation;
  int probability = random(100);

  if (probability >= 40) {
    precipitation = 0;
  }
  if (probability < 40 && probability >= 20) {
    precipitation = 1;
  }
  if (probability < 20 && probability >= 8) {
    precipitation = 2;
  }
  if (probability < 8) {
    precipitation = 3;
  }


  //precipitation = 1;
  correspondingPrecValue = precipitation;

  Serial.print("Predicted Precipitation : ");
  Serial.print(precipitation);
  Serial.println("mm");

  return precipitation;
}
```

Figure II: Random precipitation method

Control Logic

```
void controlLogic() {

  Serial.println("CONTROL LOGIC CHECKLIST:");

  if (correspondingPrecValue > 0) {
    Serial.println("- RAIN EXPECTED");
    if (bufferCapacityAvailable) {
      Serial.println("- CAPACITY OK");
      if (soilStatusValue == 0) {
        Serial.println("- SOIL OK");
        Serial.println();
        shadowSurfaceIn();
        transparentSurfaceOut();
      }
      else if (soilStatusValue == 1) {
        Serial.println("- SOIL TOO DRY");
        Serial.println();
        shadowSurfaceIn();
        transparentSurfaceIn();
      }
      else if (soilStatusValue == 2) {
        Serial.println("- SOIL TOO WET");
        Serial.println();
        shadowSurfaceIn();
        transparentSurfaceOut();
      }
    }
    else {
      shadowSurfaceIn();
      transparentSurfaceIn();
      Serial.println();
      Serial.println("ATTENTION!  NOT ENOUGH CAPACITY TO COLLECT PREDICTED RAIN");
    }
  }
  else if (correspondingPrecValue == 0) {
    Serial.println("- NO RAIN EXPECTED");
    if (soilStatusValue != 2) {
      Serial.println("- SOIL NOT TOO WET");
      if (lightStatusValue == 0 && correspondingTempValue >= 20) {
        Serial.println("- SUNNY AND HOT");
        Serial.println();
        transparentSurfaceIn();
        shadowSurfaceOut();
      }
      else if (shadowSurfaceOut) {
        Serial.println("- NOT SUNNY OR HOT");
        Serial.println();
        transparentSurfaceIn();
        shadowSurfaceIn();

      }
    }
    else if (soilStatusValue == 2) {
      Serial.println("- SOIL TOO WET");
      if (lightStatusValue == 0 && correspondingTempValue >= 20) {
        Serial.println("- SUNNY AND HOT");
        Serial.println();
        transparentSurfaceIn();
        shadowSurfaceIn();
```

Figure III: Control Logic Method

Appendix B: Interview Questions

Why do you think the community garden could use a system like this?

- Why do you think the shadow feature can be interesting

What do you think of the size of the system?

- Do you think one large system could be placed in the community garden? Why? Why not?
- Do you think multiple smaller systems could be placed in the community garden? Why? Why not?

The system would be placed above a garden. To what extent do you think the current height of the system would affect the reachability/accessibility of the garden?

Besides rainwater harvesting the system also intends to control the soil humidity. From you perspective as a gardener, do you think you would miss the aspect of you controlling the humidity yourself or does it make the system more interesting? Why?

What do you think of the ability to move both the transparent and the shadow surface manually?

Imagine the system would be fully functional. Would you like to have the system for your own garden? Why? Why not?

Appendix C: Component List

Component	Amount	Obtained at:
Galvanized scaffolding pipes (1m)	2	[46]
Galvanized scaffolding pipes (2m)	6	[47]
Pipe coupling pieces	4	[48]
Pipe pedestals	4	[49]
Gutter (2m)	1	[50]
Gutter end outlet	1	[51]
Gutter end piece	1	[52]
Wooden plank (2.4m)	3	[53]
Tube steel galvanized (2m)	2	[54]
Dual pulley	2	[55]
Pipe clamping bracket	4	[56]
Grove Light Sensor	1	[57]
LM35DZ temperature sensor	1	[58]
Soil moisture sensor	1	[59]
Ultrasonic Sensor	1	SmartXP
Plastic transparent oilcloth (2x1.4)	1	HOZA Apeldoorn
Fabric cloth (2x1.4)	1	Novizon Zonwering Apeldoorn
Wantai NEMA17 Stepper Motor 42BYGHW811	2	SmartXP
PVC tubes (2m)	4	SmartXP
3D printed angle piece	4	SmartXP
3D printed bearing	4	SmartXP
3D printed tube piece	2	SmartXP
3D printed gear (12 teeth)	2	SmartXP
3D printed gear (80 teeth)	2	SmartXP
Adhesive tape		SmartXP
Electrical wires		SmartXP
Lubricant		SmartXP
Bolts, nuts, rings, etc.		SmartXP and own stock
Wire (10m)		Own stock