LIVING GREEN WALL SYSTEMS

A STRATEGY TO LIMIT MAINTENANCE

Graduation thesis

Msc Architecture, Urbanism & Building technology

Building Technology studio

Aria Hassanzadeh

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Delft University of Technology
Faculty of Architecture & the Build Environment
Department of Building Technology

Julianalaan 134
2628 BL Delft
The Netherlands

Msc Architecture, Urbanism & Building technology

Graduation studio AR3B025

Author	Aria Hassanzadeh
Student ID	5443008
First mentor	Dr. A. Luna Navarro
Second mentor	Dr. Ir. M. Ottelé
Delegate examiner	Prof. Dr. W.K. Korthals Altes

PREFACE

This thesis was written as a graduation research for the MSc Architecture, Urbanism and Building Sciences at Tu Delft. This research titled 'Living wall systems: A strategy to limit maintenance' was written based on my personal interest in sustainability, facade technology and a green living environment. I enjoyed working on this research and was able to expand my knowledge on this subject. Besides the fact that this report has been written as a formality for graduation, I hope that this report informs you as a reader and can be of added value to you.

This report would not have been the same without the support and cooperation of a number of people. First of all I would like to thank my mentors Dr. A. Luna Navarro and Dr. Ir. M. Ottelé for their guidance throughout the process. Their experience and expertise have ensured that I was able to get the most out of this research. I want to specifically thank you for your support, time and commitment.

In addition, I would like to express my gratitude to external persons and companies who have cooperated by sharing their knowledge and experience with me for the importance of this research. Mr. Alistair Law and Mr. Rafael Carlos who, on behalf of the vertical meadow company, have been involved in this research from the start. Your knowledge and experience about living wall systems have guided me in this research. I also want to thank Mr. de la Barra Luegmayer from TU Delft for his help and contribution in the preparatory work for the experiment.

Finally, I would like to thank my friends and family for their support. To my parents and sister, thank you for always supporting me. My cousin Aryen, thank you for always believing in me. Your love and support gives me the strength and motivation to do this. Serhan, my friend and fellow student, thank you for standing by my side since the bachelor’s degree. Without you I would never have had so much fun and enjoyment during my studies.

Here’s hoping you will enjoy your reading

Aria Hassanzadeh

Utrecht, June 26 2023

ABSTRACT

This research is about the problems related to the maintenance of living wall systems. The literature review and interviews with living wall manufacturers have shown that the irrigation system is the source of many problems. The irrigation system is an essential part of a living wall system. This ensures that the plants get water and are provided with sufficient nutrients. Nowadays there are advanced irrigation systems where you can set exactly how much water is supplied and what the total water use is. However, it has been found that this does not mean that the water actually reaches every plant. Which can lead to plants getting too much or too little water. In both cases this has a negative effect on the health of the plant and can lead to maintenance of the living wall. The problem lies in the method of assessing whether the water content and water distribution of the living wall is in order. At the moment there are no reliable assessment methods for this and these inspections are based on observations. For this purpose, an answer is given to the main question "What is the best strategy for monitoring the water distribution of the irrigation system on a living wall system that ultimately leads to more effective maintenance?". To answer this question, various monitoring methods have been tested. For the monitoring methods, an NDVI camera is used to measure plant quality. Furthermore, moisture sensors and a thermal camera are used to measure the water distribution and water content. In addition to this, the run-off water is measured. The results show that the reliability of the results strongly depends on various factors such as the presence of plants and climatic factors. This report describes the correct way to carry out these methods in order to obtain reliable results. A key factor here is that the monitoring methods must be applied together so that they compensate for each other's limitation.

Scotscape, 2020

CONTENT

LIST OF SYNONYMS, ABBREVIATIONS AND UNITS

Biophilia	An affinity of human beings with the natural world
Emitters	Also known as drippers, nozzles on water pipes of the irrigation system
Hypoxic stress	Lack of oxygen in plants as a result of excessive water, which negatively effects plant growth
Irrigation capacity	The amount of water that is irrigated, expressed in litres per minute
Maintenance frequency	Number of visits per year made to carry out maintenance or inspections.
Plant stress	A condition of plants where growth or development is blocked
Run-off water	Excess water dripping off the living wall mats
Water content	Amount of water absorbed by the living wall mats
Water distribution	The distribution of the water over the living wall mats. In a sense, the degree of uniformity of the water
Water retention capacity	The capacity of the total amount of water that can be absorbed by the mats

EC-value	Electric Conductivity value
LW	Living Wall
NIR-light	Near Infrared light

°C	Degrees Celsius
µS/cm	Microsiemens per centimetre
L/m²/d	Litres per square meter per day
l/min	Litres per minute
≈	Approximately

‘’THE MEGA-CITIES BECAME INHOSPITABLE TO **NATURE** AND **HUMANS** BECAME DISTANCED FROM THEIR NATURAL CONTEXT’’

Grazuleviciute-Vileniske, 2022

01

RESEARCH FRAMEWORK

RESEARCH FRAMEWORK

1.1 Introduction

This thesis is about the maintenance of living green wall systems. There is plenty of research and literature to be found about the positive effects of a living green wall system. However, there is limited information about the maintenance of green walls, while maintenance is a major obstacle (Pérez-Urrestarazu & Urrestarazu, 2018). It is important to limit this obstacle in order to increase the use of green walls in the built environment. As a society, we are becoming increasingly aware of the essential role of nature in our environment. We spend almost 90% of our time in buildings (Samudro et al., 2022), which are often buildings where the user is isolated from natural elements. Studies on Sick Building Syndrome (Murphy, 2006) and Biophilia (Wilson, 1984) support the idea that the role of natural elements plays an essential role in our well-being. Human preference for natural elements and settings is a well-known phenomenon supported by several studies (Joye & Van Den Berg, 2011; Grazuleviciute-Vileniske et al., 2022). An important reason people are attracted to natural elements is because they offer opportunities for relaxation and restoration from stress (Joye & Van Den Berg, 2011). Nevertheless, the human-nature connections continue to decline by spending much of our time inside buildings. Some researchers even say that our living environment has become anti-biophilic (Samudro et al., 2022; Grazuleviciute-Vileniske et al., 2022).

There are various ways to bring nature back into our living environment, for example through living green wall systems. Studies (Sheweka & Magdy, 2011) show that a living green wall system does indeed make a positive contribution to the built environment. This is further described in chapter 1.2 of this report where the results of the exploratory literature review are discussed. Although the positive effects of a living green wall system are known, there are still obstacles that mean that a living green wall system is not always preferred. A major obstacle is maintenance (Pérez-Urrestarazu & Urrestarazu, 2018). The problem related to the maintenance of living green wall systems is explained in more detail in chapter 1.2 and 2.1. There is clearly a research gap when it comes to the maintenance of this type of façade. This research aims to contribute to filling the research gap. When the maintenance problems of a living wall system can be reduced, it will become more attractive to use it more often in the built environment. This helps to restore the link between people and nature. Where hard materials are taking over the built environment, nature will now reclaim our living environment. This can even lead to the expansion of cities without this having to be at the expense of nature. Because where nature reserves are sacrificed for the expansion of cities, the sacrificed nature returns to the built environment. This is done in the form of parks, trees, water and now also in the form of green buildings or green facades.

The research question addressed in this study is "What is the best strategy for monitoring the water distribution of the irrigation system on a living green wall system that ultimately leads to more effective maintenance?". To get an answer to this, the first step is to try to fill the research gap as well as possible in order to be provided with as much information as possible. This is done through a targeted literature search and interviews. Since not all information can be obtained from the literature, interviews are conducted with companies and people who have experience with the maintenance of living walls. Subsequently, measurements will be carried out on a self-made living wall model. The measurements are intended to monitor the water content and water distribution in a living wall and test the reliability of the monitoring methods. Based on this, a recommendation is written to use certain monitoring methods which eventually limit maintenance.

Chapter **01** presents the research framework. Here, the focus is mainly on the background information based on an exploratory literature review from which the problem statement, objective and research questions emerge. In chapter **02** the results of the targeted literature search are described. Chapter **03** shows the results of the interviews. In chapter **04** the materials and methods are described, here the experimental set-up is explained with the measurement plan. In chapter **05** the results from the measurements have been analysed with which conclusions can be drawn and a recommendation can be presented. This report ends with chapter **06**. Here the conclusions, discussion, reflection and relevance of the research are described.

1.2 Background

The application of living green elements as a building construction material is not something new. Live vegetation was used in architecture as early as 600 BC. King Nebuchadnezzar II ordered the theso-called 'hanging gardens of Babylon' to be built. Living green elements were used in the past not only for visual reasons, but also for practical reasons. In Scandinavian countries, for example, green facades were used as thermal insulation in vernacular houses (Amorim & Mendonça, 2017). Nowadays green wall systems can be applied in different ways. Variation is possible in composition, weight and assembly (Manso & Castro-Gomes, 2015). From literature it can be concluded that green walls can be divided into two main categories, namely living walls and green facades. Green facades are based on the application of climbing or hanging plants along the wall and can be further divided into 'direct green facades' and 'indirect green facades'. Living walls can be further divided into 'continuous living walls' and 'modular living walls' (Manso & Castro-Gomes, 2015). These systems can be used in different ways. Figure 1.1 provides an overview of this.

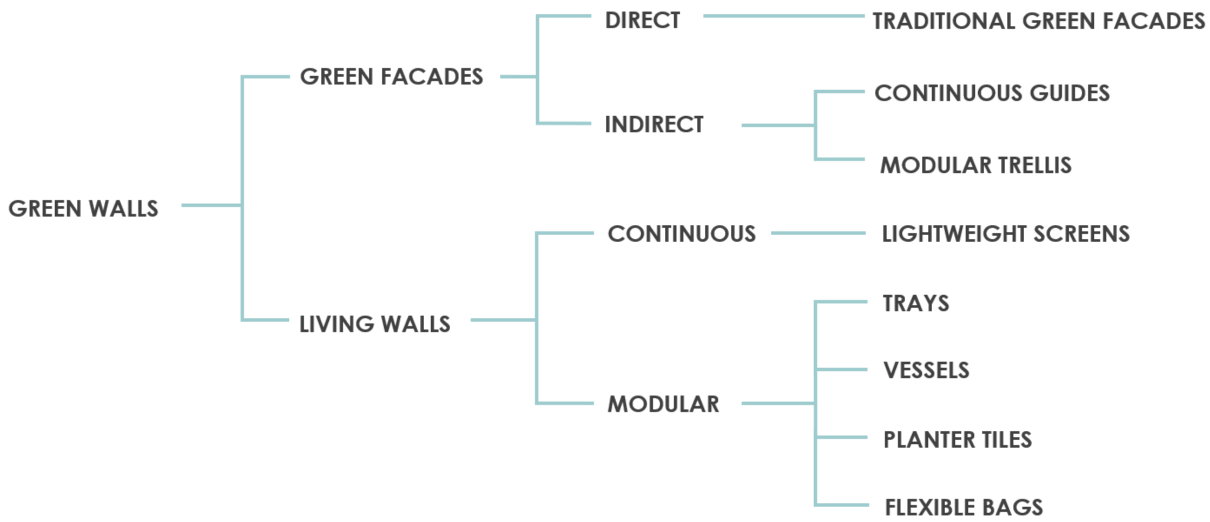


Figure 1.1: *An overview of green wall systems (Own work and Manso & Castro-Gomes, 2015).*

'Direct green facades' refers to traditional green facades. These consist of self-clinging climbers, rooted directly in the ground. Indirect green facades are similar, the difference is that they are equipped with a vertical support structure. This guides the plants along the support structure. the support structure can be applied in a modular or continuous way (Manso & Castro-Gomes, 2015). 'Continuous living walls' are based on the application of lightweight and permeable screens in which plants are inserted individually. Modular living walls are elements in which plants can grow, such as flexible bags, planter tiles, vessels or trays. Each element is supported by a complementary structure or fixed directly on the vertical surface (Manso & Castro-Gomes, 2015). The substrates in the living wall systems vary with options including hydroculture felt, peat chunks, peat moss, clay balls, mineral wool, coconut fibres, or grades soils (Gunawardena & Steemers, 2020).

It can be concluded that the biggest difference between green facades and living walls is that one grows directly out of the ground and the other from elements applied to the façade. This means that green facades often do not need an irrigation system, because rainwater can be used for this, which is absorbed by the soil. Living walls do not grow out of the ground and therefore need an irrigation system that ensures that the plants get enough water. An overview of this is shown in figure 1.2.

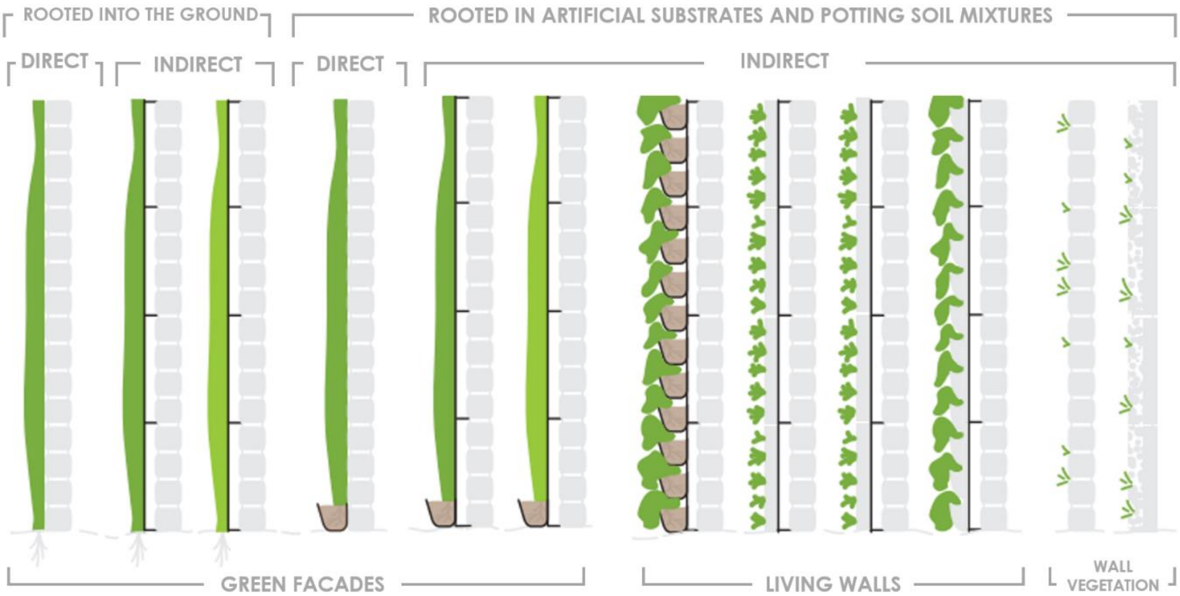


Figure 1.2: *An overview of green wall systems (Own work and Wagemans & Kok, n.d.).*

Advantages and limitations

The literature research shows that a living green wall system has many advantages. It appears that, if properly designed and maintained, it can be a useful tool for passive thermal control of buildings. This can be done in the form of thermal insulation, shade and evaporative cooling (Manso & Castro-Gomes, 2015). In winter, the evergreen vegetation layer reduces the wind flow around the façade. In addition, heat radiation from the external walls is insulated by the dense plant foliage. In this way, the green acts as an extra insulation layer (Perini & Rosasco, 2013). This system also makes a positive contribution in warm climates. Of the sunlight that falls on the green wall, only 5-30% of the energy comes through the leaves of the green wall. The rest of the energy is reflected. Blocking part of the direct sunlight provides a cooling effect in warm climates and helps to reduce the heat island effect (Rakhshandehroo et al., 2015). In the presence of water, such as the irrigation system, the water can provide a cooling effect in hot climates through evaporation (Rakhshandehroo et al., 2015). In addition to their thermal properties, living walls also influence air quality. Research has shown that there is a big difference between areas with and without green walls when it comes to the level of carbon dioxide and carbon monoxide (Manso & Castro-Gomes, 2015). This is because plants are natural filters, taking carbon dioxide from the air and replacing it with oxygen (Perini & Rosasco, 2013). In addition, the roots of the plants can remove toxic chemicals from the soil. These are chemicals such as volatile organic compounds, trichloroethylene, benzene, toluene and xylene. The result of this is that the air in the vicinity of the green wall is less polluted (Perini & Rosasco, 2013). It should be noted that the capacity with which the green wall can reduce air pollution depends on the type of plant used (Perini & Rosasco, 2013). From an acoustic point of view, it can also be a reason to apply living wall systems to the façade. Research shows that green walls can serve as a noise buffer, reducing noise that comes from outside by up to 40 dB (Perini & Rosasco, 2013; Özyavuz et al., 2013). The degree of sound insulation depends on the depth of the growing media, the type of plants, material used for the structural components of the living wall system, and the layer of air between the plants and the wall (Perini & Rosasco, 2013; Haggag, 2010).

Despite the many advantages of a living wall, there are also complications. The irrigation system can complicate the living wall system (Rakhshandehroo et al., 2015). For example, it must be taken into account that sufficient water is supplied, that the water is clean enough, that a pump is present and that the water in the pipes do not freeze (Perini & Rosasco, 2013). In a circular system it is therefore also important that there is a gutter that does not get clogged. This shows that a living wall needs more maintenance than a green façade. One of the concerns that follows from this is maintenance costs (Gunawardena & Steemers, 2020). Another problem that can occur is poor water uniformity. There are studies (Segovia-Cardozo et al. 2019; Pérez-Urrestarazu et al., 2014) that show that the water is not always well distributed over the facade, which means that there are plants in the facade that receive too much or too little water . This ultimately affects the health of the plant and can lead to maintenance. For example, leaves that fall and plants that die faster (Fadli et al., 2019). The studies, in which measurements were made with a living wall system consisting of pots, show that the water volume of the top of the living wall differs from that of the bottom. A higher water volume is measured in pots at the bottom of the facade. This has to do with the fact that the water sinks in the facade and eventually accumulates at the bottom. From research by Segovia-Cardozo et al. (2019) it can be concluded that living wall systems are very complex where the performance depends on a number of factors. These are the hydraulic substrate properties, plant water requirements, the design and operation of irrigation systems. Following on from this, Pérez-Urrestarazu (2021) shows in his research that not only does the water sink downwards, but also drips off the facade. This happens because the water at the bottom of the living wall system is so much that the living wall system reaches its water retention capacity and can no longer hold water. This means that water is lost and that the amount of water supplied is not equal to the amount of water consumed. It is important to mention that the difference between water supply and water consumption is not only due to the run-off water. This is also influenced by the climate, for example by evaporation at higher temperatures. These findings are shown in figure 1.3, where it is indicated that the amount of water supplied is not equal to the amount of water consumed. Chapter 2.1 discusses the irrigation system in more detail.

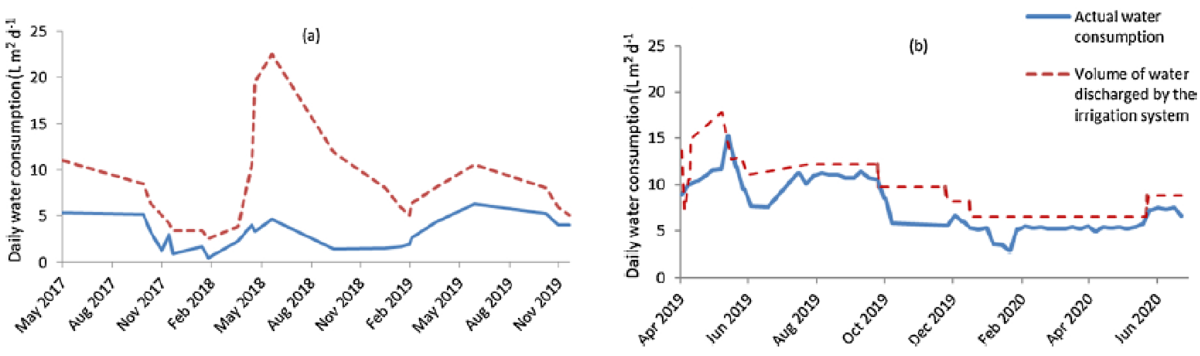


Figure 1.3: *Actual water consumption compared to the volume of water discharged by the irrigation system (Pérez-Urrestarazu. 2021)*

Maintenance

Compared to green facades, living wall systems require more maintenance. This is mainly due to the irrigation system, nutrients, materials involved and the design complexity (Perini & Rosasco, 2013). As a result, the maintenance of living wall systems is seen as one of the main constraints for their installation (Pérez-Urrestarazu & Urrestarazu, 2018). Maintenance includes fertilization, pruning, pest and disease management and weed control. With a living wall system it is common practice that fertilizers are applied with the irrigation water. Here it is important that the pH and Electric

Conductivity of the nutrient solution is continuously monitored. Fertilization requirements depend on the type of system. Hydroponic systems with bare root plants will have greater fertilization requirements than systems with root balls containing growing media (Pérez-Urrestarazu & Urrestarazu, 2018). The maintenance on pest and disease depends on many factors. These are factors such as, local climate, location and plant species. In temperate region, living wall systems can attract aphids, spider mites, whiteflies, mealybugs or leaf miners. These can be controlled with a foliar spray or dissolution in irrigation water containing commercial pesticides (Pérez-Urrestarazu & Urrestarazu, 2018). Weed control is an important part of the maintenance of a living wall system. This is often done manually by removing the weed during the pruning operations. It is not recommended to use chemicals for weed control due to pollution problems. In the prevention of weed, it is also important to regularly check the emitters, pipes, hydraulic devices, filters, pumps and water tanks (Pérez-Urrestarazu & Urrestarazu, 2018). The maintenance of the living wall system requires qualified personal with the necessary knowledge. This is why maintenance is often carried out by the installation company (Pérez-Urrestarazu & Urrestarazu, 2018). Case studies can be found in literature where the maintenance of a living wall system has been mapped out. Table 1.1 shows an overview of the maintenance from one of the case studies from literature (Perini & Rosasco, 2013).

Table 1.1: *Overview of maintenance of a living green wall based on a case study (Perini & Rosasco, 2013).*

COMPANY	CATEGORY	TYPE	TIME FRAME
Literature Research *Cost-benefit analysis for green facades and living wall systems.* *K. Perini, P. Rosasco (2013)*	Initial	Plant species	One time
		Panels and transportation	One time
		Irrigation system	One time
		Installation	One time
	Maintenance	Pruning and panels adjustment	Annual
		Irrigation (H_20)	Annual
		Panels replacement (5%)	Annual
		Plant species replacement (10%)	Annual
		Pipes replacement (irrigation system)	Annual
		Cladding renovation	One time – 50th year
	Disposal	Green layer disposal	One time – 50th year

Table 1.1 shows that maintenance is required at the beginning, during and at the end of the life of the living wall system. Annual maintenance is necessary here to have a healthy system. These are activities such as pruning, plant replacement (10%), panel replacement (5%), fertilization and pipes replacement. Most of these tasks are performed manually (Gunawardena & Steemers, 2020). The stated percentages may differ depending on the type of living wall system. For example, another study (Ottelé et al., 2011) assumes 10% for plant replacement if it concerns a system based on planter boxes and 30% for a system based on felt layers.

Innovative systems

Efficient maintenance of living wall systems is essential for the future of this system. There are currently no techniques to monitor the health status and water stress of living wall systems (Yuan et al., 2020). To limit the maintenance of living wall systems, there are manufacturers and researchers who are working on smart systems for this. A number of examples of this are shown below.

To ensure that the water is well distributed over the facade, there are systems on the market such as those of 'gsky pro wall'. These are green panels that have a dripline for each row of panels and each panel has six emitters. This system ensures that there are no longer any dry spots on the living wall (Fadli et al., 2019). However, you may wonder whether this system uses water efficiently. The bottom line is that the water is better distributed, but it is not monitored whether each plant receives too much or too little water.

Figure 1.4*: Living wall system gsky ProWallWater (Exterior Walls, n.d.).*

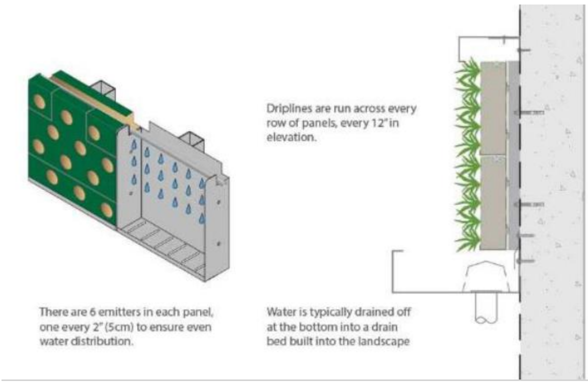


Figure 1.5: *Green panel element gsky ProWallWater (Fadli et al., 2019)*

Vicinity green wall system consists of planting modules with soil as the planting media. This system includes a smart watering system that uses sensors and a remote monitoring unit. The sensors detect irrigation failures. Customers and operators receive a signal when failures are detected. Using the web-based management platform, customers can anticipate the notification themselves by making changes to the pump and irrigation timing (Fadli et al., 2019).

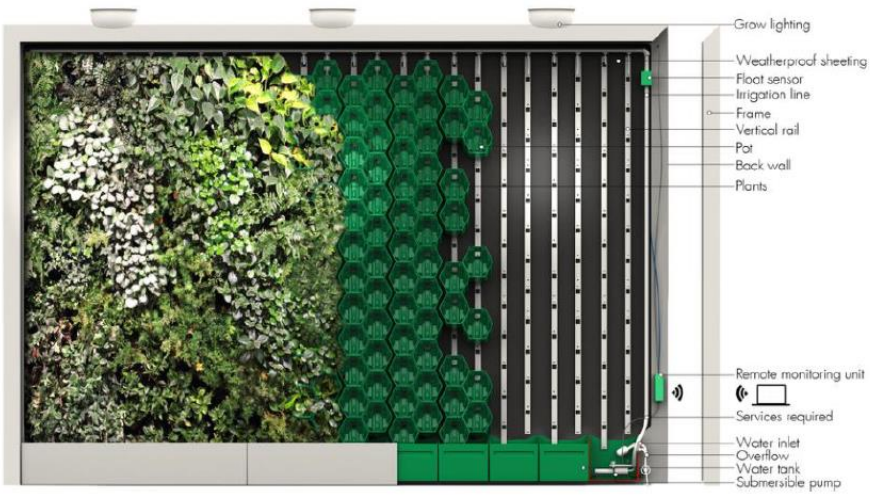


Figure 1.6:
Living wall system Vicinity
(VICINITY | Modular Vertical Garden, n.d.

To ensure an even distribution of moisture and nutrients, Sage Green Life has developed a replacement for the planting soil medium. This is the BioTile. These are soil-less modular tiles that consist of layered rockwool that ensures that the water, oxygen and nutrients are distributed evenly. This is due to the water absorbing property of the material (Fadli et al., 2019). This system is also equipped with sensors and programmable irrigation controllers. It is not specified what exactly is measured with the sensors. According to their website, the BioTile system one of the most water-efficient systems in the industry.

Figure 1.7: *Biotile modular tiles by Sage Green Life (Vertical Garden Watering System & Technology | Sagegreenlife, 2021).*

The POD system is an experiment by Qatar University. PODs are custom made planting boxes that are attached to the building exterior with vertical rails. The water requirement is determined using an in-built manual sub-irrigation system. This is equipped with a water level indicator, which assists on checking the water requirement based on the soil moisture of the plants. The water is added via the plant root zone from below the soil surface (Fadli et al., 2019). It is not explained exactly how the water level indicator works. The question is whether this system would also function in a system where PODs are not used.

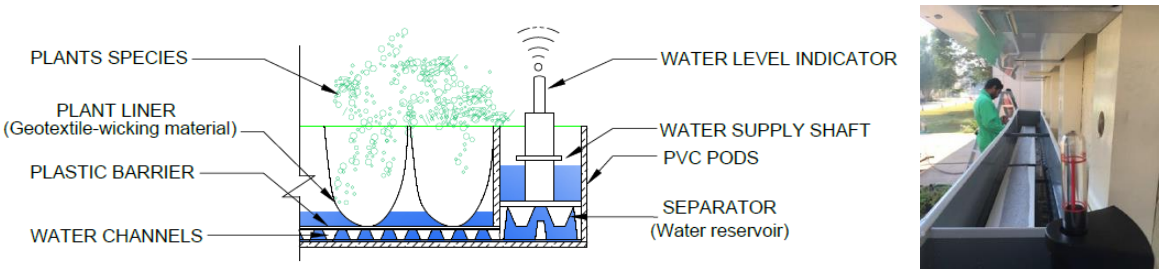


Figure 1.8: *Sub-irrigation POD system by Qatar University (Fadli et al., 2019).*

‘’THE WATER VOLUME USED TO **IRRIGATE** LIVING WALLS WILL NOT BE EQUAL TO THE ACTUAL WATER TRANSPIRED BY THE **VEGETATION**‘’

Perez-Urrestarazu, 2021

1.3 Problem statement

The maintenance of a living wall system is seen as one of the biggest constraints for their installation (Pérez-Urrestarazu & Urrestarazu, 2018). The literature review has shown that a large part of the maintenance is related to the irrigation system, such as replacing filters, unclogging the drainage, pest and disease management, weed control, fertilization, remedying leaks and removing invasive root growth into pipework (Pérez-Urrestarazu & Urrestarazu, 2018; Gunawardena & Steemers, 2020). In addition to maintenance of the irrigation system, general maintenance is also necessary such as pruning, panel adjustment and panel replacement and plant replacement (Perini & Rosasco, 2013). The need for maintenance is often determined conservatively, namely through observation and experience (Gunawardena & Steemers, 2020). As a result, proper maintenance is not carried out. It would be more effective if certain factors were monitored, such as the quality of the plants, the water distribution and water content. This would help to determine which maintenance is necessary and when it is necessary. Despite the fact that maintenance is a major constraint, there is little literature and information available about the maintenance of living walls. This makes it difficult to compare findings from different literature. The information in the literature regarding solutions is even more limited. Apart from a number of manufacturers and researchers who are developing smart irrigation systems, there is almost no information available about this. We can say that this is a research gap with regard to maintenance of living wall systems. The problems mentioned in the literature study regarding the maintenance of living wall systems are summarized in figure 1.9. From this it can be seen that the irrigation system is most often mentioned as a cause of maintenance. To be more specific, much could still be improved in the effectiveness of the irrigation system. In many living wall systems, the water consumption of the system is monitored. But the question is what happens between the moment the water leaves the water tank and the moment the used water comes back into the water tank. In other words, how is the water distributed over the living wall and how much water actually reaches each plant. This is something that is not yet monitored but can be crucial for the health of the plants, as it can anticipate when a plant is getting too much or too little water.

> ''The best maintenance program is the one that **anticipates** problems
> with appropriate **prevention** operations''
>
> *Pérez-Urrestarazu, 2018*

So the problem statement for the graduation research is that it is difficult to adequately anticipate the need for maintenance of living walls. This is because the **quality of the plants** and/or the **effectiveness of the irrigation system** is not monitored. If it were to monitor how the water spreads over the living wall and what the water content is, it would be easier to estimate where too much or too little water ends up, which could lead to unnecessary maintenance.

1.4 Research objective

The research goal is to improve the **effectiveness of the irrigation system** by providing measure methods that gives insight into the water content, water distribution and plant quality. When it can be made clear how the water is being distributed in the living wall system, which has effect on the quality of the plant, it can help to limit the maintenance. The ideal scenario is that the effect can be measured by, for example, looking at the grow time, energy use, frequency of pruning, water use and maintenance intensity. However, it is not expected that this effect can already be measured within the time frame of this thesis. That is why the research will focus purely on monitoring the water distribution and water content in the living wall. Despite the fact that improving the effectiveness of the irrigation system does not directly affect the plant quality due to the time frame of this research, this research still strives for a method to measure plant quality. Based on the exploratory literature search it is assumed that this can help to increase the effectiveness of the irrigation system and therefore limit maintenance. The end product delivered with this research will be a strategy to apply certain measurement methods that ultimately limit maintenance. For this, measurements are first taken to try out these measurement methods and to validate that they actually work. An optimal scenario is that the **method of monitoring** used for this is made applicable to more systems and that **guidelines** can be drawn up for an effective irrigation system. Provided this goal is achieved, this will have an effect on the maintenance listed in chapter 1.2. If the water distribution is monitored, so that it can be ensured that each plant receives an optimal amount of water, hypoxic stress can be prevented. In addition, the irrigation system can be used more effectively where inspections will be limited and plants need to be replaced less quickly. The problems mentioned in the literature study regarding the maintenance of living wall systems are summarized below. The above-mentioned research objective can be used to limit the most frequently mentioned problems.

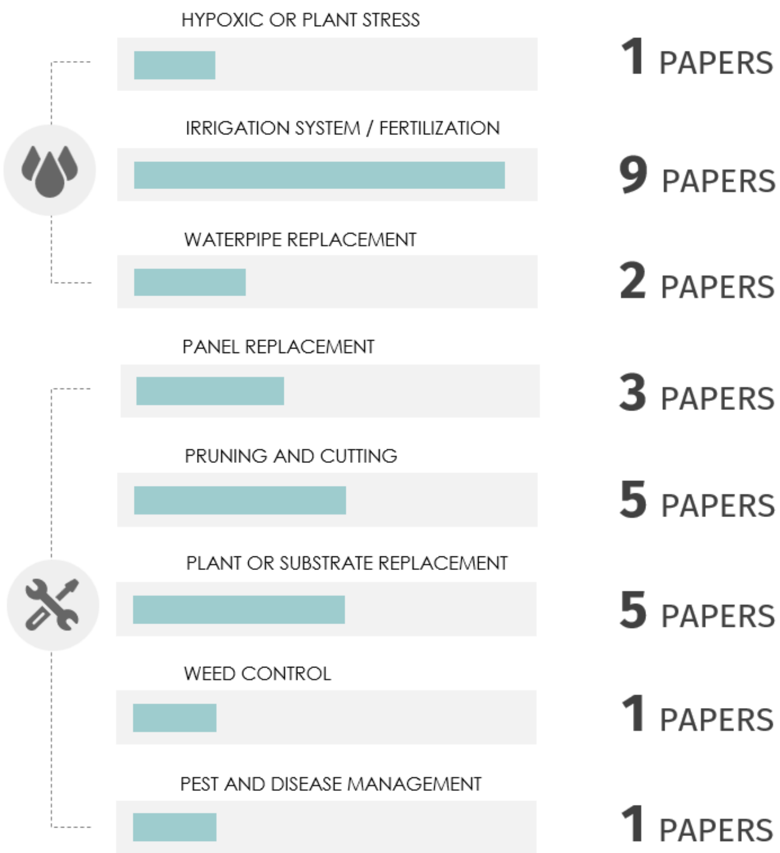


Figure 1.9: *Problems according to literature regarding to the maintenance of living wall systems. (Own work).*

1.5 Boundary conditions

There are a number of boundaries within the research that can affect the result. The research takes place between the time period from February 2023 to June 2023 in the Netherlands. The climate in which the measurements and monitoring take place can influence the result. For example, different results may be obtained depending on parameters such as relative humidity, temperature and shade. It is therefore important to map out these parameters and include them in the result. During this research it is not possible to influence these factors. We do try to carry out the measurements as much as possible under the same conditions with regard to temperature, humidity, orientation and weather influences. When writing a conclusion and design guidelines, it is unlikely that these can be validated due to the relatively short time frame of a few months. More time is needed to be able to see whether the aforementioned guidelines and recommendations actually lead to an effective irrigation system and can therefore limit maintenance. Another boundary may be that a specific type of living wall system is used for this research, according to Pérez-Urrestarazu (2021) the living wall system can influence the water consumption. The results are based on this specific living wall system. Nevertheless, the aim is to generalize the result, so that advice and recommendations can be given for living wall systems in general. Or at least for comparable living wall systems.

1.6 Research question

The research objective is about finding the right method to monitor the water distribution in a living wall. In order to achieve the research objective, this research aims to answer the following main research question:

WHAT IS THE BEST STRATEGY FOR **MONITORING** THE WATER DISTRIBUTION OF THE **IRRIGATION SYSTEM** ON A LIVING GREEN WALL SYSTEM THAT ULTIMATELY LEADS TO MORE EFFECTIVE **MAINTENANCE**?

With this research question, an attempt is made to find a way to monitor the water distribution in the living wall. This makes it possible to determine how much water each plant receives, which, according to literature, has a direct influence on the quality of the plant.

1.7 Research sub-question

To get an answer to the research question, it is important to first find answers to sub-questions. The following sub-questions apply to this research:

1. Which systems exist that can be used to monitor the water distribution and plant quality in a living wall?

2. What are the external factors that may influence the water need for a living wall system?

3. What is the effect of different types of irrigation systems on the maintenance of a living wall system?

4. How can monitoring the water distribution, water content and plant quality help to improve the effectiveness of the irrigation system?

5. How can the irrigation system be optimized so that the water distribution is more uniform?

6. How can the strategy, which is tested on the homemade test model, be made applicable to more systems?

1.8 Hypothesis

It is difficult to estimate what the research will yield, because not many comparable studies have been conducted on this topic. Nevertheless, it is expected that certain measurement methods such as thermal imaging and moisture sensors can help to provide insight into how the water is distributed over the facade. Furthermore, it is expected that it will be difficult to validate this because it is expected that many factors can influence the result. This is, for example, the climate, type of living wall system and accuracy of the measurement methods. The hypotheses that we can derive based on the exploratory literature review are that maintenance is currently often determined based on observation and that this is not always reliable.

1.9 Research methodology

Various research methods will be used to answer the sub-questions. The table below provides an overview of the research methods that are applied to each sub-question and what information is attempted to be collected with them.

Table 1.2: *An overview of the sub-questions and research methods (own work).*

QUESTION	AIM	METHOD
1. Which systems exist that can be used to monitor the water distribution in a living wall?	Find different methods to monitor with when doing the measurements	Interviews Literature review
2. What are the external factors that may influence the water need for a living wall system?	To put the measured results in the right context and to take these factors into account when measuring.	Literature review
3. What is the effect of different types of irrigation systems on the maintenance of a living wall system?	Finding a connection between the irrigation system and results.	Interviews Literature review
4. How can monitoring the water distribution, water content and plant quality help to improve the effectiveness of the irrigation system?	To test the monitoring methods to see if they actually give reliable results and then to determine how they can best be used.	Monitoring
5. How can the irrigation system be optimized so that the water distribution is more uniform?	To determine, based on the measured results, how the effectiveness of the irrigation system can be improved.	Analysing
6. How can the strategy, which is tested on the vertical meadow system, be made applicable to more systems?	To ensure that monitoring the water distribution and plant quality has a positive effect on multiple living wall systems.	Analysing

Interviews

The literature research has shown that there is relatively limited information available about the maintenance of living green wall systems. The information that can be obtained from literature is often not specific enough to determine the exact cause of the maintenance. From the literature review it can be concluded that there is a research gap regarding this topic. To fill this research gap as well as possible, interviews will be held with manufacturers of living green wall systems. These are companies that maintain green facades and know a lot about this based on their experience. The aim of these interviews is to gain insight into the types of activities, their frequency, intensity, impact and costs. For reasons of privacy, the names of the interviewed companies are not mentioned in this research.

Monitoring

Monitoring is all about measuring and observing certain factors. During this research, the water distribution and water content is monitored. So we look at where the water from the irrigation system ends up in the living wall system. The plant quality is also monitored. The method and technique used for this is described in chapter 2.2 and 4.2. This becomes clear after answering sub-question 1. The measurements will take place in the Netherlands on a homemade living wall model, In Utrecht to be more specific.

Targeted literature review

During the desk research I collect existing information, for example from literature, studies or other available data. During the research I will come up with new findings and results that will create a new research gap and new questions. As a result, I will have to take a step back to the literature or other available information to supplement this information before continuing the research. Mainly the literature database of *scopus.com* has been used to find literature. Table 1.3 provides an overview of the search terms used per subject, including results.

Table 1.3*: An overview of the keywords that are used to find literature (own work).*

TOPIC	AIM	KEYWORD 1#	KEYWORD 2#	KEYWORD 3#	RESULTS
Limitations and problems	To obtain information about the disadvantages and problems related to living walls in general	Living wall OR Green wall OR Green facade	Problems OR Disadvantage OR Limitation	Cost OR Frequency OR Intensity OR Maintance OR Irrigation	11 Documents
Maintenance	To obtain information about the type of maintenance performed on living walls	Living wall OR Green wall OR Green facade	Maintenance OR Quality OR Preservation	Type OR Work OR Tasks	28 Documents
Irrigation system	To obtain information about the complications of a living wall in regard to the irrigation system.	Irrigation OR Water	Living wall OR Green wall OR Green facade	Maintenance OR Problems OR Damage	14 Documents
External factors	To obtain information about the external factors that influence the water use of living walls.	Water OR consumption OR Irrigation	Living wall OR Green wall OR Green facade	External factors OR Parameters OR Conditions	7 Documents
Smart systems and Monitoring methods	To obtain information about current smart systems that help to limit maintenance, such as monitoring plant quality and water use of the plants.	Living wall OR Green wall OR Green facade OR Plants OR Greenery	Monitoring OR Measurements OR Water OR Plant quality OR Assessment	Smart OR Innovative OR Sensors OR Camera OR High tech	2 Documents

Analysing

After performing the measurements, the results are analysed. The analyses are an important part of this research. Here the measured results are translated into conclusions and findings. The measured results are here converted into graphs and tables in order to draw conclusions. The main focus is on the reliability of the results and how the measurement methods can be combined to perform certain measurements.

Research process

The research is an iterative process. During the research, findings are made based on the interviews, experiments, literature research and analyses. Based on this, the research objective and the research question are refined during the research. Figure 1.10 shows roughly how the order of the research will be. This is only an indication, as the research is an iterative process that may deviate from the structure in Figure 1.10. The basis of the research is an exploratory literature review. This forms a starting point for determining the objective and problem statement. It is important to determine what the research gap is during the exploratory literature review. thereafter, an attempt is made to fill this gap as much as possible by means of interviews and a targeted literature review. In this phase it will be clear with which techniques the water distribution of the irrigation system and the plant quality will be monitored. If the monitoring yields good results, these will be further tested in order to arrive at a final recommendation.

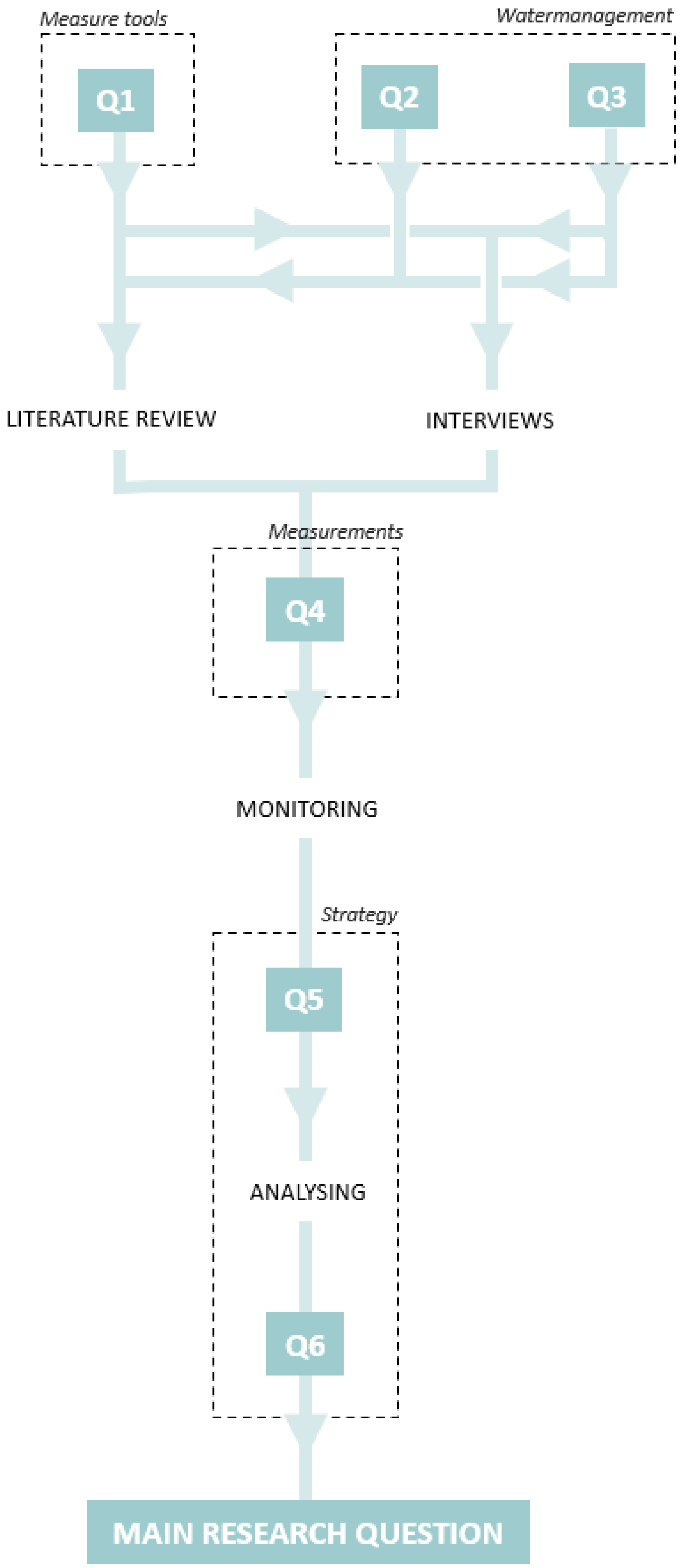


Figure 1.10: *Research strategy (Own work).*

1.10 Thesis structure and workflow

The structure of the thesis is divided into four parts. Schematic overview of this is shown in figure 1.11. The thesis has a chronological order consisting of a literature review, interviews, monitoring and improvements. As explained in chapter 1.9 the research is an iterative process. During the exploratory literature review, the problem statement, research objective, research gap and hypothesis are determined. Interviews are then held with researchers, manufacturers and contractors. After this, the monitoring of the living wall system is started. If the results are promising, an improvement proposal can be made for living wall systems with regard to water use, plant health, efficient maintenance and an assessment tool for maintenance. The structure and progress of the research is tracked by means of a timetable.

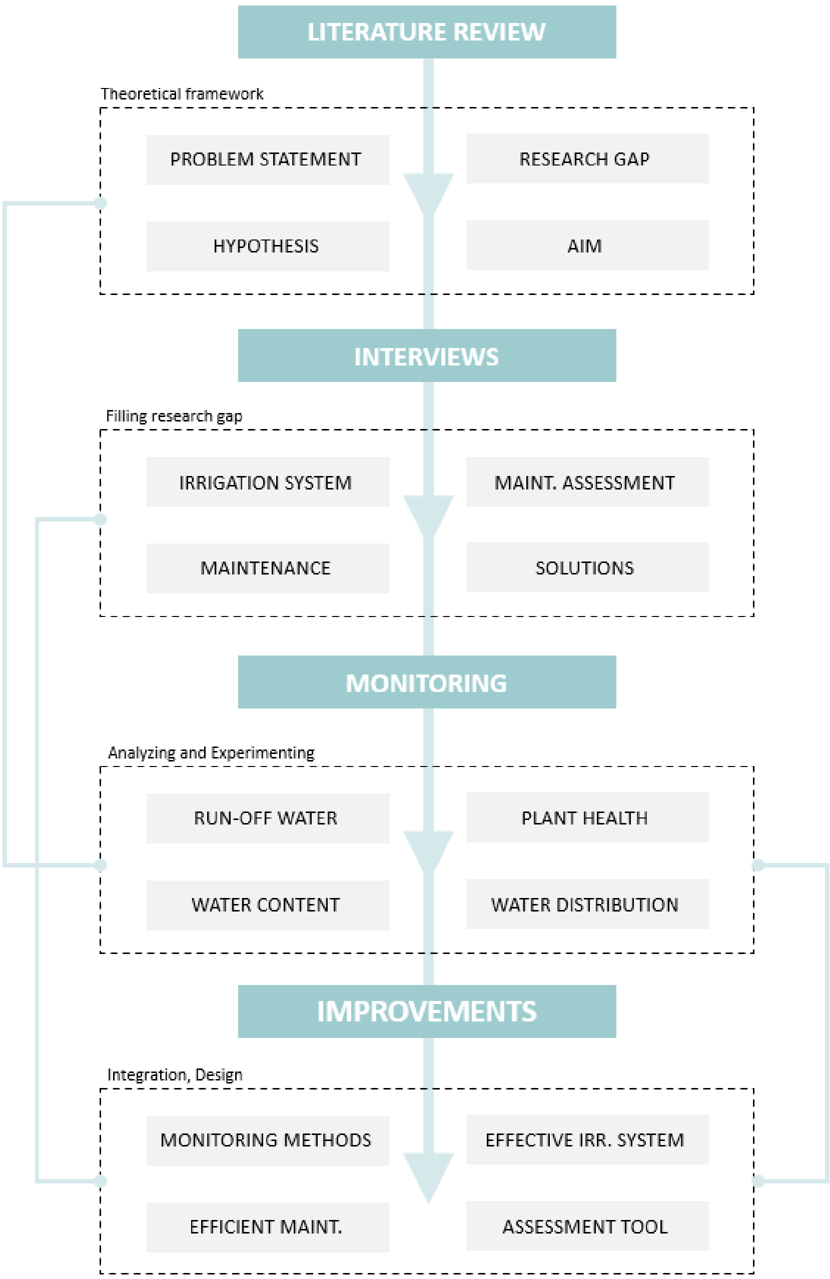


Figure 1.11: *Research structure (Own work).*

02 LITERATURE STUDY

LITERATURE STUDY

After the exploratory literature review, the problem statement, objective and research questions were determined. To answer certain research questions, a targeted literature study is needed on certain topics such as the irrigation system, monitoring methods and external factors.

2.1 Irrigation system

The exploratory research that can be found in chapter 1.2 has shown that the irrigation system is an important factor in the maintenance of living wall systems. In this chapter, interviews and literature are used to answer the research question ‘What is the effect of different types of irrigation systems on the maintenance of a living wall system?’.

Living wall systems with a hydroponic system must be permanently supplied with water and nutrients. this is a disadvantage in terms of durability, due to the high maintenance costs. However, this depends on the irrigation needs. For sustainable water use it is important to apply vegetation with low irrigation needs. The vegetation must also be able to adapt to the local conditions of exposure and weather conditions (Manso & Castro-Gomes, 2015). From an existing case study (Pérez-Urrestarazu & Urrestarazu, 2018) it can be concluded that the water consumption of a living wall varies approximately between 3 to 5 litres per m² per day. The case study was carried out in the warm season in the south of Spain. The choice for the type of irrigation system depends on various factors. This depends on building properties such as orientation, accessibility and height. In addition, climatic conditions also play a role, such as sun, shade, wind exposure and rainfall (Manso & Castro-Gomes, 2015). The effect of these factors are shown in chapter 2.3. Some living wall systems are equipped with sustainable irrigation systems where rainwater is collected in a tank and reused. An example of such a tank is shown in figure 2.2. In addition to this, some systems monitor the water supply needs using sensors. The sensors monitor the collecting water tank level, the irrigation time and weather conditions (Manso & Castro-Gomes, 2015). These systems are explained in more detail in chapter 2.2. An important aspect in the sustainable use of water is the circulation flow and the working pressure. Because this determines the choice for the pump and filters. The circulating flow depends on the number of emitters and the working pressure depends on the type of emitter, height of the living wall and head losses throughout the network (Pérez-Urrestarazu & Urrestarazu, 2018).

Water timing and control *Drainage gutter* *Waterpipes and emitters*

Figure 2.1: *Components of an irrigation system (Plant On Walls, 2023)*

The effective use of water is not only important for sustainability, but also for the health of the plants. An excess of water can lead to hypoxic stress (Gunawardena & Steemers, 2020). One of the main causes of excess water is the drainage capability of the substrate used. The substrate must hold water, but at the same time prevent saturation to keep the roots zone oxygenated. The water coming out of the substrate falls and collects at the bottom of the living wall system. This creates an excessively high concentration of water at the bottom of the facade system. To prevent this, a recirculated system must be installed, whereby the run-off water can be collected in a tank. An example of such a tank is shown in figure 2.2. These are sometimes complex systems due to the need for filters and pumps (Pérez-Urrestarazu & Urrestarazu, 2018). With these types of systems it is advised to apply lower flows and short irrigation times in combination with a higher frequency (Pérez-Urrestarazu et al., 2014). To collect this water and store it in a tank, it is important that there is a gutter to lead this water to the tank. These are equipped with a filter to purify water from i.e. toxins and heavy metals (Manso & Castro-Gomes, 2015). Maintenance with regard to the drainage is, for example, replacing filters and unclogging the drainage (Pérez-Urrestarazu & Urrestarazu, 2018).

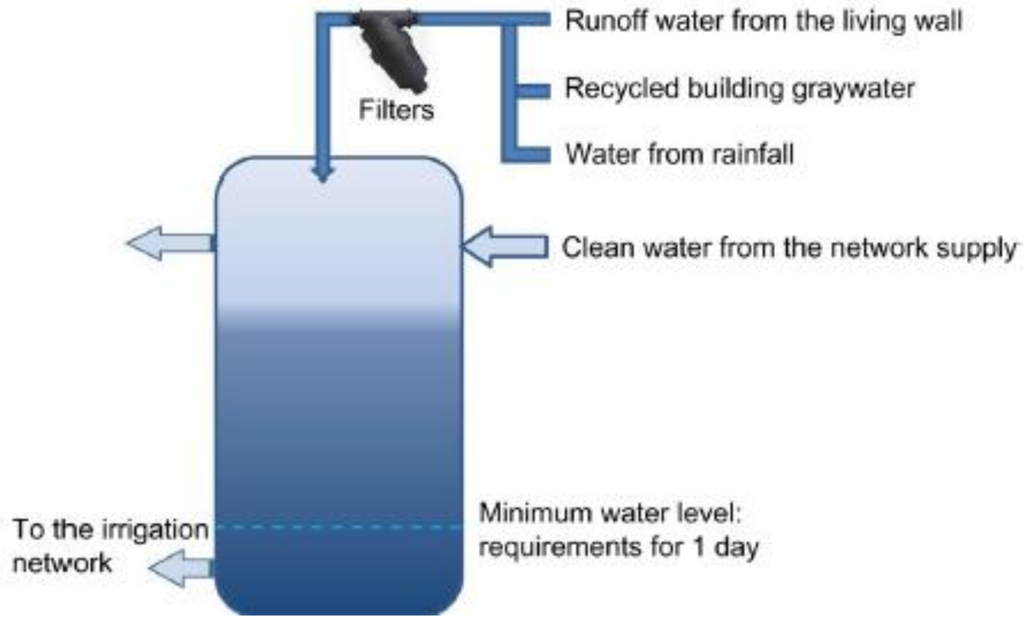


Figure 2.2: *Water recirculation system (Pérez-Urrestarazu & Urrestarazu, 2018)*

To keep the irrigation system working properly, regular maintenance is required to remedying leaks, blockages or removing invasive root growth into pipework (Gunawardena & Steemers, 2020). The water must also be completely replaced every so often to improve system operation (Pérez-Urrestarazu & Urrestarazu, 2018). The irrigation system can also indirectly affect the maintenance of the living wall system. With a living wall system, it is possible that the water from the irrigation system does not reach every plant. If a plant does not get enough water, this has consequences for the health of the plant and therefore its lifespan. This has consequences for maintenance (Fadli et al., 2019). To improve the quality of the vegetation, irrigation water can be enriched with nutrients, fertilizers, minerals, phosphates, amino acids or hydroponic materials (Manso & Castro-Gomes, 2015). The use of sensors can not only be used to deal effectively with water consumption, but also to deal effectively with nutrients. Sensors placed in the growing media monitor the nutrients needs quantification (Manso & Castro-Gomes, 2015).

2.2 Monitoring methods

Previous studies (Pérez-Urrestarazu, 2021) have shown that the amount of water sprayed by the irrigation system is not equal to the amount of water absorbed by the plants in a living wall. The water distribution in a living wall and its water content is something that we generally have no insight into, partly because there are no simple and effective methods for this yet. In this chapter, desk research and interviews are used to collect information about possible methods that could be suitable for this purpose. This addresses the following sub-question: 'Which systems exist that can be used to monitor the water distribution and plant quality in a living wall?'. The purpose of this sub-question is to collect information about possible methods that can be used and tested to provide insight into the water distribution and water content of a living wall. Through the interviews, information was collected from manufacturers and people who have experience in monitoring the quality of living wall systems. In addition, literature was reviewed to obtain information about measurement methods from previous studies.

Thermal imaging

Literature (Yuan et al., 2020) shows that there are studies that record the water content of the living wall using infrared images. Water has different thermal properties than the other materials in the living wall, which creates a contrast on the infrared images between places where there is water and where there is no water. Figure 2.3 shows an example of a living wall captured with an infrared camera. The infrared radiation captured by the infrared camera is electromagnetic radiation that is not perceptible to the human eye (Warren et al., 2015). Infrared radiation is mainly emitted by warm objects. Warm objects contain molecules that move. This movement heats up the internal temperature and emits infrared radiation (Warren et al., 2015). Unlike many other materials in a living wall, water has a cooling effect due to its thermal properties. Water absorbs heat from the environment, causing the water to evaporate. Because it draws heat from the environment, it cools the environment (Baltimore airoil company, n.d.). An infrared image therefore simply shows how much heat the captured object radiates. In the living wall this would mean that the wet substrate layer should theoretically be colder than the dry substrate layer. In other words, a wet substrate layer emits less infrared radiation than a dry substrate layer. The amount of infrared radiation is translated by the camera into a colour so that the temperature differences can be read from the infrared image. The advantage of this measuring method is that large surfaces can be measured. Although infrared is useful for detecting water in a living wall, this does not necessarily say anything about the amount of water in the living wall. It should be taken into account that there are certain factors that can influence the result, such as shading (Warren et al., 2015). If dry areas of the living wall are shaded, they will be less warmed up by the sun, so it may appear that they are wet. Furthermore, the result can be influenced by reflection. To filter out these reflections so that a reliable image of the surface temperature of the measured objects is obtained, the emissivity can be set on the camera (Fluke, n.d.). When applying this measurement method, it is important to record the climatic conditions properly. Although it is not expected that these factors can cause problems because we are not necessarily interested in the measured temperatures, but more in the contrast that provides insight into whether water is present in the facade.

Figure 2.3: *Infrared image of a living wall (Grant,2018)*

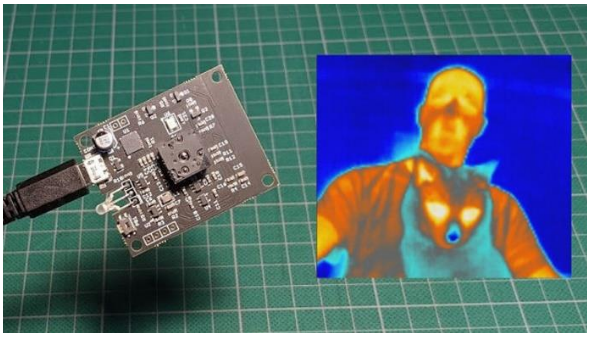


Figure 2.4: *Infrared Camera (Raptor supplies, n.d.)*

Infrared cameras can be used for the measurements, as shown in figure 2.3, as well as thermal cameras that can be connected to a raspberry Pi, as shown in figure 2.4. A Raspberry Pi is a single board computer based on an ARM processor. A thermal camera unit can be connected to this single-board computer, which can then be used to create thermal images based on a written script. The advantage of this is that it is relatively cheap and that the raspberry Pi can be used to connect other measuring instruments such as moisture sensors and NDVI cameras. Another advantage is that certain preferred settings can be made on the single-board computer, such as automatically taking several photos at a certain time. Which would mean that you place the camera in the right place and don't have to control it until the photos are generated.

NDVI

The 'Normalized Difference Vegetation Index' is a graphical indicator that can be used to make an inventory of whether certain places contain living vegetation. Vegetation uses a large part of the visible light for photosynthesis, especially red and blue light is absorbed. In contrast, near-infrared is not used by plants and is reflected (GISGeography, 2022). When a plant is less healthy, more red and blue light is reflected and less near-infrared light is reflected (GISGeography, 2022). An NDVI camera captures a graphic image in which the difference in reflected near-infrared light can be used to determine how healthy the plant is. An example of this can been seen in figure 2.5. The amount of near-infrared also depends on the amount of light that falls on it. Therefore, the values are corrected with the formula below, resulting in a value between -1 and 1. Values above 0.2 indicate living vegetation (GISGeography, 2022).

$$NDVI = \frac{\text{NIR}-\text{red light}}{\text{NIR}+\text{red light}}$$

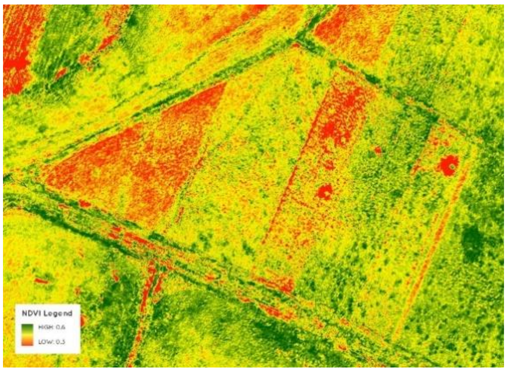


Figure 2.5: *NDVI image of a piece of land (Reich,2016)*

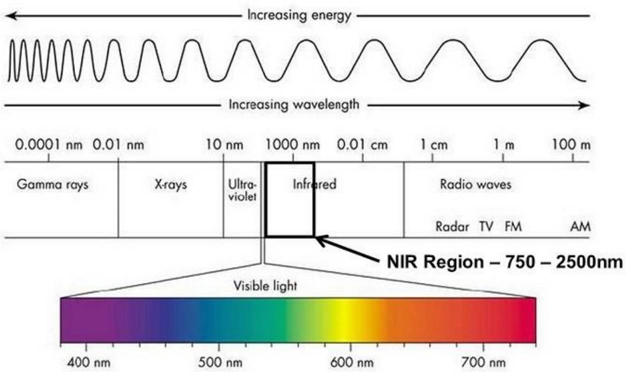


Figure 2.6: *Electromagnetic spectrum (KPM Analytics, n.d.)*

There are now simplified cameras to capture the NDVI. These are NDVI starters kits provided by *infragram*. These are simple cameras without a near-infrared-block filter to which you can add a red-light filter yourself that blocks red light. As a result, near-infrared light is captured and this image gives an indication of whether there is healthy vegetation (Infragram, n.d.). An example of this is shown in figure 2.7. Unlike these simplified cameras, NDVI cameras can calculate the exact NDVI value, making the result more accurate and measurable. The advantage of the simplified cameras is that they are relatively cheap. To convert the taken images into an NDVI image, an online tool can be used at *www.infragram.org*. Here the images, made by the simplified camera, can be loaded and converted into an NDVI image. These cameras can be obtained by purchasing an infragram starter kit. This is shown in figure 2.8. However, it is also possible to purchase a camera unit yourself and connect it to a Raspberry Pi.

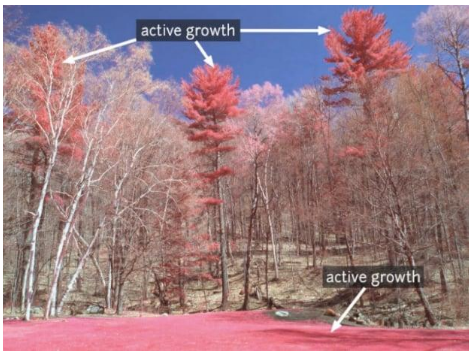


Figure 2.7: *Infragram image (Public Lab contributors, n.d.)*

Figure 2.8: *Infragram starterskit (Public Lab contributors, n.d.)*

Sensors

Moisture sensors can be used to measure the water content of the substrate layer. To be more precise, the volumetric water content in the soil is measured. The sensors are normally used to measure the loss of moisture in the soil to gain insight into how much water the plants are using or how much water is being evaporated. Dry soil consists of approximately 55% solid material and 45% pore space. When water is added to the dry soil, the pore spaces are filled with it. The volumetric water content is the percentage of water present relative to the pore spaces and solid material. When dry soil consists of 45% pore spaces, the maximum volumetric water content could therefore be 45% (TechZeero, 2020).

The volumetric water content is measured by measuring the dielectric permittivity of the surrounding medium using capacitance (techZeero, 2020). The dielectric permittivity is a property of the water content. Simply put, the sensor creates a voltage proportional to dielectric permittivity. Since the amount of dielectric permittivity is a property of the water, it can be determined how large the dielectric permittivity is and thus what the water content is. To be precise, the sensor works like a capacitor. With the voltage that is created, the capacitor is activated. The time it takes to activate and deactivate the capacitor is influenced by the moisture in the soil, in other words the capacitance. The length of this time therefore says something about the amount of moisture in the soil (techZeero, 2020). The advantage of this measuring method is that it is relatively accurate and that it not only tells you what the water content is, but that it also tells you something about how much water is consumed by the plant. A disadvantage of this system is that the range is relatively short at approximately 2-10 cm.

In addition to the sensors that measure the dielectric permittivity using capacitance, there are also sensors that measure the moisture content in the soil using conductivity. The sensor consists of two probes that act as conductors. One probe produces an output voltage that is picked up by the other probe (Shawn, 2021). The moisture content is determined by means of the resistance between the two probes. The higher the moisture content, the higher the electrical conductivity in the soil. Dry soil conducts electricity less well, which creates a higher resistance. This is because water generally has a higher conductivity than soil. This value is expressed in 'EC-value'. Soil for plants has an EC value of around 0.8 and 1.8 µS/cm. The EC value of water depends on the type of water. Only pure water (0 µS/cm) and distilled water (1 µS/cm) have a lower EC value than soil. Rainwater has an EC value of 30-60 µS/cm and drinking water even has an EC value of 300-700 µS/cm. This has to do with the amount of salt in the water (Nieuwkoop BV, n.d.). It is important to know that fertilizer affects the resistance, making the measured value less reliable. A disadvantage of this type of sensor is that the pin can oxidize, making it unusable. That's because the DC current running through the sensor reacts with the water and damages the sensor (Shawn, 2021). A disadvantage of this system is that the range is relatively short at approximately 2-10 cm.

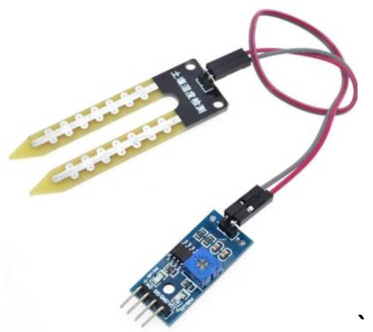


Figure 2.9: *Moisture sensor (Arduinodiy, 2020)*

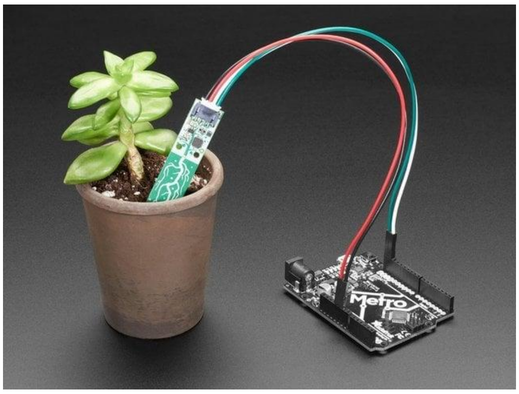


Figure 2.10: *Moisture sensor in soil (Adafruit indrustries, n.d.)*

Run-off water

A simple method to know the water content of the living wall is to collect the run-off water and measure it. If you know how much water is supplied and how much water drips off the facade, you know how much water has been absorbed by the facade. For this purpose, a water flow meter can be placed at the location of the water supply to see how many litres of water are supplied per minute. This, in combination with the irrigation time, can be used to calculate how much water has been supplied in total. This ultimately says nothing about the water uniformity, but it can say something about the effectiveness of the irrigation system. This result will very much depend on the water retention capacity of the living wall system. The more water the facade can absorb, the less run-off water there will be. The less water the facade can absorb, the more water will drip off the facade.

Previous research

Research (Pérez-Urrestarazu et al., 2014) has been carried out into possibilities to monitor the moisture content of the substrate using thermal imaging and Moisture Index (MI). The research took place at the Urban Greening Laboratory of the School of Agricultural Engineering, University of Seville. With thermal imaging, it is possible to monitor exactly how the water spreads and how much water reaches each plant. the water distribution uniformity and water losses are examined in this way. This makes it possible to use water more efficiently, because water can be replenished where necessary and water can be saved where there is already sufficient water. The study anticipates this by adjusting the emitters, drip line spacing, emitter flow and duration of irrigation event to the results. The results from the thermal images have been converted into an MI value using a formula. The results show that thermal imaging can help to apply the right parameters for sustainable water consumption, such as emitters, drip line spacing, emitter flow and duration of irrigation event (Pérez-Urrestarazu et al., 2014).

Another research (Yuan et al., 2020) has been carried out into the possibilities of monitoring water distribution by mapping the dry and wet spots on a living wall. This was done by measuring the surface temperature (Ts) with an infrared camera and weighing this against a vegetation index (VI) in a formula. The resulting value is then the Normalized Difference Vegetation Index (NDVI). This is called the triangle method. In this study, the measurements were performed with a thermal infrared camera. The temperature, relative humidity and the distance to the living wall were measured. The measured temperatures on the living wall are adjusted on the basis of this data using a software. After the NDVI values have been measured, they are converted into scatter points for dry and wet zones using a formulas. These scatter points are processed in a graph, making the boundaries between the wet and dry zones visible. Finally, the values from the graph are projected and translated into dry and wet zones on the photo (Yuan et al., 2020).

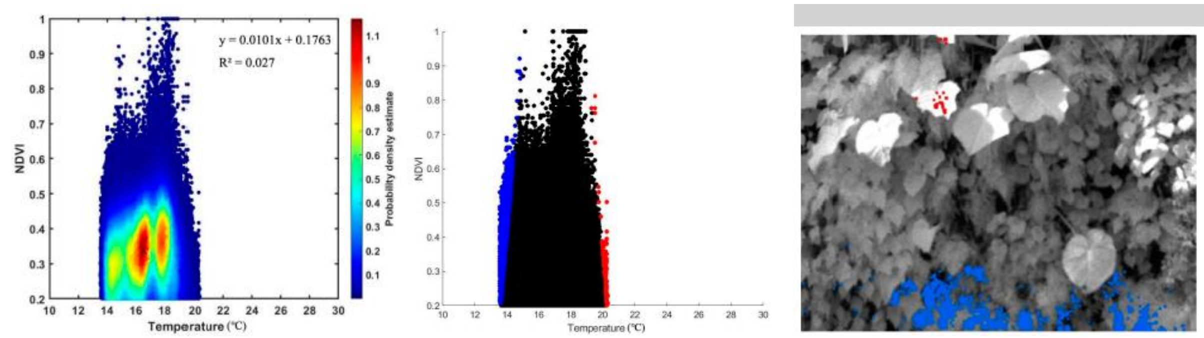


Figure 2.11: *measuring dry and wet zones on a living wall using thermal imaging (Yuan et al., 2020)*

In addition to thermal imaging, the use of sensors is also a researched method for measuring the moisture content in the substrate of a plant. Sensors were used in a study (Daniels et al., 2012) that investigated the optimum moisture content in the substrate of plants. The disadvantage of this method is that sensors often only have a short range. In this study, the sensors had a range of 10 centimetres. This would not be practical when measuring larger areas. When applying this measurement method, it is important that the sensors are placed in a location that is representative of the rest of the facade. In addition to the research by Daniels et al. (2012), there is also a study by Klamkowski & Treder (2017) that uses moisture sensors. Dielectric sensors based on the capacitance method are used here. This measurement method was used in this study to measure the water content and to map its relation to the weight of the plant containers. This research is not based on a living wall system, but it is still an interesting method to apply for a living wall system.

Conclusion

From the literature review and interviews, several methods emerged that can be used during this research. These are measurement methods that are not normally used in a living wall system. Whether the mentioned measurement methods will work is therefore not guaranteed, the aim of this research is precisely to see whether these measurement methods will work and then be applied in practice. The selection of measurement methods applied during this research is based on previous studies and shared experience and knowledge of the interviewees. The mentioned methods all have limitations and advantages. They each measure a different aspect of the living wall system. It is therefore important that the measurement methods are applied together to compensate for each other's limitations. For example, the sensors are used to measure water content, but have a very short range of approximately 2-10 centimetres. For this reason, the thermal camera is also used because it has a large range, but does not provide accurate data about the water content. When these methods are combined, they can compensate each other's limitations. Furthermore, an NDVI camera is used to measure plant quality. Based on the interviews, it is expected that the NIR light that is recorded with the camera can also provide a picture of the water content of the facade. Although this is not the main purpose of the NDVI camera, it is interesting to see whether this can actually be a reliable measurement method for water content and water distribution in addition to plant quality. Furthermore, the run-off water is measured to eventually compare this result with the result of the moisture sensors. Moisture sensors and the NDVI camera have been chosen for this research that are based on a single-board computer such as a Raspberry Pi or Arduino. More information about this can be found in chapter 4.2. The advantage of this is that this is a relatively cheaper alternative and can therefore be used more easily by individuals or smaller companies. In addition, a single-board computer can be used to write a script about how you want the information processed, and the camera and sensors can be set so that they automatically take measurements instead of having to operate them manually. The original idea was to also control the thermal camera using a single-board computer. Unfortunately this brought too many difficulties and was time consuming. It was finally decided to use a professional thermal camera. To measure the run-off water, the water flow is measured using a water flow meter and the run-off water is collected in a gutter from which the content can be read.

Table 2.1: *Overview of monitoring methods that will be used (Own work)*

METHOD	BENEFITS	LIMITATIONS
NDVI	· Accuracy · Easy to use · Big range · Indicates plant health	· Doesn't say anything about water content · The result can be strongly influenced by the presence of artificial light
Thermal imaging	· Big range · Indicates water distribution · Easy to use	· Does not immediately give a value for the water content
Moisture sensors	· Says something directly about water content · Accuracy	· Small range (2-10 centimeters) · Result can be strongly influenced by the type of growing medium
Run-off water	· Easy to measure · Says something directly about the water content	· Doesn't say anything about the water distribution

2.3 External factors

The purpose of monitoring the water distribution and water content of the living wall is to better anticipate on maintenance. The amount of water that reaches the plants has an effect on the health of the plant (Gunawardena & Steemers, 2020). It is therefore important to know what an ideal water content would be for a living wall. However, there are external factors that can influence this. This addresses the following sub-question: 'What are the external factors that may influence the water need for a living wall system?'. The external factors that have the most influence on the water consumption of the living wall are the dimensions, plant density, shading, plant species, type of LW system, orientation, irrigation scheduling and climatic conditions, such as temperature, rainfall and humidity. Various case studies have shown that these factors do not have much effect individually, but that the effect becomes significantly large when they are combined (Pérez-Urrestarazu, 2021).

Climatic conditions

Several studies (Pérez-Urrestarazu, 2021; Segovia-Cardozo et al., 2019) has shown that the location of the living wall has a significant effect on the water consumption of the LW. This mainly has to do with the temperature, air humidity and rainfall in the location. For example, large differences in water consumption have been measured between an LW in Bilbao that has a Marine West Coast climate and an LW in Seville that has a Mediterranean climate. Seville has very hot and dry summers while Bilbao is slightly colder and more humid. The measured water consumption of the LW in Bilbao is 5.7 $L/m^2/d$ in summer while that of Seville is about 12.7 $L/m^2/d$. There are also differences between the summer period and winter period. The research by Pérez-Urrestarazu (2021), in which measurements were carried out in 16 case studies, showed a higher water consumption in summer compared to winter for all these LW systems. An extreme example is the measured LW system in Malaga. A water consumption of 10.1 $L/m^2/d$ has been measured in summer, while in winter this is less than half with 4.82 $L/m^2/d$. The research by Segovia-Cardozo et al. (2019) shows that water consumption starts to increase from spring, peaks in summer, and starts to decrease again in autumn. However, it turns out that these differences also depend on other factors. As mentioned earlier, the differences in water consumption are often the result of several factors.

Shading and facade orientation

Although large differences were measured between the summer and winter period, the size of the differences depends on other factors such as orientation and shading. The research by Pérez-Urrestarazu (2021) shows that the water consumption of an LW in Madrid that is oriented towards the northeast is 1.6 times greater in summer than in winter. While another LW in Madrid that is oriented towards the southeast uses only 1.01 times more water than in winter. Living wall systems oriented towards the south (including southeast and southwest) have an annual average between 4 and 8.2 $L/m^2/d$. And Living Wall systems oriented towards the north (including northeast and northwest) have an annual average between 2.8 and 9 $L/m^2/d$. From this it can be concluded that LW systems oriented towards the north have greater differences between warm and cold seasons. Furthermore, the water consumption is also influenced by shading. This can be clearly seen in the difference between two LW systems in Madrid that also have the same orientation. Of which one of the LW systems without shading has twice as high water consumption compared to another LW system with shading, in the same city and with the same orientation. The shading in this case is caused by surrounding buildings.

LW systems without shading normally have a lower water consumption compared to LW systems that are more exposed to incident radiation. Higher exposure results in higher evapotranspiration rates that influence water consumption (Pérez-Urrestarazu, 2021). This principle is also reflected in the results measured by Segovia-Cardozo et al. (2019). It has been established here that the water consumption of LW systems oriented to the south is greater than those oriented to the north. This is mainly because LW systems oriented to the south are more exposed to incident radiation.

Living wall system and dimensions

The type of LW system influences both water distribution and water consumption. For example, research by Segovia-Cardozo et al. (2019) shows that in a LW system consisting of plant pots, the water movement only takes place in a vertical direction. Research (Pérez-Urrestarazu, 2021) has shown that LW systems consisting of boxes or containers, from which plants grow, have an advantage over felt-based systems when it comes to water distribution. Felt-based systems present a lower water retention capacity and poor water distribution uniformity. Research by Pérez-Urrestarazu (2021) concludes that this can lead to excessive water use when the irrigation is not properly managed. In addition, the measurements by Pérez-Urrestarazu (2021) show that the water consumption at the lower part of the LW is greater than the upper part. This simply has to do with gravity. The water drips vertically downwards, so that the lower part receives more water. In one of the measured LW in the study by Pérez-Urrestarazu (2021) it is even found that the lower part contains 8 times more water than water is sprayed on the upper part. In addition, it also plays a role that the bottom part is less exposed to incident radiation. For this reason, plants with higher water requirements are often assigned to the lower part of an LW. It is also interesting to see that even the dimensions of an LW have an effect on water consumption. Living wall systems that are longer and narrower have a greater water consumption than living wall systems with the same surface that are shorter and wider. This is because the excess water from the upper part is retained and used in the lower part.

Plant species and density

Finally, it appears that the plant species and plant density play a significant role in the water consumption of an LW system (Pérez-Urrestarazu, 2021). However, the possible effect of this on water consumption is not expressed in figures. As for the effect of the plant species, this will depend on the plant species itself.

03 INTERVIEWS

INTERVIEWS

The interviews are an important source of information for this research. As mentioned earlier, there is limited information and literature available on the maintenance of living walls. Based on the available literature, a problem statement has been identified and the literature gap has been exposed. Interviews with companies and people who have experience with the maintenance of living walls are therefore an important source of information that can be used to reduce the research gap on the one hand and to refute or support the information from the available literature on the other. The interviews were held online. The interviews were recorded and transcripts were made. Subsequently, the answers to the questions from the interviews were analysed on the basis of the recordings and transcripts.

3.1 Hypothesis

A hypothesis can already be made based on the literature study and the problem statement. It can be concluded from previous studies that the need for maintenance is mainly determined based on observation (Gunawardena & Steemers, 2020). This can be a problem without the companies themselves being aware of it, because certain aspects that influence the quality of the plants are difficult to measure with the eye. This is the water distribution and the water content of the living wall. Research by Gunawardena & Steemers (2020) shows that too much or too little water affects the quality of the plant. Research by Segovia-Cardozo et al. (2019) and Pérez-Urrestarazu et al., (2014) has shown that when irrigating the living wall, the water is often not evenly distributed everywhere. So one hypothesis is that the interviewee mainly judges based on observation whether maintenance is required and whether every plant in the facade gets enough water. Questions are asked to confirm or disprove this hypothesis.

3.2 Questions

The questions can be divided into three categories, these are background information, maintenance of living walls and improvements. The questions that can be placed under the category 'background information' are intended to put the answers from the interview into context. The questions are about the position of the interviewed person within the company. This is important because a manager of a company may have a different view on the maintenance of living walls than a maintenance worker. Furthermore, the interviewee is asked about the amount of experience he has with his job and how long the company has existed. It may be that the maintenance can differ for companies depending on their experience in carrying out maintenance. The questions that fall under the category 'Maintenance of living walls' are about maintenance, irrigation system and plant quality. These questions are intended to collect information about the type of maintenance performed and the frequency thereof. It is also asked how it is assessed whether maintenance must be carried out. Finally, questions are asked about other possible maintenance problems such as labour intensity and costs. The questions that fall under the category 'improvements' are about the objective of this thesis. Here they are asked for their opinion on possible solutions to limit maintenance and for methods to provide insight into the plant quality and water content of the living wall. A list of all questions can be found in appendix

A. The questions consist of clusters. This means that several questions can be asked to collect certain information. For example, if they are asked about the labour intensity of the maintenance, they will also be asked about the type of Living wall and the type of maintenance that must be carried out. In this way, the information obtained is placed in the right context and conclusions can be drawn better from the answers obtained. The clustered questions can be found in appendix B of this report. Each cluster has a purpose with which specific information is collected. The questions from the clusters are posed in such a way that the answers can be placed in the right context and are compiled on the basis of hypotheses. Below is an overview of the aim of each cluster and the context in which it should be placed. It also indicates which hypothesis is applicable.

Table 3.1: *Aim, context and hypothesis of the clusters (own work)*

CLUSTER	AIM	CONTEXT	HYPOTESIS
1	To understand how it is assessed when maintenance is required	The answer will depend on the type of maintenance and the cause of the maintenance.	Based on information from the literature, assessment will be based on observation.
2	To find out how they know or do not know whether the water is distributed well over the facade.	For this it is important to take into account whether they think that the water distribution can be a problem.	Since there are no official measurement methods for this, I expect that they have no insight into this.
3	To find out what consequences the maintenance can have, such as high costs and high labor intensity.	The answer may depend on the design and whether it was anticipated during the design phase.	Since maintenance has to be carried out at high altitudes, I think that the maintenance has an indirect effect on the high costs and difficulty of carrying out the maintenance.
4	To find out how they make sure each plant gets enough water. Because too much or too little water has indirect effect on the need for maintenance.	To put the question in the right context, it is important to know whether they adjust the irrigation system accordingly and how they know when the water content is too low or too high.	Based on information on the website of some companies, the water content is monitored by means of certain sensors.
5	To find out if they are aware that the water content and water distribution influences the quality of the plants.	For this it is important to know whether they already have a way to monitor the quality and water consumption of the plants.	The literature has shown that the amount of water supplied is not equal to the water content of the living wall. While many companies may see this different.
6	To find out if they think this research can help to limit maintenance.	For this it is important to know how they assess the need for maintenance. Whether they use measurements for this or by observing.	if they are convinced that the measurement methods from this research really work, they will agree that this can help limit maintenance.
7	To find out how often maintenance is required. And whether they think this research can help to lower the frequency.	To put the answers in the right context, it is important to ask what maintenance work is involved.	I think they will agree that at least the frequency of inspections can be limited because measurements can be done from a distance.
8	To find out if the frequency of maintenance is a problem	This will depend on the required skills and intensity. The frequency will be a problem if the maintenance is difficult to perform	This will probably be very subjective. Nevertheless, it is important to find out how they experience this.

3.3 Participants

For the interviews it is important that as much information as possible is collected from different companies. Preferably from companies all over the world with different climates and different living wall systems. By speaking to companies from different climates with different systems, the effect of the climate and system on maintenance can become more visible. Although many companies around the world have been approached for the interviews, only a few have cooperated. Most companies come from the Netherlands. All spoken companies work in the same climate. In relation to privacy, the names of the interviewed companies are not mentioned, the companies are listed below.

Table 3.2: *List of interviewed companies (own work)*

COMPANY	LW-SYSTEM	LOCATION	CLIMATE
A	Foam including felt layer with pockets with plants	The Netherlands	Temperate oceanic climate
B	Rockwool as a substrate with holes for plants	The Netherlands	Temperate oceanic climate
C	Rockwool system with modular elements	The Netherlands	Temperate oceanic climate
D	Modular system with interchangeable cassettes. The cassettes have slots for plants	The Netherlands	Temperate oceanic climate
E	Panels that consist of rock wool. It has holes for plants to fit in.	The Netherlands	Temperate oceanic climate
F	Pre-grown system that consists of planter boxes	Australia	Temperate oceanic climate

3.4 Results

Framework

The answers from the interviews are processed based on a framework. This is a framework specifically created for this research that applies to the interviews. The framework in figure 3.1 shows that answers to the questions are based on facts and opinions of the interviewee. The facts and opinions are based on their experience. It is important to distinguish the facts from the opinions. To do this properly, background information is collected during the interview, such as position within the company, number of years of experience and information about the company they work for. The answers to the questions are processed in graphs and citations. For this, the graphs will mainly be based on facts and the citations will be based on opinions.

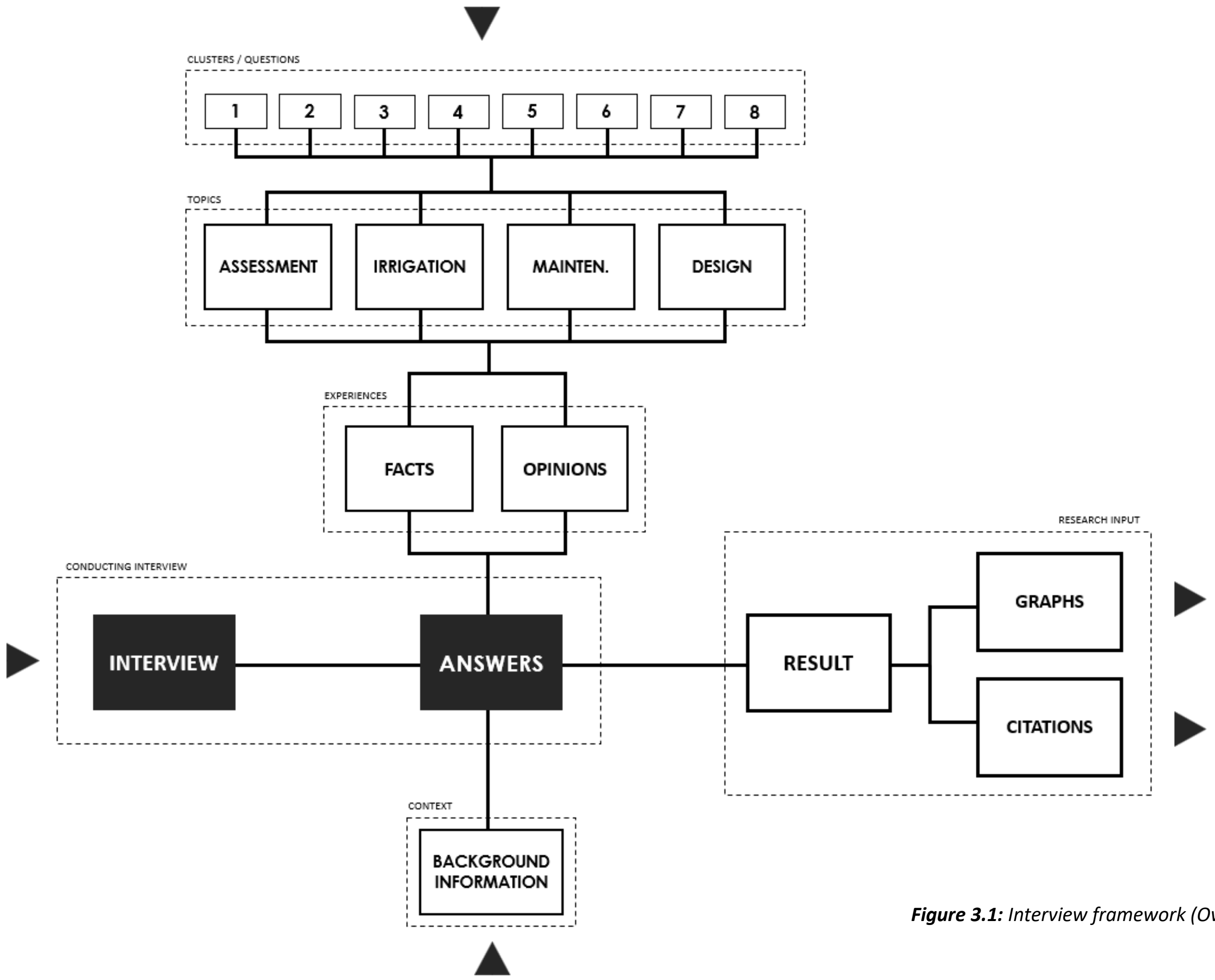


Figure 3.1: *Interview framework (Own work)*

CONDUCTING INTERVIEW	This is the core of the framework. this is where the interview is conducted
TOPICS	These are the topics the questions are about.
CONTEXT	Background information is asked to place the answers in a certain context.
EXPERIENCES	The interviewees answer based on their experience. These will be facts and opinions. it is important for this study to distinguish between them.
CLUSTERS/ QUESTIONS	These are the clustered questions as shown in chapter 4.2.
RESEARCH INPUT	The answers from the interview are input for the research in the form of graphs and quotes.

Results and discussion

In order to analyse the answers and to reach conclusion the answers from the interviews have been processed into graphs and tables. The recordings and transcripts were analysed to process the information.

Figure 3.2 shows how often the companies carry out inspections or maintenance work per year. Interesting conclusions can be drawn from this graph without looking at the context. The relationship between inspections and maintenance work differs greatly between companies. This may be because certain companies carry out more reliable inspections, so that the need for maintenance is better identified, resulting in more maintenance work being carried out. Another conclusion is that it is possible that other factors such as LW system and the irrigation system play a role in the frequency of maintenance. The latter seems unlikely because the type of LW systems between the companies with high and low frequency of maintenance is about the same.

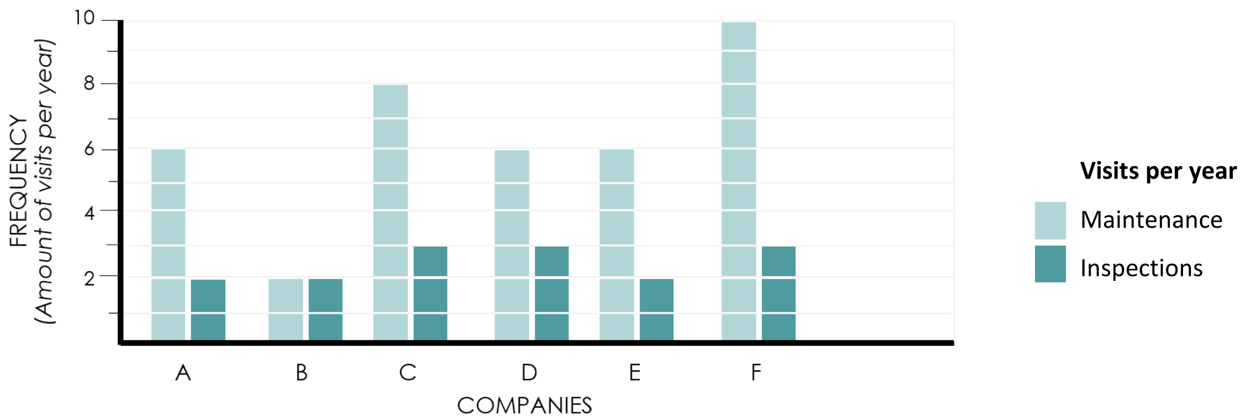


Figure 3.2: *Amount of inspections and maintenance visits per year per company (own source).*

The interviews showed that despite all companies carrying out inspections based on observation, some of them also use sensors. In the interviews it is mentioned that the sensors cannot be fully trusted and their assessment is mostly based on the visual inspections. Nevertheless, a graph has been made to see whether the frequency of visits is related to the presence of sensors. The results of this can be seen in figure 3.3. Here you can see that the companies that pay the most visits (inspections and maintenance) to the living wall use sensors. An important fact is that, as can be seen in figure 3.2, the number of inspections between the companies is relatively equal. So the difference is in the frequency of maintenance. Figure 3.3 shows that companies C and F make the most visits to the living walls. These are also the only companies with green facades where sensors are present. One hypothesis was that the presence of sensors would limit maintenance, because maintenance can be better anticipated and unnecessary maintenance could be avoided. However, this graph shows the opposite. This may be because the presence of sensors generates notifications so that more visits are scheduled for the living walls. The next question that can be asked is whether this means that the plants in the living wall are healthier or that these high number of visits have no effect on the quality of the plants. The interviews showed that each company replaces unhealthy plants on average 3-5% per year, except for two companies. These are companies C and F. They indicated that they replace about 2% plants per year.

Although this is a difference of 1%, this could be related to the presence of sensors and the number of maintenance visits to the living wall.

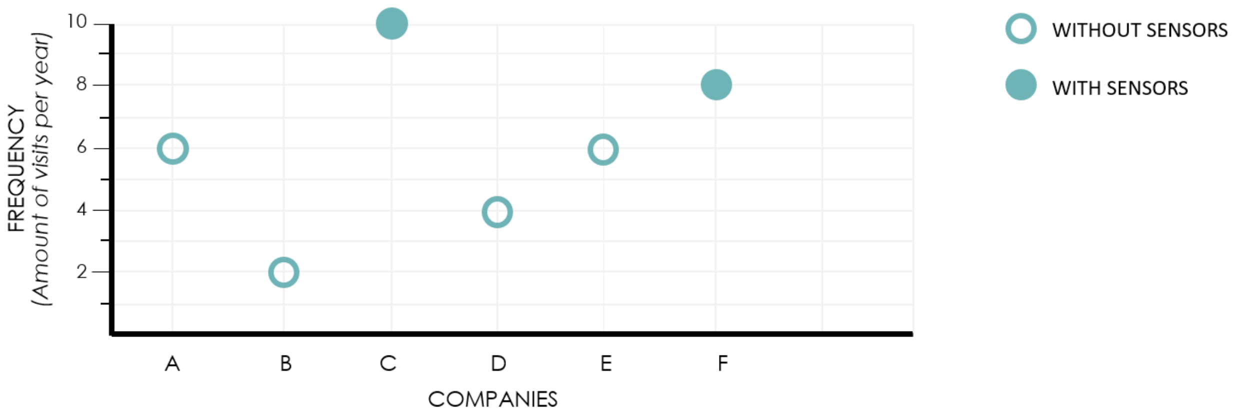


Figure 3.3: *Maintenance frequency by companies with and without the help of sensors (own source).*

During the interview it is also being asked about the type of maintenance that is carried out. Figure 3.4 shows that all companies include pruning as one of their maintenance activities. This makes sense since all plants will have to be trimmed at some point anyway. Plant replacement is also mentioned relatively often by companies. It has also been indicated that maintenance activities are related to the irrigation system, these are activities such as checking the filters, checking the PH level, cleaning the gutter and inspecting driplines. It is important to know that the graph only shows which maintenance activities are mentioned in the question "what type of maintenance is being carried out?". There may be more maintenance work not mentioned or overlooked. An interesting conclusion that can be drawn is that the activities in which employees have to work at height are mentioned most often. It could be possible that these activities are mentioned most often because they are the most complicated in relation to the height at which they have to be carried out.

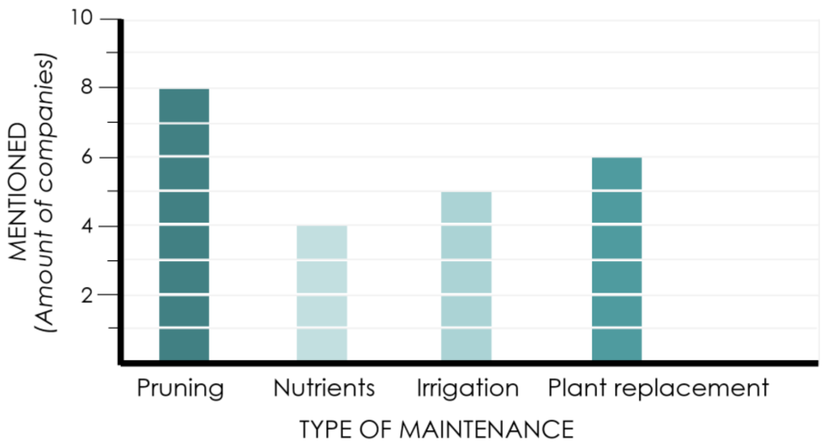


Figure 3.4: *maintenance mentioned by companies (own source).*

To confirm the conclusion from figure 3.4, figure 3.5 shows an overview of the problems mentioned in relation to the living wall. The literature study has shown that the irrigation system can cause complications, which was also apparent from the interviews. During the interviews, it turned out that these are mainly minor malfunctions that are not difficult to solve, but are often unnecessary, which means that a lot of time can sometimes be lost because employees have to be sent to the living wall. What's even more interesting is that frequency is mentioned the most. It is important to mention that frequency, cost and height are related. The interviews showed that the frequency of maintenance in itself is not a major problem, but that this becomes a problem when the work has to be carried out at height. The result of this is that costs have to be incurred for aerial work platforms and other means to be able to work safely at height. If we compare the results from figure 3.4 and 3.5, we can conclude that the fact that work has to be done at heights, and therefore extra measures have to be taken, is seen as a problem when the frequency is too high and therefore many costs must be incurred.

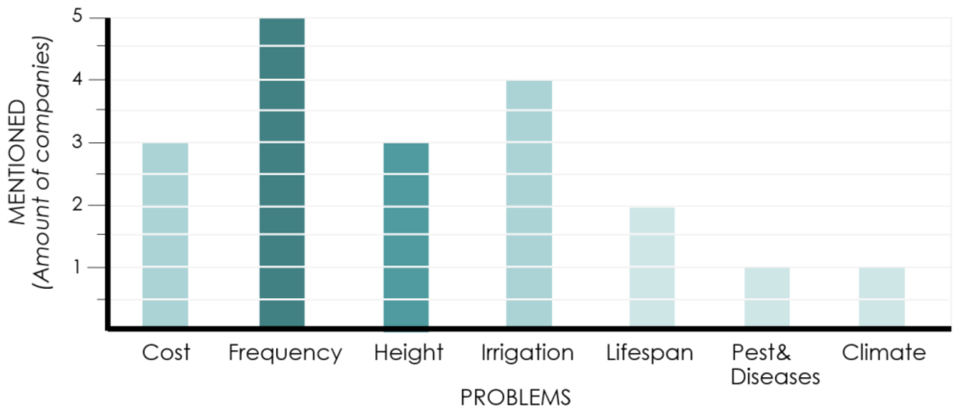


Figure 3.5: *Problems mentioned by companies in regard to living walls (own source).*

The companies were asked how they assess whether each plant receives sufficient water. This is interesting because the problem statement of this study is that the way in which the need for maintenance is assessed can often be improved. The literature study has shown that this is done by observation. This is also apparent from the interviews. All interviewees indicated that they do this on the basis of observation. Not only when it comes to maintenance, but also when assessing whether all plants receive sufficient water. Apart from the fact that companies often indicate that they do this by observing, there are also companies that add that measurements have been taken before, for example, or that they adjust the irrigation cycle in such a way to ensure that all plants get water. In figure 3.6, this is linked to the frequency of maintenance carried out by the companies. Figure 3.6 shows that the average of the frequencies is between 6 and 8. However, there is a company where the frequency is relatively low, they indicate that they know for sure that each plant receives enough water by adjusting their irrigation cycle in such a way that the water is distributed well. To elaborate on this, they indicate that their facade is divided into irrigation zones. The amount of water can be determined per zone, they do this based on factors such as the sun, shading and height. Plants that are higher up get more water than plants that are below, because the water sinks down.

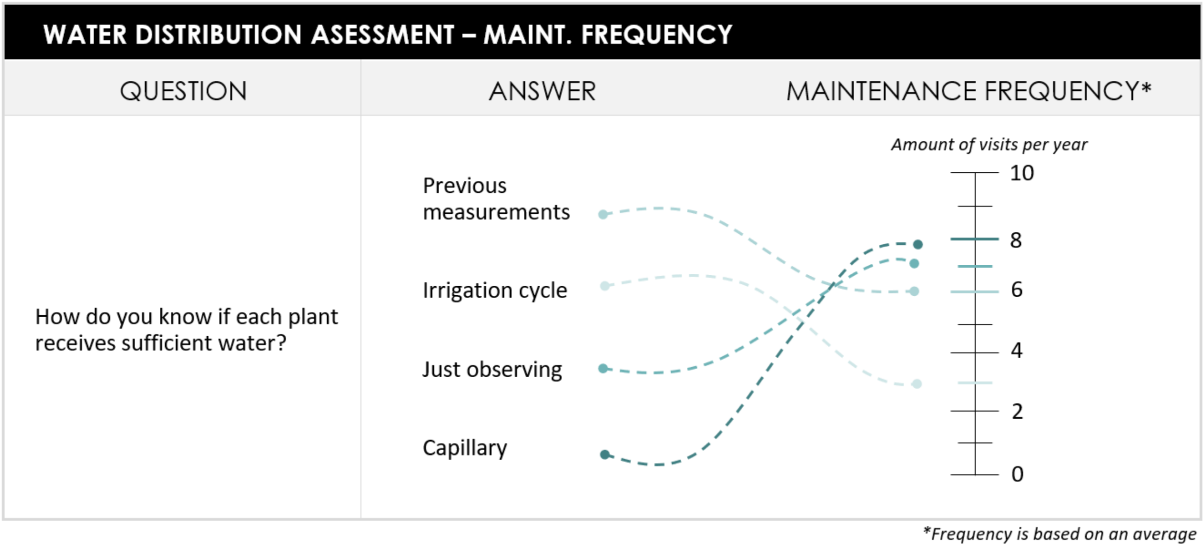


Figure 3.6: *Link between water distribution assessment and maintenance frequency (own source).*

Conclusion

Conclusions can be drawn from the analysis of the interviews that both confirm and refute the previous hypotheses. The interviews showed that the need for maintenance is mainly determined based on observations, confirming previous hypotheses. It is important to add that the reason for this is that there are no reliable measurement methods to do this differently. Another important conclusion is that the maintenance work itself is not necessarily a problem. It only poses a problem for companies when the work has to be carried out at certain heights. In combination with a high frequency of maintenance, this can cost a lot of time and money because extra provisions have to be made, such as aerial work platforms. In addition, the interviews showed that the frequency of maintenance does not necessarily decrease when the need for maintenance is better assessed through measurements. At the most, it improves the quality of the plants. This could possibly have an effect on the plant replacement rate. In order to limit the frequency effectively, it is concluded from the answers given that an effective irrigation system can influence this. For example, by knowing exactly how much water each zone of the facade needs and adjusting the water capacity to the right factors.

04 MATERIALS & METHODS

MATERIALS AND METHODS

The measurements are an important part of this research. The purpose of the measurements is to initially gain insight into the water content and water distribution in a living wall. Subsequently, based on the measurements, it is examined how this is influenced by certain factors and finally how this can be improved. To obtain accurate results, the measurements are carried out on living wall mats from Vertical Meadow. Vertical Meadow is a living wall company from London, UK. The prefabricated mats are seeded. Chapter 4.2 shows how the mats are applied to the model where the measurements are performed. Four measurement methods are used for the measurements. The measurements are carried out with an infrared camera, NDVI camera, moisture sensors and by measuring the run-off water.

4.1 Testing equipment

Good preparation is necessary to perform the measurements as well as possible. In chapter 2.2, based on interviews and literature, it was determined which measurement methods may be effective for this study. In chapter 2.3, based on a literature study, it was determined which external factors can have an effect on the water distribution and water content of a living wall. Before the measurements are performed on the test model, a small scale model is built to test the measurement methods. With this small scale model I can get an impression on a small scale of which factors can have an effect on the measurements. The small scale model is planted on one side. This allows me to see whether the measurement methods allow me to measure differences between the planted part and the non-planted part. In addition, I can already see whether a difference in results is measured when I add a lot or little water to the small-scale model. The small-scale model can be seen in Figure 4.1 and 4.2. during the testing of the measurement methods it became clear how important this preparation was. When using the NDVI camera it became clear that there are factors that influence the accuracy of the photos. The measurements were repeated several times to measure accurate and reliable results. The first few times it was not possible to get good pictures. This is because the camera has a filter that blocks NIR light. This was subsequently removed manually in order to be able to take photos where NIR light can be collected. After capturing the images, they are converted into an NDVI image via an online tool from *Infragram.org*. During testing of the NDVI camera, it appeared that a number of factors can influence the result that must be taken into account for the real measurements. The NDVI test has shown that it is important that the measurements take place outdoors, because the camera records the reflected NIR light. In the presence of artificial light, the camera cannot capture NIR light. Figure 4.1 shows the set-up of these test measurements and chapter 5 shows the results of the NDVI images. The test with the sensors has been carried out successfully. Connecting the sensors is relatively simple, so that little can go wrong with the measurement. The test measurements were initially performed on the small scale test model and then in a plant pot. Figure 4.2 shows the test set-up where the sensors were tested using the small scale test model. An important conclusion from the measurements is that the type of soil or growing medium has a major influence on the measured results. It is therefore important that the sensors are properly calibrated based on the living wall mats where the measurements will be carried out.

According to the product specifications, the sensor gives a value between 0 and 950. Here 0 - 300 stands for dry soil, 300 - 700 for moist soil and 700 - 950 for wet soil. When testing the sensors, the sensors are placed in a cup of water. All sensors gave a value of ~ 756 here. This is why ~ 756 is used as the maximum moisture content for the measurements. The reason the sensors do not reach a value higher than ~756 is because voltage is lost through the connection between the cables and the sensors. As explained in chapter 2.2, the sensors work by sending a voltage from one pin to the other pin. In the open air, the moisture sensors give a value of 0. This is why 0 is kept as the minimum for the moisture content for the measurements.

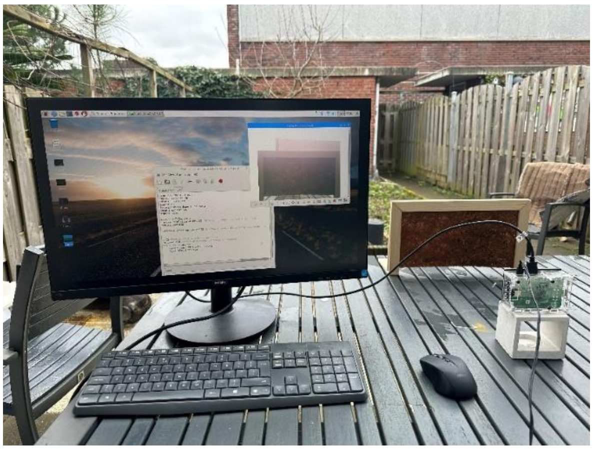


Figure 4.1: *Testing the Raspberry Pi camera (Own work)*

Figure 4.2: *Testing the moisture sensor (Own work)*

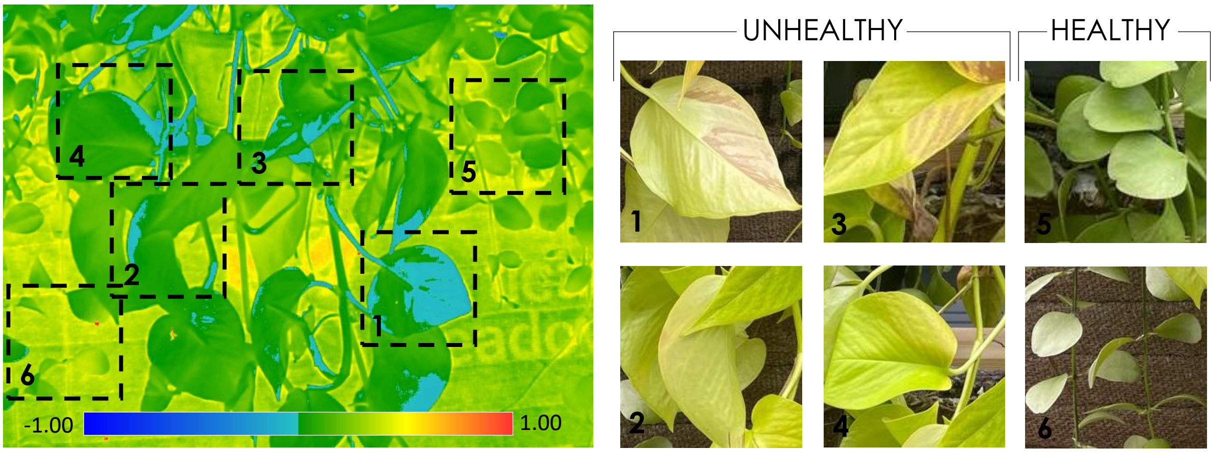


Figure 4.3: *NDVI image test (Own work)*

4.2 Experimental set-up

The measurements are performed on a homemade model. With this model an attempt has been made to recreate a real living wall in a simple way. The model consists of a wooden frame on which prefabricated living wall mats are hung. The prefabricated mats were provided by the company Vertical Meadow from England. The prefabricated mats consist of recycled fabric, seed paper and coir mesh. Water pipes are mounted behind the frame with which the mats can be watered. The total width of the model is 940 mm and the total height is 1000 mm. The mats are each 900 mm wide and 400 mm high. For more dimensions see figures 4.5 to 4.7. The frame is made in such a way that the mats can be removed and that the frame can be folded together. this makes the model easy to transport. The model will eventually be located in the city of Utrecht where the measurements will be carried out. A 3d model of this test model is shown in figure 4.4. Photos of this test model can be found in appendix C of this report.

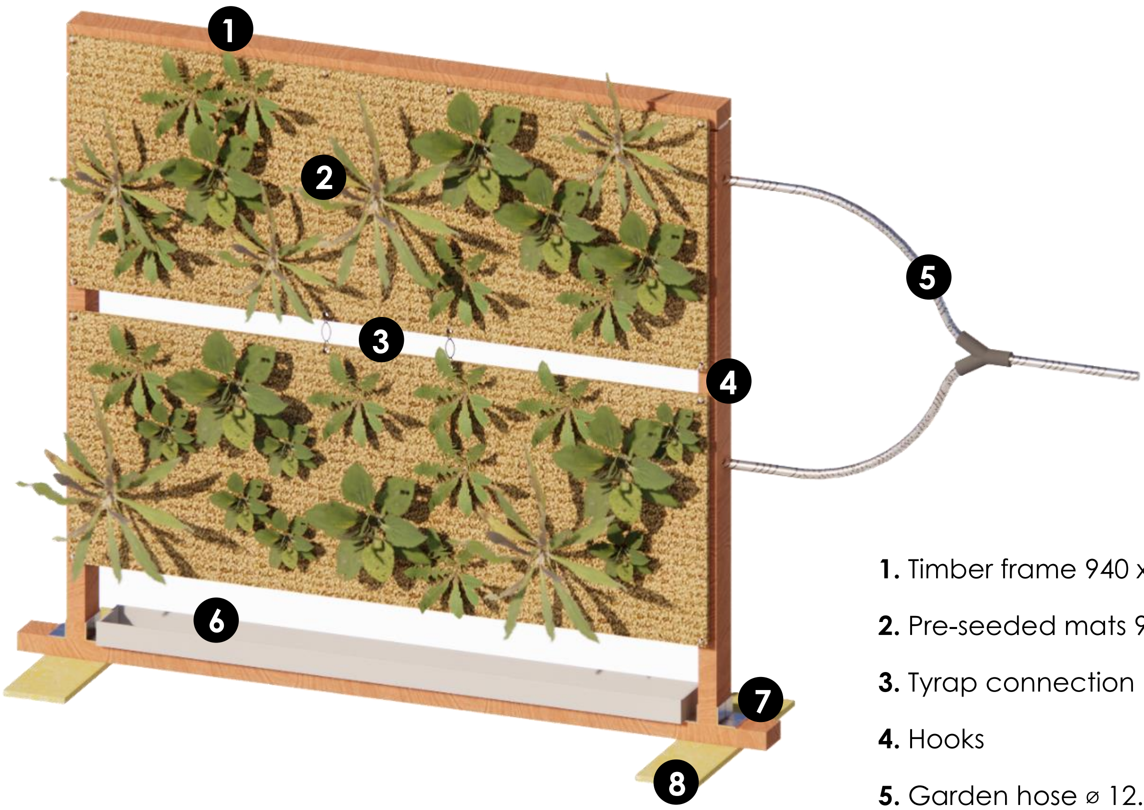


Figure 4.4: *3d model of the living wall model (own work)*

1. Timber frame 940 x 1000 mm

2. Pre-seeded mats 900 x 400 mm

3. Tyrap connection

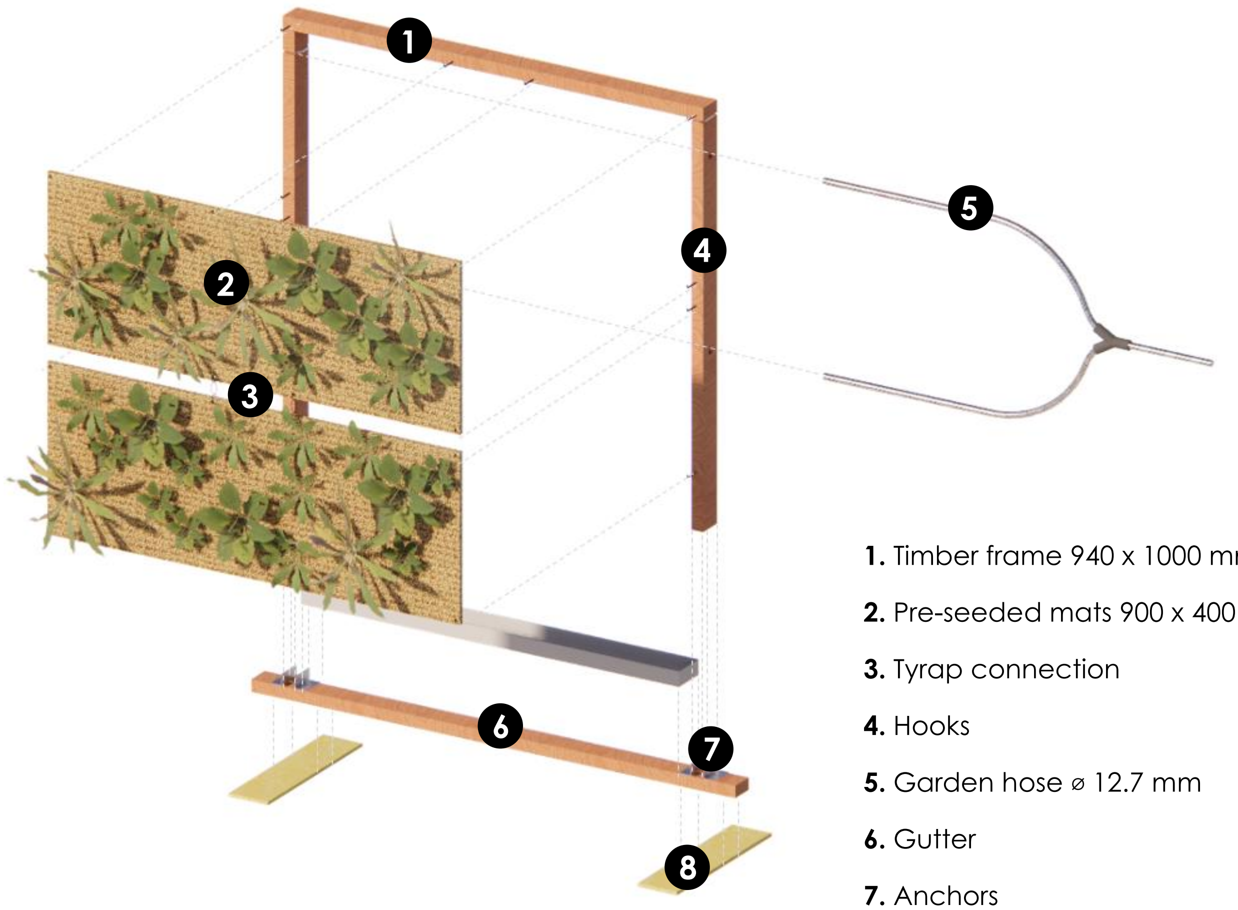
4. Hooks

5. Garden hose ⌀ 12.7 mm

6. Gutter

7. Anchors

8. Timber plates for stability



1. Timber frame 940 x 1000 mm

2. Pre-seeded mats 900 x 400 mm

3. Tyrap connection

4. Hooks

5. Garden hose ⌀ 12.7 mm

6. Gutter

7. Anchors

8. Timber plates for stability

Figure 4.5: *Exploded view of the model (own work)*

As described earlier, the model consists of a wooden frame on which the living wall matts are hung. Steel anchors are attached for the stability of the frame and wooden plates are placed under the frame to serve as legs. Holes are drilled in the frame for the garden hose to pass through. Furthermore, the mats are connected vertically with tyraps so that the mats are stiffer and hang less. It is important to note that the plants in the above images are fictional. Although the mats are provided with seeds, they have not yet grown into plants. The plants have been added to the image to give an impression of what it would look like when the plants had grown.

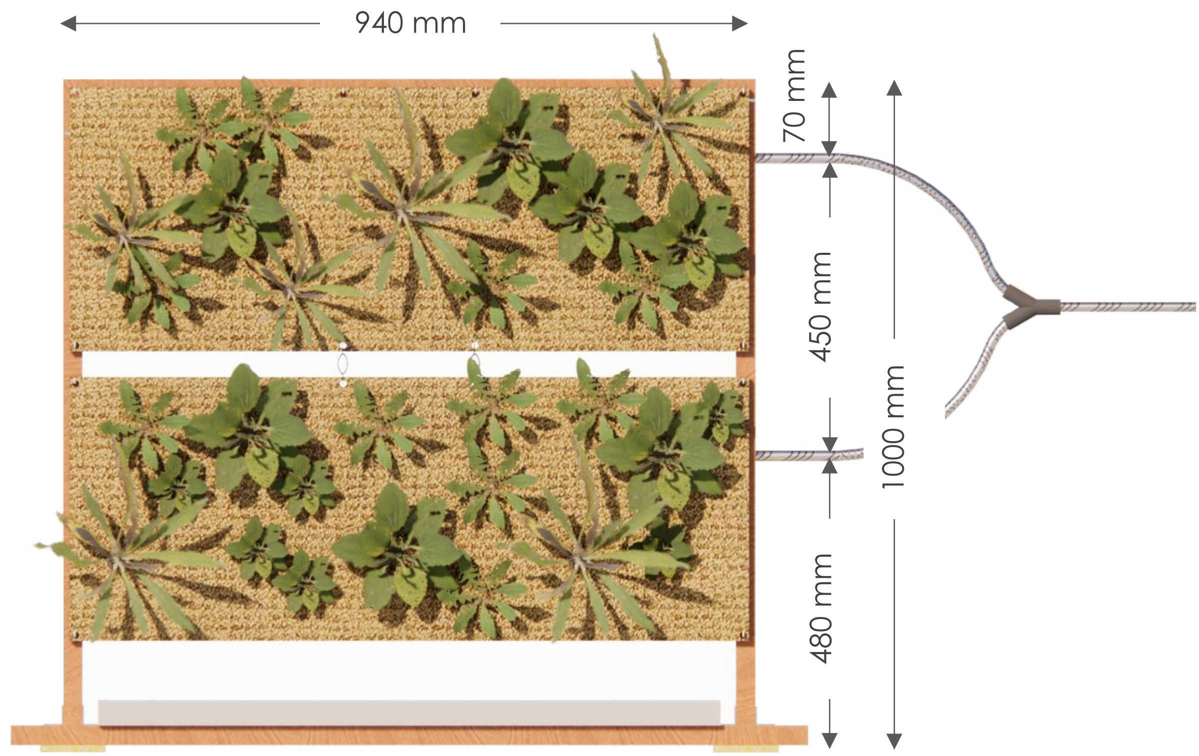


Figure 4.6: *Front side of the model (own work)*

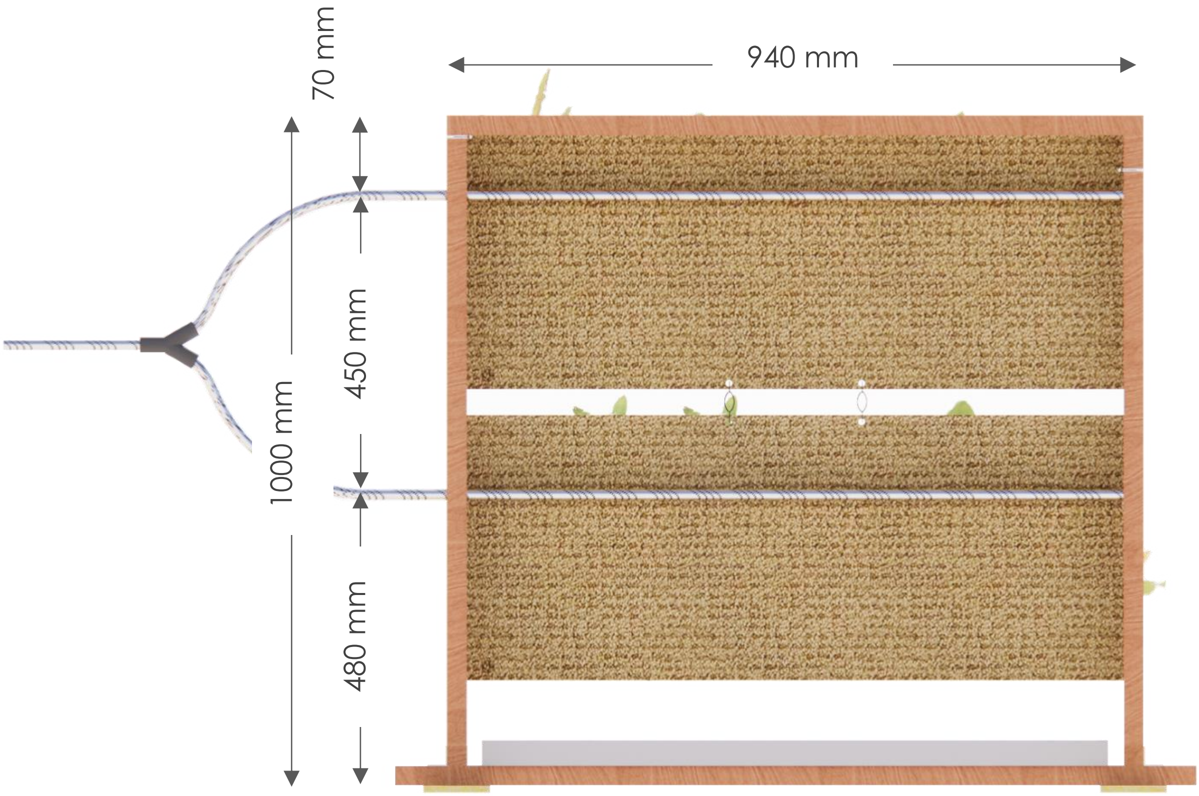


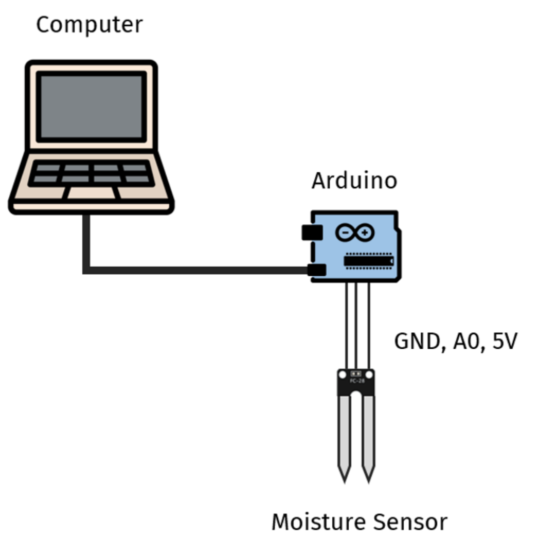
Figure 4.7: *Back side of the model (own work)*

Measure equipment

One of the equipment used for the measurements are moisture sensors. The sensors work based on conductivity. The measurements are controlled and processed by means of a single-board computer. The single-board computer can be controlled by means of a software on the computer. In this software, a python script can be created that controls the sensors for measurements. It is important for the sensors that they are correctly calibrated. The calibration procedure that has been performed is explained in chapter 4.1. Table 4.1 shows the specifications of the moisture sensors and single-board computer.

Table 4.1: *Product specifications of the moisture sensors (Dfrobot, n.d.)*

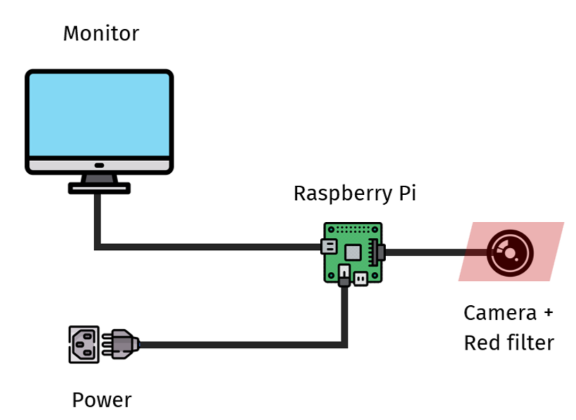
SPECIFICATIONS	
Single-board computer	Elegoo UNO R3 Compatible with Arduino software
Sensors	Dfrobot analog soil moisture sensor V2
Power supply	3.3V or 5V
Output voltage signal	0 ≈ 4.2V
Size	60 x 20 x 5 mm
Software	Arduino IDE 2.0.4
Python script:	See appendix D



Another measure equipment that is used is the NDVI camera. The camera consists of two main components. This is a Raspberry Pi (single-single board computer) and a High quality camera. The Raspberry Pi is connected to a monitor and keyboard that controls the single-board computer. The camera is equipped with a red colour filter. As explained in chapter 2.2, reflected red light from plants is absorbed. The Raspberry Pi is equipped with a script with which the camera can be controlled. This script can be found in appendix D of this report. The specifications and a schematic drawing of the raspberry Pi connection can be found in table 4.2.

Table 4.2: *Product specifications of the NDVI camera (Elektronica Voor Jou, n.d.)*

SPECIFICATIONS	
Single-board computer	Raspberry Pi 4B + 16 GB memory card
Camera	C/CS Mount HQ Camera + HQ lens 16 mm 10 mp
Filter	Red color filter
Python script:	See appendix D



In addition to the sensors, a thermal camera is used to provide insight into the water content. A professional thermal camera is used for this measurement. This is a thermal camera from Flir. The camera has a range of -20 °C to 400 °C (Gereedschapverhuur, n.d.). In addition, the camera has an emissivity correction of 0.1 to 1.0. This is important as the results of the thermal image can be affected by reflections. To filter out these reflections so that a reliable image of the surface temperature of the measured objects is obtained, the emissivity can be set on the camera (Fluke, n.d.). During the measurements, the emissivity is set to 0.69 and the temperature range of the captured images is set to 14.5 °C to 31.4 °C. Below are the specifications and an image of the thermal camera shown.

Table 4.3: *Product specifications of the thermal camera (Gereedschapverhuur, n.d.)*

SPECIFICATIONS	
Camera	Flir E5 XT
Resolution	160 x 120 Pixels
Temp. Range	-20 °C - 400 °C
Field of view	45° x 34°
Emissivity correction	0.1 – 1.0 MSX
Accuracy	+- 2 °C
Spectral range	7.5 -13 µm

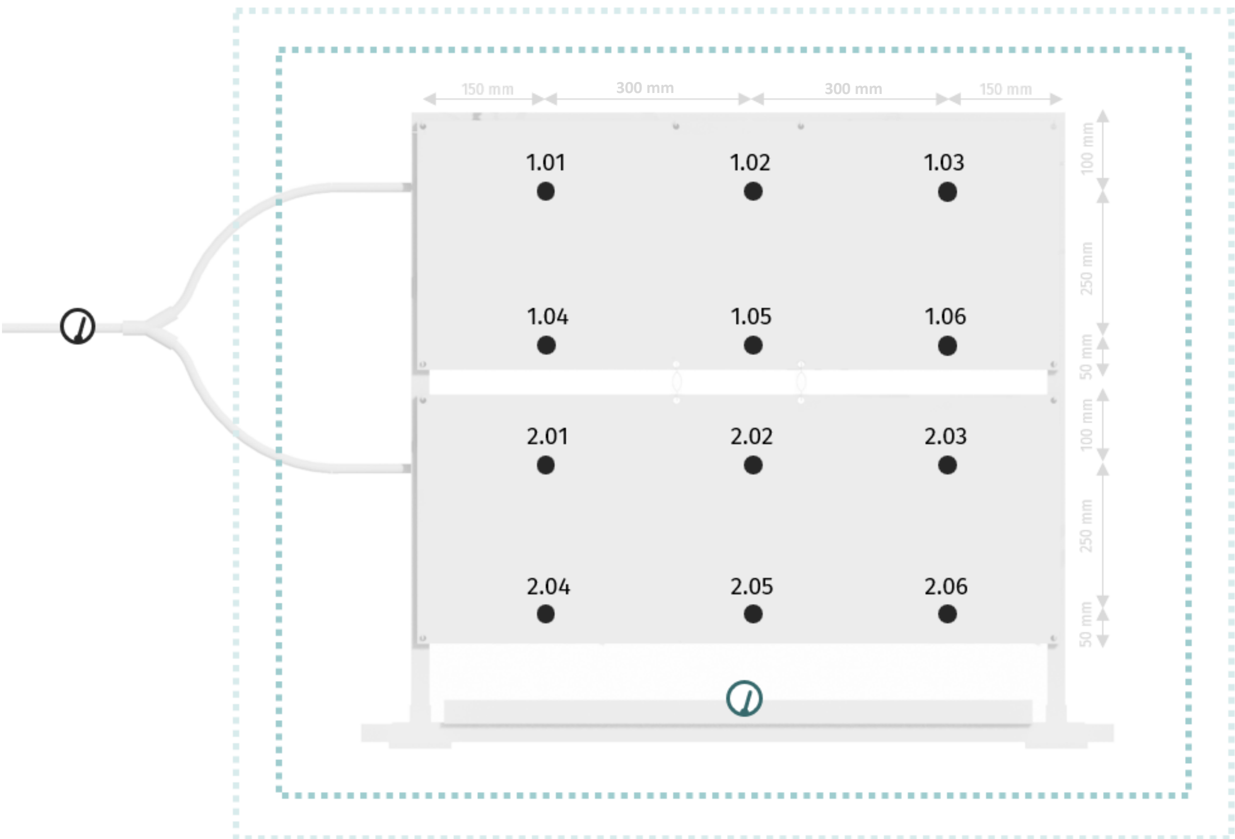
The run-off water is measured by collecting the water in a container that acts as a gutter. This is a homemade wooden container with a plastic layer on the inside. The water from the gutter can be poured into a measuring cup to see how many litres this is. When measuring the run-off water, it is also important to know how much water is supplied, a flow meter is used for this. The flow meter is placed at the water supply point. The water flow meter shows how many litres per minute are supplied. Below are specifications of the water flow meter used in this study.

Table 4.4: *Product specifications of the water flow meter (Coolblue, n.d.)*

SPECIFICATIONS	
Water flow meter	Gardena AquaCount E4
Designated standard	EN ISO 12100
Unit	L/min
Range	2 – 50 L/min
Tolerance	± 5%

4.3 Measurement plan

As mentioned earlier, the plant quality and water content/water distribution are monitored using sensors and cameras. The measurements using the thermal camera and the NDVI camera speak for themselves. The entire model is photographed. With regard to the sensors, the image below shows at which points on the model the sensors are placed. The sensors are placed on both mats at the level of the drip lines and at the level of the bottom of the mats. This makes it possible to measure what the moisture content is at the level of the water supply and at the location where the water is likely to accumulate. Furthermore, the water flow is monitored by means of a water flow meter that is attached to the water supply hose and the run-off water is measured by measuring the water content in the gutter. During the research, the difference when the sensors are placed closer together was also examined. To be able to see at what distance the sensors provide reliable information about the water content in the facade, due to the range of the sensors. The location of these extra sensor points and their results can be found in chapter 5.6.



PLANT QUALITY

INFRAGRAM CAMERA [NDVI]

WATER CONTENT

THERMAL CAMERA [°C]

MOISTURE SENSORS [%]

RUN-OFF WATER [L]

WATER FLOW METER [L/MIN]

Figure 4.8: *Measurement plan (Own work)*

In addition to measuring the water content and water distribution, it is also important to measure how these are influenced by certain factors. For this reason, the measurements are performed in different scenarios. The scenarios are based on information from the literature study and interviews. Chapter 2.3 describes which factors influence the water consumption of living walls. These are non-variable factors that cannot be changed during the measurement and variable factors that can be changed during the measurement. The non-variable factors in this measurement are climate, LW-system, plant species and plant density. The variable factors in this measurement are orientation, temperature, relative humidity and shading. Furthermore, the interviews with the companies have shown that there are companies that indicate that there are more factors that can influence the water content and water distribution. These are the water time, water flow and the distance between the emitters. For this reason, it was decided to include these factors in the measurements. However, in the first instance no measurements will be performed under different orientations and shading. Since the model is relatively small, the effect of the orientation and the presence of shading is considered negligible. Nevertheless, these factors are recorded during each measurement to put the results in the right context if necessary. Below is an overview of the measurement scenarios. In test round A, two measurements are performed that serve as a standard from which changes are made in test rounds B, C,D and E in order to measure the effect of these changes. The default measurements from test round A are performed with a water flow of 4 l/min and a water time of 1:30 minutes. In test round B, two measurements are performed with different irrigation capacities of 5 l/min and 6 l/min. In test round C, two measurements are also performed with two different water times of 3:00 minutes and 6:00 minutes. And in Test Round D, two measurements are also performed with adjustments in the dripline. Here a measurement is performed with an emitter spacing of 100 mm and a measurement where the dripline is placed inside the mat rather than behind the mat. Finally, measurements are taken before irrigating. to see what the difference is in a dry state

TEST A *BENCHMARK*

A.01 Default

A.02 Default

TEST B *IRRIGATION CAPACITY*

B.01 5 l/min

B.02 6 l/min

TEST C *IRRIGATION TIME*

C.01 3:00 minutes

C.02 6:00 minutes

TEST D *DRIPLINES AND WATERPIPE*

D.01 Dripline distance 100 mm

D.02 Waterpipe distance 0 mm

TEST E *DRY*

E.01 Before irrigating

Figure 4.9: *Measurement scenarios (own work)*

4.4 External Factors

Chapter 2.3 shows that external factors can play a major role in the water consumption of a living wall. Chapter 2.3 showed that these are factors such as orientation, plant species, Climatic condition, LW system and plant density. It is therefore important to determine these factors during the measurements. External factors can be divided into non-variable factors and variable factors. Non-variable factors are factors that are stable and do not change during measurements. These are shown in table 4.5. Variable factors can differ per measurement and thus influence the results. An overview of the variable measurement is displayed with each measurement in appendix E.

Table 4.5: *Non-variable factors during the measurements (own work)*

NON-VARIABLE FACTORS	
Plant species	Disschidia & Hoya carnosa
Plant density	Very low
Climate	Temperate Maritime Climate (Cfb)
LW system	Pre-seeded mats, from a LW company, attached to a timber frame with hooks

4.5 Limitations

Since these measurements are not performed on a real living wall system, but only on a replica, there are limitations. Because the pre-planted mats were received relatively late, there was not enough time to wait until the plants had completely grown out of the mats. As a result, the measurements were carried out on Living wall mats without the presence of plants. The presence of plants could possibly influence the results, because plants themselves absorb water and that plants themselves can act as shading on the mats. Nevertheless, pre-grown plants are hung on the mat in order to carry out measurements that are as realistic as possible. In addition, the back of the model is open, exposing the back of the mat to the outside air. This may mean that the influence of the orientation relative to the sun is smaller. Because if you orient the model towards the north, the sun can still shine against the mat through the back of the model. To exclude this limitation as much as possible, an attempt was made to position the living wall against a closed construction, such as a wall or fence. But it is still possible that the effect of the orientation will be smaller than with a real living wall. Another limitation is the height of the model. Compared to real living wall systems, the model is relatively low. As a result, it is not possible to measure whether the height of a living wall system actually influences water consumption. Another limitation is setting the water supply. Since the water is supplied from a water tap, it is difficult to set the desired amount. There is, however, a water flow meter. This can be used to check what the water supply is and to try to adjust the desired water supply.

05

RESULTS & ANALYSIS

RESULTS AND ANALYSIS

In chapter 5.1 the results of the measurements are presented. In chapter 5.2 to 5.6, these results are analysed in order to draw conclusions. The results from the moisture sensors are looked at in relation to the irrigation time, irrigation capacity and change in driplines. By analysing and comparing the results of the moisture sensors, findings can be made regarding the water distribution and conclusions can be drawn regarding causes that lead to a higher or lower moisture content. Furthermore, the images made by the NDVI camera and thermal camera are analysed. Based on these images, analyses are made with regard to the plant quality and water content of the living wall. Finally, the results of the moisture sensor are compared with those of the NDVI camera and thermal camera to arrive at a correlation. As explained, the type of living wall model and its dimensions can influence the results. For this reason, in collaboration with the company vertical meadow, the moisture sensors have been placed on a living wall in London where measurements have been carried out with the moisture sensors. This is further explained in chapter 5.7.

5.1 Overview

During the measurements the NDVI camera, thermal camera and the moisture sensors were used. In addition to this, the run-off water was also measured. In order to analyse the results as well as possible, all measurements and all measuring methods were carried out both with and without the presence of plants. The plants were manually added to the mat during each measurement. The measurements were carried out on different days because each measurement can only be carried out after the mats are dry. The NDVI images, Thermal images, moisture sensor results and measured run-off water can be found in Appendix E of this report. In chapter 5.2 to 5.6 these images and measured values are analysed and compared. Below is an overview of the measurements that have taken place.

Table 5.1: *Overview of all measurements (own work)*

Measurement	$T_{outdoor}$*	Humidity*	Orientation	Waterflow	Irrigation time	+Plants	- Plants
A.01	13 °C	62 %	East	4 l/min	1:30 min	●	●
A.02	15 °C	47 %	East	4 l/min	1:30 min	●	●
B.01	16 °C	44 %	East	5 l/min	1:30 min	●	●
B.02	16 °C	44 %	East	6 l/min	1:30 min	●	●
C.01	14 °C	49 %	East	4 l/min	3:00 min	●	●
C.02	13 °C	49 %	East	4 l/min	6:00 min	●	●
D.01	11 °C	56 %	East	4 l/min	1:30 min	●	●
D.02	12 °C	56 %	East	4 l/min	1:30 min	●	●
E.01	15 °C	50 %	East	-	-	●	●

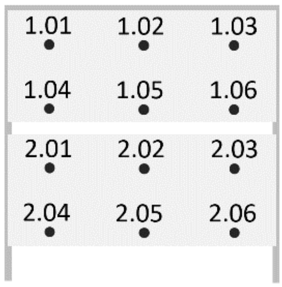
**temperature and humidity according to weather.com*

Table 5.2 shows the results of the moisture sensors. As mentioned earlier in this report, the moisture sensors have a range of 0 to 756. A value of 756 was measured in a cup of water. The table below shows that large differences are measured between different measurement scenarios. These results are further analysed in chapter 5.2.

Table 5.2: *Overview of the results from the moisture sensors (own work)*

Moisture sensor results									
Sensor	A.01	A.02	B.01	B.02	C.01	C.02	D.01	D.02	E.01
1.01	76	295	178	192	186	346	277	263	0
1.02	88	266	370	349	177	462	370	310	0
1.03	85	241	135	279	163	363	290	232	0
1.04	140	321	513	605	230	609	487	546	0
1.05	190	532	622	669	361	645	516	470	0
1.06	174	521	508	593	348	632	505	617	0
2.01	303	350	303	361	326	532	426	323	0
2.02	314	309	174	330	312	370	296	255	0
2.03	309	255	156	673	282	313	250	260	0
2.04	483	552	578	631	518	651	520	604	0
2.05	502	491	545	626	497	613	490	436	0
2.06	525	479	449	625	502	575	460	327	0

Location sensors:



Tables 5.3 and 5.4 provide an overview of a number of measurements that were made with the thermal camera and NDVI camera. These images were taken in the presence of plants and after irrigating. The thermal images and NDVI images without the presence of plants, also in a dry state, can be found in appendix E of this report. These tables clearly show that the thermal camera is able to measure changes in water content and water distribution. At first glance, the NDVI images also seem to tell something about the water content and water distribution. The images taken with the NDVI camera were uploaded and converted with the *infragram.org* online tool. With this online tool, images from which the NIR light has been captured can be converted into an NDVI image. For the thermal images, the scale for all images is set to 14.5 °C – 31.4 °C. In chapter 5.4 to 5.6 these images are further analysed to see if this is a reliable monitoring method for this.

Table 5.3: *Overview of the results from the thermal camera (own work)*

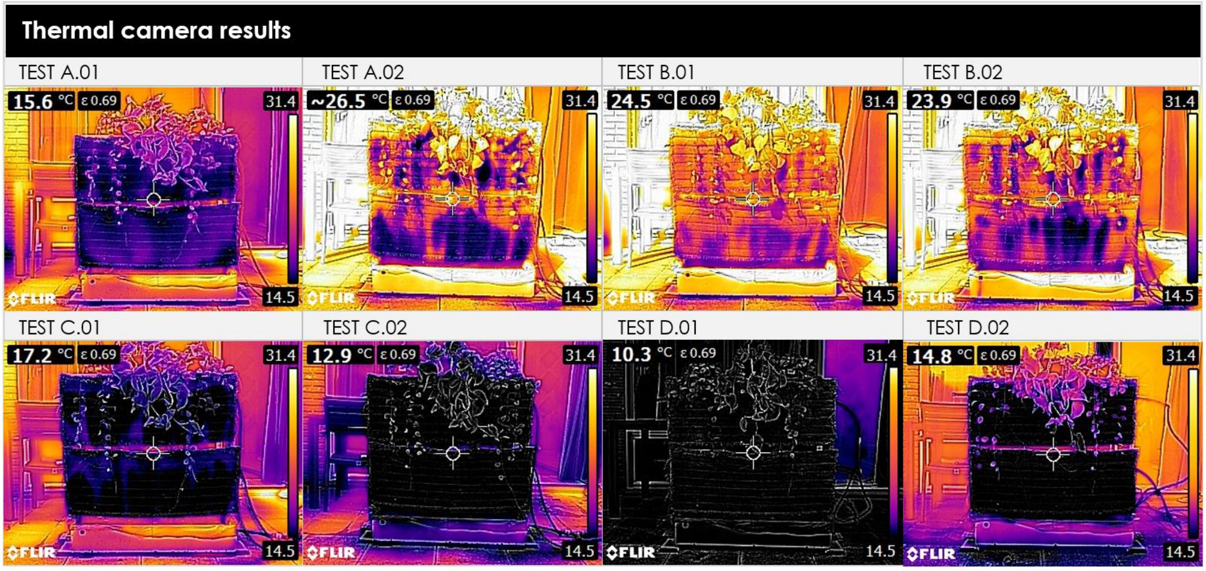
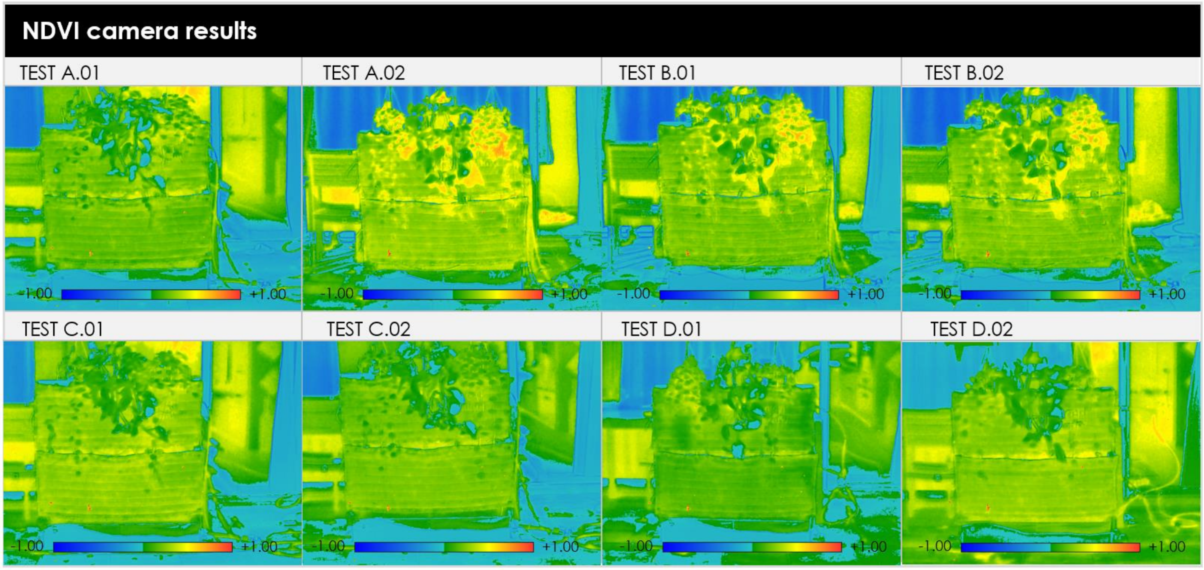


Table 5.4: *Overview of the results from the NDVI camera (own work)*



5.2 Moisture sensors

In test B, measurements were done in relation to the irrigation capacity. In test A, the moisture content was measured at an irrigation capacity of 4 l/min with an irrigation time of 1:30 minutes. In test B.01 the irrigation capacity has been increased to 5 l/min and in test B.02 the irrigation capacity has been increased to 6 l/min. From table 5.5 it can be concluded that in general a higher moisture value is measured with a higher irrigation capacity. This can be seen especially between measurements B.01 and B.02. Between measurement A and B.01, less moisture content is measured in a number of places, despite the fact that most sensors measure an increase. If you look at the location of the sensors, it can be concluded that a drop in moisture content is mainly measured on the first and third row. These are the tops of the mats. This may mean that at the first increase of 1 l/min, the water in the mats becomes too much and sinks more downwards. This effect is only visible with an irrigation capacity of 5 l/min. With an irrigation capacity of 6 l/min, an increase in moisture content is measured throughout the mats. From this it can be concluded that an irrigation capacity of 6 l/min is so high that a high moisture content is measured despite the water sinking downwards. It can be concluded from this that a higher water capacity does not necessarily mean that a higher moisture content is measured. This will mainly be determined by the water retention capacity of the mat. A lower irrigation capacity can lead to a more uniform water content and water distribution because the mat has enough water retention capacity to hold the water. A more uniform water content and water distribution means that the difference between the measured values of the various sensors is smaller. This can also be seen in figure 5.4.

Table 5.5: *Relation between test A and test B (own work)*

Sensor results irrigation capacity					
TEST A*		TEST B.01		TEST B.02	
Sensor	Value	Value	Difference	Value	Difference
1.01	186	178	- 4 %	192	+ 8 %
1.02	177	370	+ 109 %	349	- 6 %
1.03	163	135	- 17 %	279	+ 107 %
1.04	230	513	+ 123 %	605	+ 18 %
1.05	361	622	+ 72 %	669	+ 8 %
1.06	348	508	+ 46 %	593	+ 17 %
2.01	326	303	- 7 %	361	+ 19 %
2.02	312	174	- 44 %	330	+ 90 %
2.03	282	156	- 45 %	673	+ 331 %
2.04	518	578	+ 12 %	631	+ 9 %
2.05	497	545	+ 10 %	626	+ 15 %
2.06	502	449	- 11 %	625	+ 39 %

*Values are based on averages between A.01 and A.02

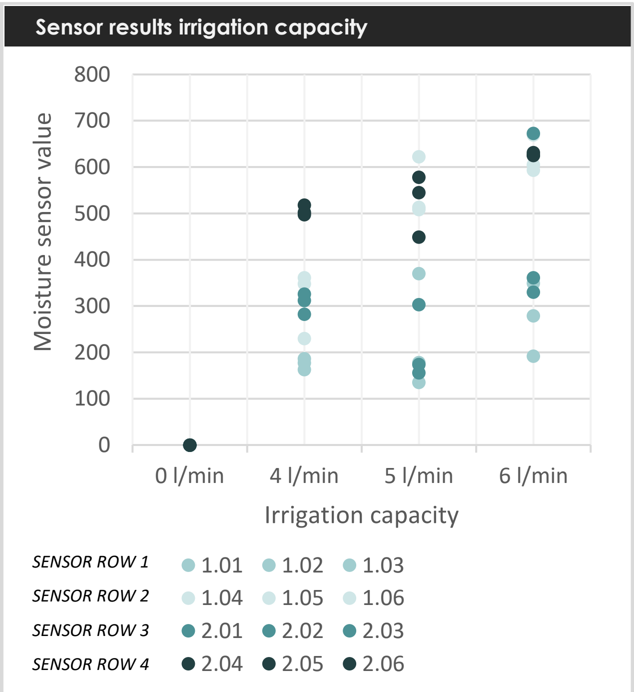


Figure 5.1: *Result from moisture sensors from test A and B (own work)*

In test C, measurements were done in relation to the irrigation time. In test A, the moisture content was measured at an irrigation time of 1:30 minutes with a water flow of 4 l/min. In test C.01 the water time has been increased to 3:00 minutes and in test C.02 the water time has been increased to 6:00 minutes. From table 6.2 it can be concluded that a higher moisture value is measured with a longer irrigation time. This makes sense and was no different than expected. Nevertheless, a lower value was measured at sensor 2.02 between irrigation time 1:30 minutes and 3:00 minutes. This can have several causes. It could simply be an error in the measurement, but it could also be that the water has dropped a lot in that time, so that a lower value is measured. A more important conclusion that can be drawn from table 5.6 is that the measured values of 3:00 minutes increase enormously compared to 1:30 minutes. Much more than the values between 3:00 minutes and 6:00 minutes. It can be concluded from this that the moisture value rises strongly in the beginning and rises less quickly over time. This makes sense, because the mat reaches its water retention capacity over time and more water drips through than is held by the mats. This can also be seen in figure 5.2.

***Table 5.6:** Relation between test A and test C (own work)*

Sensor results irrigation time					
TEST A*		TEST C.01		TEST C.02	
Sensor	Value	Value	Difference	Value	Difference
1.01	186	313	+ 68 %	346	+ 10 %
1.02	177	431	+ 144 %	462	+ 7 %
1.03	163	339	+ 108 %	363	+ 7 %
1.04	230	522	+ 127 %	609	+ 17 %
1.05	361	629	+ 74 %	645	+ 3 %
1.06	348	646	+ 86 %	632	- 2 %
2.01	326	478	+ 47 %	532	+ 11 %
2.02	312	255	- 18 %	370	+ 45 %
2.03	282	305	+ 8 %	313	+ 3 %
2.04	518	648	+ 25 %	651	0 %
2.05	497	523	+ 5 %	613	+ 17 %
2.06	502	530	+ 6 %	575	+ 8 %

*Values are based on averages between A.01 and A.02

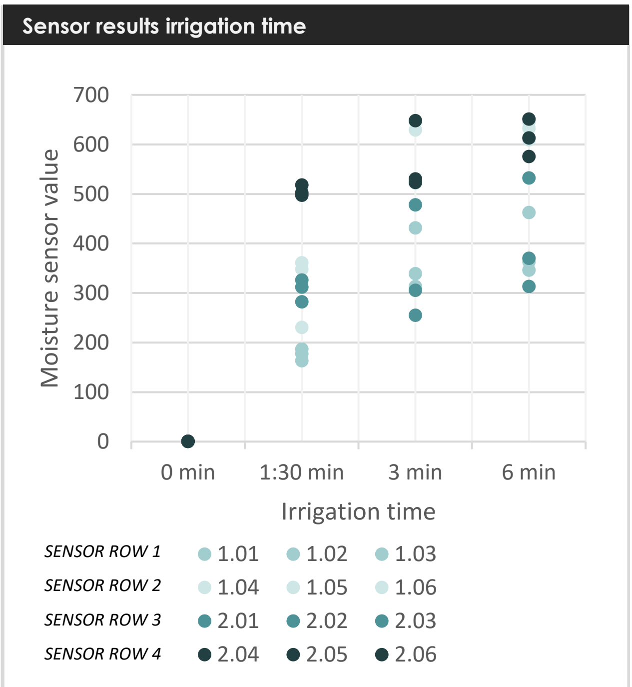


***Figure 5.2:** Result from moisture sensors from test A and C (own work)*

In test D, measurements were made where changes were made to the waterpipes compared to measurement A. In measurement D.01 the distance between the emitters has been shortened from 200 mm to 100 mm and in measurement D.02 the distance from the waterpipes to the mats has been shortened to 0 mm. The waterpipe was placed in the mat instead of behind the mat during measurement D.02. The results are compared in table 5.7 with the results from the default measurements of A. From the table below it can be concluded that at D.01 there is an increase in water content over the entire facade. An interesting observation is that the increase mainly takes place at the upper mat. These are sensors 1.01 to 1.06. The measurements of D.02 have shown that, in particular, less moisture content is measured compared to measurement D.01. This was against expectations, because it seems more logical that the water is absorbed more by the facade when it is placed in the slab. This could possibly have to do with the fact that the water is less distributed over the facade when the water pipe is directly in the mat.

Table 5.7: *Relation between test A and test D (own work)*

Sensor results irrigation pipes and emitters					
TEST A*		TEST D.01		TEST D.02	
Sensor	Value	Value	Difference	Value	Difference
1.01	186	277	+ 49 %	263	- 5 %
1.02	177	370	+ 112 %	310	- 16 %
1.03	163	290	+ 78 %	232	- 20 %
1.04	230	487	+ 112 %	546	+ 12 %
1.05	361	516	+ 43 %	470	- 9 %
1.06	348	505	+ 45 %	617	+ 22 %
2.01	326	426	+ 31 %	323	- 24 %
2.02	312	296	- 5 %	255	- 14 %
2.03	282	250	- 11 %	260	+ 4 %
2.04	518	520	+ 0 %	604	+ 16 %
2.05	497	490	+ 1 %	436	- 11 %
2.06	502	460	- 8 %	327	- 29 %

*Values are based on averages between A.01 and A.02

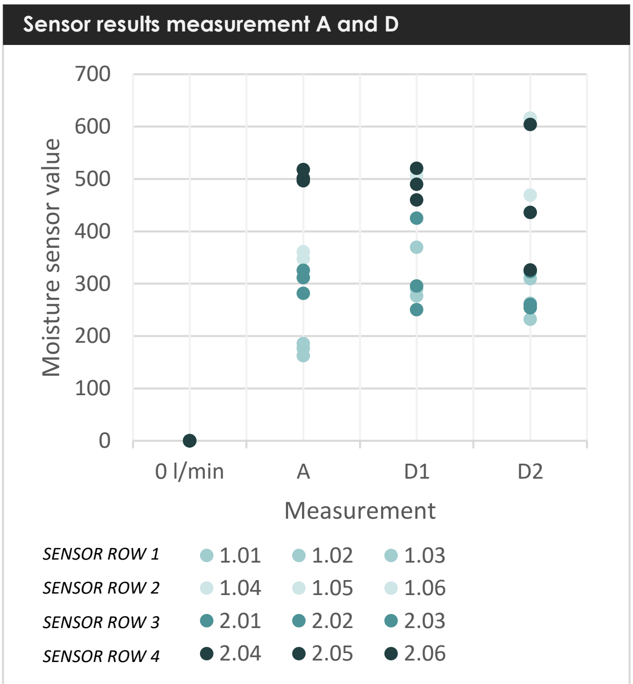


Figure 5.3: *Result from moisture sensors from test A and D (own work)*

Based on the measured values with the moisture sensor, information can be obtained about the water uniformity and water distribution. Table 5.2 lists all measured values of the moisture sensors for each measurement. This makes it possible to see what the range of the measured values is and what the average measured values are. When the range is as small as possible, this means that the results of the moisture sensors are close together and therefore that the water is evenly distributed over the mats. From the table below it can be concluded that the water uniformity is the best with measurement D.01 where the distance between the emitters was shortened to 10 centimetres. measurement C.02 has the second best water uniformity. This is the measurement where a water flow of 4 l/min is applied at an irrigation time of 6:00 minutes. The worst water uniformity was measured at measurement B.01 and B.02. Here a water flow of 5 l/min and 6 l/min is maintained at a water time of 1:30 minutes. Measurement A.01 and A.02 were both performed with a water flow of 4 l/min with an irrigation time of 1:30 minutes. Nevertheless, there is a relatively large difference between the uniformity. Measurement A.01 was performed on a different day than measurement A.02. It could be that the wind or other external factors influenced the results. The sensors have a small range of about 2-10 centimetres. If the mat or water pipe only moves a little, it could be that other values are measured.

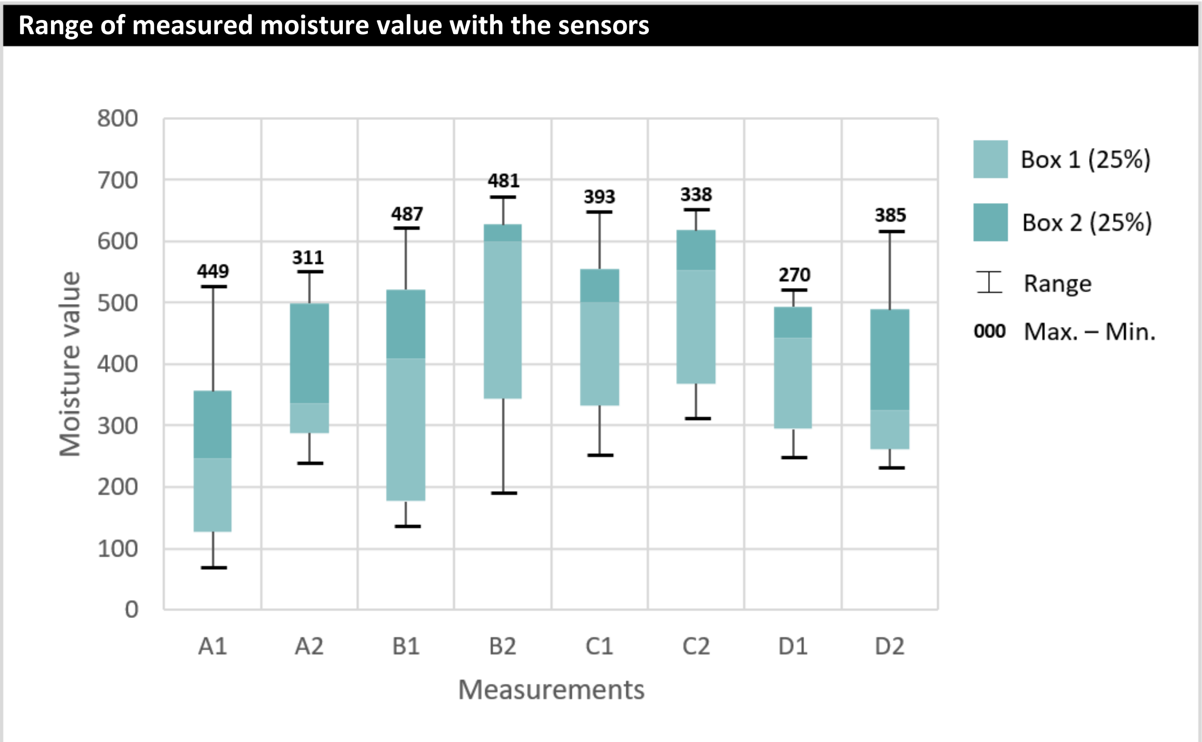


Figure 5.4: *Range of measured moisture sensor results (own work)*

5.3 Run-off water

During the tests, the run-off water was measured and the water flow was recorded. Table 5.8 provides an overview of this. By measuring these two factors, it can be determined how much of the supplied water is absorbed by the mats that technically could be consumed by the plants. This is determined by calculating how much water has been used in total based on the water flow and the water time. The total water used can be subtracted from the run-off water, the absorbed water then remains. This can then be expressed in percentages to indicate the water retention.

Table 5.8: *Overview of measured run-off water in relation to the water capacity and water time (own work)*

Water retention comparison					
Measurement	Water flow	Water time	Total water	Run-off water	Water retention
A.01	4 L/min	1:30 min	06.0 L	04.9 L	18.3 %
A.02	4 L/min	1:30 min	06.0 L	04.3 L	28.3 %
B.01	5 L/min	1:30 min	07.5 L	05.5 L	26.7 %
B.02	6 L/min	1:30 min	09.0 L	07.5 L	16.7 %
C.01	4 L/min	3:00 min	12.0 L	07.0 L	41.7 %
C.02	4 L/min	6:00 min	24.0 L	18.9 L	21.3 %
D.01	4 L/min	1:30 min	06.0 L	4.1 L	31.7 %
D.02	4 L/min	1:30 min	06.0 L	3.8 L	36.7 %

In table 5.8 and figure 5.5 it can be seen that the water retention increases at a water time of 3:00 minutes compared to 1:30 minutes, but decreases again at a water time of 6:00 minutes. This could mean that the mats have reached their water retention capacity after 3:00 minutes, so that the extra water at 6:00 minutes is mainly collected as run-off water. This confirms the hypothesis that a higher irrigation capacity does not necessarily mean that more water is consumed by the mats. The water retention capacity of the mats ensures that there is a limit to how much water is consumed by the mats.

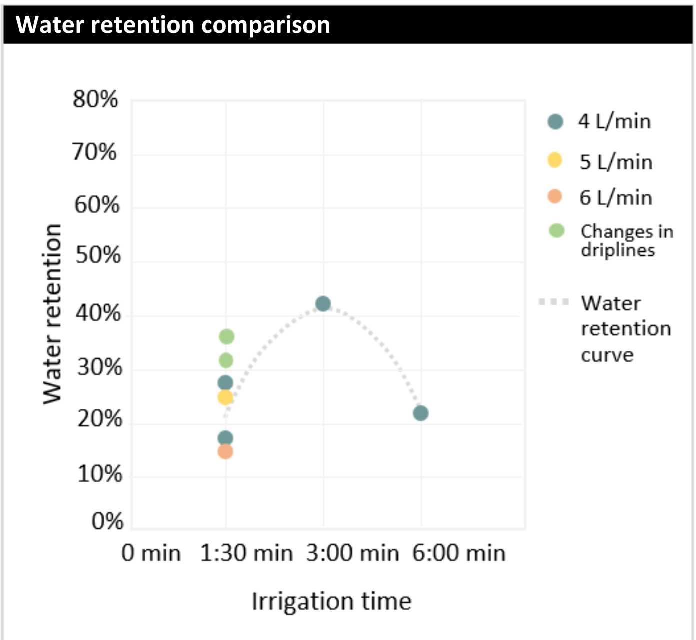


Figure 5.5: *Overview of measured run-off water in relation to the water capacity and water time (own work)*

5.4 NDVI camera

The NDVI images shown in table 5.4 showed that the images made with the NDVI camera can be interesting in obtaining information about plant quality as well as water content. Since the plants do not grow out of the mat, but are only placed in front of the mat, this does not say anything about the plant quality in relation to the water content. However, it can be analysed whether the images actually provide reliable information about the water content. This can be done in a simple way, using Adobe photoshop software. Images can be loaded into this software and pixels can be filtered out. Then the remaining pixels can be counted. In this case, all pixels that do not represent water are filtered out, leaving only the pixels that represent water in the image. In photoshop, colour #d7ef00 is held as representative of water. Of course, a range is set so that pixels that are slightly lighter or darker than this colour are also included. Table 5.9 shows an overview of the number of pixels.

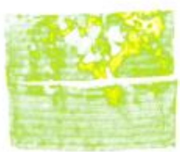
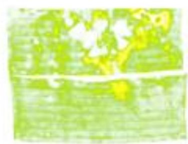
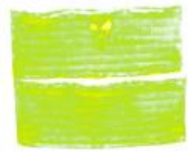
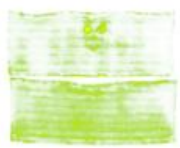
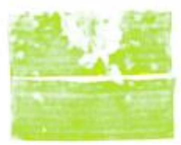
Table 5.9: *Overview of amount of pixels that represent water for each image (own work)*

Amount of pixels that represent water			
	Without plants	With plants	Difference
TEST A.01	25.822	24.741	4.4%
TEST A.02	142.795	99.184	44%
TEST B.01	150.336	55.802	169.4%
TEST B.02	144.035	66.710	115.9%
TEST C.01	26.679	9.334	185.8%
TEST C.02	127.094	20.886	508.5%
TEST D.01	26.847	6.154	336.3%
TEST D.02	44.183	68.940	56%
BEFORE IRRIGATING	22.250	30.707	38%

From the table above it can be concluded that there is a big difference in the number of pixels, which represent water, between images with and without the presence of plants. This is to be expected in advance because the NDVI camera is normally used to record plant quality and not the water content. So it makes sense that the presence of plants has a major influence on the images. However, further research needs to be done to ensure that the NDVI camera provides reliable information about the water content and water distribution in the absence of plants. For this, the results of the NDVI pixel analysis must be compared to the results of the moisture sensors to see if there is a correlation. This is done in chapter 5.6.

Table 5.10 shows an overview of the filtered NDVI images. The pixels that represent the water content, including the number of pixels, are shown here for each image. In chapter 5.6, the NDVI images are correlated with the results from the moisture sensor. Nevertheless, interesting conclusions can be drawn from the table below. It can be stated in advance that the NDVI images do not provide reliable information about the water content in the presence of plants. This can be clearly seen in the table below. It is interesting to see that, in the absence of the plants, there does seem to be a reliable picture of the water content and water distribution. We can't know for sure until we compare the moisture sensor results with the NDVI images. In chapter 5.6 it is analysed whether the results of the moisture sensor agree with the NDVI images without plants.

Table 5.10: *Overview of filtered pixels from the NDVI images (own work)*

Filtered NDVI images			
TEST A.01 With plant	TEST A.01 Without plant	TEST A.02 With plant	TEST A.2 Without plant
24.741 pixels 	25.822 pixels 	99.184 pixels 	142.795 pixels 
TEST B.01 With plant	TEST B.01 Without plant	TEST B.02 With plant	TEST B.02 Without plant
55.802 pixels 	150.336 pixels 	66.710 pixels 	144.035 pixels 
TEST C.01 With plant	TEST C.01 Without plant	TEST C.02 With plant	TEST C.02 Without plant
9.334 pixels 	26.679 pixels 	20.886 pixels 	127.094 pixels 
TEST D.01 With plant	TEST D.01 Without plant	TEST D.02 With plant	TEST D.02 Without plant
6.154 pixels 	26.847 pixels 	68.940 pixels 	44.183 pixels 
Before irrigating with plant	Before irrigating without plant		
30.707 pixels 	22.250 pixels 		

5.5 Thermal camera

During the measurements, thermal images were made with both the presence of plants and the absence of plants. As with the NDVI images, the images have been analysed by filtering the pixels that represent water. This can be done with Adobe Photoshop software. In photoshop, colour #090d4d is held as representative of water. Of course, a range is set so that pixels that are slightly lighter or darker than this colour are also included. Table 5.11 shows an overview of the number of pixels. Despite the fact that every effort has been made to have all measurements take place under the same climatic conditions, the effect of the outside temperature is still visible. For example, the thermal image of Test D.01 shows that the water content is difficult to read because it has the same temperature as the outside temperature at that moment. This can be seen in table 5.12. In order to be able to compare the images properly, a different colour has been used for these measurements in Photoshop that is representative of the water. This is colour #232b2d.

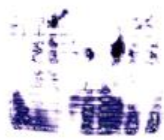
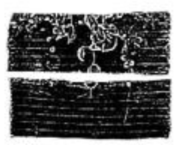
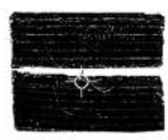
Table 5.11: *Overview of amount of pixels that represent water for each image (own work)*

Amount of pixels that represent water			
	Without plants	With plants	Difference
TEST A.01	2.609	6.920	165.2%
TEST A.02	3.180	4.315	35.7%
TEST B.01	5.022	2.393	109.0%
TEST B.02	2.629	6.363	142%
TEST C.01	21.742	14.776	47.1%
TEST C.02	25.678	21.965	16.9%
TEST D.01	20.088	19.898	1%
TEST D.02	20.169	18.995	6.2%
BEFORE IRRIGATING	0	0	0%

From table 5.11 it can be concluded that the difference in pixels that represent water between the measurements with and without plants is relatively small, except for a number of outliers. This could be explained by the fact that the outside temperature can influence the thermal images. Although attempts have been made to carry out the measurements under the same climatic conditions, there are still differences in outside temperature during the measurements. The outliers mainly occur in measurements carried out on warmer days of around 19° C compared to the other measurements carried out at around 13° C. The moment it is warmer outside, and the living wall is exposed to a higher sun radiation, there is a greater contrast on the mats between warm and cold. As a result, the influence of factors such as the presence of plants can have a greater influence. Conversely, the small differences can be explained by the fact that these measurements were carried out on the colder days, so that the plants have the same low temperature as the plants, so that they get the same pixel colour as the water in the mats. Finally, a possible explanation could be that the water content of the living wall is so high during the measurements with small differences that the presence of the plants forms minimal to no obstacle for the thermal camera. For now, these are assumptions and possible theories. In chapter 5.6 these results are related to the results of the moisture sensors in order to draw better conclusions.

Table 5.12 shows an overview of the filtered thermal images. The pixels that represent the water content, including the number of pixels, are shown here for each image. Interesting conclusions can be drawn from the table below. The fact that no pixels are measured in the dry situation is a good sign. This means that when the mats are dry they have an uniform temperature and that temperature differences are only measured when water is added. It can also be clearly seen that the outside temperature has a major influence on the measured result. Measurements A and B were carried out at outside temperatures of 17° C -20° C, while measurements C and D were carried out at outside temperatures of 12° C -15° C. It can be seen that the water content in measurement A and B is more clearly visible because the contrast of the cold water is greater with the rest of the mats. Measurements C and D also measure the water content, but with a less clear contrast, which raises the question of whether the number of pixels gives a reliable picture of the water content at colder temperatures.

Table 5.12: *Overview of filtered pixels from the thermal images (own work)*

Filtered thermal images			
TEST A.01 With plant	TEST A.01 Without plant	TEST A.02 With plant	TEST A.2 Without plant
6.920 pixels 	2.609 pixels 	4.315 pixels 	3.180 pixels 
TEST B.01 With plant	TEST B.01 Without plant	TEST B.02 With plant	TEST B.02 Without plant
2.393 pixels 	5.022 pixels 	6.363 pixels 	2.629 pixels 
TEST C.01 With plant	TEST C.01 Without plant	TEST C.02 With plant	TEST C.02 Without plant
14.776 pixels 	21.742 pixels 	21.965 pixels 	25.678 pixels 
TEST D.01 With plant	TEST D.01 Without plant	TEST D.02 With plant	TEST D.02 Without plant
19.898 pixels 	20.088 pixels 	18.995 pixels 	20.169 pixels 
Before irrigating with plant	Before irrigating without plant		
0 pixels	0 pixels		

It is important to emphasize again that the thermal camera ,initially, is manually set to a fixed range of 14.5 °C – 31.4 °C during the measurements. This is done so that the thermal images can be better compared, the disadvantage of this is that the effect of the outside temperature becomes greater. It is also possible to set the range to 'automatic'. The thermal camera then automatically sets the range based on the measured temperatures at that time. This may make it possible to read the water better. The disadvantage of this would be that the images are difficult to compare with other thermal images because the colour scale is not the same. Figures 5.6 and 5.7 show an example of a thermal image where the camera is set to a fixed range and the same image was taken with the camera automatically determining the range. This concerns measurement D.01. This is the same measurement under the same climatic influences. The only difference is the scale of the temperature.

Figure 5.6: *Measurement D.01 with pre-set scale (own work)*

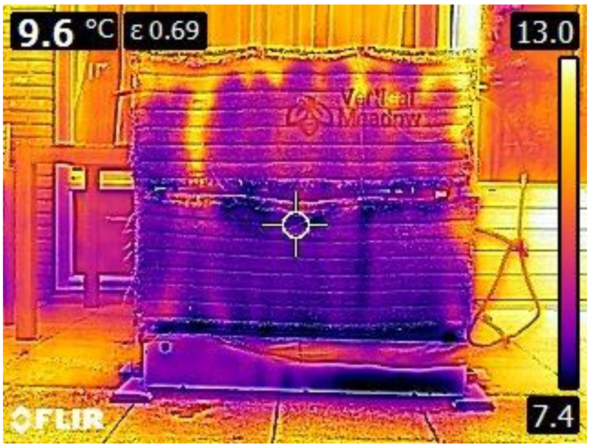


Figure 5.7: *Measurement D.01 with automatically set scale (own work)*

An example is shown below which shows the benefit when the same scale is used. This concerns measurement B.01 and B.02. These measurements were performed under the same climatic conditions and with the same temperature scale. What you see is that it is clearly perceptible what the difference is in water content. As explained, the measurements were initially carried out with a manually set temperature scale. In the course of the research, the images were converted to an automated temperature scale using the FLIR Tool software to see how this affects the reliability of the thermal camera in relation to the moisture sensors. The results of this are shown in chapter 5.6, figure 5.14 and 5.15.

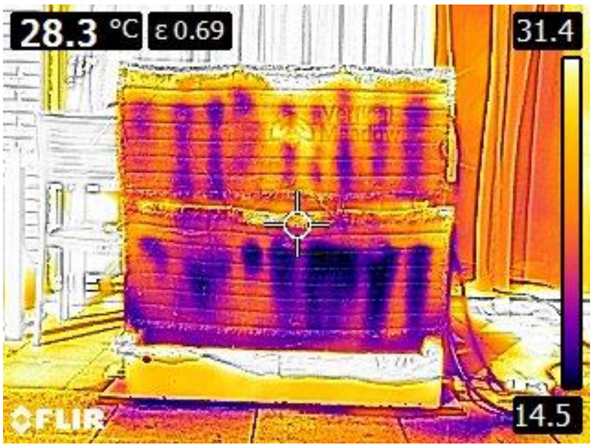


Figure 5.8: *Measurement B.01 with pre-set scale (own work)*

Figure 5.9: *Measurement B.02 with pre-set scale (own work)*

5.6 Correlation

In chapters 5.1 to 5.5 the results of the run-off water, moisture sensors, NDVI camera and thermal camera are presented. In chapter 2.2 it was concluded that these monitoring methods work best and provide reliable input when they are combined. In this chapter the results from different monitoring methods are compared and it is determined whether the measurements indeed provide reliable information when the monitoring methods are combined. The main function of the NDVI camera is to provide insight into plant quality. However, earlier in this study a hypothesis was made that the NDVI camera may also be able to provide insight into the water content and water distribution. The analysis from chapter 5.4, in particular the results from table 5.10, seem to lead to the fact that the NDVI camera does indeed provide insight into the water distribution and water content. Whether the NDVI camera is indeed a reliable measurement method for this, the measured pixels that represent water are compared to the results of the moisture sensors. These are the pixels from Table 5.10 and the moisture values from Table 5.2. Figure 5.10 shows the measured pixels of the NDVI images without plants in relation to the average moisture values per measurement. If the ratio to moisture value and number of pixels for all measurements is reliable, there should be a pattern in the graph. To investigate this, a line has been drawn in the graph that follows the measurements. There is a reliable correlation if this is a line that is linear or growing exponentially with measurements close to the line. Figure 5.11 shows the same principle but of the NDVI images in the presence of plants.

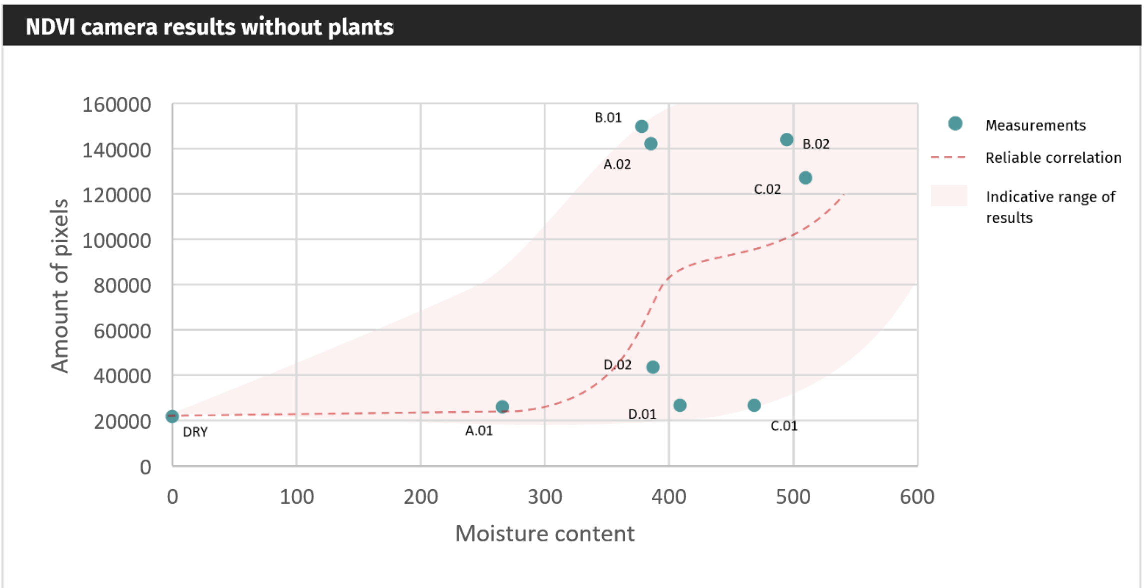


Figure 5.10: *Correlation between moisture sensor results and NDVI camera results without plants (own work)*

From the graph above it can be concluded that the NDVI camera does not provide a reliable picture of the water content. A line is drawn in the graph that follows the measurements. Although the NDVI images seemed to show that they capture water content, the graph shows the opposite. There is no correlation between the number of pixels and the measured moisture content. This can be seen because there is no pattern in the relationship between the measurements. Figure 5.11 shows the situation in the presence of plants. Here you can see that the values, just as in the absence of plants, are not aligned at all and are therefore completely unreliable. This makes sense since the NDVI camera is intended to measure plant quality. Here even lower number of pixels are measured at higher moisture contents. So the presence of plants completely overshadows the water content.

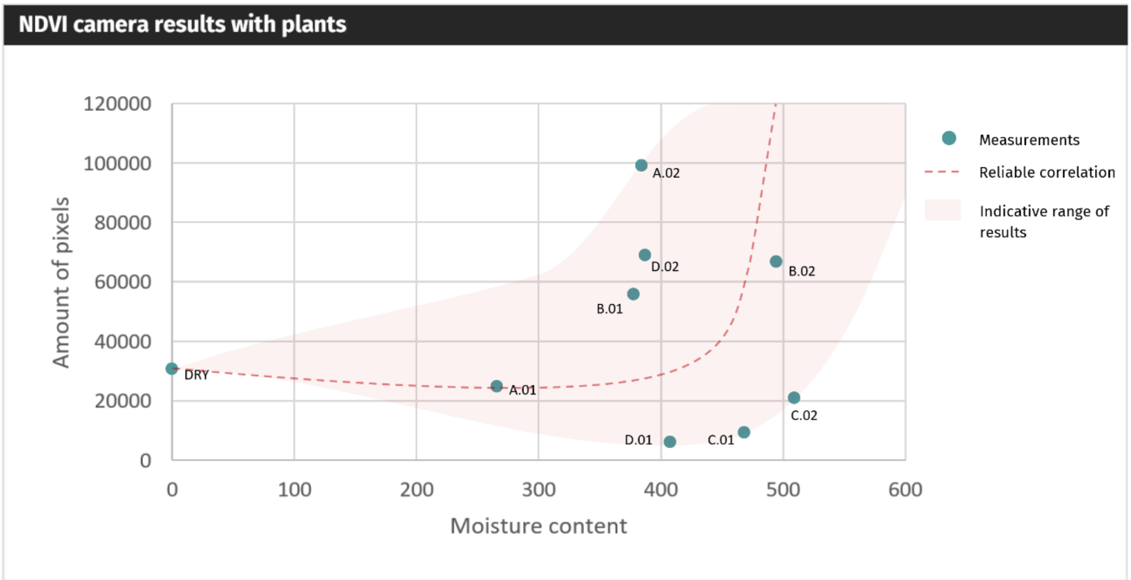


Figure 5.11: *Correlation between moisture sensor results and NDVI camera results with plants (own work)*

The same method was used to establish the correlation between the moisture values and thermal images. In figure 5.12 and 5.13 these results are shown for thermal images with and without the presence of plants. The number of pixels is influenced by the outside temperature in such a way that two lines are drawn because the ratio between the measurements with an outside temperature of ≈ 12° C deviates from that of ≈ 16° C. Figure 5.12 shows that the values are approximately on the linear line. This means that the values are reliable and that there is a constant correlation between the results of the moisture sensor and the measured pixels. This can be concluded because the linear line means that relatively higher number of pixels are measured at higher moisture contents. Figure 5.13 shows that the lines are no longer linear, which does not necessarily mean that the thermal camera is unreliable. As long as the growth is exponential or linear, so that there is a fixed pattern in the growth. Nevertheless, it can be seen that the measurements deviate somewhat more from the line, which indicates a decrease in reliability in the presence of plants. This means that the reliability decreases in the presence of plants. Nevertheless, they do not deviate extremely from the linear line as with the NDVI camera. It can be assumed that the thermal camera can only be used as a global estimate for the water content and water distribution in the presence of plants and that the thermal camera is only really reliable in the absence of plants.

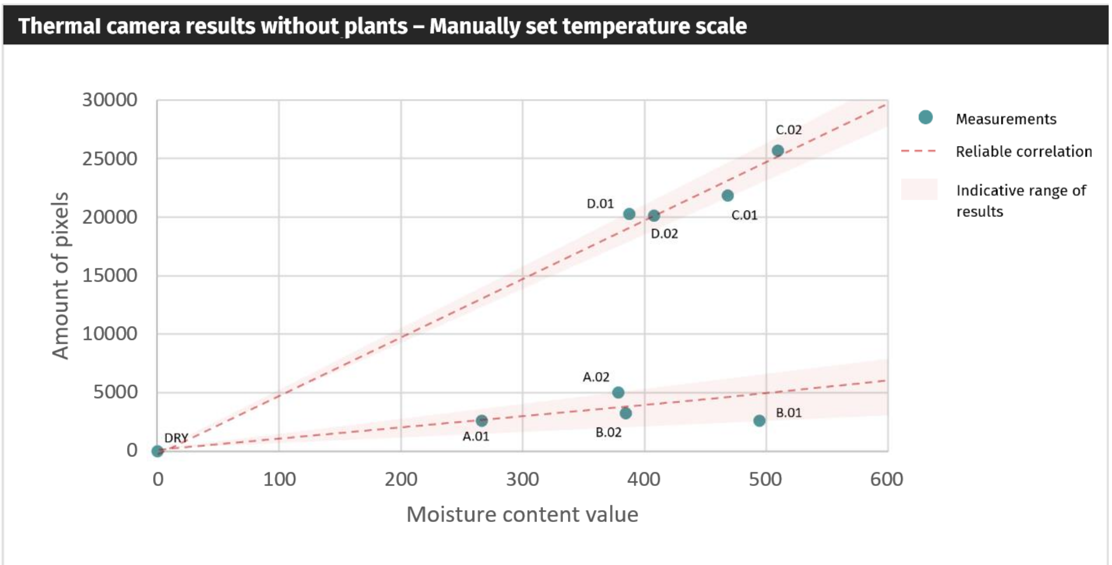


Figure 5.12: *Correlation between moisture sensor results and thermal camera results without plants (own work)*

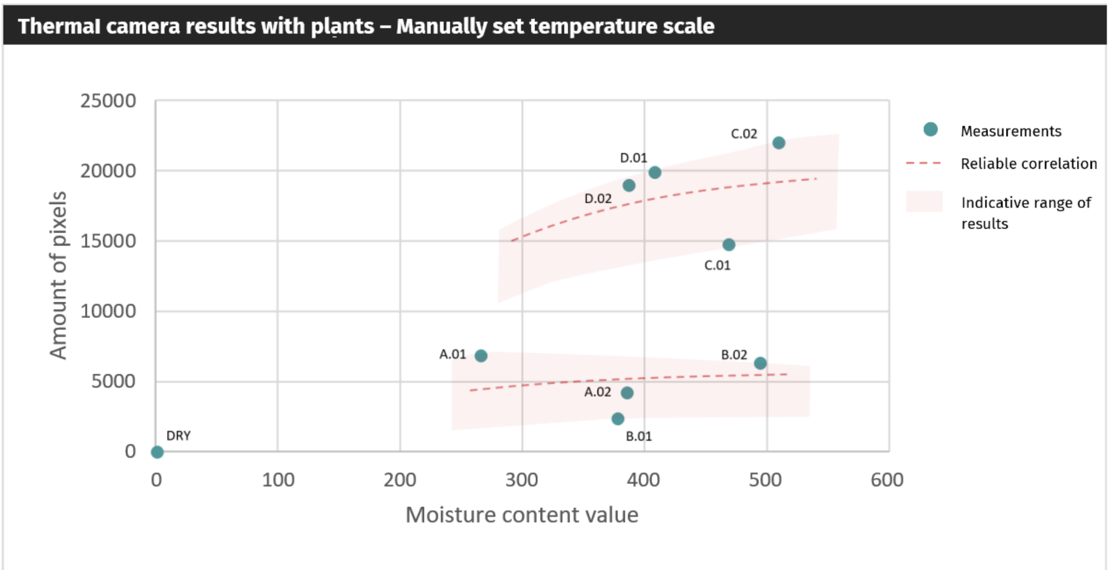


Figure 5.13: *Correlation between moisture sensor results and thermal camera results with plants (own work)*

As indicated in chapter 5.5, the temperature scale of the thermal camera has a major influence on the result. The temperature scale is initially set manually. Later during the research, the temperature scale of the thermal images was converted to 'automatic' using the 'FLIR Tools' software. This has been used to investigate whether more reliable measurements can be made as a result. Figure 5.14 and table 5.13 shows the results of this. The figure below shows the results of the thermal camera with and without plants in relation to the measured sensor results. Pixel colour #000942 is held as representative of water.

Table 5.13: *Overview of amount of pixels (own work)*

Amount of pixels that represent water			
	Without plants	With plants	Difference
TEST A.01	12.485	12.967	3.9%
TEST A.02	10.181	10.865	6.7%
TEST B.01	8.763	10.410	18.8%
TEST B.02	7.870	9.392	19.3%
TEST C.01	12.064	10.483	15.1%
TEST C.02	20.738	18.152	14.2%
TEST D.01	9.621	11.230	16.7%
TEST D.02	11.678	10.686	9.3%
BEFORE IRRIGATING	333	886	166%

Figure 5.14 and 5.15 shows that when the temperature scale of the thermal images is set to 'automatic', they can no longer be compared with each other. The ratios between pixels and moisture content vary so much that no pattern can be found and they deviate greatly from the line that was drawn. When the images are taken in different outside temperatures, they have different temperature scales, so that the water in the facade is always represented by a different pixel colour. It can be seen from table 5.13 that only small differences are measured between the number of pixels between the images with and without plants. This may indicate that the presence of the plants has less effect when the thermal camera is set to 'automatic'.

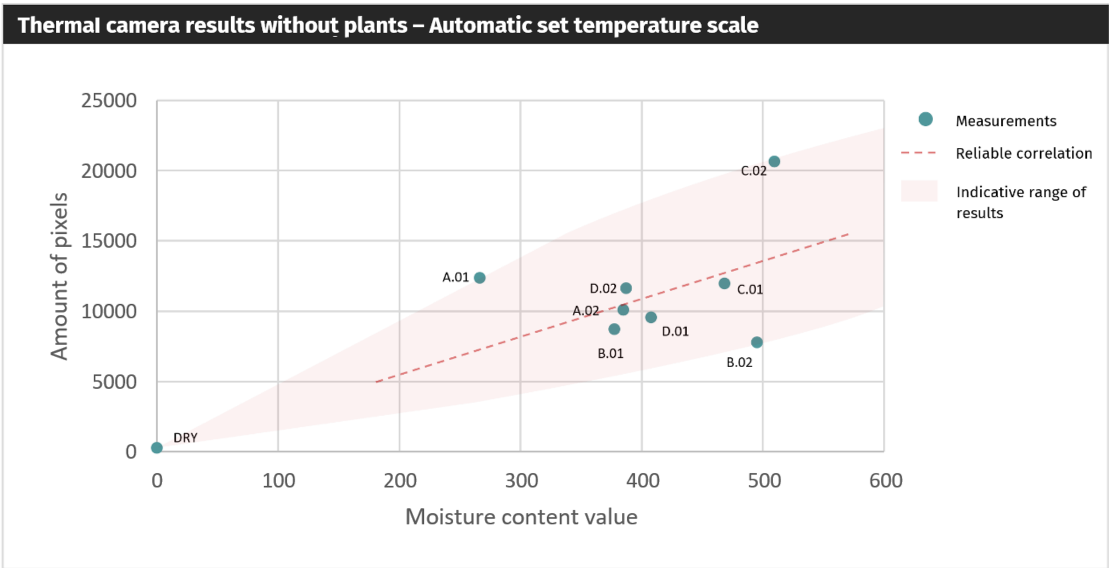


Figure 5.14: *Correlation between moisture sensor results and thermal camera results without plants (own work)*

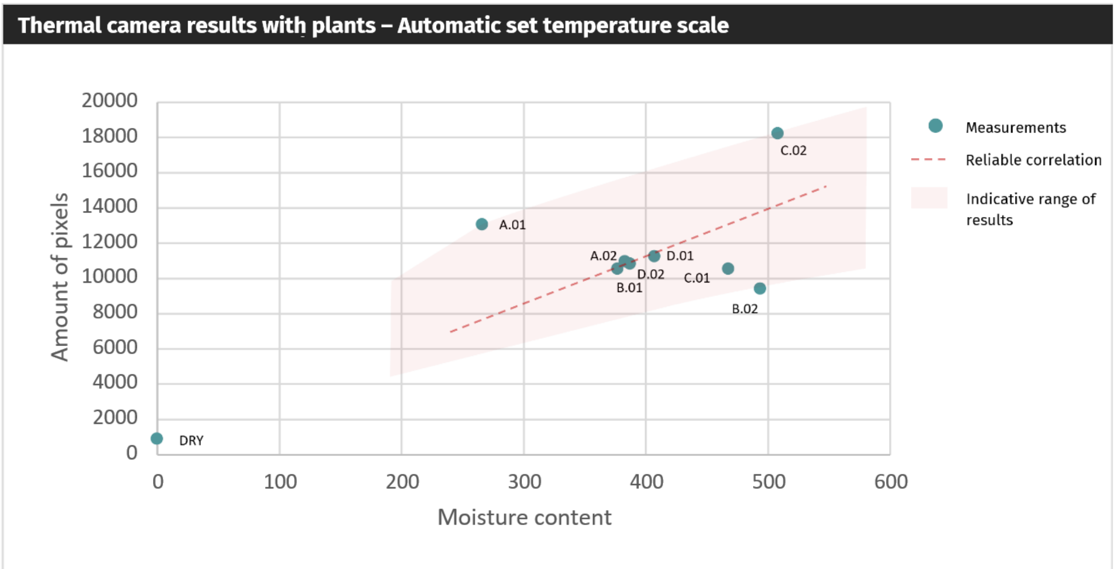


Figure 5.15: *Correlation between moisture sensor results and thermal camera results with plants (own work)*

In addition to comparing the images from the thermal camera with the results from the moisture sensors, they were also compared with the results from the run-off water. For this, the thermal images with the temperature scale set manually were compared to the water retention of each measurement. Figure 5.16 shows the result of this in the presence of plants and Figure 5.17 shows the result of this in the absence of plants. From the figures it can be concluded that the reliability of the thermal camera is strongly influenced by the presence of plants. Figure 5.16 even shows that the number of pixels representing water decreases with higher amounts of water content. However, the thermal images do seem to give a relatively reliable picture of the water content of the mats in the absence of plants. This can be seen by the distance between the points from the line. The distance is relatively short to the linear line. This indicates that there is a stable relationship between the number of pixels of the thermal camera and water retention from the water run-off measurements.

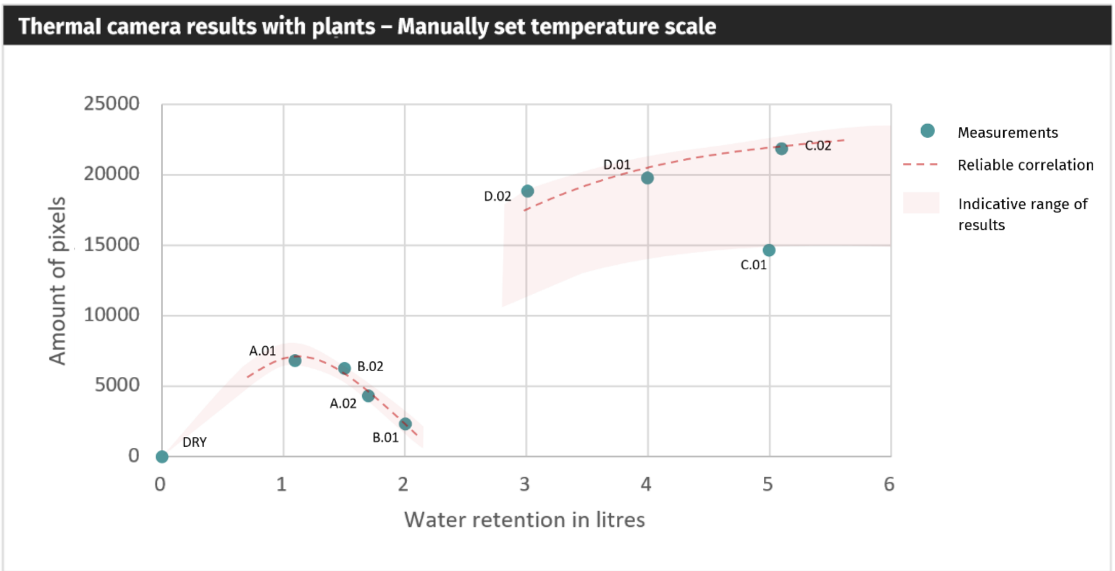


Figure 5.16: *Correlation between water retention in litres and thermal camera results with plants (own work)*

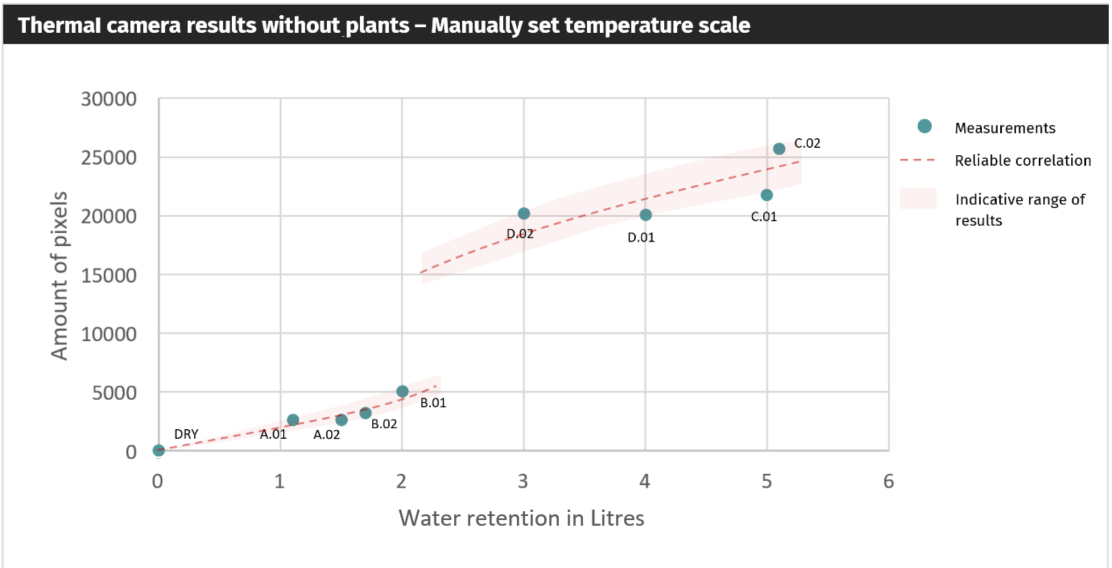


Figure 5.17: *Correlation between water retention in litres and thermal camera results without plants (own work)*

Furthermore, the run-off water was compared with the results of the moisture sensors to see if the results of the moisture sensors provide reliable information about the water content. This is important because the moisture value was measured at only twelve points in total. With a distance of 20-30 centimetres, while the sensors have a range of 2-10 centimetres. The location of the moisture sensor is, as explained in chapter 4.3, at the water supply and the bottom of the mat where water accumulates. This was determined following the literature review and interviews with companies. Initially, it turned out that the distance between the sensors was too large to provide reliable information about the total water content of the mats. For this reason, it was examined whether the reliability increases if more sensor points are used, so that the mutual distance becomes shorter. Table 5.8 indicates the water retention per measurement and table 5.2 shows the measured moisture values. These values have been processed in figure 5.18 to see if the ratio between water retention and average moisture value per measurement is constant. Figure 5.18 shows that the water content of the mats, which is based on the calculated water retention, is not proportional to the measured moisture values in the presence of 12 sensor points. This assumes that the water distribution in the mats is so poor that the number of moisture sensors used is too few to get a reliable picture of the water content based on the moisture sensors. The moisture sensors have a range of 2-10 centimetres and were about 25 to 30 centimetres apart during the measurements with 12 sensor points. To find out whether the sensors can provide a reliable picture of the water content, the measurements were performed again at more sensor points. The measurements were performed at 20, 30 and 54 sensor points. The more sensor points, the shorter the distance between the sensors. The location of the sensor points are shown below. The table below shows that the measurements become more aligned when the sensor points are raised. This indicates that there is a stable relationship between the water retention and measured sensor values and that the sensor therefore gives reliable results. The conclusion that can be drawn from this is that the sensors give reliable results at a distance of approximately 10 cm.

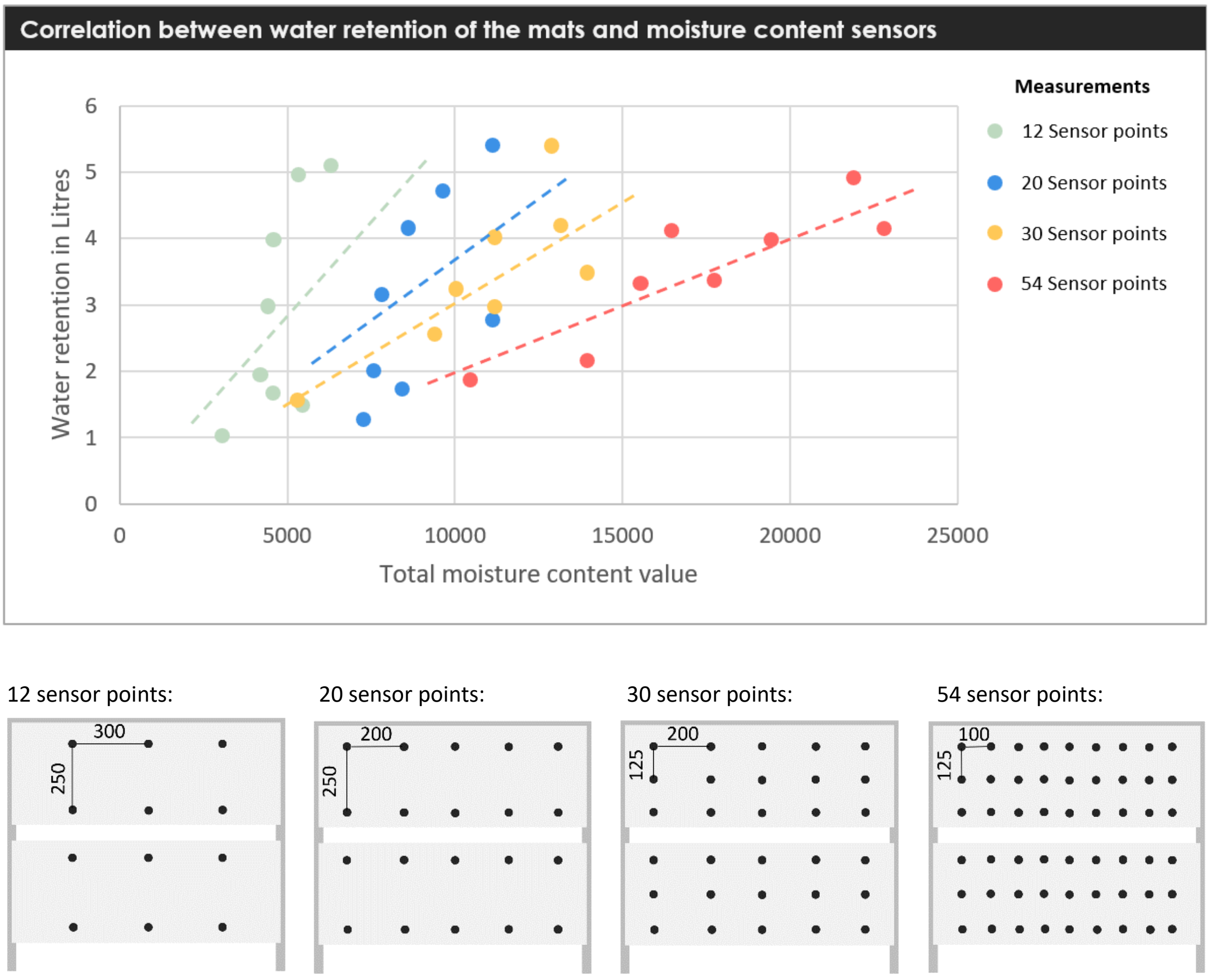


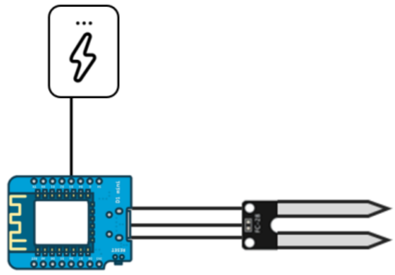
Figure 5.18: *Correlation between moisture sensor results and water retention with different amount of sensor points (own work)*

5.7 Remote measurements

In addition to measurements being carried out on the homemade test model, measurements have been carried out on a real living wall. As described in chapter 4.5, this study has a number of limitations caused by the type of model on which the measurements are performed. To test whether the measurement methods can also be applied to a real living wall, the company vertical meadow from London has made one of their living walls available for this purpose. Unfortunately, it was not possible to test all measurement methods there. Only moisture sensors have been used for these measurements. The moisture sensors send the measured values remotely using WI-FI because they are connected to a WEMOS and a battery that powers the sensors. WEMOS is a low-cost, low-power system on a chip microcontrollers with integrated Wi-Fi and dual-mode Bluetooth. The figure below shows the specifications of the connection of the moisture sensor.

Table 5.14: *Product specifications of the moisture sensor for remote monitoring (Own work)*

SPECIFICATIONS	
Single-board computer	ESP32 WeMos LOLIN32
Sensors	Dfrobot analog soil moisture sensor V2
Power supply	3.3V
Range sensors	0 – 2734 (callibrated)



The measurements were carried out in London on a living wall consisting of the same pre-seeded mats that were used for the homemade model. The main difference between the living wall in London and the homemade test model is the size, irrigation settings, presence of plants and measurement frequency. The moisture content was measured approximately every three minutes with a moisture sensor for two weeks. The measurements were performed between 26-05-2023 and 09-06-2023. These measurements are not about the differences that are measured between the real living wall and the test model, but to see whether the measured values correspond to the irrigation settings, to find out whether the sensors provide reliable information and to see what an ideal and reliable measurement frequency would be. Below are photos of the living wall model where the measurements were carried out.

Figure 5.19: *Living wall from London where the remote measurements took place (A. Law & R. Carlos, 2023)*

Frequency

The moisture sensor measured the moisture content every three minutes between 26-05-2023 and 09-06-2023 for two weeks at the location of the sensor. It has been examined whether the measurement frequency can be lower, so that the measurement can be carried out more effectively and more energy-saving. Figure 5.20 shows the results of the measurements where inputs were received every three minutes regarding the moisture content. The moisture sensor has a range from 0 to 2734. where 2734 is the value when the sensor is placed in a cup of water. The same graph shows the results with moisture content per hour, per day, per 12 hours and per half hour.

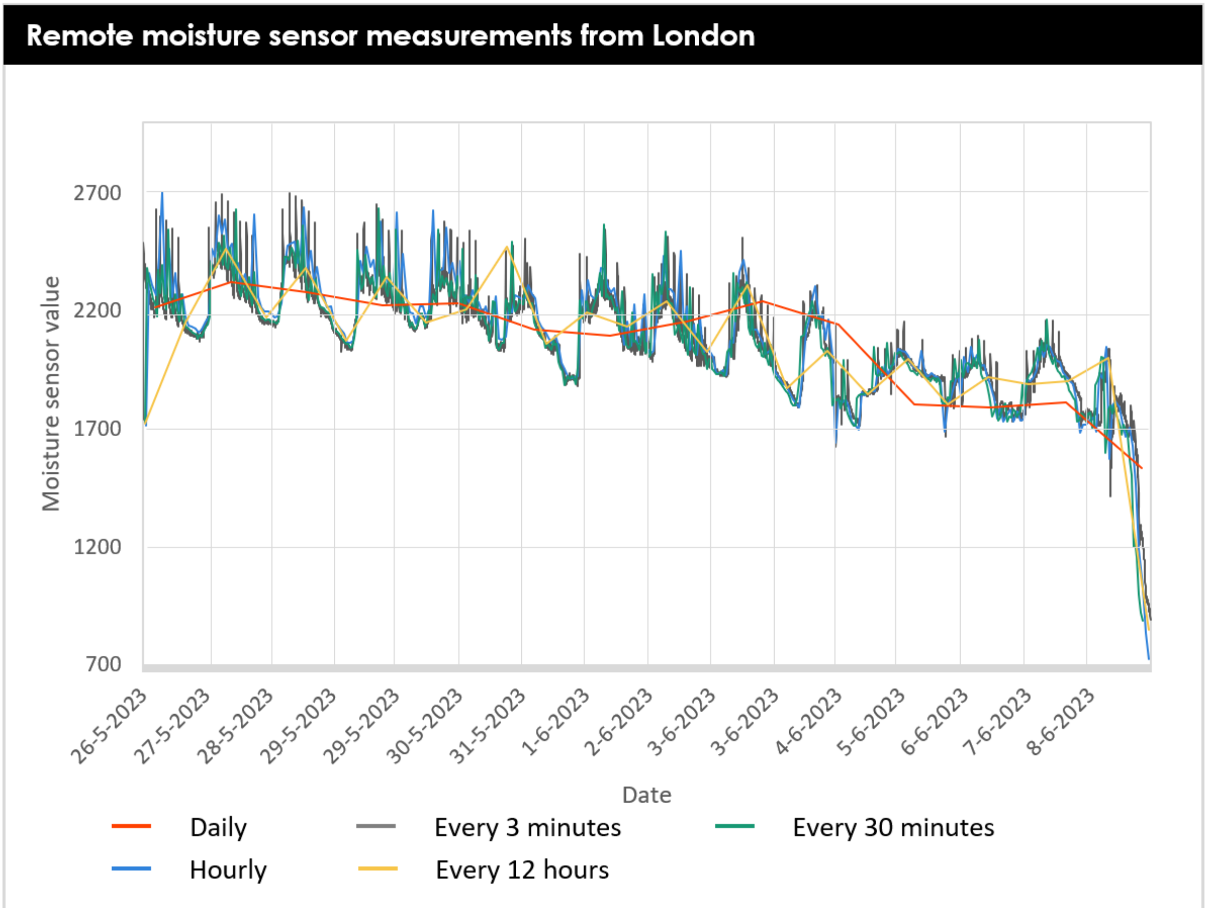


Figure 5.20: *Measured moisture content with different frequencies (own work)*

Figure 5.20 shows that the accuracy decreases as the measuring frequency increases. It can be concluded that the accuracy at a frequency of 30 minutes and an hour is reliable enough, because it is not very different from that of 3 minutes. On the other hand, the accuracy decreases with a measuring frequency of one day. This accuracy decreases further at a 12-hour frequency. It can be concluded that it is not necessary to set a measurement frequency of 3 minutes for the moisture sensors to reliably receive data. A frequency of 30 minutes and even an hour is reliable enough. However, it should be noted that this depends on certain factors. The moisture sensors show how much water content is present in the mat. The type of mat and the water retention capacity can therefore influence the time that the mat can retain the water. In addition, fluctuations in outside temperature can also affect the water content. If there is a lot of change in temperature within a certain frequency, whereby higher temperatures are reached and as a result of which water can evaporate, this difference is less likely to be detected at large measurement frequencies.

Reliability

Furthermore, the measurements on the living wall in London were used to find out whether they provide reliable information in relation to the irrigation settings that apply. figure 5.21 shows the graph again with the results of the moisture sensor. The same graph shows the water supplied per litre per zone. It is important to mention a few things. The amount of water in litres applies to the zone in which the sensor is located, this does not mean that all the water has been applied at the location of the sensor. Furthermore, a number of malfunctions occurred during the measurement, which are also indicated in the figure below. The irrigation system is set up to irrigate 14 times a day. The duration of irrigation varies and depends on climatic factors such as precipitation and temperature. The irrigation time is about 6 minutes.

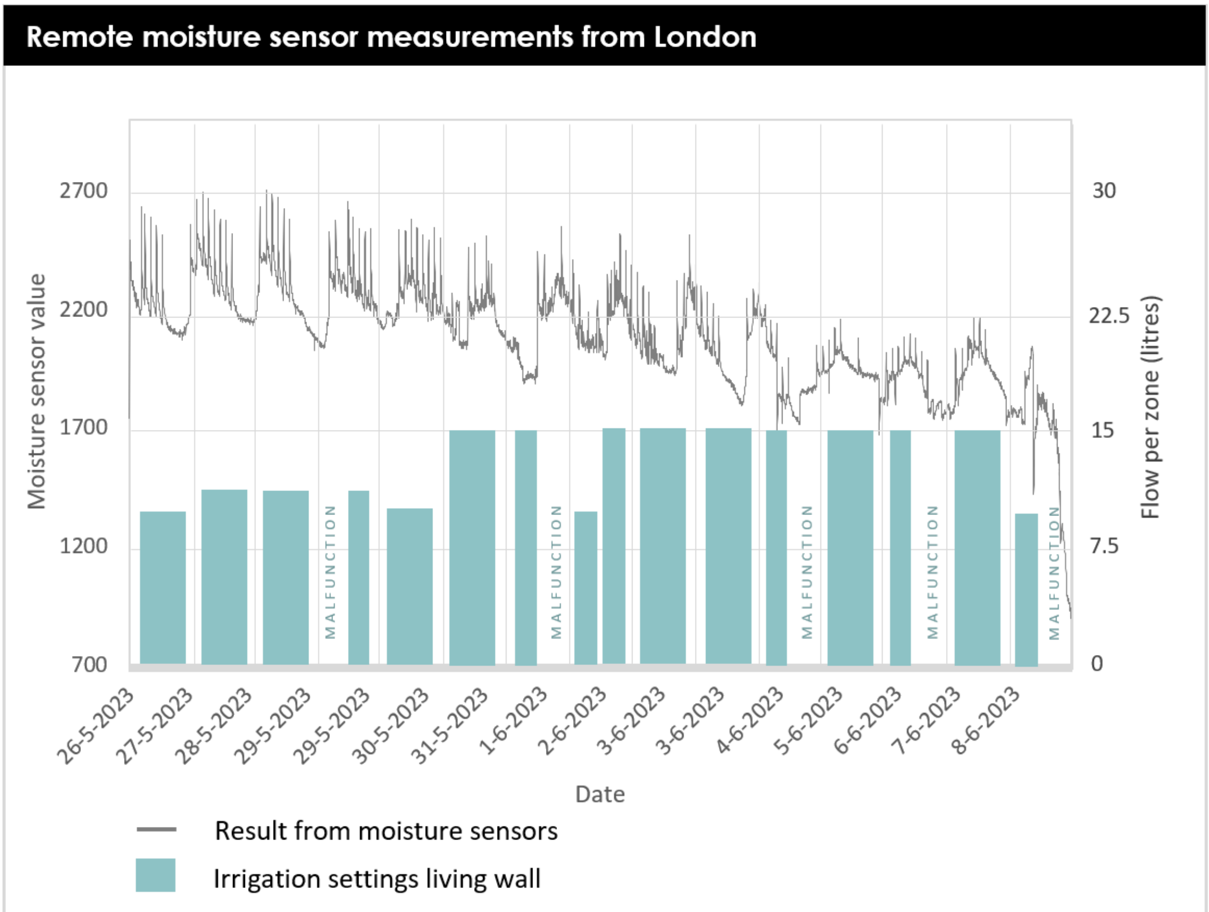


Figure 5.21: *Comparison between irrigation settings of the living wall and measured moisture content (own work)*

Figure 5.21 shows that the moisture content value slowly decreases over time, while the water supply is fairly stable and even increases slightly over time. The drop in moisture content may be related to the malfunctions taking place. A more logical explanation may be that this has to do with the warm outside temperatures in the last week of the measurement. In the first week of the measurements, the outside temperature was an average of 16° C and in the last week an average of 19° C. At warmer temperatures, the irrigation water condenses more quickly, which explains why the water content in the facade has decreased. This principle corresponds to the literature study in chapter 2.3. Where is described how external factors, such as climate, influence water consumption. This is an important finding because it confirms that the amount of water supplied does not always say something about the actual water content.

06 CONCLUSIONS

CONCLUSIONS

6.1 Conclusion

This research answers the question 'What is the best strategy for monitoring the water distribution of the irrigation system on a living wall system that ultimately leads to more effective maintenance?'. This study has therefore shown that the monitoring methods all have limitations and advantages. depending on a number of factors, these monitoring methods can be used together to compensate for each other's limitation, so that they can be used to make reliable measurements of water content, water distribution and plant quality. The right use of the monitoring methods can provide the right input to set up the irrigation system more effectively, leading to a uniform water distribution that will ultimately improve plant quality and will have a positive impact on future maintenance.

It can be concluded from the analyses that the presence of plants is an important factor in the application of some monitoring methods. When no plants are present, the thermal camera provides a reliable picture of the water distribution and water content. If you are only interested in whether the living wall is wet and whether the water is more or less evenly distributed, an NDVI camera can also be used. An NDVI camera only provides an indicative image. In the presence of plants, the reliability of the thermal camera decreases with greater densities of vegetation. The camera settings for the temperature scale also have a major influence. The results show that the thermal images are not comparable when performed at a temperature scale automatically determined by the camera. It is therefore not possible to determine whether these give reliable results. It is advised to manually set the temperature scale, but it must be taken into account that fluctuating outside temperatures can affect the images. The manual setting will depend on the outside temperatures during the measurements that will take place. On the other hand, it has been found that the advantage of a camera that adjusts the scale itself is that the presence of plants has less effect, so that the water content can still be read properly. Despite the fact that the thermal camera no longer provides a completely reliable picture in the presence of plants, the NDVI camera can map the plant quality. However, it is important to note that if plant quality is negatively affected by too low or high water content, it is probably too late to prevent unnecessary maintenance. It is also important to mention that the NDVI camera only works in outdoor situations, in the presence of natural light. So not with indoor living walls. Moisture sensors are a reliable way to monitor the water content in the presence and absence of plants. The disadvantage, however, is that the range of the moisture sensors is relatively small at 2-10 cm. For a reliable result, it is advised not to place the moisture sensors further apart than 10 centimetres. Unfortunately, this is expected to be an obstacle for large area LW systems. Follow-up studies should show whether the moisture sensors can provide a reliable picture in situations involving large facade surfaces by only installing them at a number of points on the facade that can be representative of the rest of the facade. Finally, measuring the run-off water can provide a reliable picture of the water content. Unfortunately, this says nothing about the water distribution, but in combination with the thermal camera and moisture sensors, these can give a reliable picture of both the water content and water distribution. For these methods it is important that this is already taken into account during the design phase. To measure the run-off water, for example, there must be facilities to measure the water flow and there must be a gutter that collects and measures the run-off water. Furthermore, based on the measurements, it can be concluded that the chance of good water distribution is greatest when the water flow is low and the irrigation time is longer. With this the mats reach their water retention capacity, which means that there is enough water in the mats for the plants. For this it is important that water is sprayed frequently, but with lower amounts so that the mats have the opportunity to absorb the water properly. This is also confirmed in the study by Pérez-Urrestarazu et al., (2014).

As described in chapter 2.2, the monitoring methods each have their advantages and disadvantages. This was also shown during the measurements. It has been found that the monitoring methods work best and provide reliable information when they are combined and compensate each other's limitations. Figure 6.1 shows an overview of the scenarios and which measurement methods must be combined to obtain reliable results. The combinations are based on the advantages and disadvantages of the monitoring methods and the measurements that have shown the reliability of the measurements. Some methods are best applied alone because a combination with another measurement method has no added value. In the combinations below, the thermal camera and NDVI camera offer the benefits of long range and visual image creation, while the sensors and run-off water provide precise and accurate data.

WITHOUT PLANTS

SCENARIOS	NDVI	THERMAL	SENSORS	RUN-OFF
Water content & water distribution		●	●	
Water content				●
		●	●	
Water distribution		●		

WITH PLANTS

SCENARIOS	NDVI	THERMAL	SENSORS	RUN-OFF
Water content & water distribution		●	●	●
Water content				●
Water distribution			●	●
Plant quality	●			

Figure 6.1: *Recommended combinations of monitoring methods for each scenario (own work)*

In the longer term, these monitoring methods can limit maintenance and make maintenance work less intensive. For this purpose, they can be used in various ways by companies and living wall suppliers. During the interviews, living wall companies and suppliers indicated that these methods could be interesting, for example, to measure plant quality remotely instead of having to travel to each location for an inspection. Furthermore, for example, a desired degree of coverage can be determined in advance for the plants and the NDVI camera can keep track of this degree of coverage. The same principle can be applied to water distribution using a thermal camera. The monitoring methods can also help with aspects that are not related to maintenance. For example in fire safety. The monitoring methods that can be used to measure the water content and water distribution in the facade can be used to monitor whether the facade is wet enough and whether there are dry spots in the facade to prevent fire hazards.

6.2 Discussion and limitations

This research has shown that a combination of monitoring methods can generally provide a reliable picture of the water content, water distribution and plant quality of the living wall. It has also been found that climatic factors can strongly influence the reliability if these are not taken into account. Furthermore, it has been found that the water distribution and water content can be strongly influenced by factors such as irrigation time, irrigation capacity and distance between the driplines. In the end, the measurements were carried out as planned, although this was done by trial and error. The results from this study are in agreement with results from the literature study. Despite the fact that other studies use a different research method and approach, we come to the same conclusions when it comes to the water distribution and water content of a living wall. This is an additional confirmation that the measurement methods used in this study give a reliable result. In addition to the water distribution and water content, the hypotheses have also come true when it comes to the best irrigation time and irrigation capacity. It should also be noted that this study has a number of limitations. Such as the fact that the measurements were carried out on a relatively small test model, the number of moisture sensors and that the measurements were carried out without the presence of plants growing out of the living wall. These are factors that may influence the result. Furthermore, this research took place in a time frame that was too short to be able to investigate whether the application of these monitoring methods can actually lead to better anticipation of maintenance, by adjusting the irrigation system more effectively, leading to uniform water content that ultimately improves plant quality. Based on the results of the literature study, in which similar measurements were performed on different LW systems, it can be assumed that the results of this study can be generalized. It is expected that these measurement methods can also be applied to different living wall systems and to different sizes. Of course, this cannot be confirmed until more measurements are applied for this. This might be an interesting topic for further research. It is important to note that this study is only an exploratory study to fill the research gap and serves as a first step towards more research. It has been established in advance that there is a large research gap when it comes to the maintenance of living walls and monitoring methods to adequately anticipate maintenance. This report brings new information and findings that narrow the original research gap.

6.3 Relevance

This thesis touches on various themes in the context of building technology. This thesis revolves around sustainability, technology and facade design. As described in the introduction as a society we are becoming increasingly aware of the essential role of nature in our environment. For example, in chapter 1.2 it is described what the contribution of a living wall can be in the built environment. Nevertheless, a living wall system is relatively rare in the built environment compared to more traditional facade cladding such as masonry. An important reason for this is the required maintenance and attention for living wall systems as described in chapter 1.2. Now that a step is made to improve the effectiveness of the irrigation system, we are a step closer to limit maintenance. Because the effectiveness of the irrigation system influences the quality of the plants and therefore the maintenance. With this research, a large research gap can also be filled that concerns the maintenance of living wall systems. This in turn can form an important basis for follow-up research.

6.4 Reflection

Research process

In my opinion, this study is different from other studies. Since this is a subject that is rarely discussed in class and relatively little research has been done, I sometimes had to be creative to get the right information and apply research methods that were new to me. Such as processing interview results, analysing images with certain softwares and using single-board computers for my measurements. There have been many uncertainties and obstacles during the research. For example, there were problems preparing the measuring equipment, the interviews took a relatively long time and building a test model also took a lot of time. I don't look back on this with a bad feeling, because these are things that I could not have realized beforehand or could have done better. Despite all the uncertainties and obstacles, I look back at the research process with satisfaction. If there are students who do research on the same subject in the future, I can advise them to seek support from people and companies that know a lot about this subject. I have discovered that many companies can be very enthusiastic about your research and would like to contribute by sharing their knowledge. The fact that I came into contact with companies and individuals has helped me enormously during this research.

Personal reflection

Before the start of this research, my knowledge on this topic was very limited. The fact that I knew very little about this, despite the fact that I think this is an important topic, triggered me to do this research. I'm glad I did, because I've gained a tremendous amount of knowledge on this subject. In addition to gaining a lot of knowledge about this, it has also taught me as a person not to be afraid to dive into a subject that is unknown. You can never go backwards in terms of knowledge acquisition. The less you know about the subject, the more you can learn from it. Of course, during the research I thought several times that the graduation research would be easier if it concerns a subject that I have more knowledge about. I think the research wouldn't be as fun and challenging in the end if I chose a subject I know more about. In the end, I pushed the research to the limit, even reaching out to companies and outsiders who know more about this topic to gather as much information as possible in a short amount of time. This was an instructive, challenging and intensive graduation project that I can look back on with pride.

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NOTE: *Figures and tables not included in this list were created by the author of this report and are referred to in the report as 'own work'.*

APPENDIX

A INTERVIEW QUESTIONS

	BACKGROUND INFORMATION
1	What is the name of your company? *Hoe heet het bedrijf waarvoor u werkt?*
2	What kind of product/services does the company provide? *Wat voor producten/diensten levert het bedrijf?*
3	How long does the company exist *Hoelang bestaat het bedrijf?*
4	what is your position within the company? *Wat is uw functie binnen het bedrijf?*
5	How long have you been doing this profession? *Hoelang doet u dit beroep al?*
6	How long have you had experience with living green wall systems? *Hoelang hebt u ervaring met living wall systemen?*
7	What activities do you perform within the company? *Wat zijn uw werkzaamheden binnen het bedrijf?*

	MAINTENANCE OF LIVING WALLS
8	What type of green facade systems do you work with? *Welke type groene gevel systemen werkt u mee?*
9	How does the facade work in terms of irrigation? *Hoe werkt het irrigatiesysteem van de groene gevel?*
10	On what parameters do you base the capacity of the irrigation system? *Op welke parameters wordt de capaciteit van het irrigatiesysteem gebaseerd?*
11	What type of maintenance is performed exactly? *Wat voor onderhoud wordt er precies verricht?*
12	Can anyone perform this work or are certain skills required? *Kan iedereen deze werkzaamheden uitvoeren of zijn daar bepaalde vaardigheden voor vereist?*
13	How often is maintenance required? If this differs per type of maintenance, please explain in more detail. *Hoe vaak is onderhoud nodig? Als dit verschilt per type onderhoud, licht dit verder toe.*
14	What are the causes that make this maintenance necessary? *Wat zijn de oorzaken dat er onderhoud noodzakelijk is?*
15	How labor intensive is the maintenance? *Hoe arbeidsintensief is het onderhoud?*

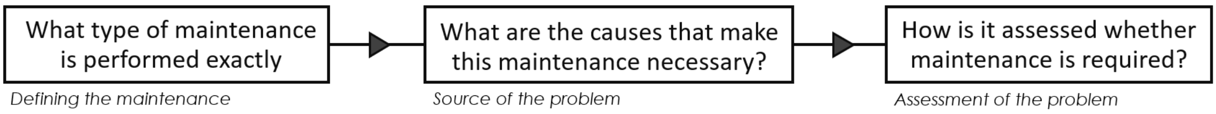
16	Is the labor intensity a problem? *Is de arbeidsintensiviteit een probleem?*
17	Is maintenance a problem in terms of costs? *Is het onderhoud een probleem met betrekking tot kosten?*
18	What is the necessity of the maintenance? For example, does this have to do with the aesthetics of the green facade or also with the quality of the plants? *Wat maakt het onderhoud noodzakelijk? Bijvoorbeeld, esthetiek van de groene gevel of kwaliteit van de groene gevel?*
19	How is it assessed whether maintenance is required? *Hoe wordt er beoordeeld of er onderhoud nodig is?*
20	Do you check the quality of the plants? if so, how? *Wordt de kwaliteit van de planten gecontroleerd? Zo ja, hoe?*
21	How do you know if each plant receives sufficient water? *Hoe weet u of elke plant voldoende water krijgt?*
22	Do you notice that the water content of the living wall is / is not the same everywhere? If so, how do you see this? *Merkt u dat de waterinhoud van de living wall wel/niet overal gelijk is? Zo ja, waar ziet u dit aan?*
23	Do you think having insight into the water distribution/water content would help you to anticipate better on the maintenance? *Denkt u dat als u inzicht krijgt in de waterdistributie/waterinhoud het u zou helpen om beter op onderhoud te kunnen anticiperen?*
24	To what extent is future maintenance work taken into account during the design phase? *In hoeverre wordt er rekening gehouden met toekomstig onderhoud tijdens de ontwerpfase?*

	IMPROVEMENTS
25	Do you think it would help to limit maintenance by monitoring the quality of the plants? so that you can carry out more adequate maintenance. *Denkt u dat onderhoud beperkt kan worden door de kwaliteit van de planten te monitoren? Zodat er adequater onderhoud uitgevoerd kan worden.*
26	Do you think it would help to limit maintenance by making the irrigation system more effective? *Denkt u dat onderhoud beperkt kan worden door het irrigatiesysteem effectiever te maken?*
27	Do you have any tips or ideas of your own to limit maintenance? Are you as a company working on this? *Heeft u zelf tips of ideeën om onderhoud te beperken? Zijn jullie als bedrijf hiermee bezig?*
28	Besides maintenance, are there other things that need to be improved? *Naast het onderhoud, zijn er andere dingen die verbeterd moeten worden?*

B
CLUSTERED INTERVIEW QUESTIONS

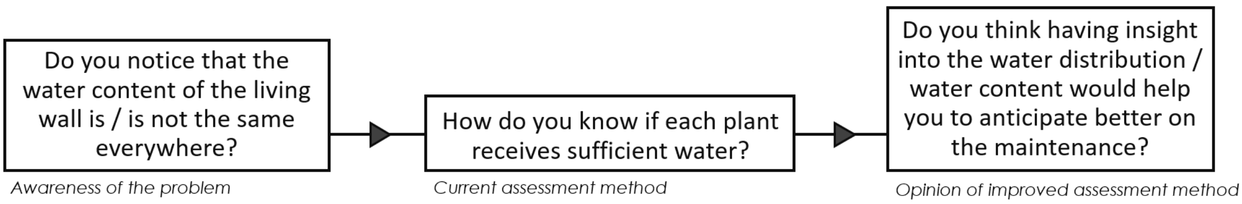
Cluster I: Need for maintenance

This cluster answers the 'what', 'why' and 'how' regarding the need for maintenance. The purpose is to obtain information about the cause of the maintenance and whether this cause is taken into account when determining whether maintenance is required. This is an important question because the literature review in chapter 2.1 of this report has shown that the assessment of whether maintenance is required is often based on observation. While for the causes of the problem, such as plant quality, water content and water distribution, measurements are required to arrive at a good assessment.



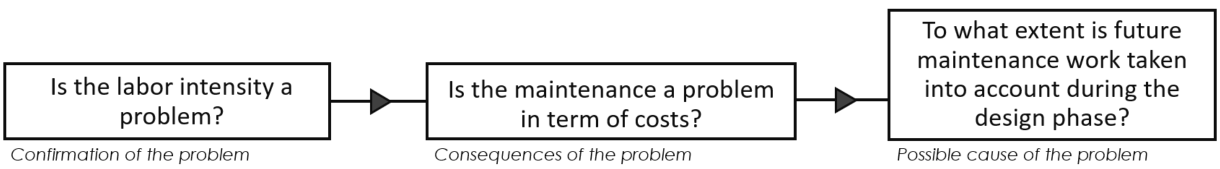
Cluster II: Irrigation system effectiveness

The literature study in chapter 2.1 has shown that too much or too little water can affect plant quality and thus maintenance. This cluster addresses this. The answer to these questions provides information about the awareness of the problem and whether the problem is correctly assessed.



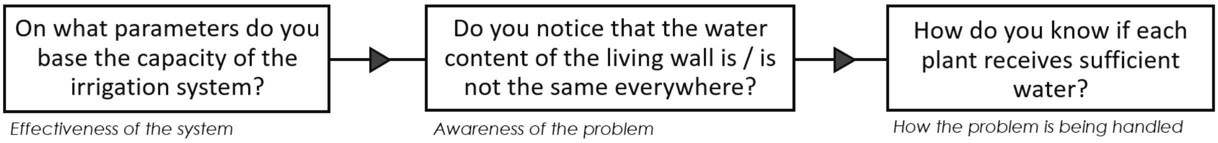
Cluster III: Consequences of the design

Maintenance is an aspect that is not or little taken into account during the design phase (Pérez-Urrestarazu & Urrestarazu, 2018), while this is an important factor in limiting maintenance. This cluster investigates whether there is a connection between the fact that maintenance is taken into account during the design phase and the consequences that this can have on labor intensity and costs. Since maintenance of living wall systems often involves working at heights, this can affect labor intensity and costs if not taken into account during the design phase.



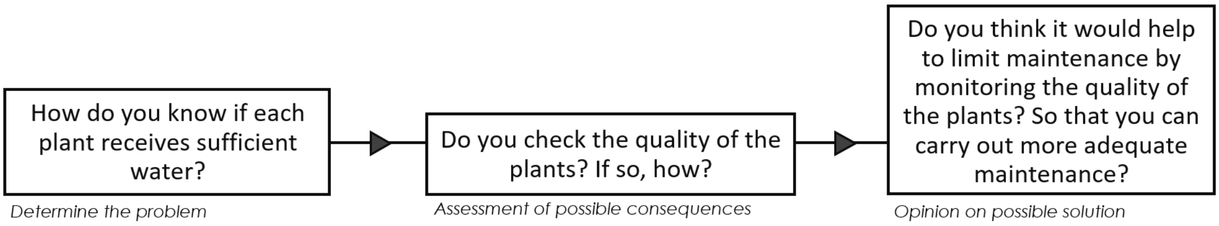
Cluster IV: Water distribution

In this cluster, it is investigated whether the water distribution and water content are related to the parameters on which the capacity of the irrigation system is adjusted. This cluster collects information about whether companies take into account that the water distribution may not be optimal and about the way in which it is determined whether or not the water distribution is good.



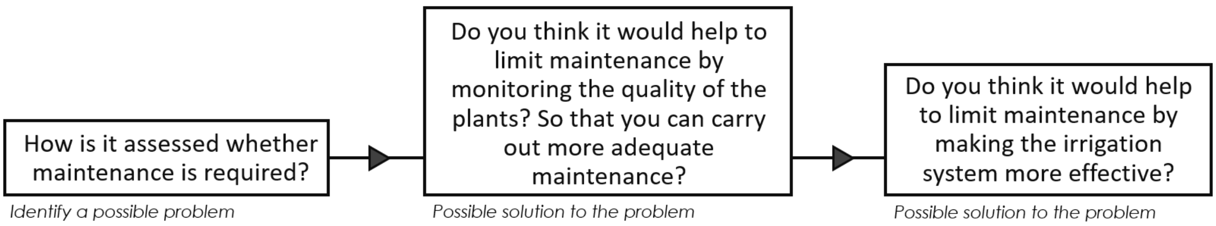
Cluster V: Correlation between water distribution and plant quality

This cluster collects information about how plants are judged whether they receive enough water or how plant quality is assessed. They are then asked for their opinion on whether a better way of assessing could have an impact on limiting maintenance. This allows conclusions to be drawn as to whether the interviewee agrees that a better way of assessing can influence the maintenance. This stems from the hypothesis that a good way of assessing, in the form of measurements instead of observing, ensures that better and more effective maintenance can be carried out.



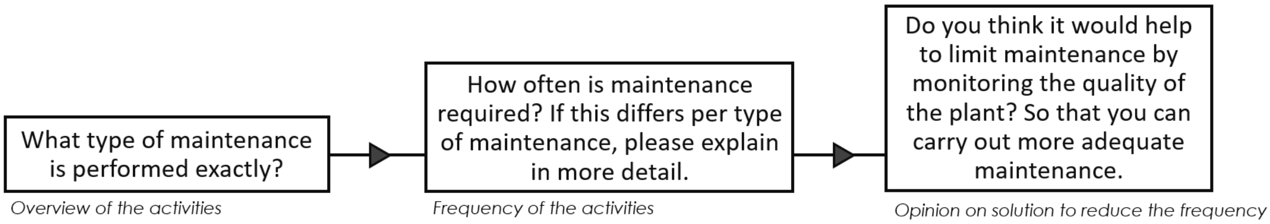
Cluster VI: Maintenance assessment

This cluster is about the way in which it is assessed whether maintenance is required. The literature review in chapter 2.1 has shown that the need for maintenance is often assessed based on observation. Here it is determined whether this is indeed the case and whether the interviewees agree with the hypothesis that the assessment could be better and more effective. An important point of information that can be obtained from this is that there may not yet be a more effective assessment method than observation, even though the interviewee may also know that observations cannot always be trusted.



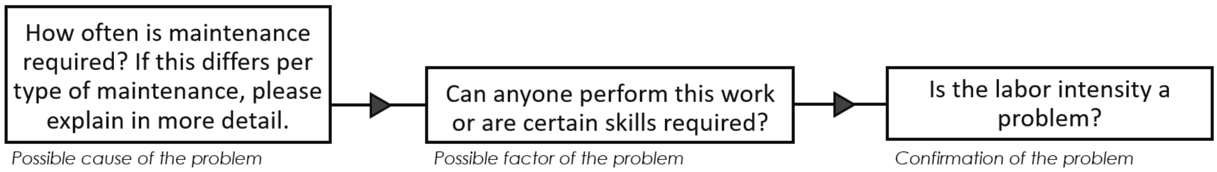
Cluster VII: Maintenance frequency

One of the hypotheses is that a problem in maintenance may be the frequency of the maintenance. The questions below collect information about the frequency of certain maintenance activities and, in the opinion of the interviewee, whether monitoring plant quality can limit the maintenance frequency.



Cluster VIII: Labor intensity

Another factor that can cause problems in maintenance is the difficulty of maintenance. In this cluster, the interviewees are asked about the maintenance frequency and its difficulty. For example, whether certain skills are required to perform the maintenance. With these questions, conclusions can be drawn whether the difficulty of maintenance is related to the high frequency of maintenance.



C
PHOTOS OF EXPERIMENT

Test model including pre-seeded mats


Connection of the mat to the wooden frame


Thermal camera measurement


Preparing the moisture sensors


Collecting run-off water


Water accumulation at the bottom of the mats

D PYTHON SCRIPTS

MOISTURE SENSOR

```
void setup(){

 Serial.begin(9600);
 int sensorValue1 = analogRead(A1);
  int sensorValue2 = analogRead(A2);
   int sensorValue3 = analogRead(A4);
    int sensorValue4 = analogRead(A5);
 int moist1;
 int moist2;
 int moist3;
 int moist4;
 }

void loop(){
int moist1 = analogRead(A1);
   delay(10);
   moist1 = analogRead(A1);
   Serial.print("sensor 1's reading: ");
   Serial.println(moist1);
   delay(500);

   int moist2 = analogRead(A2);
   delay(10);
   moist2 = analogRead(A2);
   Serial.print("sensor 2's reading: ");
   Serial.println(moist2);
   delay(500);

   int moist3 = analogRead(A4);
   delay(10);
   moist3 = analogRead(A4);
   Serial.print("sensor 3's reading: ");
   Serial.println(moist3);
   delay(500);
```

```
   int moist4 = analogRead(A5);
   delay(10);
   moist1 = analogRead(A1);
   Serial.print("sensor 4's reading: ");
   Serial.println(moist4);
   delay(500);
}
```

(Script can vary based on amount of moisture sensors that are being used)

NDVI CAMERA

```
From picamera import PiCamera
from time import sleep

Camera =PiCamera ()

For I in range (0, 15):
   Camera.start_preview()
   Camera.capture('img%s.jpg' % i)
   Sleep (3)
   Camera.stop_preview()
```

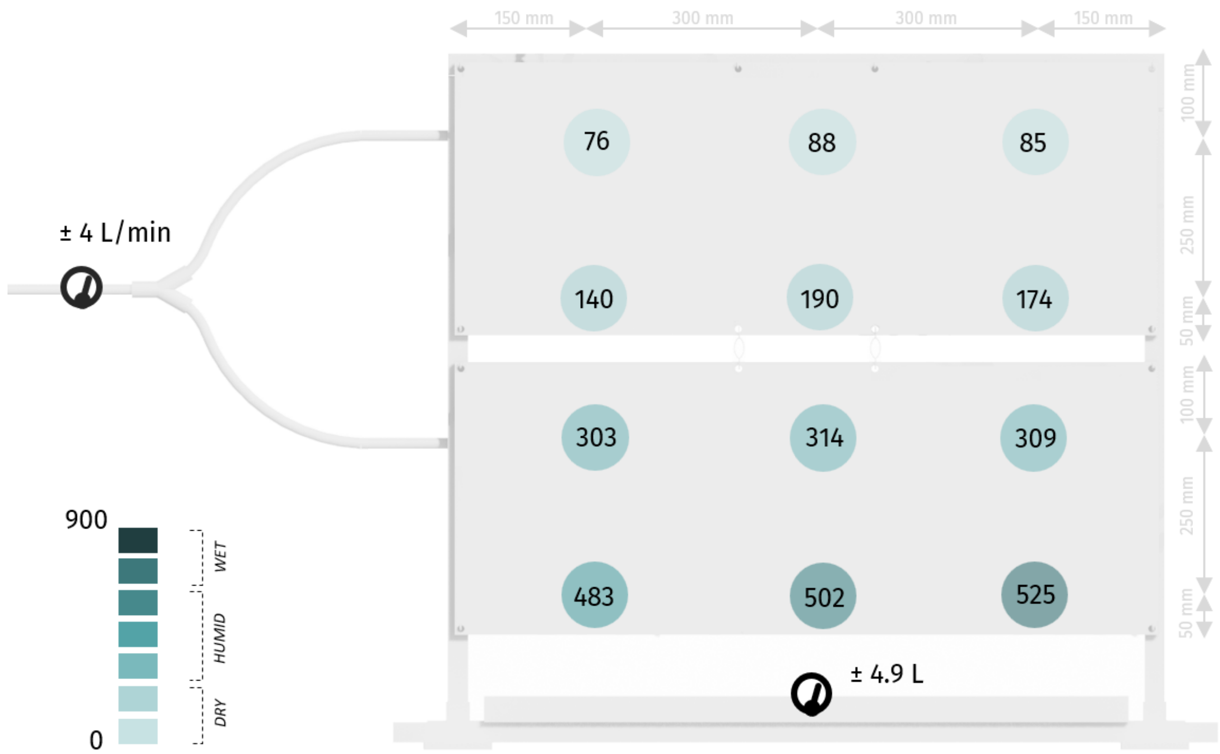
E MEASUREMENT RESULTS

Test A.01

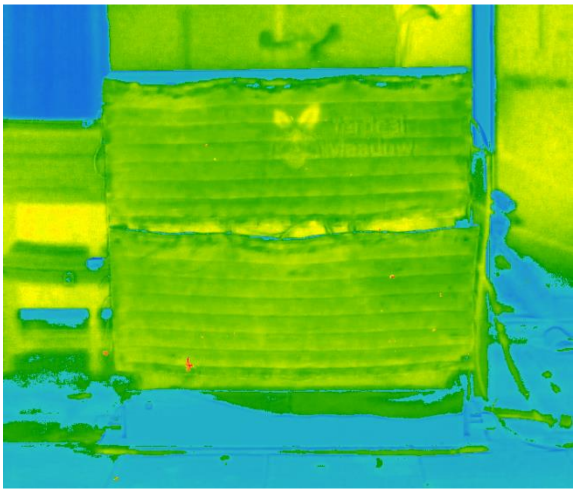
VARIABLE FACTORS	
Orientation	East
Temperature	13 ℃, according to weather.com
Shading	None (there are surrounding buildings but they do not form an obstacle)
Humidity	62%, according to weather.com

IRRIGATION	
Waterflow	4 l/min
Water time	1:30 min

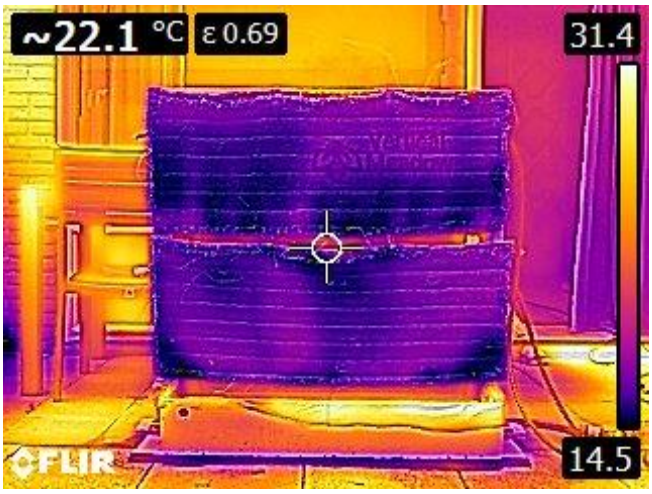
Sensor results and run-off water:



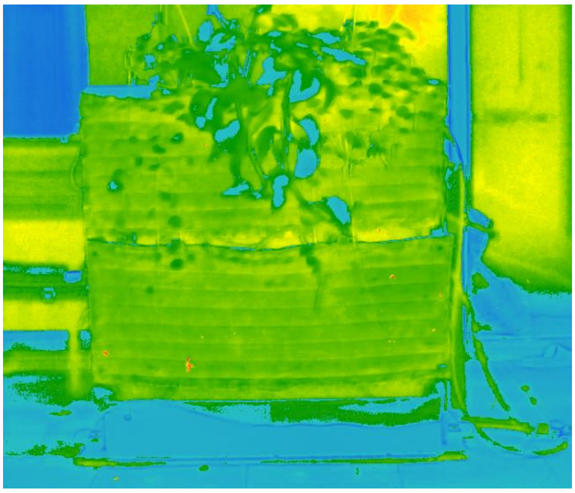
NDVI image without plants:



Thermal image without plants – scale set manually:

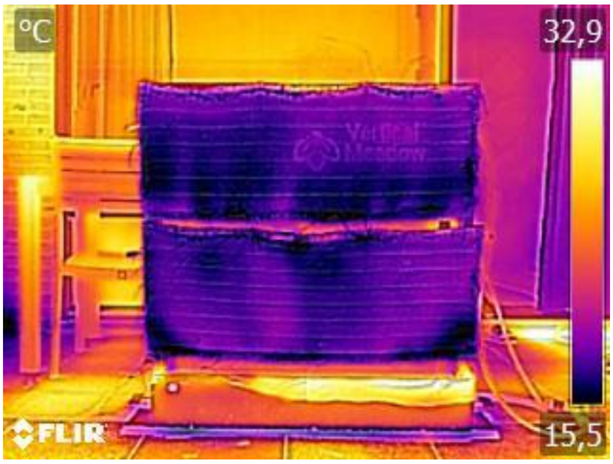


NDVI image with plants:

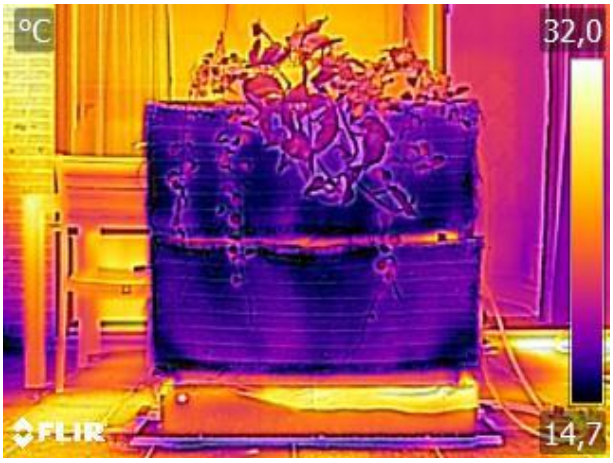


Thermal image with plants – scale set manually:

Thermal image without plants
scale set automatic:



Thermal image with plants
scale set automatic:

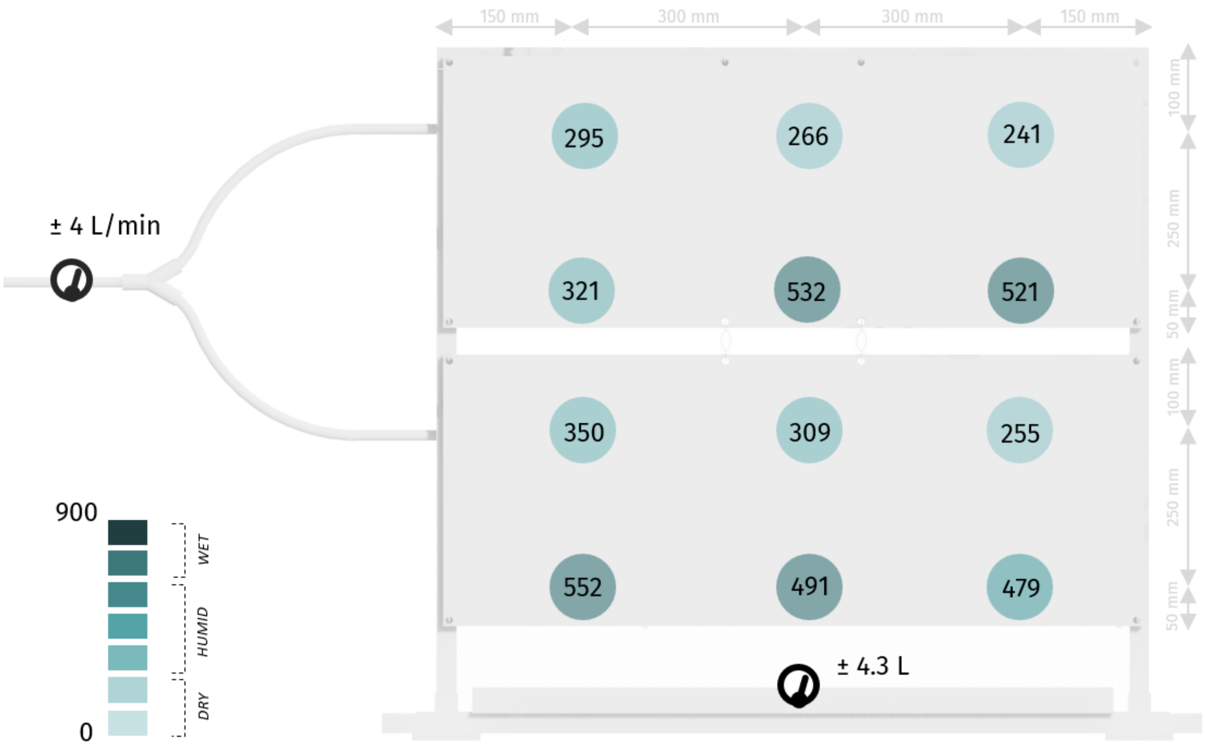


Test A.02

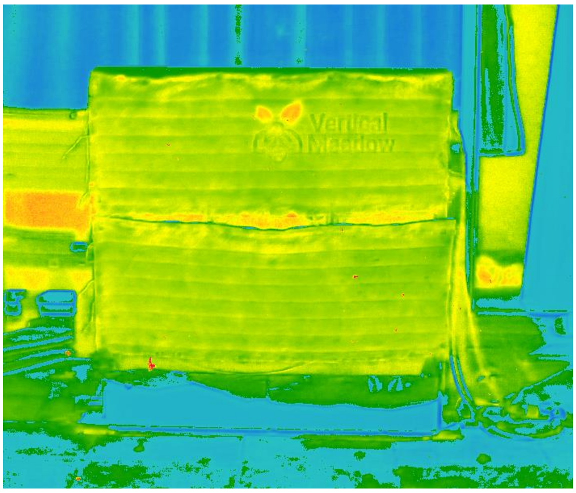
VARIABLE FACTORS	
Orientation	East
Temperature	15 °C, according to weather.com
Shading	None (there are surrounding buildings but they do not form an obstacle)
Humidity	47 %, according to weather.com

IRRIGATION	
Waterflow	4 l/min
Water time	1:30 min

Sensor results and run-off water:

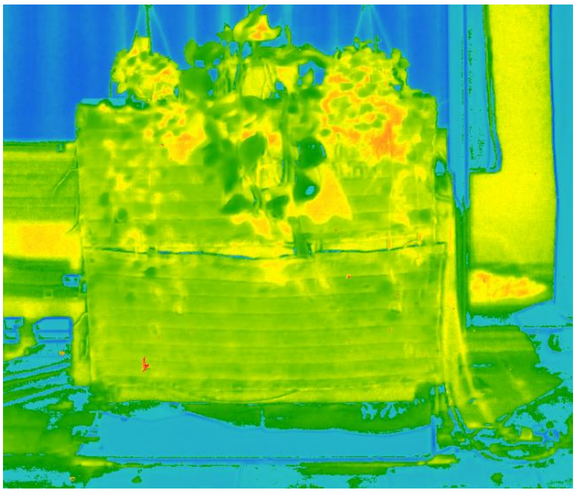


NDVI image without plants:



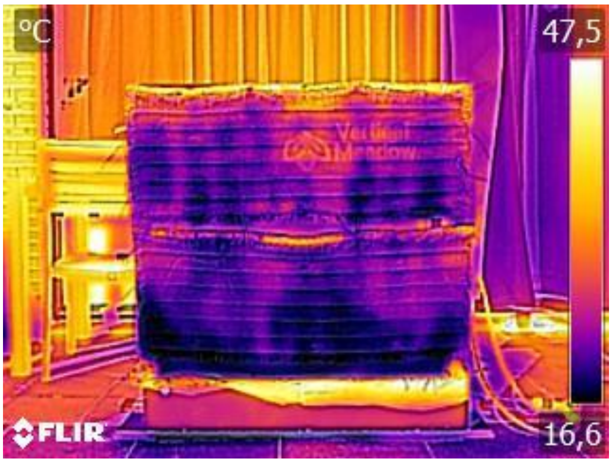
Thermal image without plants – scale set manually:

NDVI image with plants:

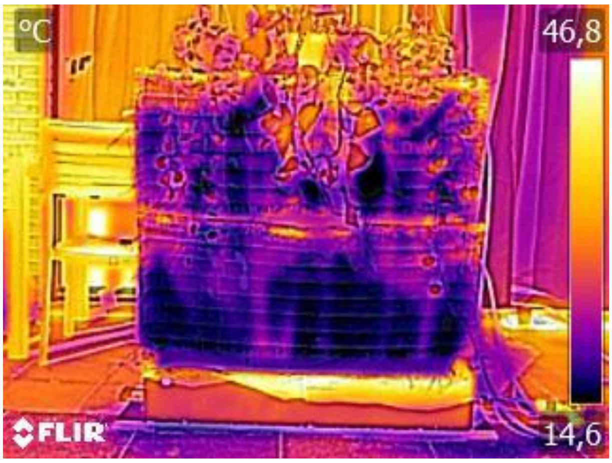


Thermal image with plants – scale set manually:

Thermal image without plants
scale set automatic:



Thermal image with plants
scale set automatic:

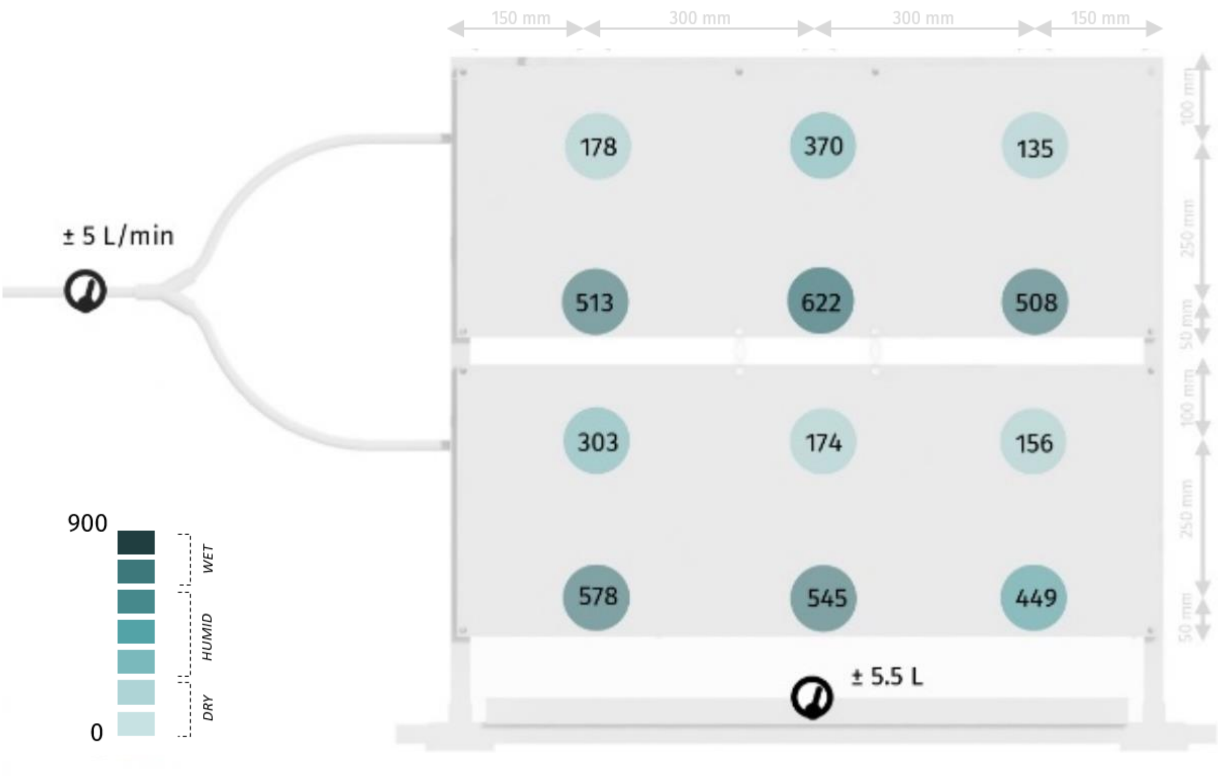


Test B.01

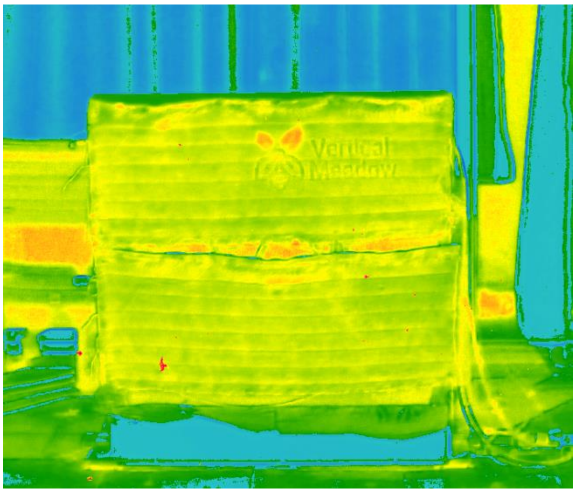
VARIABLE FACTORS	
Orientation	East
Temperature	16 °C, according to weather.com
Shading	None (there are surrounding buildings but they do not form an obstacle)
Humidity	44 %, according to weather.com

IRRIGATION	
Waterflow	5 l/min
Water time	1:30 min

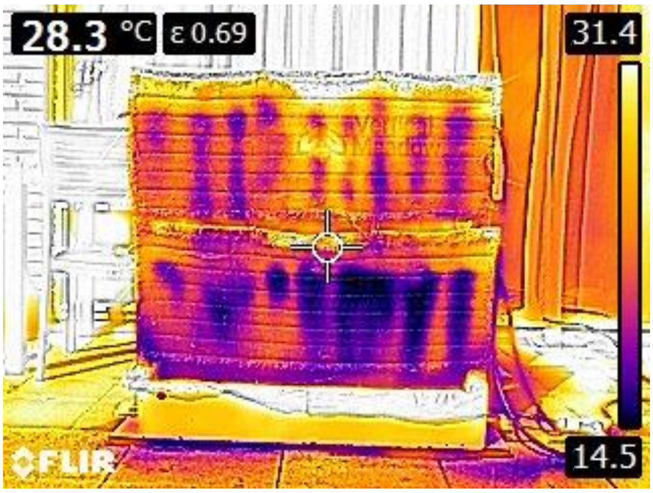
Sensor results and run-off water:



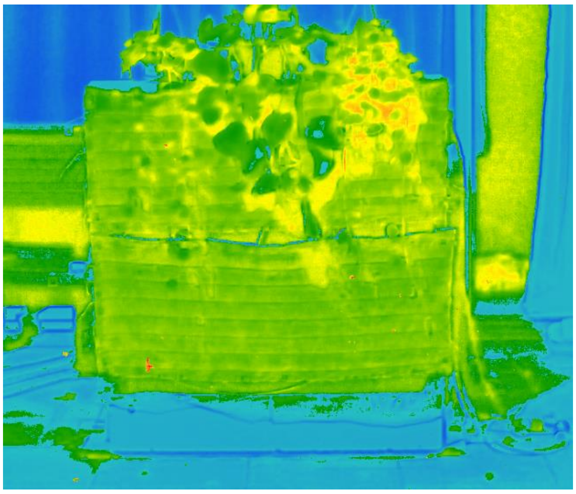
NDVI image without plants:



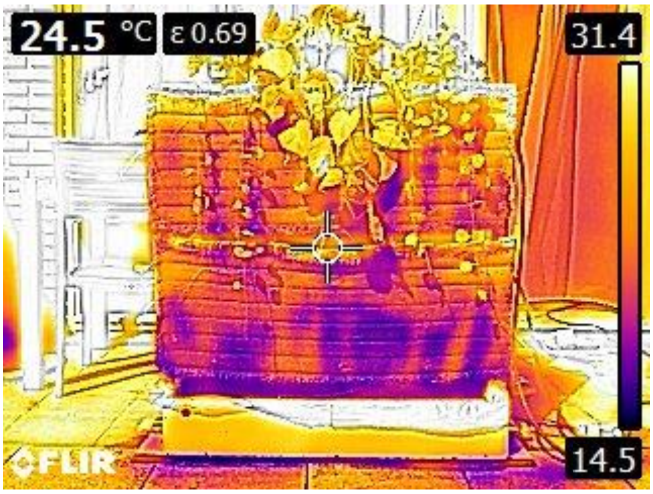
Thermal image without plants – scale set manually:



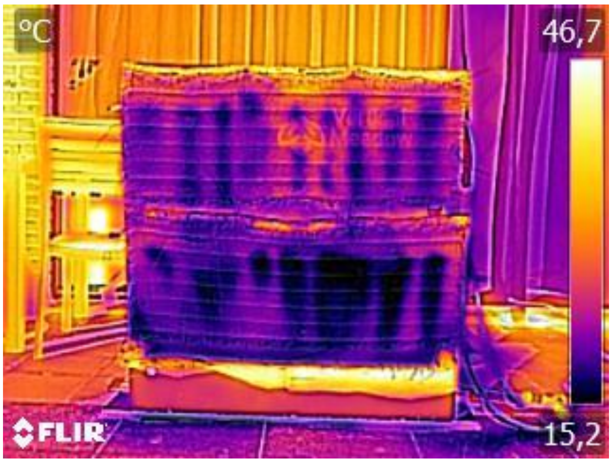
NDVI image with plants:



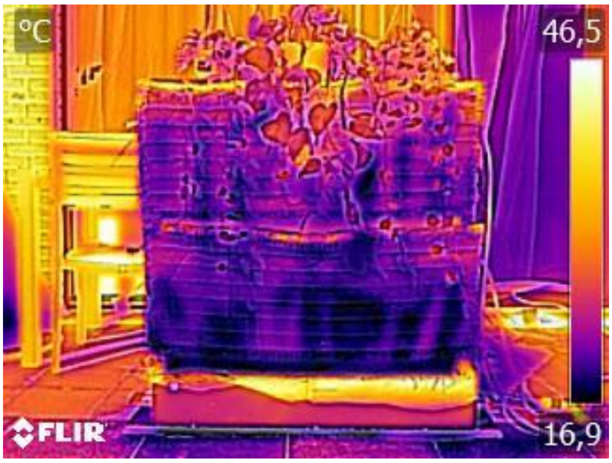
Thermal image with plants – scale set manually:



Thermal image without plants
scale set automatic:



Thermal image with plants
scale set automatic:

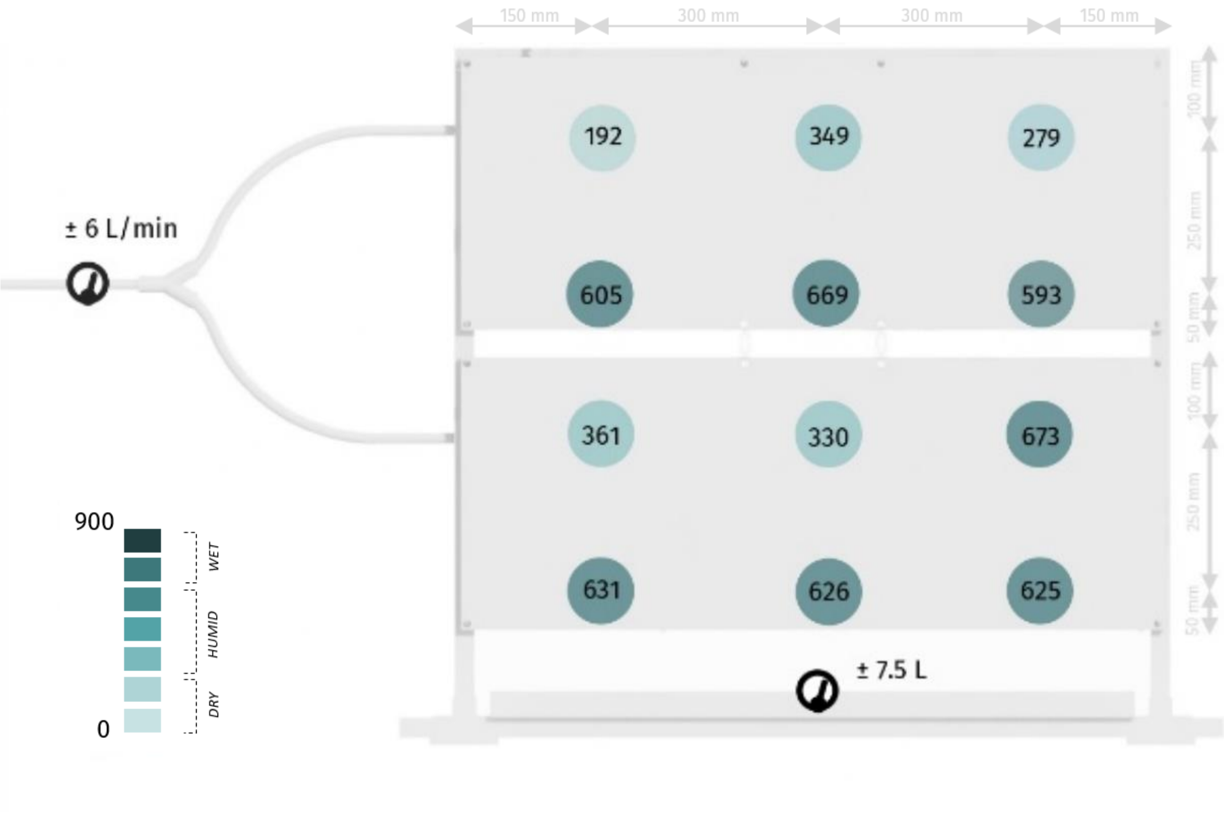


Test B.02

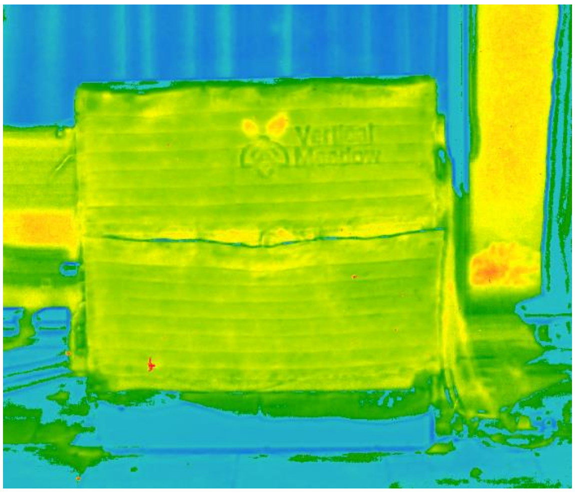
VARIABLE FACTORS	
Orientation	East
Temperature	16 °C, according to weather.com
Shading	None (there are surrounding buildings but they do not form an obstacle)
Humidity	44 %, according to weather.com

IRRIGATION	
Waterflow	6 l/min
Water time	1:30 min

Sensor results and run-off water:

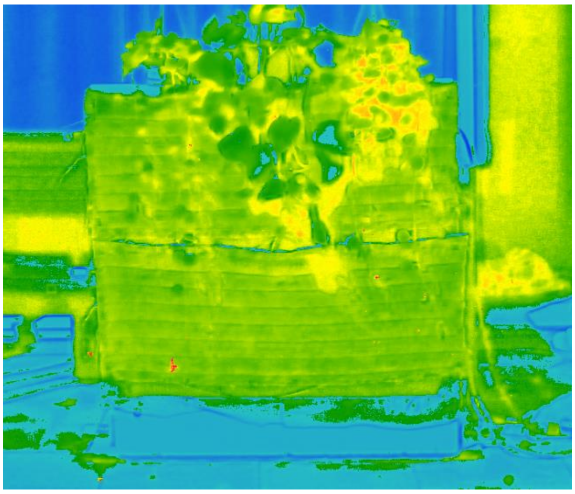


NDVI image without plants:

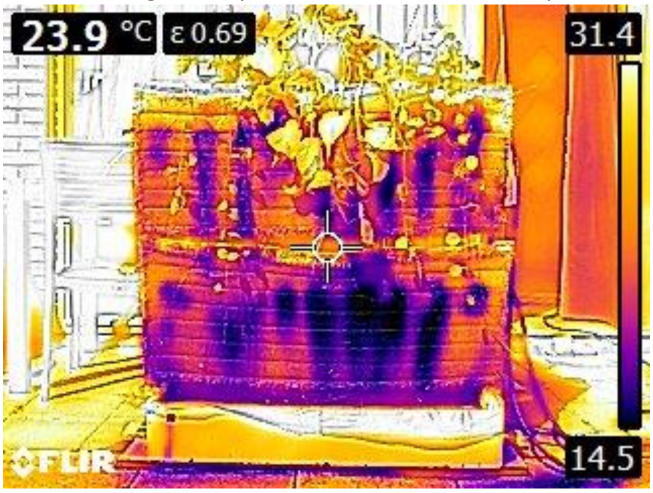


Thermal image without plants – scale set manually:

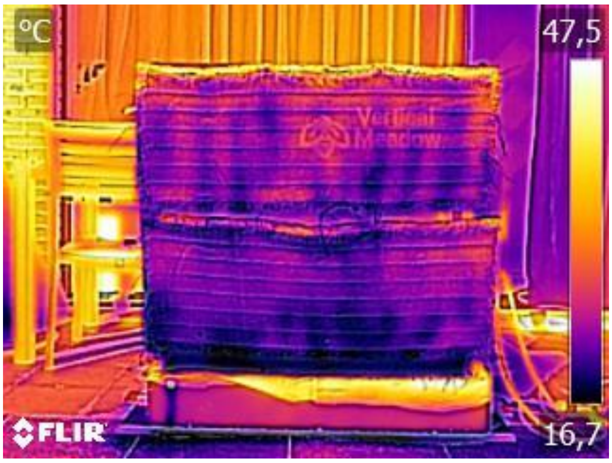
NDVI image with plants:



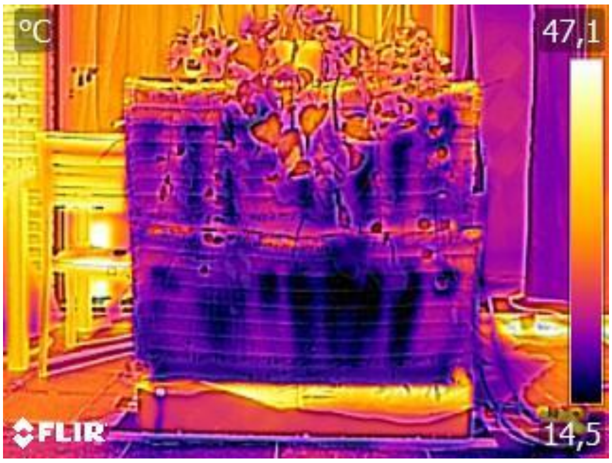
Thermal image with plants – scale set manually:



Thermal image without plants
scale set automatic:



Thermal image with plants
scale set automatic:

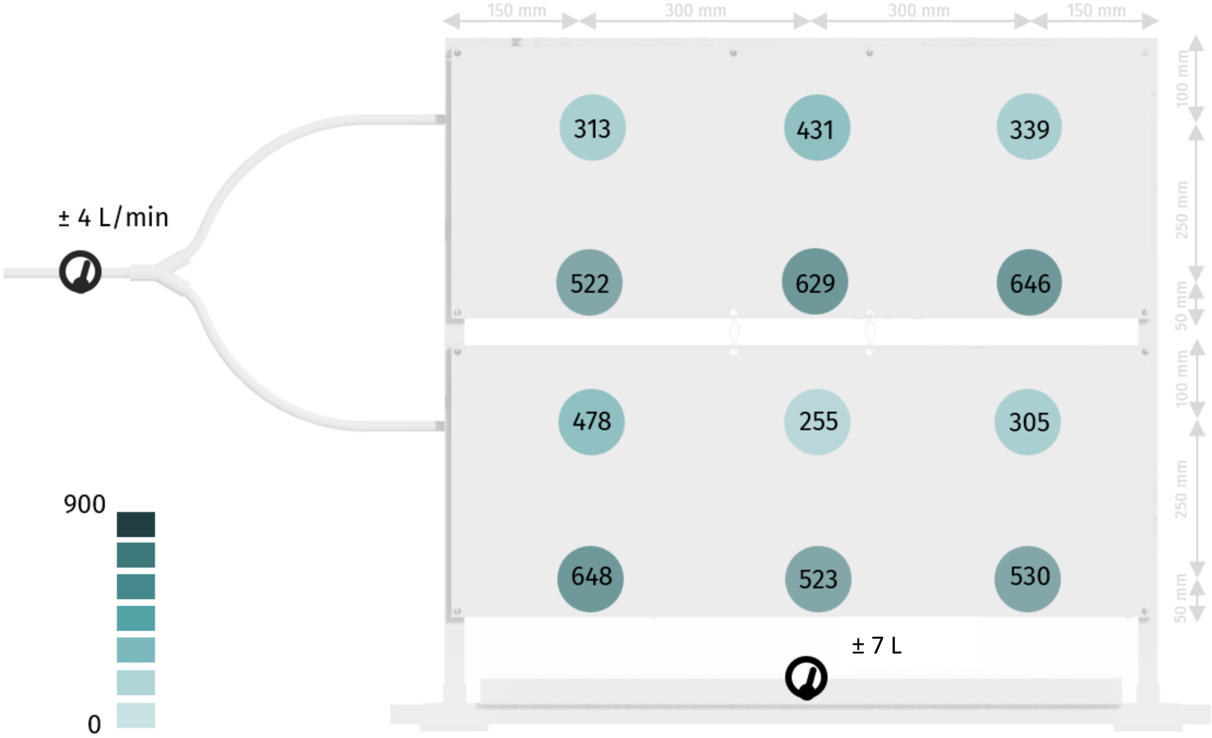


Test C.01

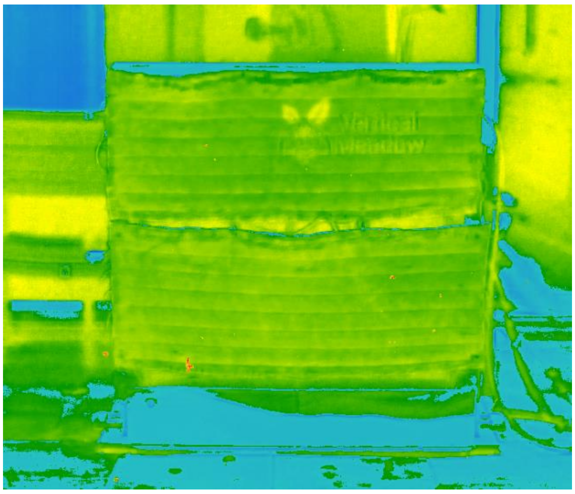
VARIABLE FACTORS	
Orientation	East
Temperature	14 °C, according to weather.com
Shading	None (there are surrounding buildings but they do not form an obstacle)
Humidity	49 %, according to weather.com

IRRIGATION	
Waterflow	4 l/min
Water time	3:00 min

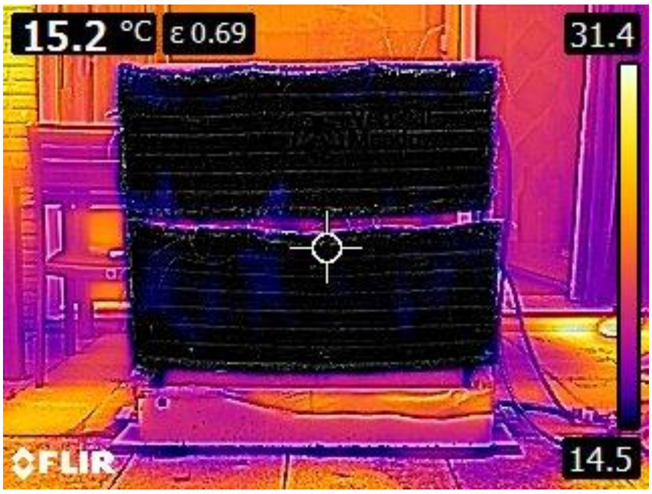
Sensor results and run-off water:



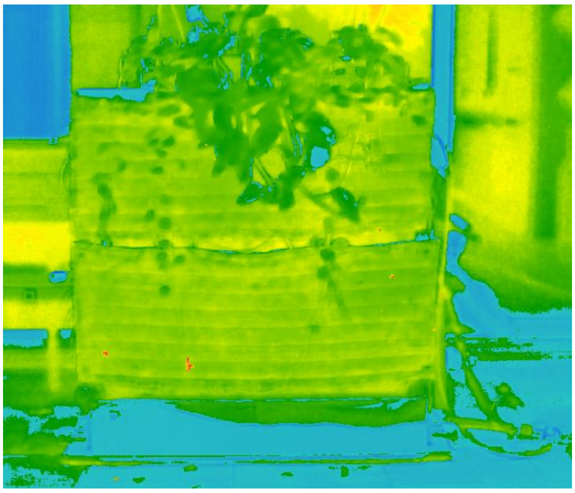
NDVI image without plants:



Thermal image without plants – scale set manually:

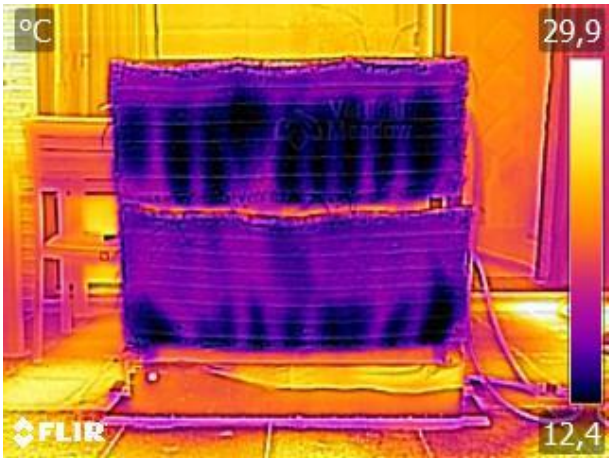


NDVI image with plants:

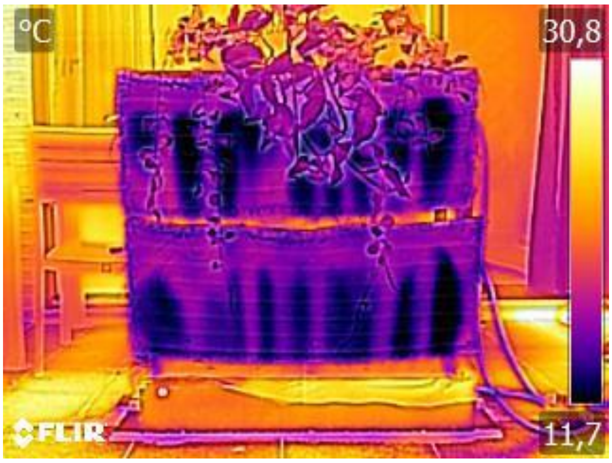


Thermal image with plants – scale set manually:

Thermal image without plants
scale set automatic:



Thermal image with plants
scale set automatic:

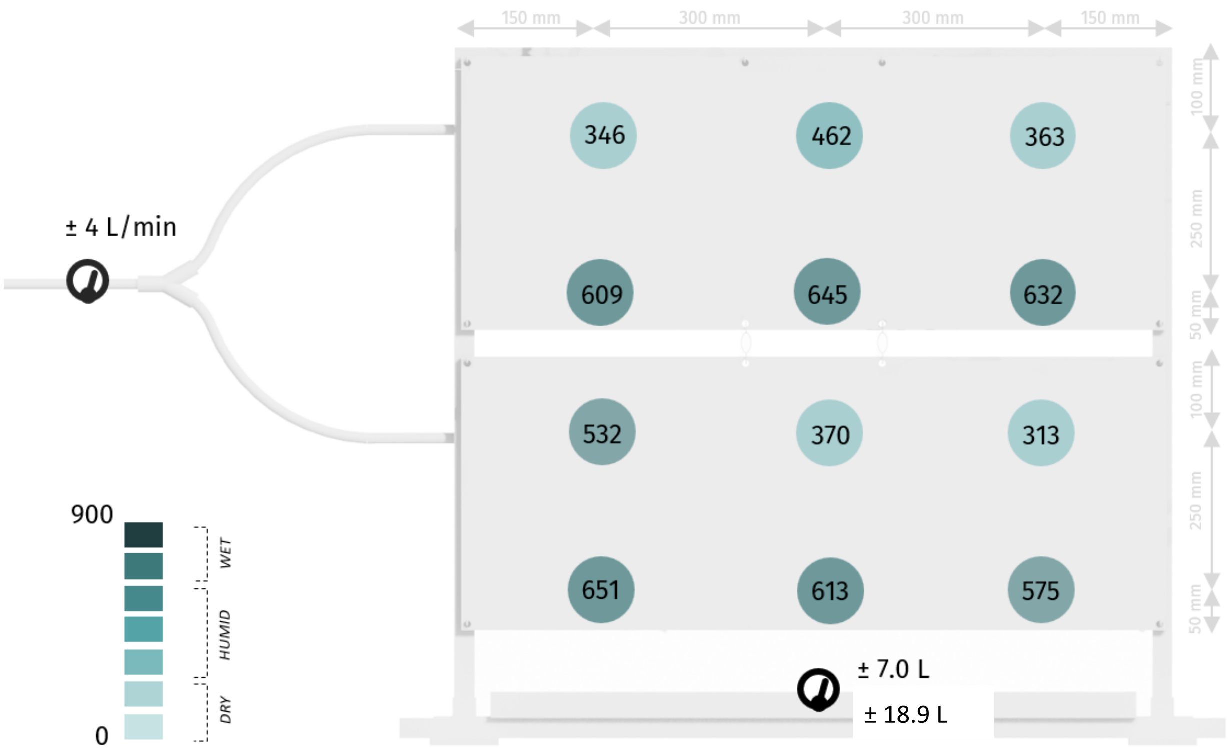


Test C.02

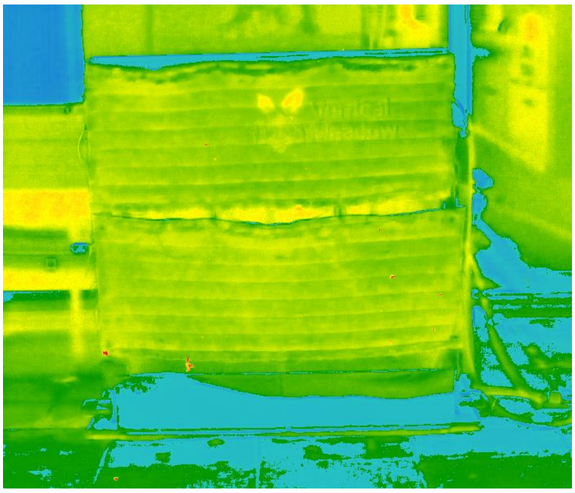
VARIABLE FACTORS	
Orientation	East
Temperature	13 °C, according to weather.com
Shading	None (there are surrounding buildings but they do not form an obstacle)
Humidity	49 %, according to weather.com

IRRIGATION	
Waterflow	4 l/min
Water time	6:00 min

Sensor results and run-off water:

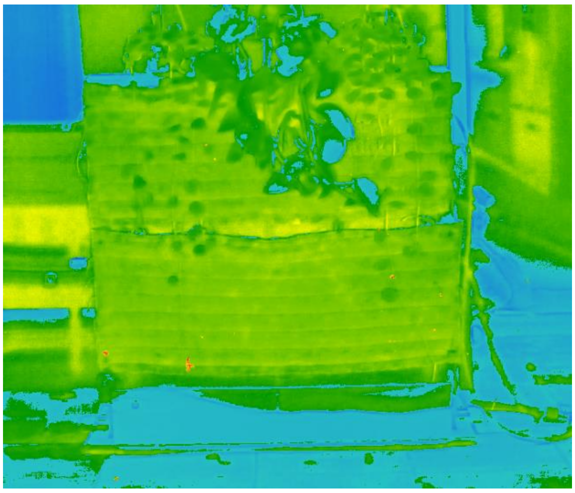


NDVI image without plants:



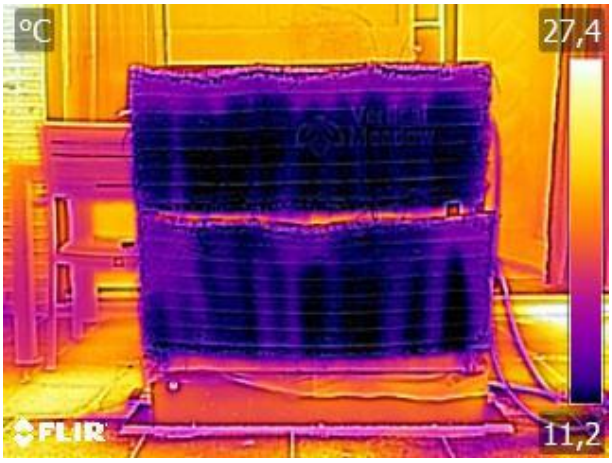
Thermal image without plants – scale set manually:

NDVI image with plants:

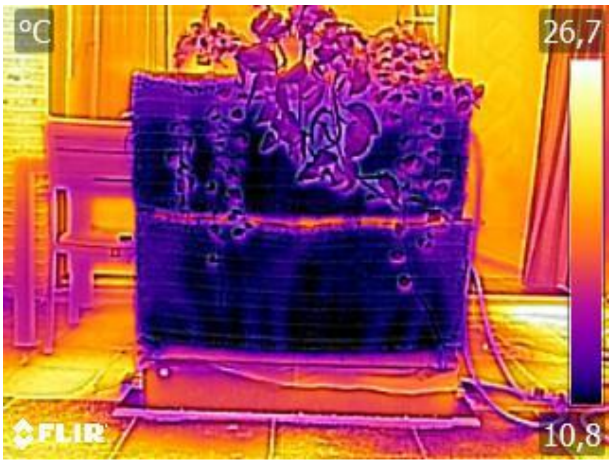


Thermal image with plants – scale set manually:

Thermal image without plants
scale set automatic:



Thermal image with plants
scale set automatic:

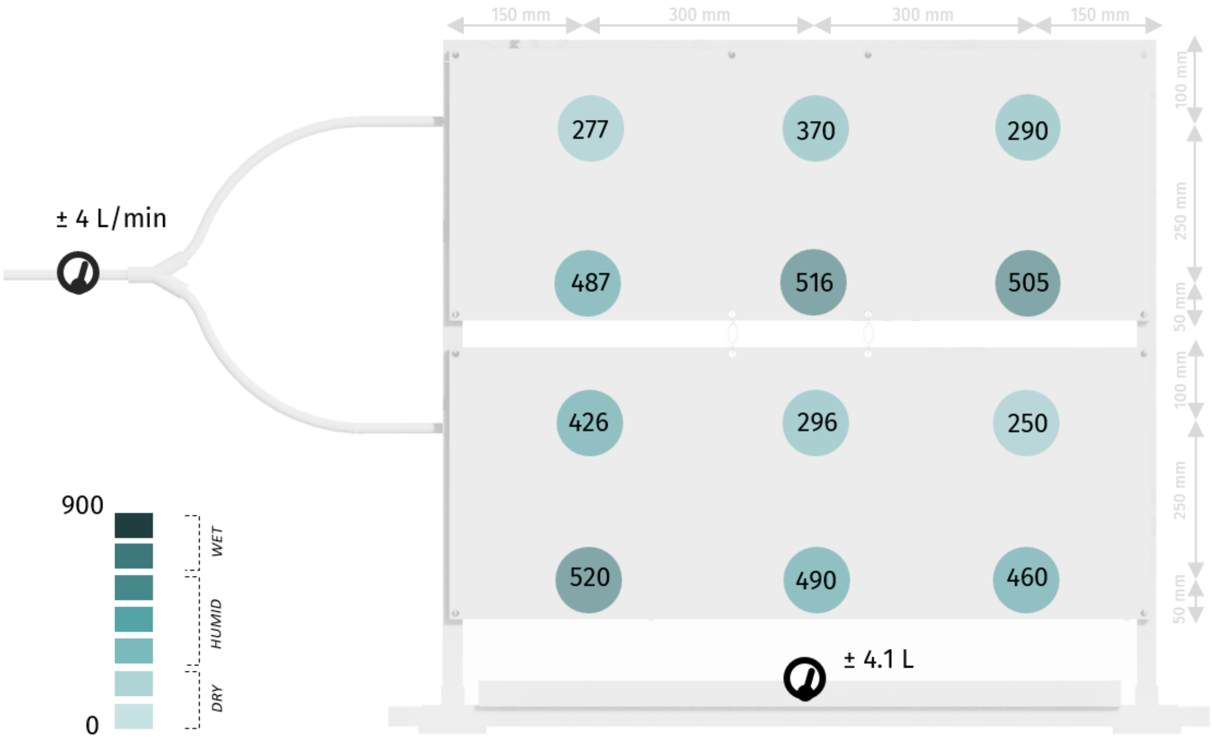


Test D.01

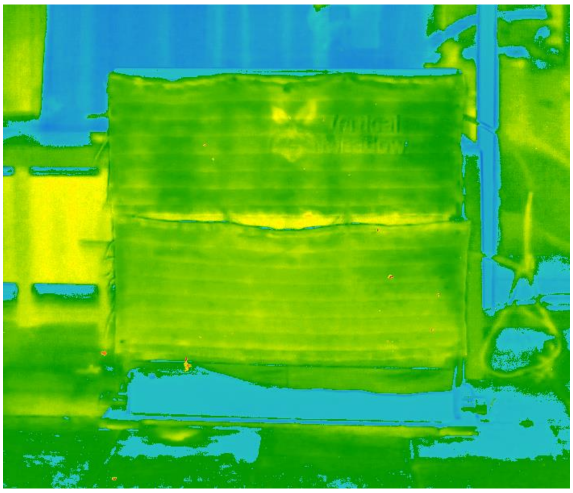
VARIABLE FACTORS	
Orientation	East
Temperature	11 °C, according to weather.com
Shading	None (there are surrounding buildings but they do not form an obstacle)
Humidity	56 %, according to weather.com

IRRIGATION	
Waterflow	4 l/min
Water time	1:30 min

Sensor results and run-off water:

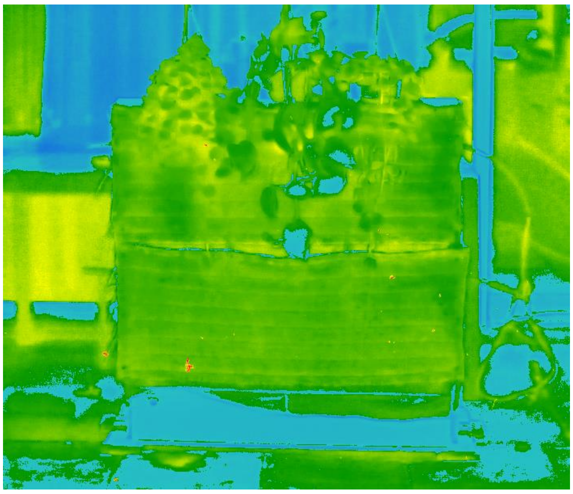


NDVI image without plants:

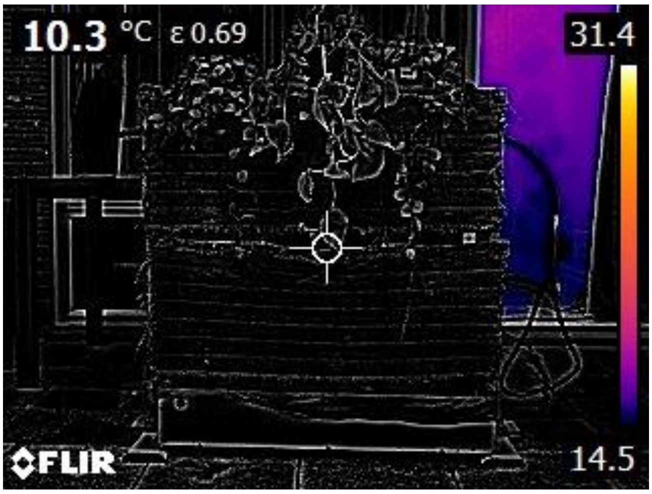


Thermal image without plants – scale set manually:

NDVI image with plants:



Thermal image with plants – scale set manually:



Thermal image without plants
scale set automatic:

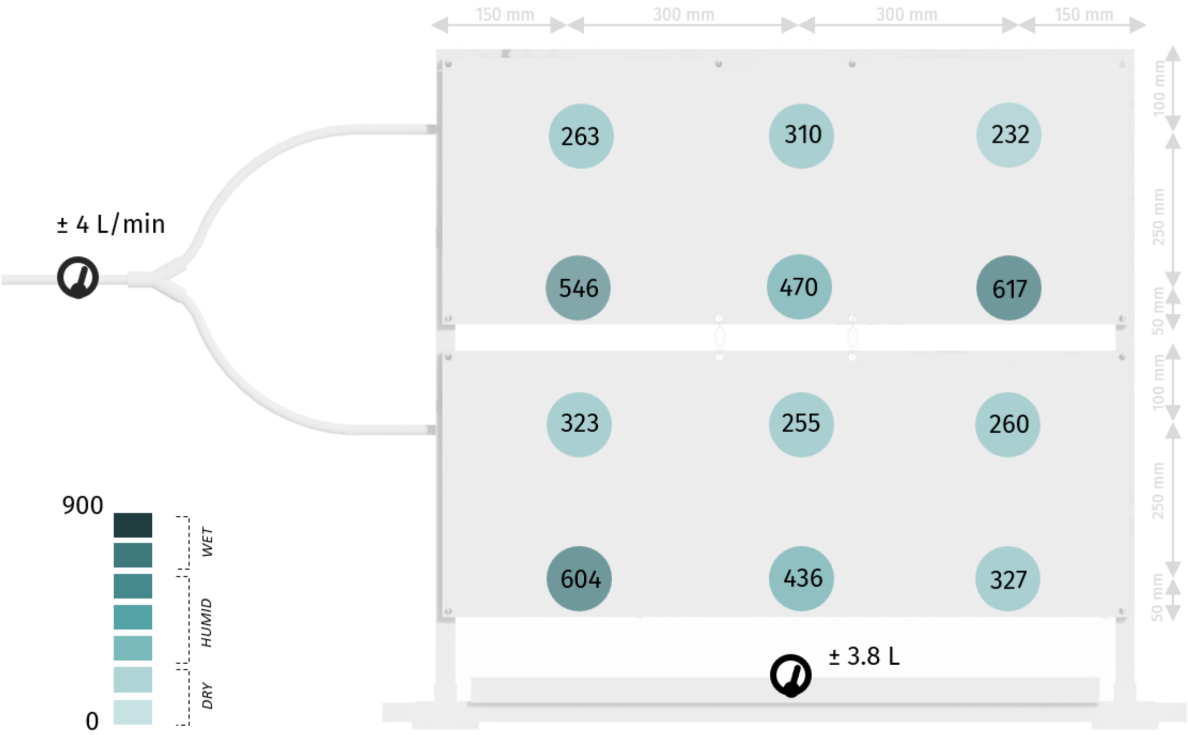
Thermal image with plants
scale set automatic:

Test D.02

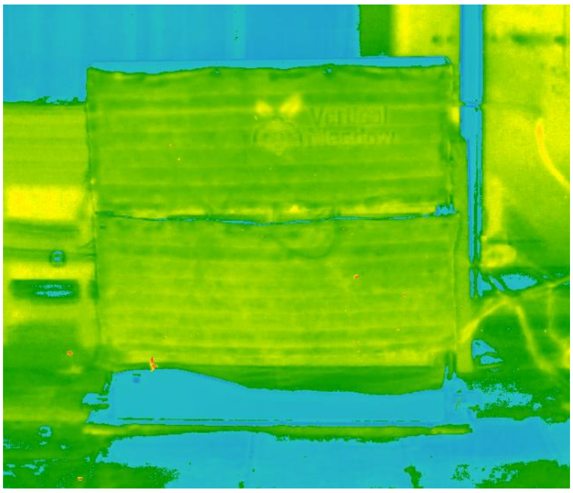
VARIABLE FACTORS	
Orientation	East
Temperature	12 °C, according to weather.com
Shading	None (there are surrounding buildings but they do not form an obstacle)
Humidity	56 %, according to weather.com

IRRIGATION	
Waterflow	4 l/min
Water time	1:30 min

Sensor results and run-off water:

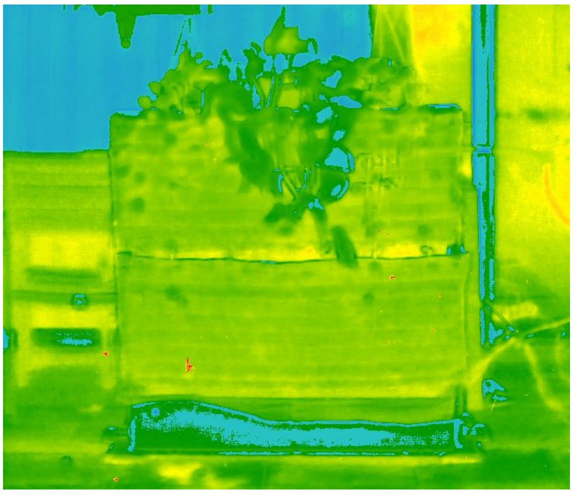


NDVI image without plants:



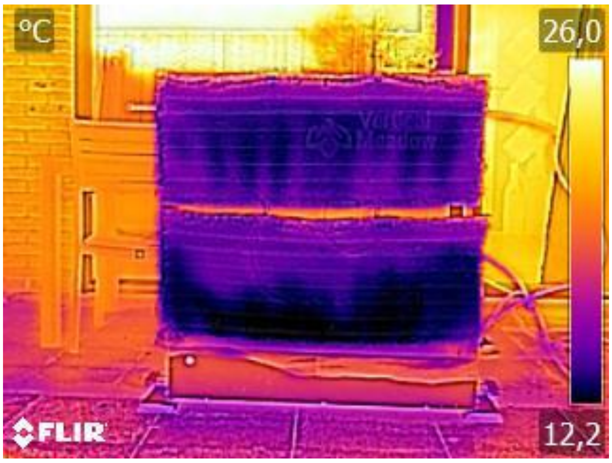
Thermal image without plants – scale set manually:

NDVI image with plants:

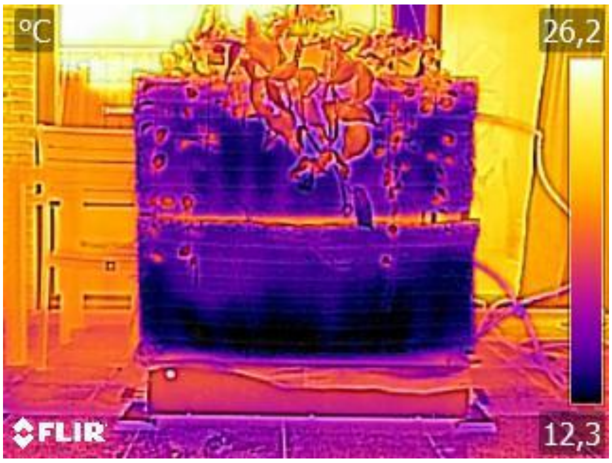


Thermal image with plants – scale set manually:

Thermal image without plants
scale set automatic:



Thermal image with plants
scale set automat

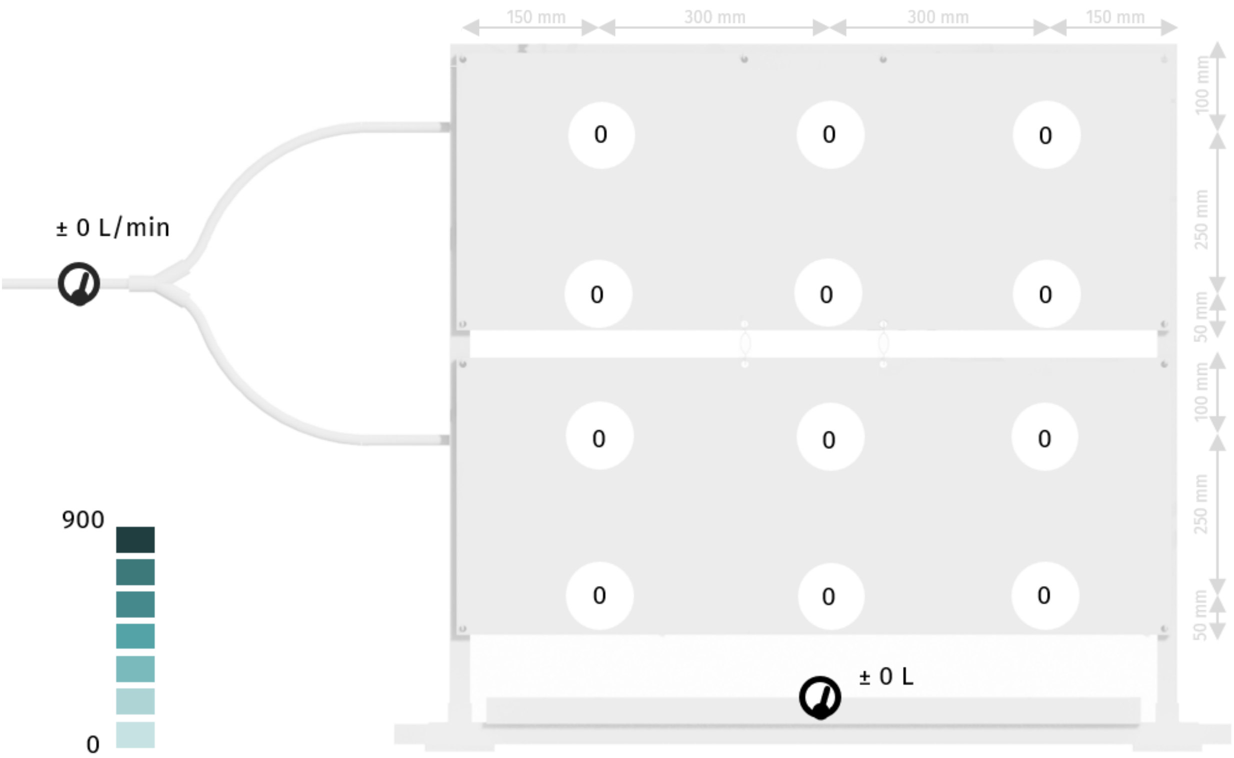


Test E.01

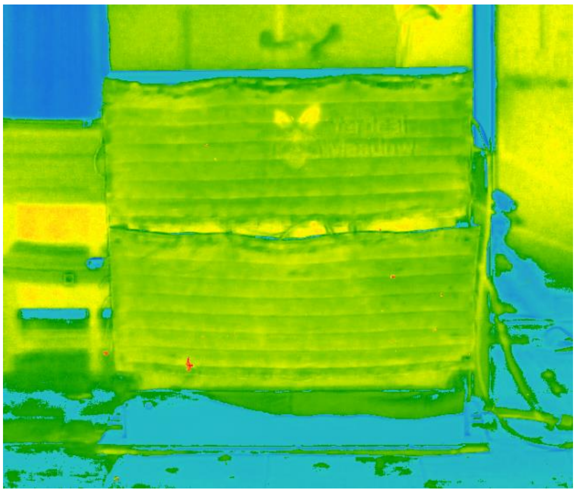
VARIABLE FACTORS	
Orientation	East
Temperature	12 °C, according to weather.com
Shading	None
Humidity	56%, according to weather.com

IRRIGATION	
Waterflow	0 L/min
Watertime	0:00 min

Sensor results and run-off water:

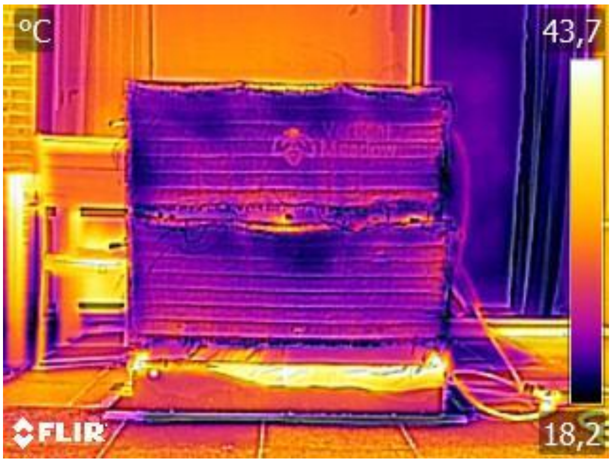


NDVI image without plants:



Thermal image without plants – scale set manually:

Thermal image without plants
scale set automatic:



Thermal image with plants
scale set automatic: