Irrigation of Urban Moss Surfaces

Making Cities Climate Resilient by Enhancing Moss Growth on Façades

Master Thesis

Industrial Design Engineering, TU Delft

Ruben van Briemen

May 2024

Irrigation of Urban Moss Surfaces

Making Cities Climate Resilient by Enhancing Moss Growth on Façades

Master Thesis

TU Delft
Faculty: Industrial Design Engineering
Master: Integrated Product Design
Student: Ruben van Briemen (4666070)
Chair: Dr. J. Soares de Oliveira Martins
Mentor: Ir. P.A. Kraaijeveld
Company coach: Auke Bleij
Company: Respyre B.V.

May 2024

ACKNOWLEDGEMENTS

This project would not have been possible without my supervisors Joana Martins and Peter Kraaijeveld. Thank you for your valuable guidance and advice during our weekly meetings.

Thank you to the Respyre team, it has been amazing working together with all of you. Special thanks to Auke Bleij and Adil Aarouss for your critical feedback, for thinking along with me, and for providing me with everything I needed throughout the project.

I would like to thank Ard Hoogervorst for helping me with setting up the prototypes in the greenhouse. Thank you Max Veeger for providing me with all required knowledge about moss. Finally, I want to thank Khalid Aarouss, Jan-Willem de Wit, and Eric Cramer for your critical feedback on the installation and functioning of the irrigation system.

SUMMARY

Moss covered surfaces are a promising way to mitigate the urban heat island effect. A layer of moss on a building's façade reduces heat absorption during summer, hence passively cooling the building and its surroundings. The startup Respyre wants to offer such moss layers as a commercial product. A bio-gel mixed with moss fragments is sprayed on a porous concrete outer layer. This is irrigated for several months until the wall is covered by a layer of living moss.

The aim of this project is to rethink the existing irrigation system, since it gives a bad water distribution, resulting in high water usage and uneven moss growth.

First, the context was analysed. Literature study and an interview with an expert provided a better understanding of what role moss has in mitigating the urban heat island effect and what moss needs from a biological perspective. Further research revealed what solutions for providing moist already exist. A stakeholder analysis provided insight into who has something to say about the irrigation system. All these findings together resulted in a list of requirements.

During a brainstorm, a set of ideas was sketched to find as many out-of-the-box solutions as possible. This is a mix of new ideas, existing ideas found during the analysis, and combined ideas.

The brainstormed ideas that are feasible were developed into concepts. They were prototyped and their water distributing performance was tested by irrigating them in a green house. The concepts have been assessed on (among others) water distribution, estimated costs, minimum water pressure, ease of installation, and the need for developing new parts.

Five promising concepts were further developed and tested on a larger prototype. Their water distribution was quantitively tested, and costs estimated.

The finally chosen solution was further improved and detailed in the last stage. The end result is a design and prototype of an irrigation system that gives a slightly more uniform water distribution at a significantly slower rate for comparable costs.

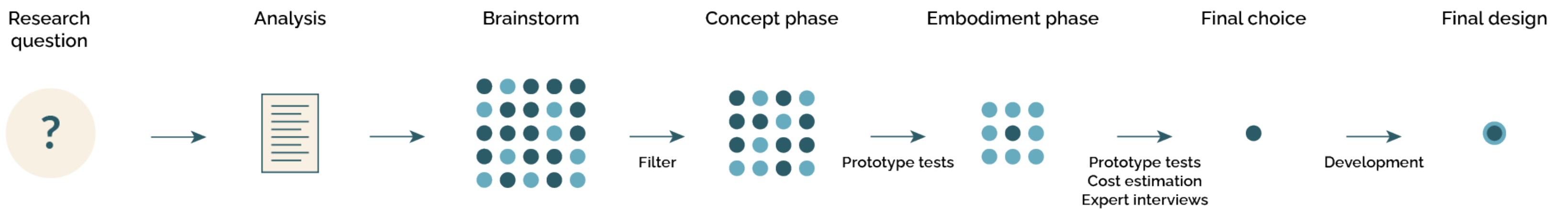


Figure 1: Visual summary of the project's process.

TABLE OF CONTENTS

1 INTRODUCTION

Without human intervention, moss grows on many places in nature and in cities, covering trees, walls, roofs, and pavements. People sometimes remove moss, while on the other hand we try to make cities greener. Moss has the potential to contribute to greener cities if we let it cover urban surfaces.

The startup Respyre goes one step further by enhancing moss growth and offering it as commercial product for urban façades and sound barriers. Before it can be viable as a product, the growth must be enhanced by providing sufficient nutrients and water. Therefore, Respyre has developed a bio-enhancing gel containing nutrients and has a prototype of an irrigation system.

1.1 Problem Definition

The irrigation system however is costly and very inefficient; most water is lost at the bottom of the moss wall. Currently, water is distributed unevenly along the wall, causing moss growth to stay behind at dry spots and causing mould growth at wet spots. Besides that, there is a need for one system that is suitable for several surface types: façades of buildings (both new and existing), sound barriers and quay walls of varying sizes. Ideally, a watering system would also be suitable for locations without electricity. There is a need to completely rethink the way water is supplied. Therefore, the core of the problem is:

How can irrigation systems provide vertical surfaces in urban areas with the optimal moisture conditions to accelerate moss growth?

Providing the optimal moisture conditions should be done in the most water efficient, cost effective, aesthetically pleasing, and low maintenance way possible. Also, the system must be removable; in most cases, irrigation is no longer needed after the first months. The answer to this main question is the missing piece to make moss a viable, desirable, and feasible way to cool cities. See 'Appendix A – Project Brief' for all goals set at the start of the project.

1.2 Scope

This project focusses on the way water is supplied to and distributed over a moss surface using an irrigation system. The irrigation regime, the programme that regulated how much and often is irrigated, is out of scope. That requires a dedicated research project by a biologist.

2 ANALYSIS

To answer the main research question, a few sub questions were formulated. Some sub questions address the core problem (water demand and solutions for water supply), others address the context in which moss surfaces are applied, such as urban heat island in general, the policies and regulations. An understanding of the wider context is essential to make sure the result of this graduation project successfully contributes to a more climate adaptive city.

2.1 Understanding the Context

2.1.1 What causes the urban heat island effect?

The urban heat island (UHI) is phenomenon where cities become warmer than surrounding rural areas. According to Atlas Leefomgeving, the average temperature in Dutch cities is up to 3 °C higher than surrounding areas from June to August. However, on some hot days it can be 7 or 8 °C warmer than surrounding areas (Atlas Leefomgeving, 2023).

Urban areas usually have surfaces with low albedo values (e.g. dark asphalt which doesn't reflect much sunlight), little evapotranspiration (less vegetation compared to non-urban area), and more anthropogenic heat sources (vehicles, air conditioning etc.) (Stone et al., 2010). Also, urban materials have a higher heat conductivity (which increases heat absorption) and heat capacity (which allows it to store the absorbed thermal energy) (Grimmond, 2007).

2.1.2 How can the urban heat island effect be reduced?

Addressing the causes mentioned above will mitigate the UHI. Several studies mention more urban green and more reflective materials as possible solutions (Mohajerani et al., 2017; Yang et al., 2016; Akbari & Rose, 2008; Grimmond, 2007). Also, reducing anthropogenic heat production by vehicles and cooling systems will probably have potential, as well as reducing the use of heat absorbing materials.

2.1.3 What role can moss play in that context?

Moss plays a role in mitigating the UHI through insulation and evaporation. First, covering concrete by a layer of moss slows the heat absorption due to its low thermal conductivity (see Figure 2). Second, by evaporating water moss absorbs latent energy (heat) from its environment (see Figure 3). The efficacy of evaporation however strongly depends on the availability of water (Stache et al., 2022). If the moss goes without rain or artificial irrigation for a long time, the urban area still benefits from the slower heat absorption due to moss's low thermal conductivity.

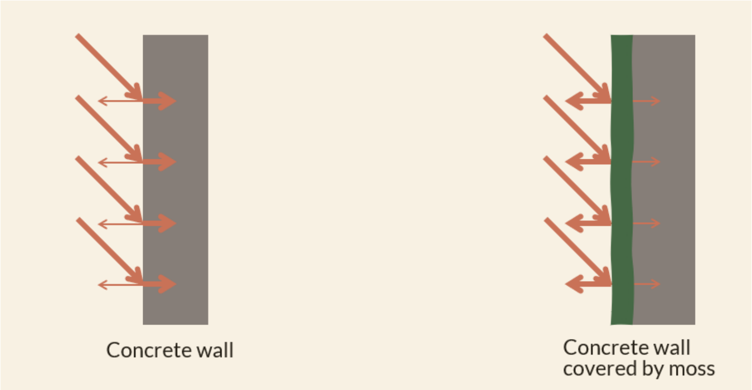


Figure 2: UHI: plain concrete absorbs more thermal energy than an insulated concrete wall.

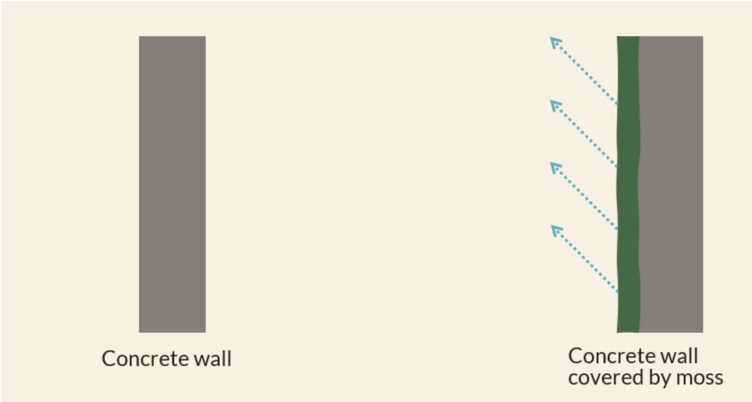


Figure 3: When sufficient water is available, moss-covered walls can cool the environment by evaporation.

2.1.4 What are the "competitors" of moss?

There are several solutions which offer one or more of the same benefits as moss. Some of these are "direct competitors"; they can replace moss (e.g.: a wall can either be painted white or covered by moss, not both). Others are "indirect competitors"; they can go together with moss but become competitors due to limited budget (e.g.: a house owner can install both a moss wall and a green roof, but might have the budget for only one of them). From a commercial perspective it is interesting to make moss walls more attractive than its competitors in terms of costs and offered benefits, especially the direct competitors. Also, for the purpose of making cities liveable, it is important to enhance moss's benefits (e.g.: maximise the cooling effect of moss) as well as competing with solutions that have disadvantages.

Urban areas can be made greener using moss and other vertical growing vegetation, using street level green (trees, grass), or by green roofs. Other green walls offer aesthetical and insulating properties just like vertical moss. Other green walls are direct competitors to moss walls, since a wall can only be equipped with one of both.

Green roofs offer the benefit of insulation too (Niachou et al., 2001), but have limited aesthetical or psychological effect as they are often not visible from street level (Williams et al., 2019). They are indirect competitors; the installation of a green roof does not hinder the installation of a moss wall, but they might have to share the same budget.

Trees provide shade and evaporation. Parks offer aesthetical value, as well as physical health and social benefits since it provides a place where people can walk, exercise, meet or recreate (Lee & Maheswaran, 2010). The challenge of adding green through parks or trees is finding the required space in a dense urban area. They are indirect competitors; they can go together with moss walls.

Buildings can be insulated using non living materials too, such as polystyrene foam. This has the potential to reduce the cooling demand (Aktacir et al., 2010). An alternative to traditional insulation is a double-skin façade, an extra glass skin in front of the building's wall with a layer of trapped air in between. This can reduce the cooling demand if combined with shading and night ventilation of the inner air layer (Hashemi et al., 2010). The advantage is that it requires no irrigation and doesn't need time to grow after installation. These are direct competitors to moss since a wall can only be equipped with one of these solutions.

Sun blinds prevent solar irradiation from entering a building through windows. It's not a direct competitor of moss, they can go together.

Buildings can be cooled actively using air conditioners. Air conditioners have a paradoxical effect: they reduce the indoor temperature by absorbing heat, but this heat is released outside. Since no electrical device has a 100% efficiency, more heat is released outside than absorbed inside. Air conditioners are listed as one of the causes of the

UHI by some (Stone et al., 2010; Grimmond, 2007). In urban areas where air conditioners are used a lot, an increased outdoor temperature can be observed (De Munck et al., 2012). This increased outdoor temperature further increases the need for cooling. Besides direct heat production on a local scale, it contributes to global warming indirectly through CO_2 emissions. Air conditioners are a competitor to moss since they both offer a reduced indoor temperature. However, solutions such as moss don't increase the UHI, therefore they should be made more attractive than air conditioners. These are indirect competitors; they don't directly stand in the way of installing moss walls.

Surfaces with a high albedo value (i.e. reflectiveness) reduce the amount of irradiation absorbed by the city. Increasing the albedo value of vertical surfaces (e.g.: painting a wall in white) is a direct competitor of growing moss, since the same surface can only be equipped with one of these solutions. Increasing the albedo of roofs is an indirect competitor.

2.1.5 How does moss relate to its competitors?

Moss has the advantage over trees that it can be implemented in streets with little space. It has the advantage over green roofs since it is visible from street level.

Cooling buildings through moss and other urban green is preferred to AC units since the latter increases electricity use, noise stress and produces direct heat, thus increasing the UHI.

Non living façade insulation, reflective façades, and other vertical green help mitigating the UHI and can be applied to the same surfaces as moss. This makes them direct competitors. Moss's advantage over other insulation and reflection is that it contributes to a greener environment as well, but the need for irrigation and the time required for growing are disadvantages. Other types of vertical vegetation are the most similar competitor. Moss can compete with those if it grows faster, needs less maintenance, and has lower investment costs.

In addition to mitigating the UHI, urban green has economical benefits as it increases property value (Mwendwa & Giliba, 2012; Heidt & Neef, 2008) and reduces energy costs from cooling (Heidt & Neef, 2008). Moss also has the potential to improve air quality as it takes up nitrogen (Fritz et al., 2014), volatile organic compounds (Gong et al., 2019), and particulate matter (Gong et al., 2019; Haynes et al., 2019). Finally, urban green space in general has a positive impact on psychological, emotional, and mental health, although these benefits are difficult to quantify and seem to apply mainly to horizontal green spaces such as parks (Lee & Maheswaran, 2010).

2.2 Moss's Biological Requirements

2.2.1 What are the optimal conditions for growing and maintaining moss?

To use the full potential of moss, it is important to understand what moss needs to grow and sustain. The information in this section is based on an interview with Max Veeger, expert on moss concrete and advisor for Respyre, as well as on literature research.

Figure 4: Silvery thread moss (Michigan State University, n.d.)

Respyre uses the moss specie *Bryum argenteum*, also known as silvery thread moss. It is drought resilient and is ideal for growing on concrete.

Moss has little internal transport of water and nutrients. It has no roots, but rhizoids which main function is the attachment to a surface. Uptake of water or nutrients occurs mainly through the leaves. Therefore, water should be distributed over the surface as uniformly as possible, especially at the start, when young moss consists of separate parts that cannot spread water to each other. Small droplets are preferred to large drops, since larger once can wash away the fragile young moss plants. More water is beneficial for growth but makes moss less resilient to drought. Abundant irrigation for three months followed by a long drought is harmful for moss. Moss can develop drought resilience if irrigation is alternated with periods of drought. It could then survive without water for months. Drought resilience can be "unlearnt"; long periods of rain followed by long droughts can harm fully grown moss too. Moss is a photosynthetic organism. Therefore, irrigation should be done in the morning since photosynthesis occurs during daylight. Little research has been done regarding moss cultivation. Finding the optimal irrigation programme requires trial an error.

Zechmeister et al. (2023) studied indoor moss growth on vertical surfaces. It studies seven moss species, but not the specie used by Respyre. The paper recommends spray irrigation (in stead of drip irrigation) from the front. This corresponds with the advice given by Veeger. However, moss seemed to grow well where dripping could reach, but drip irrigation didn't have a uniform distribution. It is unknown whether spray irrigation still grows better moss than drip irrigation if the latter can be done in a more uniform way. The researchers also concluded that spray irrigation causes less mould growth because it cleans the moss leave surfaces.

Nutrients are supplied through gas exchange at the leaves, there is no need for adding nutrients to the water supply according to Veeger. Water with too high mineral concentrations can extract moist from the leaves due to osmotic pressure. Too much moist can obstruct gas exchange through the leaves. Some nutrients are supplied to the moss through the bio-enhancing gel.

The optimal growing temperature is 15 – 25°C. Temperatures below this range are less harmful than above. The effect of high temperatures in combination with moist is unknown, however Veeger expects hot humid weather might be more harmful than hot dry weather. Varela et al. found that *Bryum argenteum* grows best at 15°C; at 20°C and 25°C it grows faster, but starts dying after a few weeks (2021).

Raudenbush et al. (2016) found that irrigating *Bryum argenteum* with water of pH 5 or 6 shows much higher surface cover compared to pH 7 or 8.

2.3 How to Provide the Optimal Biological Context Using Irrigation Systems

The aim of this section is to provide an overview of existing solutions for distributing water uniformly. The focus is on vertical surfaces, but irrigation in other situations is also considered since it might give inspiration for this project.

2.3.1 What irrigation methods for moss already exist?

Respyre has a working irrigation system installed at one of its first clients. It uses a pump, water reservoir and control panel in the basement, from where the water is transferred to the top of the outer walls through pipes. These pipes along the top of the façade are equipped with spray nozzles every ±25 cm, that spread water horizontally, after which it runs down the wall. The spread is far from perfect, most water runs below the nozzles (see Figure 5). A lot of water runs off at the bottom and is lost.

Figure 5: Respyre's current irrigation system. Spray nozzles can be seen underneath the window. On the wall below, wet and dry spots can be seen, indicating a non-uniform water distribution.

2.3.2 What irrigation methods for vertical surfaces already exist?

Often vertical green surfaces use drip irrigation. A guideline document by Urban Greening (Urban Greening, 2013) gives four examples of green wall irrigation methods, three out of which use drip irrigation.

The company Florafelt offers indoor green walls including an irrigation system. Water is distributed through tubes with holes that let water flow, not drip, from the top of the wall (Florafelt Living Wall Systems, n.d.). Water is retained because plants grow in felt bags that slow the water runoff, a uniform distribution is of less importance.

Both these examples have plants that are more vascular than moss. Water can be absorbed by roots, so a uniform distribution to leaves is not necessary. The advantage of drip irrigation is that less water is carried away by wind compared to spray irrigation. Florafelt's system lets water flow in stead of drip, which requires larger holes, reducing the risk of clogging.

2.3.3 What methods/technologies for even water distribution exist?

Regarding spraying methods, Bartok (2016) distinguishes two common ways to spray water. The first is hydraulic, using water pressure in combination with a nozzle. The second is "low volume", using an airflow.

Spray nozzles typically have a very small orifice, which is vulnerable to clogging. Since the moss irrigation system might recirculate water, which could contain moss particles, it is important to find clog free water distribution techniques.

Fire sprinklers for example don't use a nozzle (Figure 6). A strong water flow exits the sprinkler, after which it hits a metal plate, a deflector, from where it splashes aside, spreading the water (Ultrasafe Fire Suppression, n.d.). There are several sprinkler types: upright, pendent, sideways. They all use a deflector to spread the water, however its design is adjusted to the orientation. (Anderson, 2023).

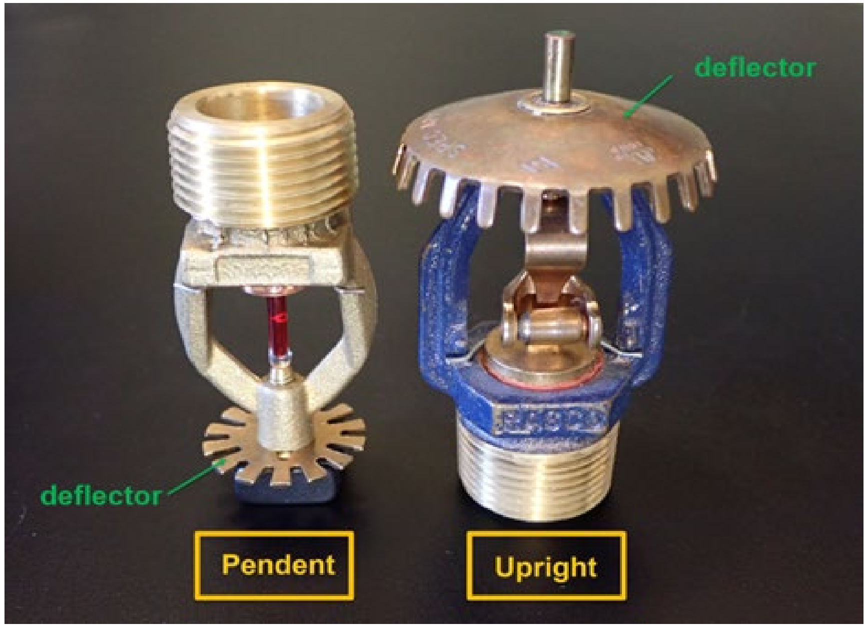


Figure 6: sprinklers of two different orientations. (Anderson, 2023)

The company BETE offers nozzles of several drop sizes and spray patterns, some of which are claimed to be clog-resistant, with an even cone-shaped distribution and fine atomisation (BETE Fog Nozzle, 2020).

The expected disadvantages are water loss due to fine atomisation carried away by the wind and the fact that it is unevenly spread over the moss surface, unless the nozzle is placed far from the wall. Advantages are the clog resistance and fine atomisation (which does not wash away young fragile moss and can be absorbed very well).

In water treatment plants cascade aerators are used to mix water with air (Ketav Consultant, n.d.). The application is different, but the result is the same: a flow of water breaks into smaller drops (Figure 7). The advantage is that water isn't spread from a single point (this has shown a bad water distribution at Respyre's client) but is evenly spread along the total length of the wall. As can be seen in Figure 8, the water flow is still quite strong, it should be tested if an adjusted design can create smaller water drops.

Figure 7: Cascade aerator (Ketav Consultant, n.d.)

Figure 8: Cascade aerator up close (PWN, n.d.)

Semananda et al. (2018) compared several capillary irrigation systems with surface irrigation. They conclude that capillary irrigation has potential to improve water efficiency, as it can "eliminate the two main water loss pathways in irrigation (evaporation and runoff)." The disadvantages of most systems are higher complexity and costs. However, they claim the wicking bed irrigation doesn't have the disadvantages and could be promising for efficient urban agriculture irrigation. (Semananda et al., 2018). This study only addresses horizontal surfaces. Besides that, it is focussed on plants with roots, while moss absorbs water through leaves. However, it could serve as inspiration for horizontal water distribution along a wall.

A water wall such as in this park in Houston (Figure 9) consists of a wall from which water runs down (Waterwall Park, n.d.). At the bottom, the water hits an inclined wall, which seems to create a more turbulent water flow.

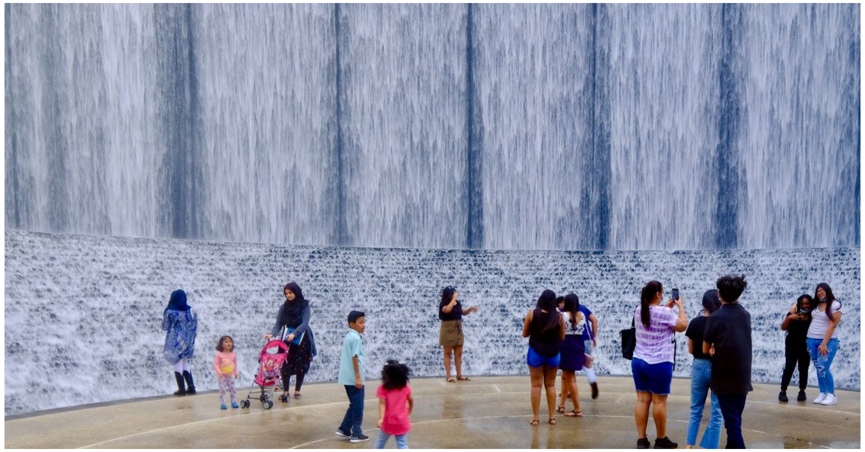


Figure 9: Water wall in Houston (Waterwall Park, n.d.)

Inspiration can be found in the way water falls from a tree's canopy. It should be tested whether a leave-like structure can also create small drops from a continuous water flow instead of rain.

Water can be spread using low-frequency ultrasonic atomisers (Sindayihebura et al., 1997). This could have potential for clog-free irrigation since it requires no nozzle orifice. It is currently applied in healthcare (HOERBIGER Motion Control GmbH). It creates a very fine mist, which can easily be blown away by the wind.

Atomising liquids using electrostatic charging can improve efficacy of insecticide sprays (Whitmore, 2000). It's unknown if this technique is efficient for irrigation, but it can serve as inspiration.

2.3.4 What methods for recirculating water exist?

The indoor green wall irrigation system by the aforementioned company Florafelt includes recirculation (Florafelt Living Wall Systems, n.d.). Its working principle is simple; runoff water is collected in a gutter below the wall, from where it is drained to a tank. From the tank it is pumped up the wall for irrigation. It is not filtered in this particular example, so clogging will be a problem when combined with spray nozzles. The simplicity of the system could be a strong advantage if it reduces investment and maintenance costs.

Figure 10: Gutter which collects water at the bottom of the wall. (Florafelt Living Wall Systems, n.d.)

Hydroblob is a rock wool block that can be placed under the ground to function as a water buffer. RWBNL B.V. for instance sells it as a solution for flooding in gardens. It absorbs water and drains it to the soil underneath (RWBNL B.V., 2021). This solution was advised by a gardener. It is currently not used to collect water, but it is worth investigating if that can be done and if it also has the potential to filter water.

2.4 Implementation of the System

2.4.1 How can the water quality and safety be guaranteed when reusing water?

If water distribution is done by standard spray nozzles, it is essential to remove any particles from the collected water to prevent clogging. Fine nozzles might also get clogged if they spray hard water; limescale can build up over time and eventually clog the nozzle's orifice. Finally, *Legionella* prevention should be considered, since these bacteria are found in reclaimed water (Pepper & Gerba, 2018). *Legionella* is a bacterium that can cause legionnaire's disease.

There are many common water drainage solutions for private gardens, such as a channel drain or French channel in the ground (Wallender, 2022). A channel drain (Figure 11) is simple but will only filter large things such as leaves. A French channel (Figure 12) uses a perforated pipe covered by gravel to keep out large particles.

Figure 11: Channel drain (Wallender, 2022)

Figure 12: French drain (Ahrens, 2022)

Coir drainage consists of polymer pipes perforated for water inlet, which are wrapped in coir (coconut fibre) to prevent it from getting clogged (Irritech, n.d.)(see Figure 13). When placed underground, water runs in through the perforations. This solution was advised by a gardener. It should be tested if the filtering performance of the channel drain, French channel and coir drainage meet the requirements for recirculating, especially when combined with fine spray nozzles.

Figure 13: coir drainage (Irritech, n.d.)

Reverse osmosis (RO) is a concentration technique. A membrane allows water to pass, while retaining 95-99% of organic and inorganic solutes (El-Salam, 2003). This is a more advanced solution than the other examples and the water delivered will probably be safe enough for recirculation.

In water treatment plants, solids are removed from water by sedimentation: solid particles heavier than water sink to the bottom. Another method for removing particles is filtration. Filters can be made of sand, gravel, or charcoal (U.S. Department of Health & Human Services, 2022).

Pepper and Gerba describe *Legionella* bacteria as a water-based pathogen. When droplets containing *Legionella* are inhaled, it can cause legionellosis (legionnaires' diseases). Small aerosols can travel further through air than larger droplets. Therefore, spray irrigation using reclaimed water is a significant risk of *Legionella* exposure. The risk of exposure depends on the concentration of *Legionella* in water, size of droplets, distance from the source, and duration of exposure. (Pepper & Gerba, 2018)

According to the National Academies of Sciences, Engineering, and Medicine (2020) *Legionella* growth occurs between 25°C and 55°C (p. 175). *Legionella* already present in water can only be killed by increasing the temperature to 70°C for 60 minutes (p. 168).

Water can be disinfected from *Legionella* chemically using chlorine, chlorine dioxide, chloramine, or ozone (p. 176), by UV irradiation (p. 180), or by copper-silver ionisation (p. 181).

Prolonged stagnation and dead legs in the plumbing should be avoided (p. 183).

Legionella growth can be prevented by limiting the availability of nutrients in water (p. 185). Also the plumbing material choice influences *Legionella* growth (p. 186). These guidelines will be implemented in the List of Requirements of this thesis.

2.4.2 What policies/ regulations/ subsidies for moss/ urban green exist in the Netherlands/EU?

The municipality of Rotterdam offers residents a €10 subsidy per square metre of vertical green they add to their house (Gemeente Rotterdam, 2023). Other subsidies or regulations for vertical green were not found.

2.4.3 What is the target group? What locations, what people should the system be designed for?

Respyre currently only focusses on large scale projects in the business-to-business market. Current projects include a contractor's building, a flat and a car park near a flat.

2.4.4 What water/electricity connections are available and what must be installed?

Respyre currently uses a normal water supply and electricity connection to power an irrigation computer and a pump. The water supply cannot meet the water flow demand of the spray nozzles; therefore, a water reservoir is installed which can deliver a high amount of water in short time. It is filled in between irrigation cycles.

2.5 Stakeholder Overview

Several stakeholders have been indicated. In this section their power and interest in moss walls is explained. These insights are mainly based on Respyre's experience.

2.5.1 Respyre

As a start-up, Respyre wants to grow, it wants to have a product that can be offered commercially. It wants to ensure a healthy business case by reducing its production, material, and payroll costs and by increasing the number of costumers. Respyre wants the technology to be as scalable as possible to ensure it is ready for the market, but does not have the financial resources to increase its. It wants to bring nature back into cities and consequently make them cooler, greener, more biodiverse, improve air quality, and reduce traffic noise.

Power: can implement the solution proposed at the end of this graduation project or disregard it. It can provide me with information or bring me into contact with the right people.

Interest: a successful outcome of this project can help Respyre to offer their clients a moss-covered surface in less time while using less water. This makes the product more desirable for both clients and Respyre.

2.5.2 Commercial Clients

Companies with privately owned real estate that order a moss wall. For example: IKEA, Ahold, and contractors.

Power: many companies have larger real estate and more budget than private homeowners, which gives them the power to make moss walls a successful product in the first place, to increase the market share of moss walls, increase visibility and acceptance of moss walls, and they can have a more significant impact on the local environment if they have a large moss wall.

Interests of commercial clients could be: a cooler indoor climate, better insulation in winter, no need for a mechanical cooling system, a sustainable image or a more aesthetically pleasing building. For the aesthetics, the moss coverage must be more uniform than it currently is at some projects. A client's interest in an improved irrigation solution includes reduced water consumption resulting in a lower water bill and faster moss growth.

2.5.3 Housing Companies

Companies that let homes to tenants.

They have the power to increase the success of this product directly through purchasing (increasing revenue) or indirectly by increasing visibility (which could inspire others). Since these companies often own many houses or apartment complexes, their impact can be significant.

An improved moss wall is in their interest as it gives them the opportunity to increase the value of their property and increase tenant satisfaction. However, in the current Dutch housing market, where demand is high, there is probably no need for housing companies to make their property stand out.

2.5.4 Urban Residents in Rental Homes

Anyone who lives in urban areas but doesn't own their home.

They can demand a greener environment form their landlord or housing company, but besides that they have little power.

Tenants have the same interests as homeowners, with one exception. An increased property value and maintenance costs could increase their rent, which is not in their interest.

2.5.5 Architects

Architects can choose to include or exclude moss walls in their design. Thus, they have the power to make moss walls a more accepted solution in the built environment. The advantages of moss should be known to them.

2.5.6 Investors

TU Delft, INH, NOW

Interest: want profit to return to them.

Power: They can make the company succeed by providing money, or influence Respyre's course by making demands.

2.5.7 Installation Mechanics

People who will install a moss surface including the irrigation solution on a wall.

If they work as employee for an installation company or for companies like Respyre, they might have little power. However, if the installation of the irrigation solution or the moss surface as a whole is very inconvenient, they could complain and put pressure on their employer to no longer use the solution. On the contrary, if they are enthusiastic about the moss wall or irrigation solution that could positively contribute to the acceptance of the product in their industry.

Independent mechanics or the company they work for, can increase their price if installation takes too much effort.

2.5.8 Gardening Company

Maintenance of the moss wall could be done by a gardening company. It is in their interest that any part in need of maintenance is easily accessible, with no need for a boom lift or tools that are not already in their tool set. Gardening companies have the power to increase prices if maintenance is too time consuming, or to not take a contract if they don't have the capacity for it.

2.5.9 Water Companies

Water companies are responsible for providing consumers in their region with enough drinking water. Also, they are responsible for taking measures to ensure they meet future demands (Overheid.nl, 2023)(article 23). High water usage could be a threat, so water saving measures such as a recirculating irrigation system can be in their interest. They don't have direct power.

2.5.10 Water Authorities ("Waterschappen")

The water authorities are regional governmental authorities that are responsible for water in their region in the Netherlands. They are responsible for water levels, wastewater treatment, dike maintenance, nature in and around water bodies, and control of quality in swimming areas (Rijksoverheid, 2021). It is their responsibility to maintain water levels, so high water usage (such as for inefficient irrigation of moss surfaces) is a problem for the water authorities. Water saving measures are in their interest.

2.5.11 Municipalities

Municipalities have the power to encourage extra green space in cities, either by legislation, by increasing awareness, by subsidising it, or by writing tenders with nature inclusive requirements. The municipality of

Amsterdam has a €7,5 million budget for increasing and improving green space in the city (Gemeente Amsterdam, 2023, p. 105). The municipality of Rotterdam has a budget of €1,25 million for “making 20 hectares greener and climate adaptation” (Gemeente Rotterdam, n.d.) and offers a small subsidy of €10 per square metre of vertical green on buildings (Gemeente Rotterdam, 2023)

Interest: according to Atlas Leefomgeving (2023), the average temperature in cities is under 3 °C higher than surrounding areas in June, July, and August. However, on some hot days it can be 7 or 8 °C warmer than surrounding areas (Atlas Leefomgeving, 2023). The RVO (Netherlands Enterprise Agency) states that heat waves can decrease productiveness, cause sleeping problems, increase alcohol use and domestic violence, cause health problems and higher death rates, decrease clientele for retail and restaurants or cafes (Rijksdienst voor ondernemend Nederland, 2013). Therefore, it is expected that municipalities have an interest to mitigate these effects to ensure quality of life.

3 LIST OF REQUIREMENTS

Discussions with Respyre, analysis of other stakeholders and findings from literature study result in the following requirements. They are listed in order of priority.

- Water is *uniformly* spread over the surface to the leaves. From a biological perspective, mist spray is preferred over large droplets.
- Water losses to the surroundings are minimised, as much water as possible is absorbed by moss.
- The solution is easy to install or deinstall. This means the number of man-hours is minimised, little tools are needed, required tools are basic tools that mechanics already have, the costs of installation are minimised, and there are little complaints from mechanics.
- The solution is suitable for both temporary use (irrigating only until surface is sufficiently covered with moss) and long-term use (irrigating for longer to increase cooling effect).
- The solution's unit price is minimised and at least low enough to compete with other cooling solutions such as green roofs, reflective façade, double skin façades, or air conditioning. Unit price refers to the cost for one client or location.
- The solution's initial costs are minimised. The development costs must at least be low enough to cover by investors. These costs include research & development costs and costs for setting up production.
- The solution can work autonomously and requires little maintenance. The need for human activity between installation and deinstallation is minimised.
- The solution's total environmental footprint is as low as possible. This means it has a low impact in all product life cycle stages according to an LCA.
- The solution can be applied at different types of surfaces (existing façades, new façades, sound barriers, quay walls) with little to no adjustment.
- There is no need for development of new parts. All parts are commercially available, which allows to scale up fast.
- The solution is aesthetically pleasing according to urban residents and architects.
- The solution is scalable, it can be applied to extremely large surfaces.
- No minerals are added to the water, to avoid harmful osmotic pressure in the moss.
- No need for boom lift during maintenance
- Irrigation does not wash away young fragile moss.
- The irrigation system does not spray water on nearby windows.
- Stagnant water is avoided to avoid mosquitos and *Legionella* growth.

Requirements in orange are related to costs

Requirements in green are biological requirements

Requirements in yellow are requirements related to sustainability

Requirements in blue are meant to enable Respyre to scale up to large projects with few people.

4 BRAINSTORM

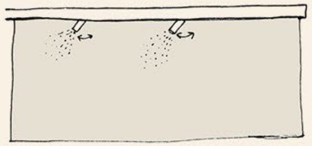
The aim of this chapter is to gather as many ideas as possible that provide a solution to (a part of) the main research question. These are newly generated ideas, existing ideas from the analysis chapter or a combination or adaptation of ideas. Ideas are divided into three categories:

1. Water distribution: how can water be uniformly spread over a vertical surface?
2. Water recirculation: how can water be collected and brought back for a next cycle?
3. Water quality: how can the risk of *Legionella* and clogging be minimised when reusing water?

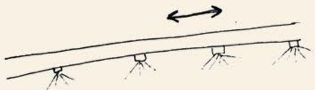
The results of the brainstorm can be seen on the next three pages.

Water distribution (spray irrigation)

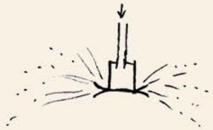
rotating nozzles for better water distribution

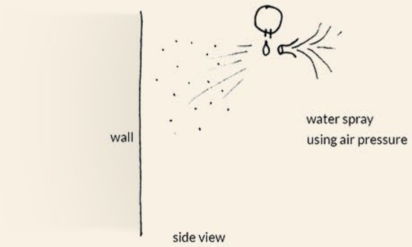


Moving nozzles for even water distribution

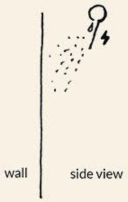


sprinkler water distribution

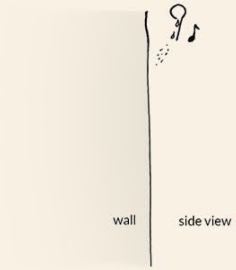




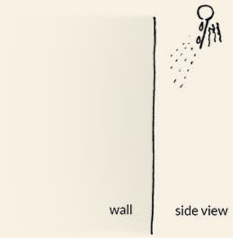
electrostatic water atomisation



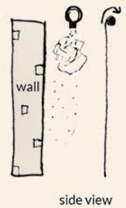
ultra sonic water spray



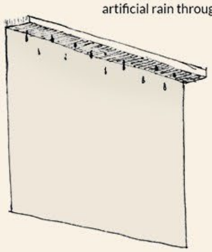
water atomisation through vibration



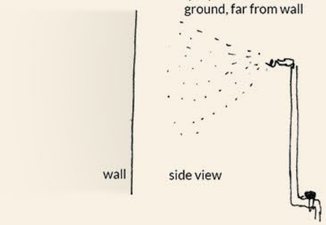
fine mist nozzle combined with wind protection curtain



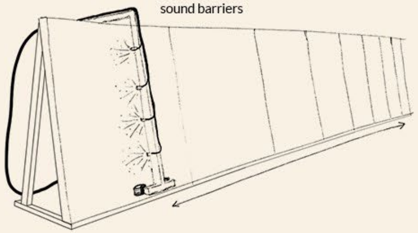
artificial rain through lattice



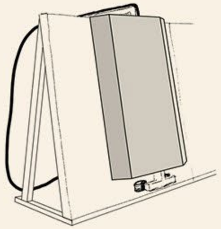
spray nozzle from the ground, far from wall



moving spray nozzles for sound barriers

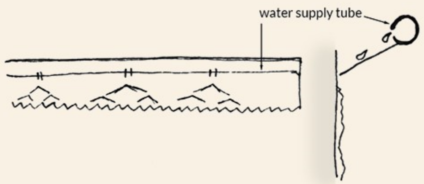


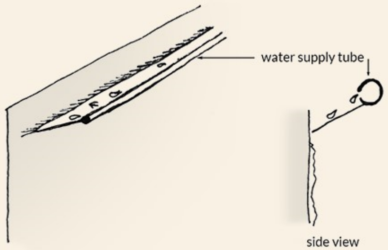
+ wind shield



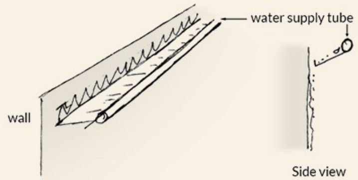
Water distribution (flow irrigation)

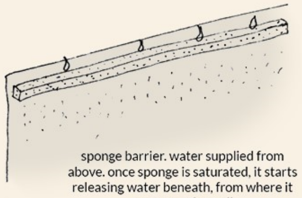
Distributing plate at top of façade





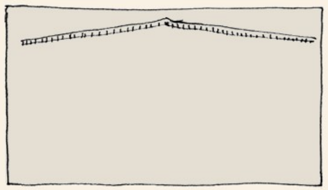
Distributing plank at top of façade. Water flows over the plank, overflows on the wall.



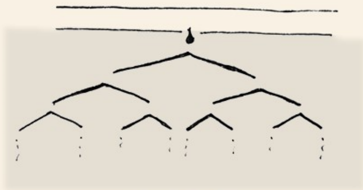


sponge barrier. water supplied from above. once sponge is saturated, it starts releasing water beneath, from where it runs over the wall

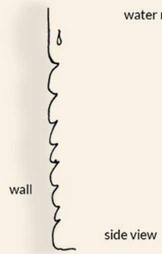
water distributing relief in concrete



water distributing relief

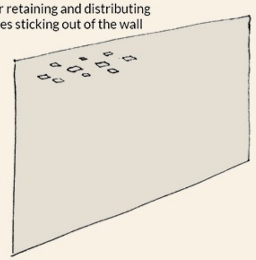


front view of the wall

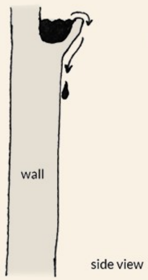


water retaining relief

water retaining and distributing plates sticking out of the wall

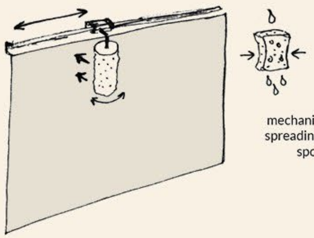


slower water run-off by sloped wall



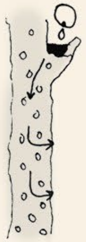
Reversed roof gutter

Water distribution (other)



mechanical water spreading through sponge

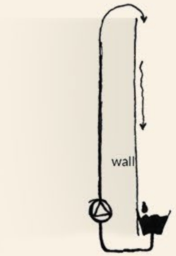
water supply through porous concrete



side view

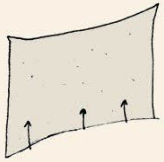
Water recirculation

basic water recirculation using a gutter and pump

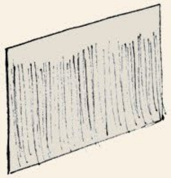


side view

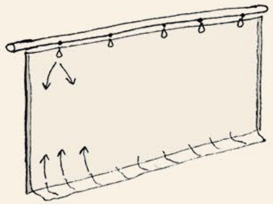
grow moss on capillary textile



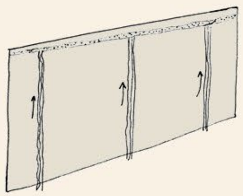
capillary water transport using reed



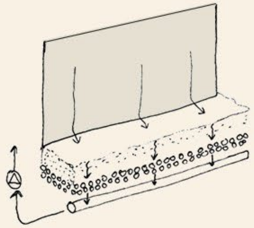
capillary water uptake



capillary water transport

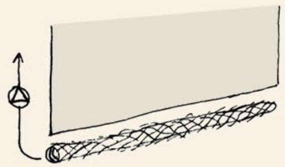


Water quality

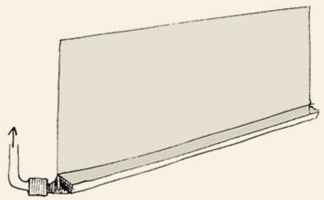


water collection in ground, filtration through sand and gravel

coir drainage water collection



gutter & filter



filter

+ the guidelines on *legionella* prevention as mentioned in the literature chapter.

Chosen ideas for water distribution

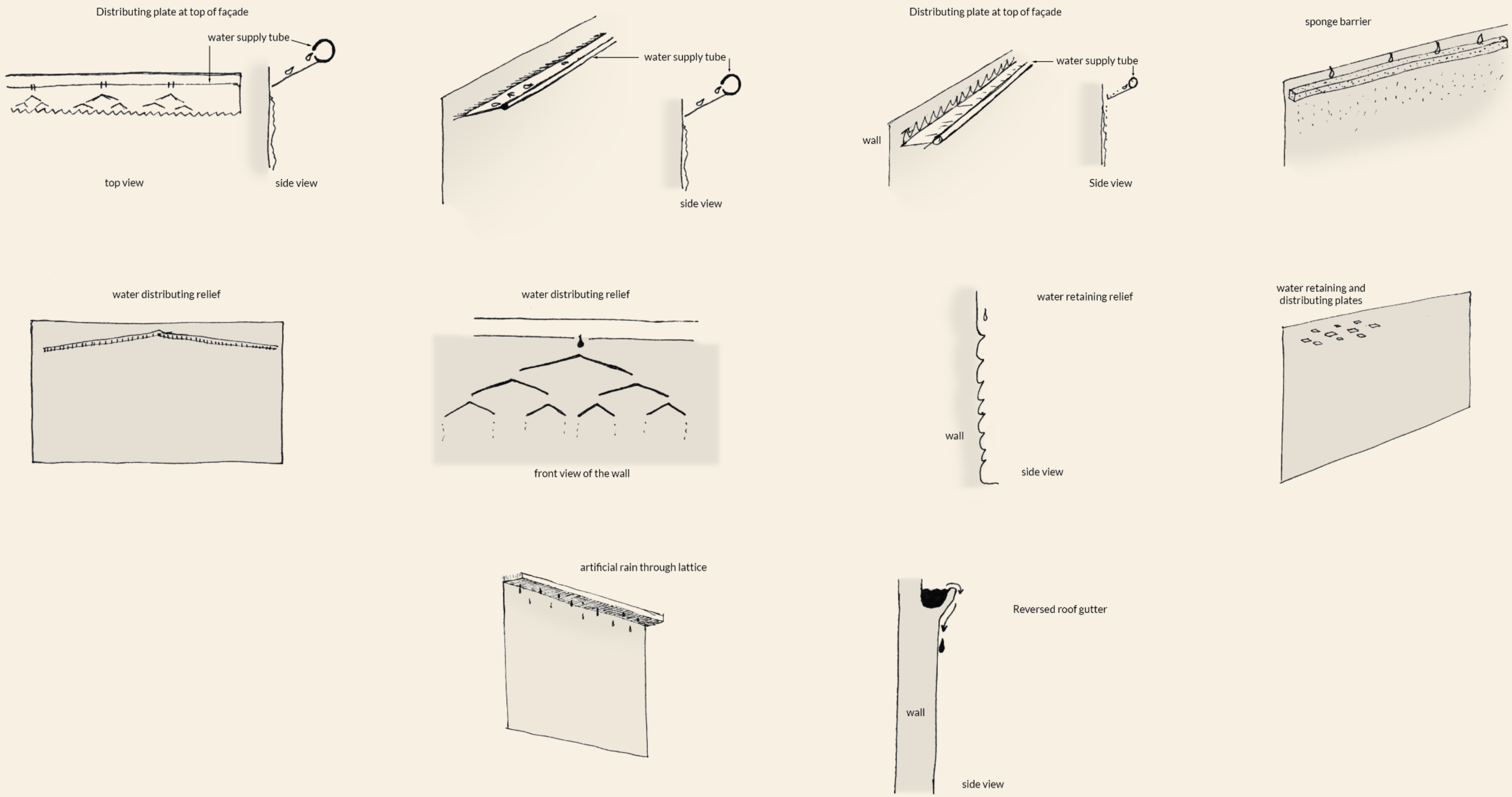


Figure 14: The ideas on this page are chosen for further investigation

5 CONCEPT PHASE

5.1 Water Distribution

In the previous chapter, 24 brainstorm ideas for water distribution are sketched. Several of these are filtered, since it is evident that they are too unrealistic. Some of them are too complex, others have already been tested by Respyre and turned out to not work. Other ideas have been combined. See the explanation in 'Appendix B – Harris Profile 1'. Ten ideas remain, they are shown in Figure 14

Most ideas for water distribution can be split into two categories: irrigation through air and irrigation along the wall. Respyre's current system is combination of both: at the top, water is spread horizontally by spraying it through the air, from there it runs down along the concrete. See Figure 15.

The aim of the next steps is to narrow down the brainstorm ideas to one of the two categories.

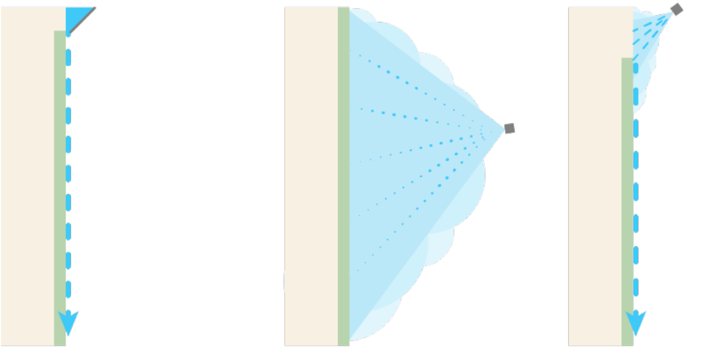


Figure 15: Irrigation medium explained. Irrigation can be done through air or along the wall. Respyre's current system is a combination of both.

Irrigation medium explained

Question: should the system irrigate through the air or along the wall?

Irrigation through the air can be done using spray nozzles or other atomisation techniques. These are the advantages (+) and disadvantages (-):

+ Water is applied to the leaves, where moss absorbs water. This is also advised by expert Veeger.
+ Young moss plants are not washed away, since there is no strong water current.
+ Zechmeister et al. found that spray irrigation reduces mould growth, probably because mould is washed away from the leaves (2023).
– A lot of water is blown away by wind.
– Vertical distribution throughout the wall must be considered. Higher walls might be difficult to cover by spray irrigation. See Figure 16.
– There is a risk of *Legionella* since it travels through air drops.
– If nozzles with small orifice are used, there is a risk of clogging. (*Note: it is possible to purchase clog-free nozzles)*

Irrigation along the wall can be done by applying water to the top of the wall, from where it runs down along the concrete. The (dis)advantages are:

+ Little water is blown away by the wind.
+ Vertical distribution is done by gravity which makes it suitable for walls of all heights.
+ There is less risk of clogging since no nozzles are used.
+ There is less risk of Legionella since water does not travel through air.

- It is unknown whether enough water gets to the moss's leaves, where it should be absorbed. However, at Respyre's project locations it can be seen that the water flow certainly gets to the leaves.
- If it is a strong stream of water, it could wash away young moss plants. (Note: at current projects, washing away of young moss seems no problem if a weak stream of water runs down.)
- Zechmeister et al. found that drip irrigation increases mould growth (2023). (At Respyre's outdoor project however (which uses spray nozzles for horizontal spread at the top but from there water runs down along the wall) it seems not too much of a problem.)

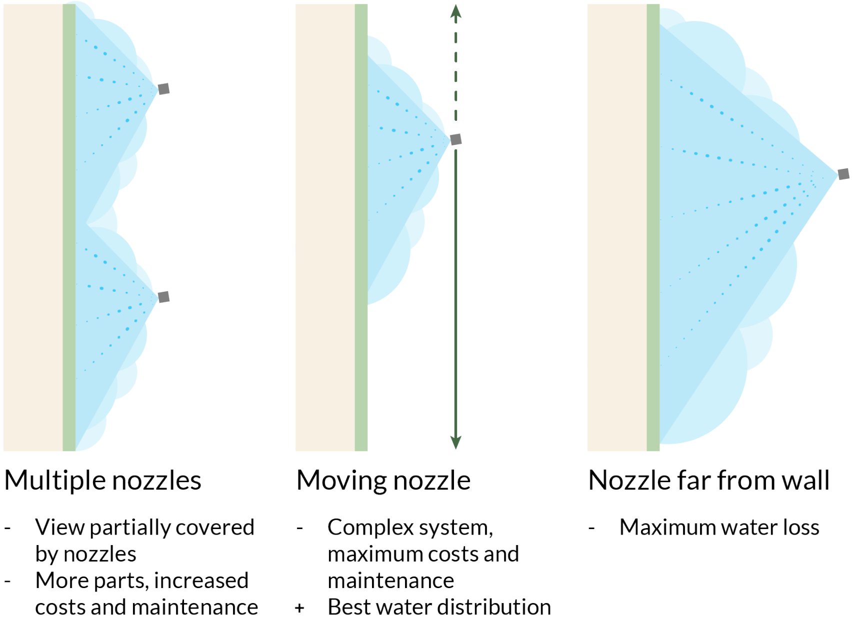


Figure 16: Vertical distribution explained. These are three different strategies to cover a wall's entire height when using spray irrigation. They all have serious disadvantages, while irrigation along the wall is easier to vertically distribute.

There is too much uncertainty to draw conclusions based on reasoning. A simple test should point out whether water gets to the moss leaves, which will be done in Experiment 0.

5.1.1 Experiment 0

Question: does the irrigation medium (through air or along a concrete wall) affect the amount of water reaching the moss leaves?

Hypothesis: the null hypothesis (H_0) is that there is no significant difference between the amount of water that gets to the leaves for both irrigation media. The alternative hypothesis (H_1) is that there is a significant difference.

This same hypothesis will be used in all following experiments too.

Method: a concrete panel with pre-grown moss on it will be irrigated in two ways with equal amounts of water. A panel with a thin layer of young moss is used, because that best represents the early stage in which irrigation is crucial to speed up moss growth. In set-up A (Figure 17) water will be poured along the concrete from the top, while in set-up B (Figure 18) it will be sprayed from the front. After irrigation, the moss leaves will be inspected visually to check to which extent the leaves are wet.

Results: As can be seen in Figures 19 and 20, the leaves get wet in both cases, but in set-up A water also gets in between the leaves. In A, water distribution was bad at the bottom of the panel, but this is because much more water was absorbed at the top half. H_0 is rejected.

Figure 17: test set-up A, water running down along the wall.

Figure 18: test set-up B, water through the air using a spray nozzle.

Figure 19: test set-up A, water on and between leaves after pouring water at the top of the concrete surface.

Figure 20: test set-up B, water droplets on the leaves after manually spraying water from the front.

Conclusion: moss leaves get covered by water regardless of the irrigation medium. However, the distribution is different. More water can be seen between and under the leaves when irrigating along the wall.

This short-term test cannot point out which irrigation medium is best for moss growth on the long-term, but it shows irrigation along the wall is possible.

Note: when water runs down along the wall, moss at the bottom gets a bad distribution when insufficient water is supplied, this should be addressed in future iterations.

Experiment 0 takes away the concern of water not reaching the leaves when irrigating along the wall from the top. Besides that, Respyre's current project location has shown that moss can grow when irrigating from the top. Also, irrigation along the wall has the advantages of less water loss, less risk of legionella and less problems with vertical distribution (and perhaps less risk of clogging compared to spray irrigation if standard nozzles are used). The disadvantages of irrigation along the wall (mould growth and washing away young moss) seem no problem at Respyre's current project location.

However, irrigation through air is not completely ruled out, more elaborate experiments are needed to test whether irrigation along concrete can provide the same level of horizontal distribution and whether the difference on moss growth is significant. This will be tested in Experiment 1A and Experiment 1B.

Experiments 1A and 1B are the same test set-up but answer two different research questions. 1A shows the water spread. This can be observed on day 1, which allows to start iterating already. 1B gives insight into the effect of irrigation on moss growth, this takes several weeks.

5.1.2 Experiment 1A

Question: What irrigation techniques show the most uniform water distribution?

Hypothesis: H_0 is that the water distribution is the same for all techniques, H_a is that some show significantly better water distribution than others.

Method: The irrigation techniques are prototyped using 18 concrete panels (45 x 60 cm). The panels are made by mixing concrete and pouring it into a mould. Some of the irrigation techniques require carving indents into the concrete while it's still wet (Figure 21). One of those is Respyre's current irrigation system, as a reference. Water will be supplied through a pipe running along the top of the panels, which has one exit hole above each panel. From there, water is spread over the panel according to its specific irrigation technique. After irrigating for a minute, the distribution can be seen on the panels.

Figure 21: Concrete panels in their mould. Some prototypes include carving indents in the concrete.

Results: Although the moss and gel have been washed away at some spots, it is still clearly visible what parts of the concrete panels remain dry or get wet (Figure 22). Panels 2, 8, and 14 have a bad distribution. Panel 9 has a good distribution, but only because the panels are leaning backwards. When standing vertically this panel would probably remain dry. Panels 1, 5, 6, 7, 9, and 15 have a good distribution, 3, 4, 10, 11, 12, and 13 have the best. Panels 16-18 use spray nozzles (16 is the original nozzle) and have are entirely wet.

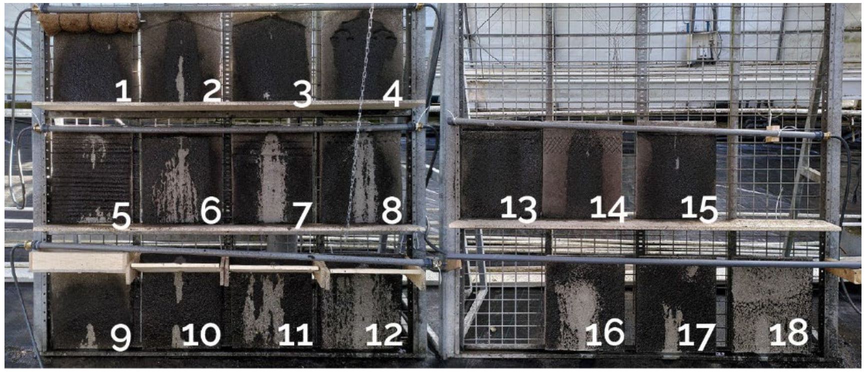


Figure 22: prototypes I in the test set-up in a green house

Conclusions: Some concepts are a promising solution for horizontally spreading water. The results of this experiment serve as input for the conclusions drawn in the last section of this chapter: '*Concept Selection*'.

5.1.3 Experiment 1B

Question: What irrigation techniques are most beneficial for moss growth?

Hypothesis: H_0 is that moss growth is the same for all techniques, H_a is that some show significantly faster growth or better coverage than others.

Method: The same 18 concrete panels with 18 irrigation techniques are placed in a green house, where they are irrigated for several weeks.

Results: Moss growth can be seen on most panels in Figure 23.

Most of the moss gel on panels 16, 17, and 18 got washed away. The moss gel on panel 17 that remained, shows less moss growth than on panels 9-12, although they should have received the same amount of water.

All parts of panels 9-12 seem to be wet, but moss coverage is inconsistent. E.g. the right half of panel 12 is green while the left is still brown (wet, but less growth). Any difference in moss coverage can be seen in vertical stripes, the variation is mainly horizontal.

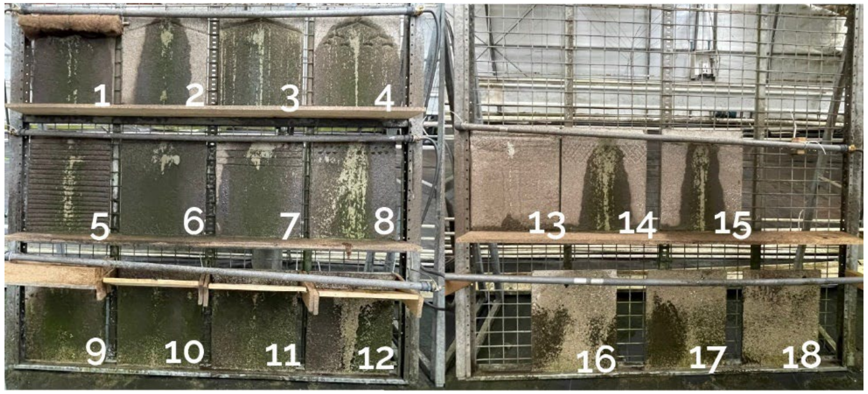


Figure 23: moss growth after 35 days

Limitations: The moss gel got washed away from the panels. It was completely removed and reapplied twice, (last time with a better gel type), but still partially washed away.

Due to pressure differences between the top and bottom rows, the bottom rows (panels 9-12 & 16-18) received water while the top two rows received none. This issue was only solved after a week. Therefore, the moss growth at the top two rows is one week behind, the final observations should be one week apart too. However, it is likely that the bottom row still receives more water, so one must be careful to draw conclusions. Also, the water flow from the nozzles (panels 16-18) is unknown and could be different from other panels.

Panel 13 didn't receive any water in the last weeks due to a defect.

Conclusions: Panel 17 received water from a nozzle from the front, but shows less moss growth than panels 9-12. Because it is unsure whether these panels received the same amount of water, one cannot conclude that one of the two irrigation mediums (along the concrete or from the front through the air) is better for growth. More tests are needed with identical amounts of water for both mediums. Also, different nozzle types must be tested since the drop size might influence growth. However, irrigation along the concrete seems not to be a problem for moss growth. Therefore, concepts based on this irrigation medium can be taken into consideration.

The inconsistent moss coverage on panels 9-12 suggests an uneven water distribution. However, this cannot be proven. More research should be done to confirm that greener parts received more water.

5.2 Water Collection & Recirculation

Several ideas for recirculation are based on the capillary effect. Respyre has done several experiments with this effect in the past, but it turned out impossible to bring water more than a metre up. Therefore, these ideas are not suitable for recirculation on walls. Recirculation aided by a pump is more likely.

The best strategy for water collection entirely depends on the project location.

At Respyre's current project locations, due to a bad water distribution, the surface needs to be over-irrigated to ensure the entire wall gets sufficient water. This causes a lot of water to run-off. In an ideal situation, the system supplies just enough water without any run-off, eliminating the need for recirculation. For this reason, water collection and recirculation will not be further developed in this phase. It will be reconsidered after a concept for water distribution has been chosen.

5.3 Water Quality

The need for water filtration depends on the use of a water recirculation system. If recirculation is not needed, water will not be filtrated. Elsewise, it will be reconsidered after a concept for water distribution has been chosen.

Legionella prevention must be considered. Following the guidelines on legionella prevention (as described in 'How can the water quality and safety be guaranteed when reusing water?' on page 14), dead ends in the plumbing will be avoided. Also, stagnation and especially in warm places, in sunlight for example, will be avoided. This is not expected to be a problem, since the usual irrigation programme sprays water every few hours, or more frequent when it gets warmer.

5.4 Concept Selection

From the 18 concepts, the most promising will be selected for further development. A Harris profile is used to assess all 18 prototypes on the requirements listed in *List of Requirements*. Therefore, the requirements are ranked from most essential to less important. On each row the concept is given a score (- - to ++) indicating to what extent it meets the requirement (see Figures 24 and 25). The scores for '*requirement 1: water is evenly spread over the surface*' are based on insights from *Experiment 1A*. The argumentation for the given scores is given in 'Appendix B – Harris Profile'. This tool allows to visually compare the concepts and choose the most promising ones.

The coconut mat (number 1), the V-shaped indent (3), the single horizontal indent (6 and 15), and the plank without pattern (10) seem to be the most promising. The original spray nozzle (16) will be used as a reference to compare them to.

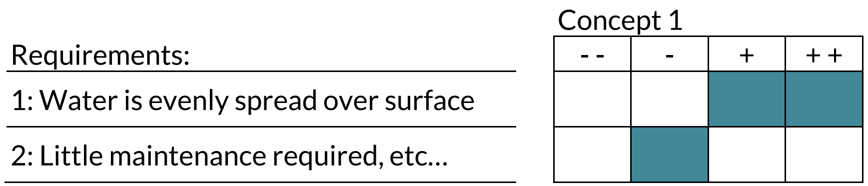


Figure 24: Example of a Harris profile

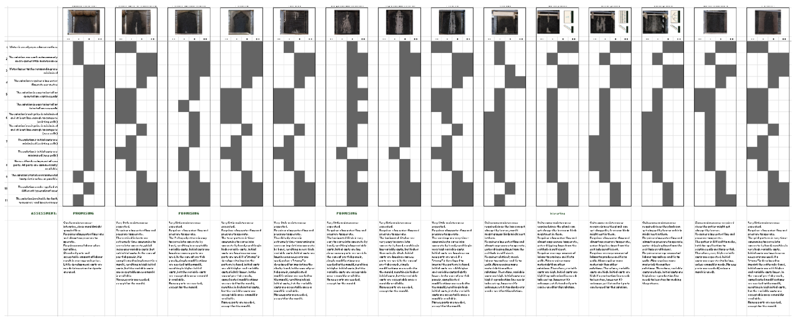


Figure 25: The entire Harris profile as can be found in Appendix C – Harris Profile 2.

6 EMBODIMENT PHASE

The aim of this chapter is to narrow the five concepts down to one final solution. The list of requirements is a guideline in assessing the concepts. Most relevant are the requirements concerning water distribution, water loss reduction, ease of installation, and costs. Before assessing the five concepts on these requirements, more insights must be gathered. Therefore, prototypes are built and tested on water distribution, a cost estimation is done, and installers are interviewed. Some requirements are not considered during the selection process, because they are equally met by all concepts. For example, *'the solution can be applied at different types of surfaces'* is met by all five concepts; they are suitable for existing buildings, new buildings, and sound barriers. Other requirements will play a role in the next phase, in which the solution is further developed. For example, a low environmental impact can best be assessed by a full life cycle assessment (LCA), but this is not done for all five concepts due to time constraints and data availability. Moreover, little difference is expected between the concepts as they use similar parts and have similar complexity. However, a low environmental footprint is also influenced by minimising material usage and water loss. These objectives are covered by the requirement of cost reduction and water loss reduction. In the next phase, 'Further Development', the chosen solution can be further optimised for a low environmental footprint.

6.1 Prototyping

The five concepts are prototyped on a larger scale. Concrete panels of 50 x 150 cm are made and placed vertically in a frame. Water is supplied at one point at the top middle. This is not a real-life scenario. In the field there will be more water supply points per 150 cm, but this allows to study the limits of a water distribution concept: how far can the concept in question spread water on this panel horizontally? When running first tests, the prototypes show a lot of teething problems that need be solved first. They have each gone through a few iterations to ensure the concepts are assessed on their full potential. These iterations are described in the following paragraphs, the testing is described in the next section, Experiment 2.

Figure 26: Concrete panel to test the various concepts.

6.1.1 Original Spray Nozzle

Nothing is changed on this concept to best resemble the currently used system.

6.1.2 V-shaped Indent

After running a first test, the V-shape showed little water distribution at all (Figure 27), while the V-shape in the prototype from the concept phase worked well. This can have multiple causes. Firstly, this panel is placed vertically, while the prototypes in the concept phase were placed under an angle, which slows water run-off and allows water to flow through the indent. Another cause is the cross section of the indent itself, by adjusting the angle water run-off can be slowed down allowing it to spread further in horizontal direction (see Figure 29). Therefore, the indent of prototype 2 is adjusted by filling it up with concrete and cutting a different angle using a grinder, (Figure 28). This improved the water retention and more water is spread to the side, but the in-between spots receive little water (Figure 30). During these iterations it became clear that the water distribution is very sensitive to inconsistencies in the indent. That is a weakness of this concept, considering it will be implemented in a rough context where precision engineering is challenging.

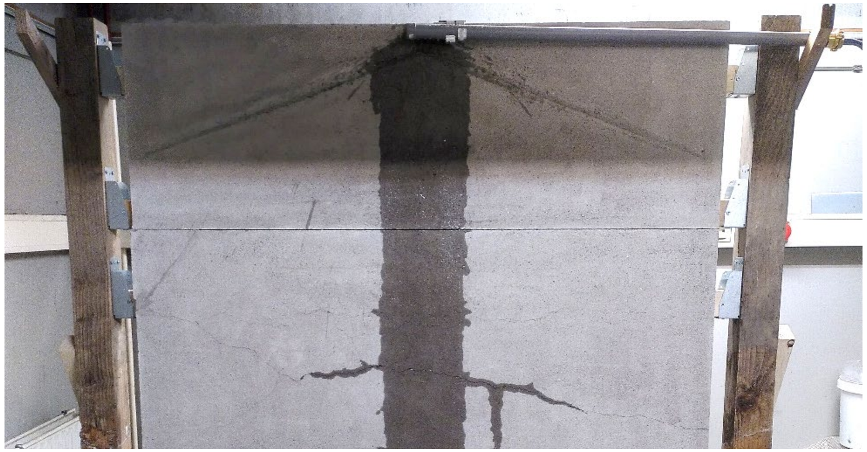


Figure 27: V-shaped indent after its first test.

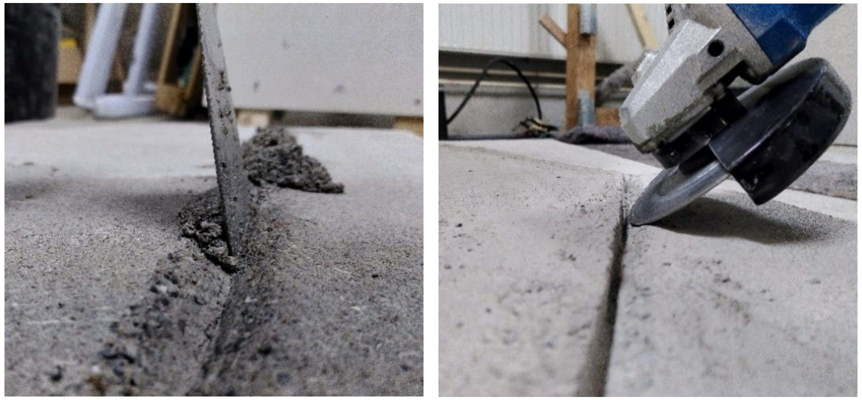


Figure 28: Adjusting the angle's indent.

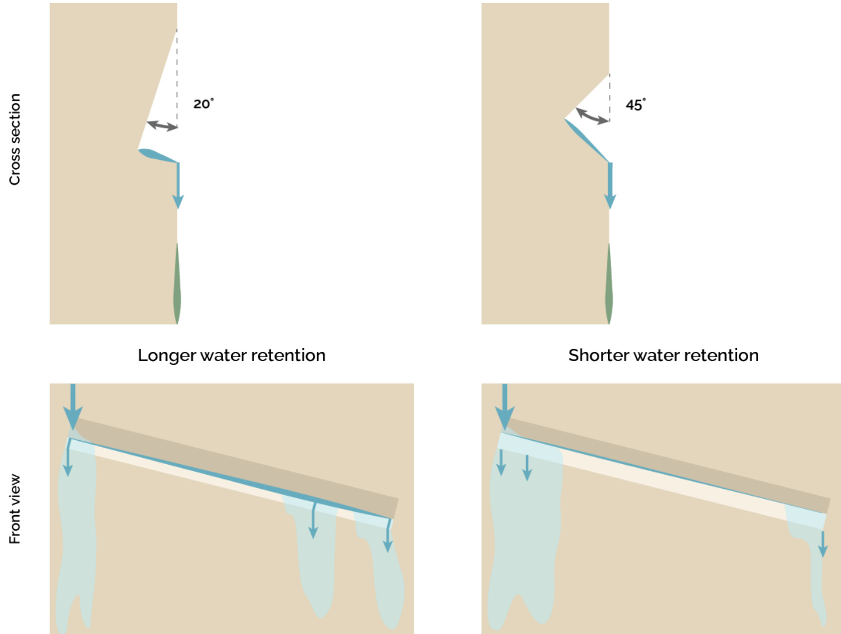


Figure 29: Adjusting the angle of the indent's cross section influences water run-off.

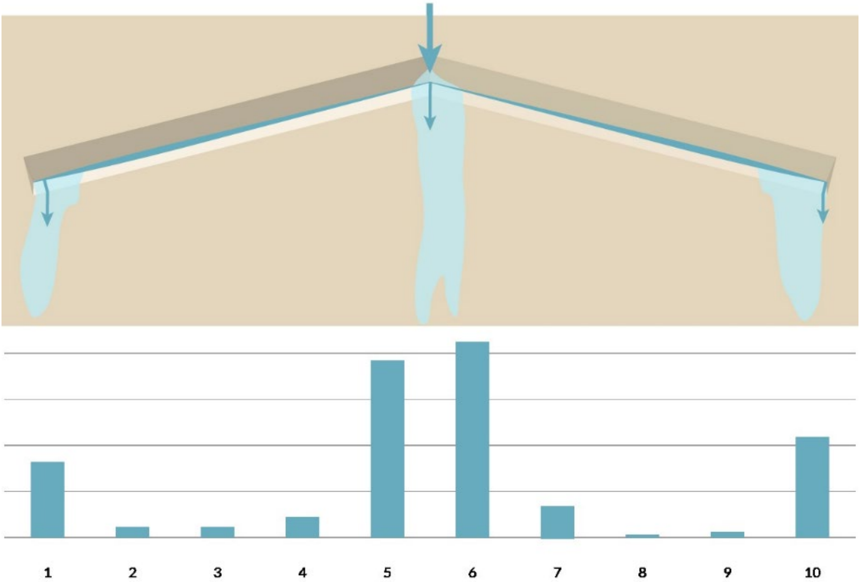


Figure 30: The improved V-shape mainly transports water to the sides and the middle, not to the spots in between.

6.1.3 Horizontal Indent

Although it seemed promising in prototype 1, the water spread is bad on prototype 2. This indent went through the same iterations as the V-shape, but still showed very little water spread (see Figure 31).

Figure 31: Horizontal indent.

6.1.4 Coconut Fibre → Soaker Hose

This concept went through major changes. The coconut fibre is replaced by two commercially available products: a soaker hose (Figure 33) and a drainage pipe (Figure 34). Both use a porous material allowing water to pass through. The soaker hose emits water over its entire length, resulting in a uniform water spread. The hose is inserted into the drainage pipe, which is then placed against the wall.

This combination shows a very good water distribution, but water does not reach the concrete. It drips down from the lowest point of the pipe, which is several centimetres away from the wall (see left illustration in Figure 35). In next iterations, the drainage pipe is replaced by a water absorbing mat which is wrapped around the soaker hose and pressed against the wall by a wooden beam. This beam is replaced by a wooden profile that clamps around the soaker hose and mat. In the last iteration, the wooden profile is slanted at the bottom to prevent water from running away from the wall along the wood (illustration right in Figure 35 and Figure 32).

Figure 32: Final iteration of the soaker hose, mat, and (wooden) profile.

Figure 33: Soaker hose (Zander, 2022)

Figure 34: Drainage pipe (Wildkamp)

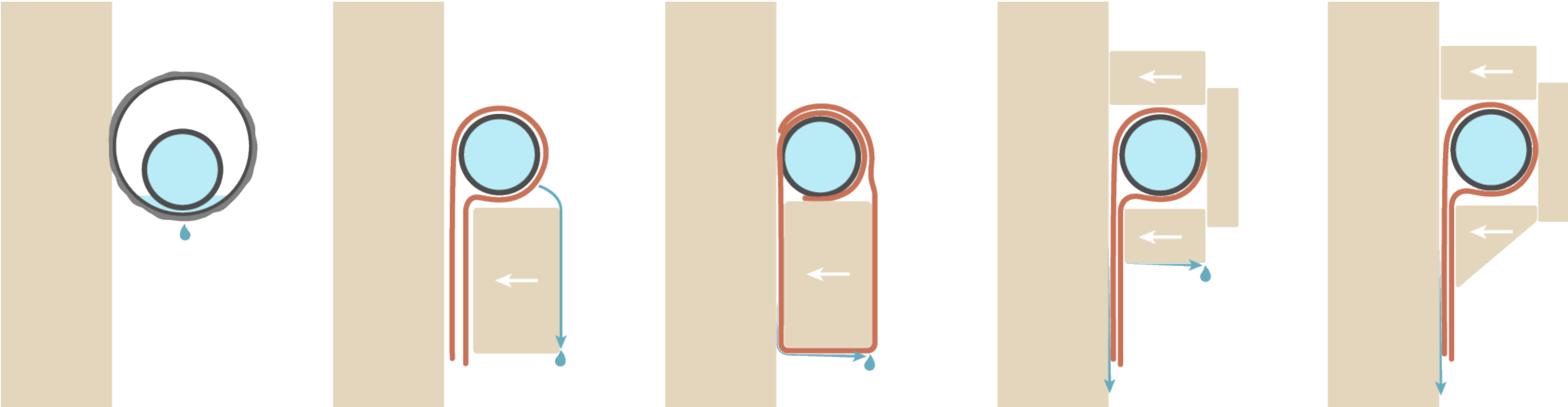


Figure 35: Evolution from the "soaker hose with drainage pipe" to the "soaker hose profile".

6.1.5 Gutter Plank

Water runs to one side and starts overflowing from there when the plank is not perfectly levelled. If it is perfectly levelled, water starts overflowing right beneath the water supply hole, as water has enough speed, thus kinetic energy to flow over the edge here. If this is solved by increasing the edge's height, water runs to the left and right up to both ends of the plank, where it starts overflowing. To avoid overflowing at certain spots, the regular edge is replaced by a ribbed edge (Figure 36), but this hardly solves the issue. In the last iteration, extra ribs are added to the plank's surface (Figure 37). This is the best version of the gutter plank that was found, but still water tends to find several spots to overflow.

Figure 36: Gutter plank with ribbed edge.

Figure 37: Gutter plank with ribbed surface.

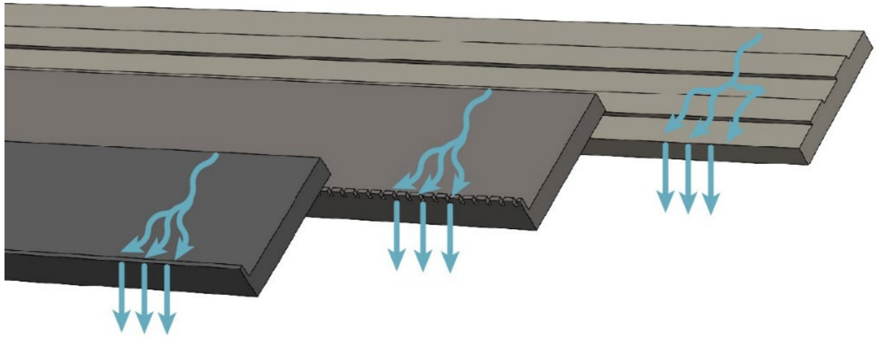


Figure 38: Evolution of the gutter plank.

6.1.6 Combined Concepts

Finally, two combinations of concepts are made. The V-shaped indent and horizontal indent are each combined with the originally used spray nozzle. This seems to benefit the distribution.

6.2 Experiment 2A

The five prototypes have been improved to show the full potential of the concepts and two concepts have been added (V-shape & nozzle and horizontal indent & nozzle) which makes seven concepts. In this section they are tested on water distribution.

6.2.1 Research Question

What technique offers the most uniform water distribution?

6.2.2 Method

Each of the seven concepts is tested on a concrete panel 150 cm wide and 50 cm high that is placed vertically. Water is supplied to one point at the top centre and horizontally spread according to the concept's distribution technique. The soaker hose is an exception: it does not supply water from one discrete point but continuously along its entire length. This is a characteristic of the concept and cannot be avoided, that is why another test will be executed later.

Under the concrete panel, water runs off and is collected in ten buckets. The 150 cm width is divided into ten 15 cm sections. The content of the buckets is weighed and together depicted in a graph (Figure 39). This graph visually shows the range and the distribution. These are two different characteristics: the range is how far water can reach horizontally and the distribution tells how homogenous or uniform it is horizontally spread (Figure 40). The uniformity of the distribution can be quantified by the coefficient of variation (CV). A CV of 0% represents a perfect uniform distribution, higher CVs indicate a bad distribution.

$$CV = \frac{standard\ deviation}{mean} * 100\%$$

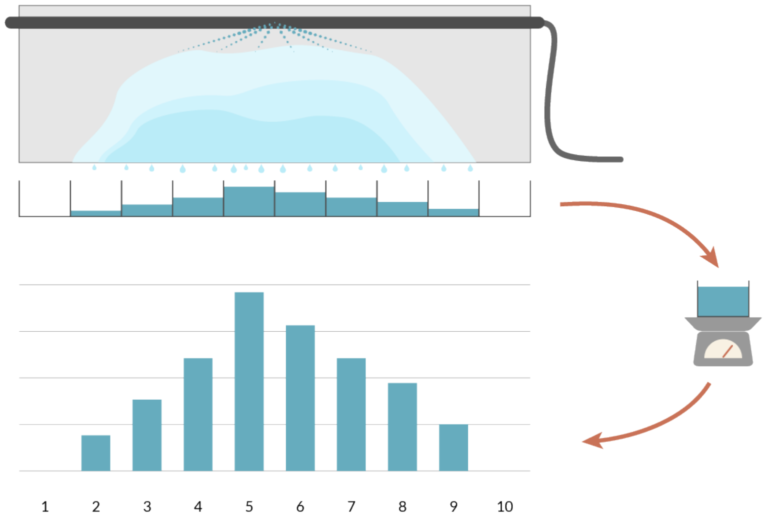


Figure 39: Method for measuring an irrigation system's water distribution.

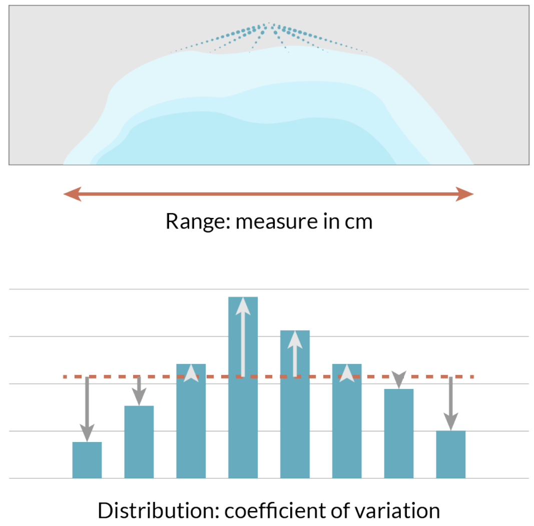
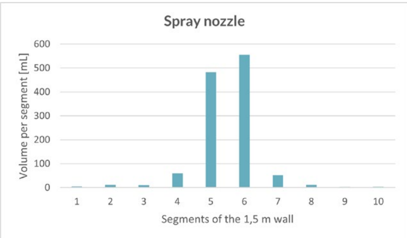


Figure 40: Range and coefficient of variation.

6.2.3 Results

Tables 1 to 7 show the graphs representing the water distribution, along with the calculated CV and the average water flow during the test. The CVs and water flows are summarised in Table 8. The measurement data can be found in 'Results experiment 2A' in 'Appendix D – Test Results'.

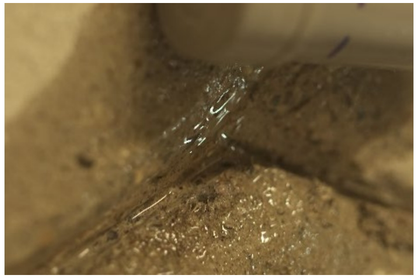
Table 1: Original spray nozzle

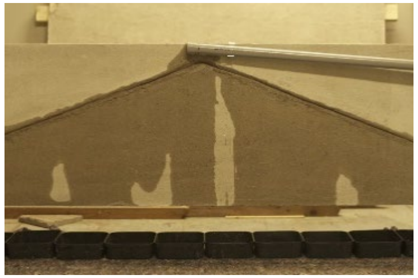


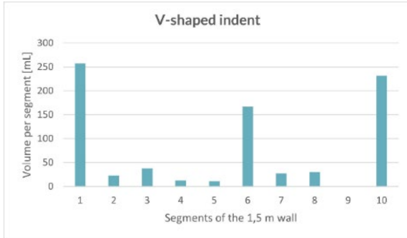
CV:
168%

Average water flow:
51 L/h

Table 2: V-shaped indent



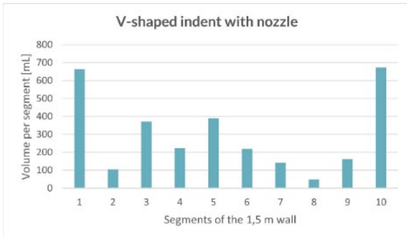




CV:
118%

Average water flow:
5 L/h

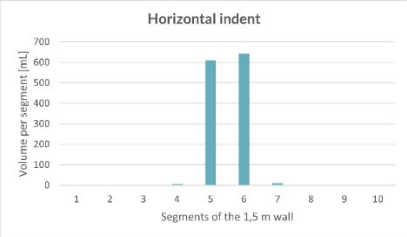
Table 3: V-shaped indent with nozzle



CV:
70%

Average water flow:
44 L/h

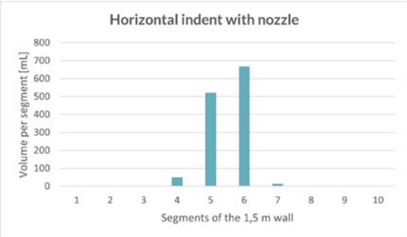
Table 4: Horizontal indent



CV:
197%

Average water flow:
42 L/h

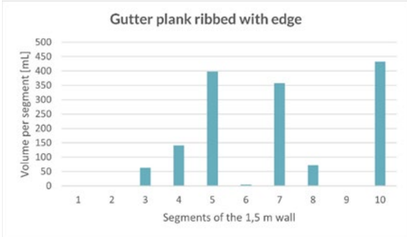
Table 5: Horizontal indent with nozzle



CV:
189%

Average water flow:
33 L/h

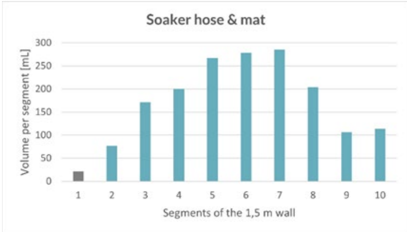
Table 6: Gutter plank



CV:
115%

Average water flow:
10 L/h

Table 7: Soaker hose, mat & profile



CV:
50% (39% when excluding outlier*)

Average water flow:
12 L/h

* Segment 1 can be considered an outlier because this is where the soaker hose came loose from the wall.

	Coefficient of variation	Average water flow [L/h]
Spray nozzle	168%	51
V-shaped indent	118%	5
V-shaped indent & nozzle	70%	44
Horizontal indent	197%	42
Hor. indent & nozzle	189%	33
Gutter plank ribbed edge	115%	10
Soaker hose, mat & profile	50% (39% ex. outlier)	12

Table 8: Summary of water distribution results. A CV of 0% represents a perfect uniform distribution.

6.2.4 Discussion and Limitations

The results of the water distribution test are summarised in Table 8. The soaker hose shows the lowest coefficient of variation, especially when excluding its outlier. The horizontal indents (with or without nozzle) show the least distribution, worse than only the single nozzle.

It is remarkable that the horizontal indent with nozzle shows less distribution than only the nozzle. It is unlikely that the indent has a negative influence on distribution. The most likely explanation is the lower water flow (33 L/h instead of 51 L/h), this probably influences the nozzle's performance.

It is difficult to compare the soaker hose, which is a continuous water supply, to the other concepts, which are discrete: they have a single supply point. On the other hand, the fact that the soaker hose is a continuous water emitter is an advantage in itself, since that simplifies a uniform water distribution.

The concrete panels used in this experiment were not coated in moss gel for practical reasons. It is unknown how this influences the water distribution, so it is advised to experiment with gel in the future. However, the small-scale prototypes in Experiment 1 were coated in gel. Figure 41 shows the V-shaped indent in both experiments; the water current seems to have a comparable downward flow.

Figure 41: Panel 3 from the first prototype compared to its large-scale counterpart in the second prototype.

Note: these test results are based on one measurement per concept. However, it is unlikely that additional measurements would give very different results, since the performance is visually observed during the iterations too.

6.2.5 Conclusions

Based on these results, the soaker hose looks most promising, due to its relatively uniform distribution in combination with a low water flow. However, additional testing is required to make a justified comparison between this continuous soaker hose system and the currently used system with discrete spray nozzles. This is done in the next section.

6.3 Experiment 2B

The currently used irrigation system is discrete: it has certain spots where it supplies water, these are the nozzles. The soaker hose is continuous: it emits water over its entire length. See Figure 42. Comparing a single nozzle per 1,5 metres to 1,5 metres soaker hose gives a distorted view. For this reason, another experiment is carried out with multiple nozzles along the concrete panel, 33 cm apart. This is how the spray nozzles are used in Respyre's current irrigation system.

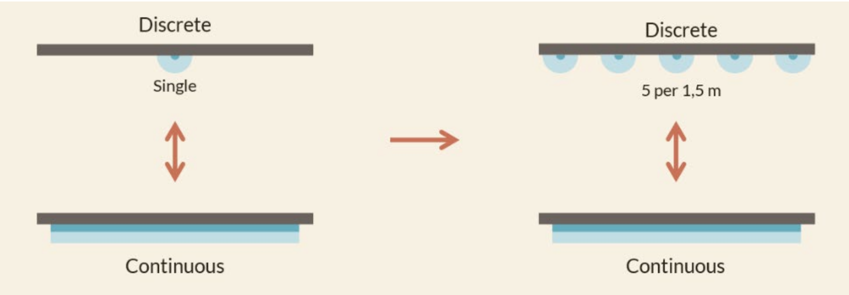


Figure 42: How to compare a discrete and continuous irrigation system.

6.3.1 Research Question

What technique (original spray nozzle every 33 cm, or soaker hose, mat, and profile) offers the most uniform water distribution?

6.3.2 Method

The same method as in Experiment 2A is used, but with 5 nozzles on the 1,5 metres surface, perpendicular to the wall at a 5 cm distance (like at Respyre's current project). See Figures 43 and 44 for the test set up.

6.3.3 Results

The water distribution is visualised in Figures 45 and 46. The calculated coefficients of variation (CV) and the average water flow during the test are given in Table 9. The two CVs are comparable, but the soaker hose has a lower CV when excluding an outlier. The first segment under the soaker hose is considered an outlier because the hose is not properly attached to the wall, as can be seen on the left in Figure 43. The soaker hose operates at a 3,6 times lower water flow.

The raw measurement data can be found in 'Results experiment 2B' in 'Appendix D – Test Results'.

Figure 43: The soaker hose, mat, and profile during irrigation.

Figure 44: The currently used spray nozzle system during irrigation.

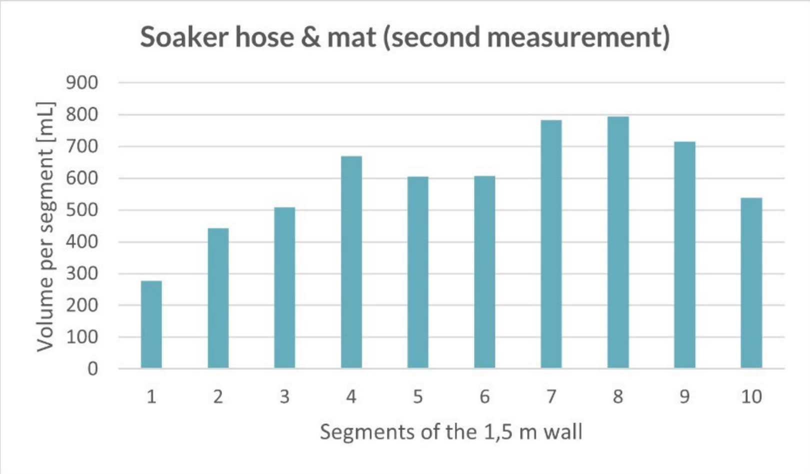


Figure 45: Water distribution of the soaker hose system.

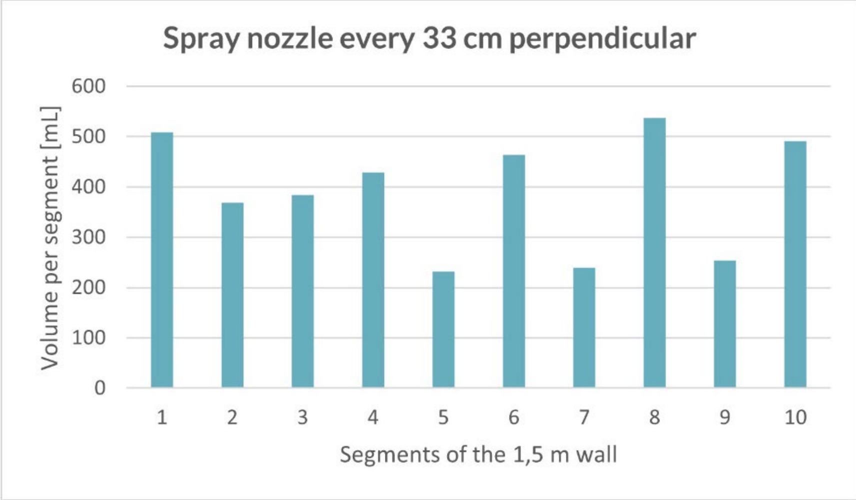


Figure 46: Water distribution of the spray nozzle system.

	Coefficient of variation	**Average water flow [L/h]**
Spray nozzle every 33 cm	28%	343 (69 per nozzle)
Soaker hose, mat & profile	26% (18% without outlier*)	95

* Segment 1 on the soaker hose system is considered an outlier since the soaker hose came loose from the wall at this part, just as during Experiment 2A.

Table 9: Summary of the results from Experiment 2B

6.3.4 Discussion and Limitations

The soaker hose system shows a lower coefficient of variation, which means it has a more uniform distribution.

For both systems only one measurement is done. Therefore, the exact numbers are not to be followed, but the difference between the two results is large enough to draw conclusions.

6.3.5 Conclusions

From the results it can be concluded that the soaker hose, mat, and profile give a more uniform water distribution (28%) than the currently used spray nozzle system (18% without outlier). The water flow is significantly lower.

6.4 Cost Estimation

Before choosing an improved irrigation system, a cost estimation is needed to ensure it is not more expensive than the current system. Costs can differ per project location and project size; hence an estimation is made for a fictional project of average size. This concerns the costs made by Respyre for acquisition and installation of the irrigation system, it excludes the costs of applying concrete and the moss gel. This fictional project is a wall 100 m long and 6 m high. Costs are based on an internal invoice from a supplier and recalculated to this project. The invoice includes detailed cost specifications for materials, but only a total price for labour. The material costs are recalculated for the fictional project, the labour costs are extrapolated from the material costs. The costs for all seven concepts are shown in Figures 47 and 48.

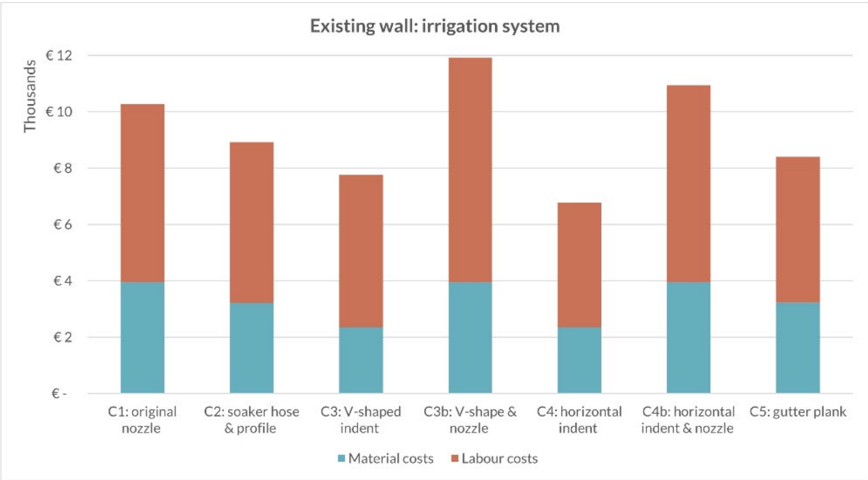


Figure 47: Estimated costs for irrigation systems on existing walls.

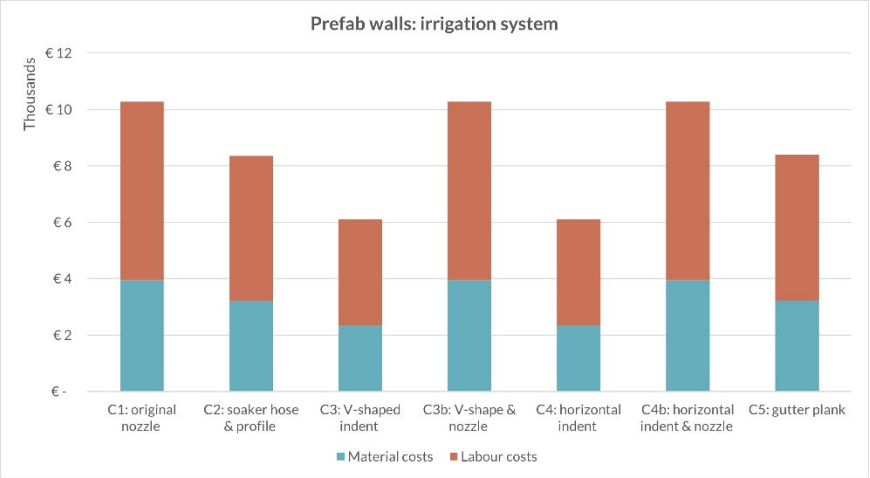


Figure 48: Estimated costs for irrigation systems on newly built prefab walls.

The current system is estimated at ± €10.000 for both existing and prefab walls. Four concepts have lower costs, with the horizontal and V-shaped indent being the cheapest at ± €6.000 for prefab walls. The V-shaped indent combined with the original spray nozzle on existing walls is the most expensive system, ± €12.000. While running calculations, the required water flow turned out to be an important factor. The irrigation is driven by a computer, reservoir and pump that can deliver a limited water flow. If the required water flow of the irrigation system exceeds the limit, the wall must be divided into multiple sectors which are than irrigated one after the other. This requires multiple water supply pipes to run to the wall in parallel (see Figure 49). More pipes require more material and more labour, hence increasing costs.

Note that a low water flow does not mean less irrigation, just slower irrigation.

The cost specification is given in 'Appendix E – Cost Estimation'.

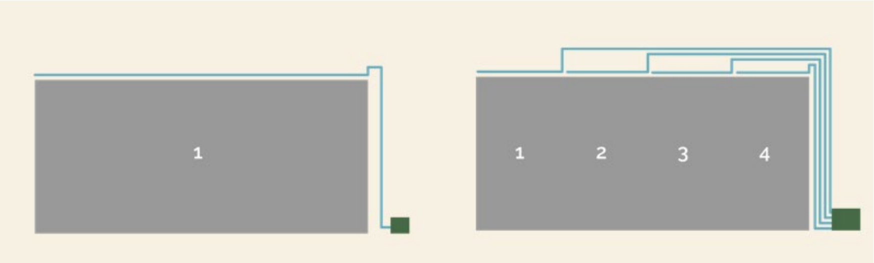


Figure 49: A wall irrigated in one go versus a wall divided into four sections. Lines in blue represent the pipes required to supply the sections.

6.5 Concept selection

A uniform water distribution and low water flow demand turned out to be essential for the product's success and are therefore the main objectives of this project. Experiments 2A and 2B show that the soaker hose, mat, and profile deliver the most uniform distribution while requiring the lowest water flow. The cost estimation shows that it will most likely not cost more than the current system. This is therefore the most promising solution to provide moss with moist. It will be further developed in the next chapter.

7 FURTHER DEVELOPMENT

The aim of this chapter is to bring the chosen concept, the soaker hose system, a step closer to a market-ready product. Therefore, a more realistic prototype is made, additional water distribution tests are carried out, the installation on a wall is tested, and the reduction in water loss is quantified.

7.1 Prototype

An improved prototype is made to test its performance in a more realistic scenario. The wooden profile is replaced by an aluminium omega profile, since these are commercially available. Due to delivery times, it was prototyped using multiple aluminium profiles that are more easily available (Figure 50).

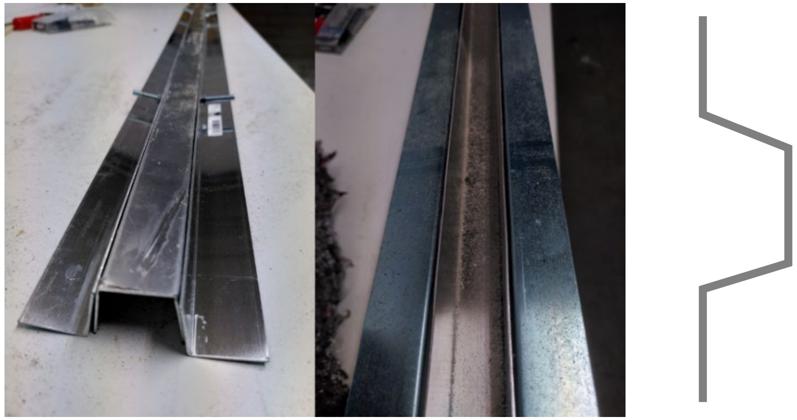


Figure 50: Prototype of the omega profile.

7.2 Installation Test

The prototype is installed on a concrete test panel as it would be on a project location: it is drilled into the concrete wall. These steps are described in Figure 51. This process is explained to two installers and their feedback is asked, see next section.

One difficulty is found during installation. To fix the profile to the wall, one must drill screws through the profile and the mat. Drilling through the mat causes screws to get entangled in the mat's fibres.

Omega profile

Lay the mat over the profile and push it in the profile's slot

Lay the soaker hose in the slot

Fold the mat

Flip the whole system and place it against the concrete surface

Once it's levelled, drill screws through the predrilled holes. Using only the holes at the top row suffices.

Make sure the end of the soaker hose sticks out at the end of the profile, connect it to the water supply.

Figure 51: Installation test on the concrete test panel.

7.3 Expert feedback

The installation process described in Figure 51 is shared with two installers. They both don't foresee problems during installation, but one installer expressed his concern that mould could grow in the mat, since the mat is covered by the profile, preventing it from drying between irrigation cycles. The description in 'Appendix G – Installers' feedback' is what was shared with them.

Additional feedback is received from a supplier of irrigation products. He got to see the prototype during an interview, not in use. His main concern is that a soaker hose will not give a uniform water supply over long distances. The output will be high at the beginning of the hose, after which pressure and output drop. He advises to use a drip hose, which can give a regulated output every 15 or 5 cm. This hose could be connected to the water supply at both ends, ensuring more consistent water pressure.

The behaviour of a long soaker hose (without mat or profile) is observed during a short experiment. Low uniformity was found, but it was clearly influenced by leaks in the soaker hose. Connecting the hose's other end to the water supply did not show significantly higher output on that side. A low pressure on one end of the hose seems not to be the problem. Leaks in the hose can cause issues. This is a simple experiment, described in 'Results experiment 4' in 'Appendix D – Test Results'. It is recommended to execute a more elaborate experiment with long soaker hoses and drip hoses.

7.4 Water Distribution (Experiment 3)

The same test as in Experiments 2A and 2B is repeated, to test the water distribution on this new prototype. A new prototype could influence the performance. Also, in this experiment five measurements per setup are done, which allows to better quantify the water distribution. While setting up this experiment, the company found a new type of nozzle with a lower water flow. This nozzle is tested in this experiment too.

7.4.1 Research Question

What is the water distribution of the original spray nozzles, the low flow nozzles and the soaker hose system?

7.4.2 Method

The same water distribution test from Experiments 2A and 2B is carried out, this time with a more advanced prototype of the soaker hose system and with the low flow nozzles.

The nozzles are placed 33 cm apart, with the spray direction perpendicular to the wall. The original spray nozzle is placed at 5 cm from the wall, like at existing projects. The low flow nozzle has a different orientation, which does not allow for the pipe to be placed at 5 cm from the wall (Figure 52). The choice was made to not place the deflection plate (where the water spray is created) at the same 5 cm, as this would require the pipe to be placed at 9 cm from the wall, which is often not possible in the field. Instead, the deflection plate is placed 2 cm from the wall, which allows for the nozzle to spread water while placing the pipe at an acceptable 6 cm from the wall.

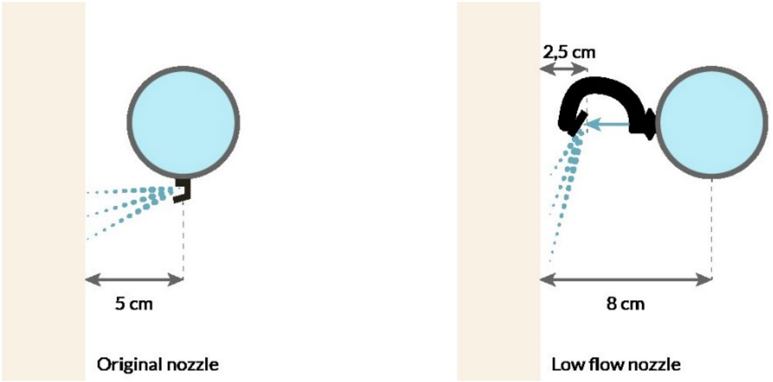


Figure 52: Side view of the two nozzles' orientation and subsequent distance to the wall.

7.4.3 Results

For all three systems, five measurements are done. For all ten segments of the wall, the average volume (in mL) of five measurements is calculated. The average volume per segment is shown in a graph, which is a visual representation of the water distribution, see Figures 53, 54, and 55.

From the average volume per segment on the wall, the coefficient of variation is calculated. A CV of 0% corresponds with a perfectly uniform distribution. As shown in Table 10, the CV is the highest for the low flow nozzles and lowest for the soaker hose system. The right column gives the water flow at which the tests are carried out. This is the lowest for the soaker hose and highest for the original nozzles. Raw data of all measurements can be found in 'Results experiment 3' in 'Appendix D – Test Results'.

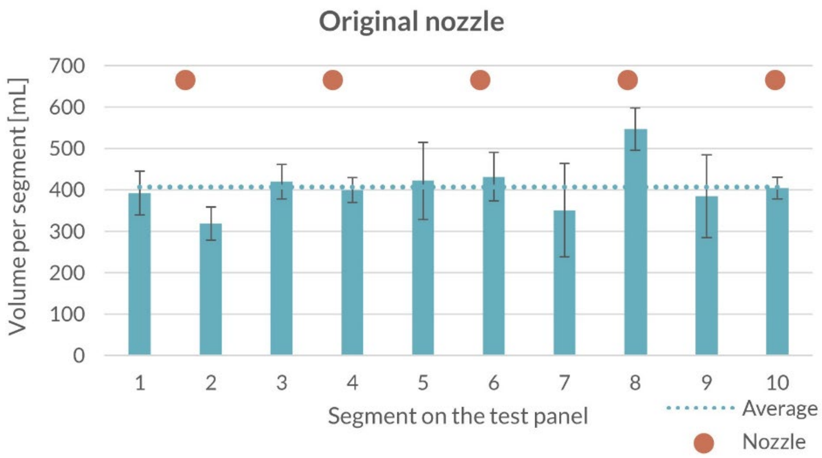


Figure 53: Water distribution original nozzle system.

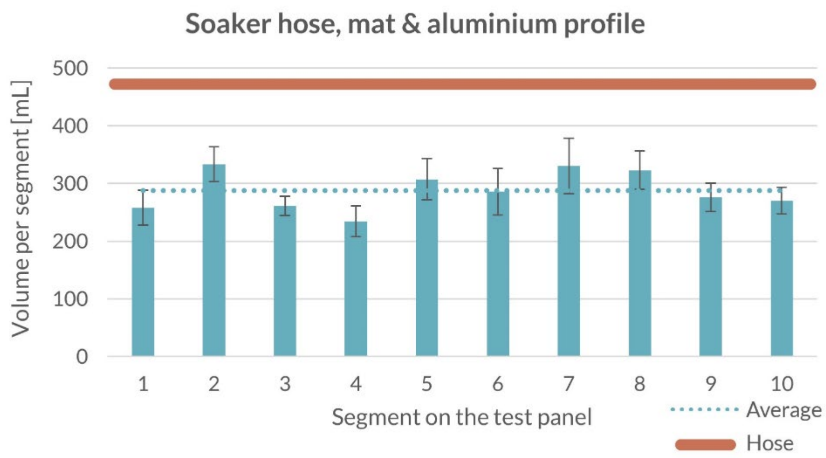


Figure 55: Water distribution soaker hose system.

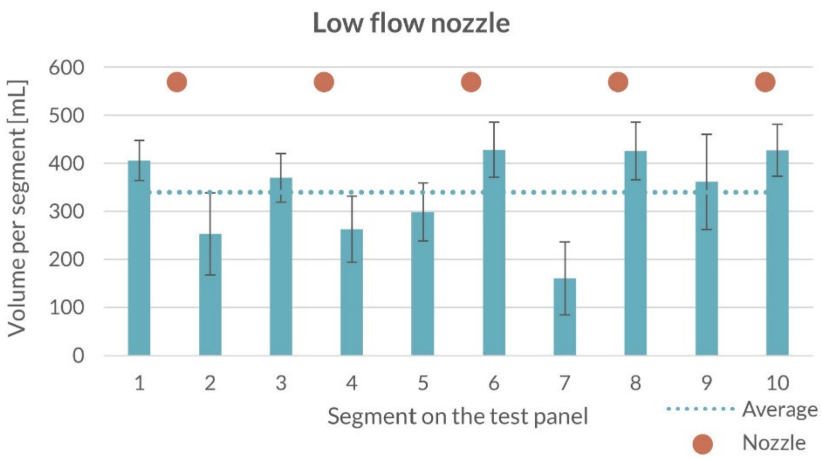


Figure 54: Water distribution low flow nozzle system.

	Coefficient of variation	**Average water flow [L/h]**
Original spray nozzle every 33 cm	14%	287 (57 per nozzle)
Low flow nozzle every 33 cm	26%	128 (26 per nozzle)
Soaker hose, mat & profile	11%	60

Table 10: Results of the three irrigation systems.

7.4.4 Discussion and Limitations

The results confirm that the distribution of the soaker hose system is more uniform than the original nozzle system, also with the new prototype (consisting of an aluminium profile). It also shows that the low flow nozzles have a less uniform distribution. These results are more reliable than experiments 2A and 2B, since it is based on five measurements per system. However, the water distribution by the original spray nozzle on this test setup is better than observed at Respyre's project location. The following paragraphs discuss possible causes for this unexpected outcome and other limitations of the experiment.

The results are influenced by the alignment of the nozzles with the segments on the wall. A certain alignment can result in a uniform distribution while the same irrigation system and a different alignment result in a bad distribution, see Figure 56. A test setup with smaller segments would give a higher 'resolution', increasing the accuracy.

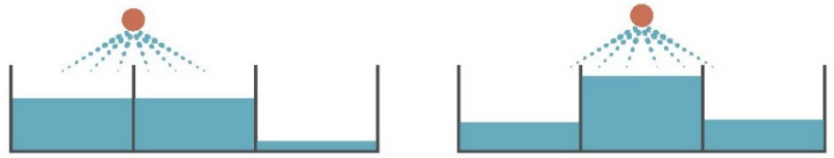


Figure 56: Alignment of nozzles with segments on the wall.

Spray nozzles need a certain minimum water flow to operate. A sufficiently strong water flow was chosen. However, in this test setup the exact flow cannot be controlled. It is unknown how different water flows influence the distribution above the minimum operating flow. While testing, it was clear that the low flow nozzles and moreover the soaker hose can operate using a significantly lower water flow, but it is not tested how low this may be. More experiments are required to find the lowest flow rate at which the water distribution is still uniform. This must be tested on a larger prototype, since a longer hose comes with more pressure drop, resulting in a minimum water flow rate different from the current prototype.

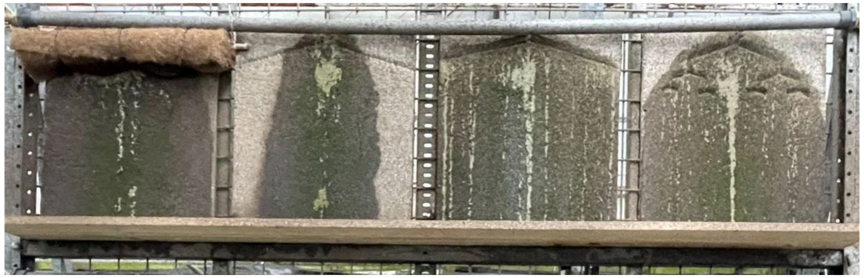


Figure 57: Looking at the gel layer on prototype 1, water seems to flow straight down.

This test is carried out on a concrete panel without gel and moss, because on prototype 1 that got washed away repeatedly. In the current water distribution test, the same concrete panel is used for all measurements. A panel where gel gets partially washed away throughout the experiment would result in inconsistencies between measurements. On the other hand, when looking back at prototype 1, which is covered in gel, it seems like water flows down in a straight line (see Figure 57). Therefore, it is assumed that an irrigation system with a good water distribution on prototype 2 will also output a good distribution on a wall covered by moss gel. However, it is still advised to execute a test with gel in the future, with a newly coated surface for each irrigation system.

The five measurements on the original nozzle system showed vastly different levels of uniformity. It is unknown what caused this. The water flow was not consistent, but the uniformity of distribution does not seem to be related to the water flow.

The distance between nozzle and wall greatly influences the uniformity. In this test setup, the most likely distance is chosen, but if a certain project location allows for a larger wall ↔ nozzle distance, better distribution might be achievable.

7.4.5 Conclusions

After this experiment with more measurements, it is more certain that the soaker hose system (Figure 58) gives the best distribution. Also, this experiment has given insight into what the water distribution exactly is, which allows to estimate the water savings. However, the difference between the CVs for the soaker hose and for the original nozzles is smaller (11% and 14%) than between the CVs found in experiment 2B (18% and 28%).

Figure 58: Soaker hose, mat, and profile.

7.5 Reduction Water Loss

A non uniform water distribution requires over-irrigating to ensure all parts receive sufficient water. A more uniform distribution requires less over-irrigation, therefore saving water (see Figure 59). Based on the water distribution results from the previous section, the currently used spray nozzle system over-irrigates by 28%, against 23% for the latest soaker hose prototype. This results in minor water savings.

However, more water is saved thanks to the fact that slower and more uniform irrigation allows for easier water absorption by the gel. The moss gel mixture which is sprayed on the concrete wall can retain water and release it to the gel. However, once the gel has dried out, it becomes water repellent. During irrigation, the gel needs some time to slowly absorb water. Due to this unwanted effect, at current project locations that use the original nozzles, the spots on the wall between two nozzles are difficult to irrigate. Currently, the walls are irrigated again before the gel can dry out and become water repellent. This means the moss wall is irrigated more often than required for the moss itself, resulting in more water usage, mould growth at the over irrigated spots, and moss that is not resilient to drought (see 'What are the optimal conditions for growing and maintaining moss?' on page 9).

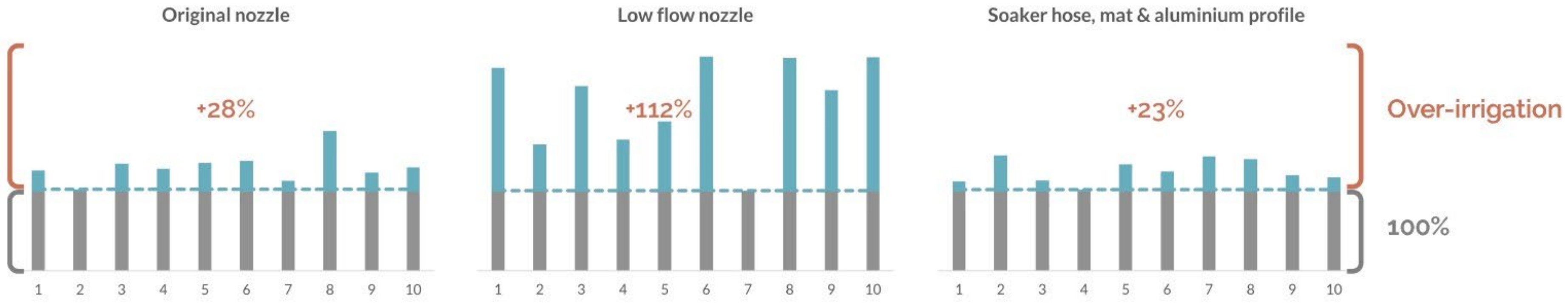


Figure 59: A uniform water distribution reduces over irrigation.

7.6 Material Choice

The soaker hose is a standard part for which the material is set. The growing mat and profile can be made from a custom material. Regarding the growing, it is best to discuss with a supplier what material is best to prevent or slow down mould growth. The profile's material can be chosen based on price, availability, performance, and environmental impact.

7.6.1 Price and Availability

Aluminium and zinc omega profiles are both commercially available. Zetwerkprofiel.nl (n.d.) offers both aluminium and zinc omega profiles for the same price. Polymer omega profiles are available as well, but harder to find and their commercial price is not available. Table 11 lists the estimated *material* price for several materials that are commonly used for extrusion or folding. Plastics seem to be cheaper, but these numbers should be considered as rough estimation since aluminium and zinc profiles are offered for the same price.

7.6.2 Performance

The installation test has been carried out with an aluminium profile, as aluminium profiles' wide availability allows to quickly make a prototype. The performance of zinc or polymer profiles has not been observed.

The chosen material must be suitable for outdoor use in combination with water and sunlight. Table 12 points out that all six considered materials have excellent durability in water. Aluminium and zinc have excellent resistance to sunlight; PC and PVC have good resistance too; ABS and PP should not be exposed to sunlight for a long time.

	Estimated mass per 1 m profile*:	Material price**:	Price per 1 m profile***:
Aluminium	0,386 kg	€ 3,93 / kg	€ 1,52
Zinc	0,672 kg	€ 3,37 / kg	€ 2,26
ABS	0,366 kg	€ 2,50 / kg	€ 0,92
PC	0,285 kg	€ 3,25 / kg	€ 0,92
PVC	0,488 kg	€ 2,20 / kg	€ 1,07
PP	0,506 kg	€ 1,62 / kg	€ 0,82

* The estimations for the mass are described in 'Appendix F – Profile LCA'.
** Material price is an average value given by the Granta material database (ANSYS, Inc., 2022).
*** The price per metre is the estimated mass multiplied by the material price.

Table 11: Profile's mass and price for several materials.

	Durability in fresh water	Durability to UV radiation
Aluminium	Excellent	Excellent
Zinc	Excellent	Excellent
ABS	Excellent	Poor
PC	Excellent	Fair
PVC	Excellent	Fair
PP	Excellent	Poor

Table 12: Properties of several materials, according to the Granta material database (ANSYS, Inc., 2022)

7.6.3 Environmental Impact

The environmental impact of a product can be assessed using a life cycle assessment (LCA). This is done for aluminium, zinc, and four common polymers: ABS, PC, PVC, and PP. The LCA's outcome is summarised in Figure 60. When including the recycling credits at the product's end-of-life, the total impact value (given as a monetary value) is highest for zinc. Aluminium has an impact twice as low. The polymer profiles have the lowest impact. Polycarbonate has the lowest impact, around two thirds of that of aluminium. The LCA is based on many estimations and assumptions, due to limited time and data availability. Therefore, the impact is only an indication. The full LCA and an explanation of the assumptions can be found in 'Appendix F – Profile LCA'.

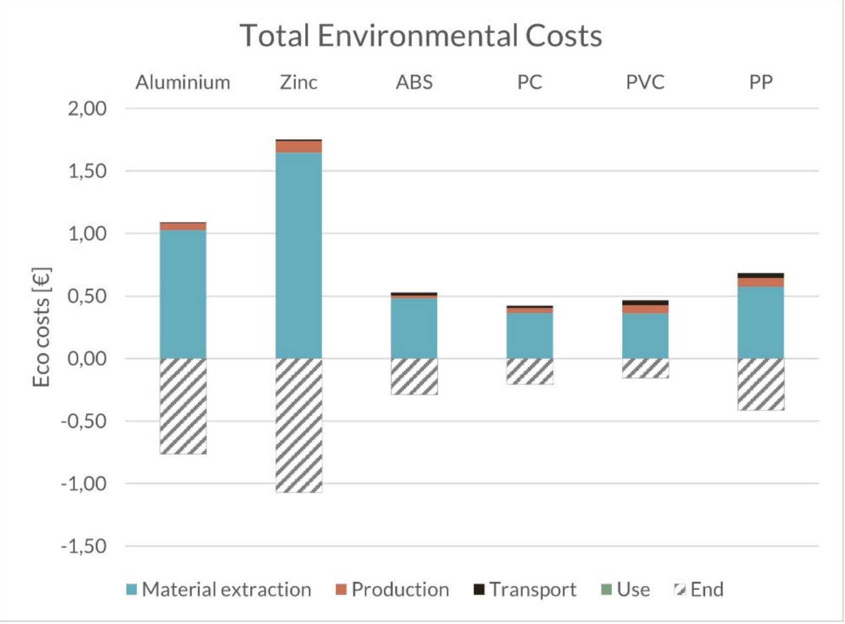
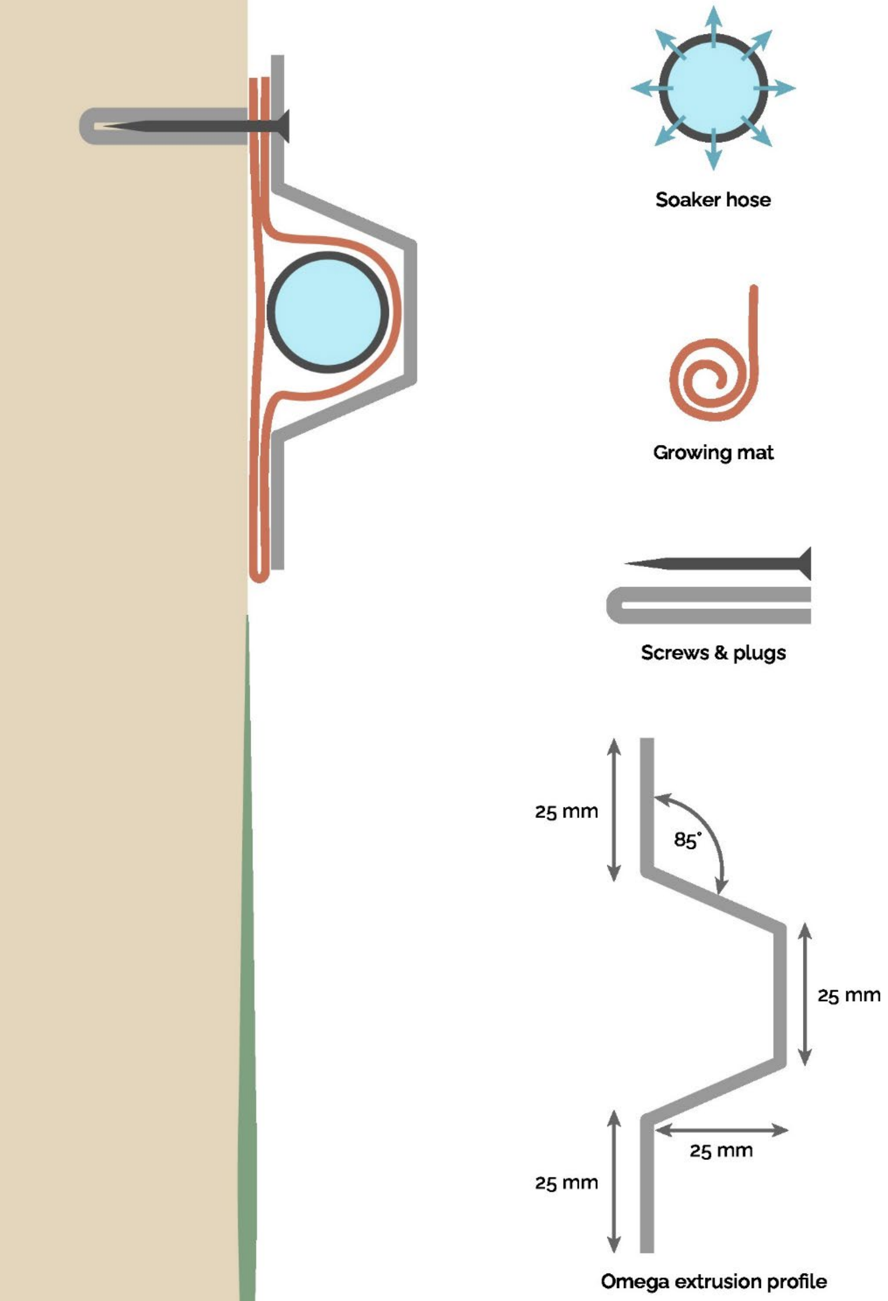


Figure 60: Environmental impact of the profile for five materials.

7.6.4 Conclusion

The metals are more suitable than the polymers, considering their durability to sunlight and better availability. Aluminium has a lower environmental impact and lower mass than zinc, therefore aluminium is advised.



8 FINAL DESIGN PROPOSAL

The design iterations lead to the following design for an irrigation system. It consists of a soaker hose, a growing mat wrapped around it, which are held together and fixed to the wall by an aluminium omega profile. See the Figure on the left and the profile in Figure 61.

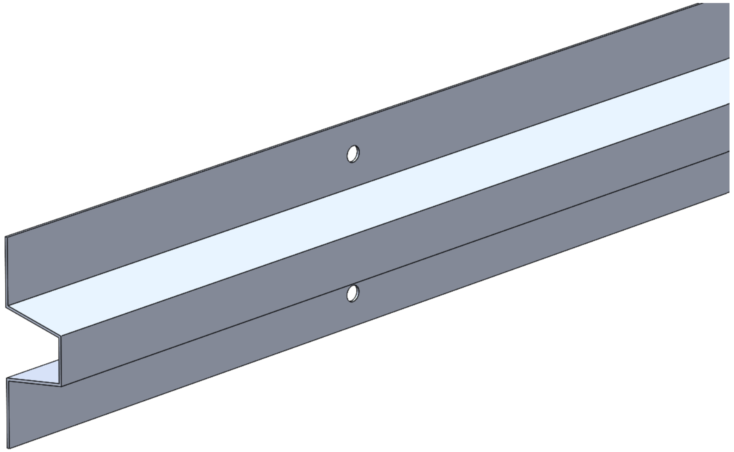


Figure 61: Solid Works model of the aluminium profile.

9 CONCLUSIONS AND RECOMMENDATIONS

The main research question is:

How can vertical surfaces in urban areas be provided with the optimal moisture conditions to accelerate moss growth?

At the start of this project, I tried to look further than irrigation systems and approached 'providing moisture' in a more abstract way. The extensive list of requirements ruled out various novel ideas and directed the project towards more conventional solutions, although the way in which these solutions are applied is new.

The optimal moisture conditions for moss are fine droplets, supplied to the leaves as uniformly as possible over the surface. The outdoor urban context comes with several practical issues. The optimal water supply is a trade-off between moss's optimal biological needs and practical feasibility in the city.

This design project is an important step towards this optimal water supply. It has led to an irrigation prototype that shows more uniform (CV = 11% instead of 14%) and significantly slower irrigation (at least 4 times slower for aforementioned CVs, 12 times in some tests), and that is estimated to have similar material and labour costs compared to the currently used irrigation system.

Slower irrigation allows for a lower water flow. A large wall no longer needs to be divided into many sections, resulting in less parallel supply pipes, saving labour and material costs. Slower irrigation also gives the bio-gel time to slowly absorb water. This is beneficial since the gel is water repellent when dry. A high waterflow on a water repellent surface causes water to run away. The slower supply thus saves water.

The more uniform water distribution is expected to result in a more uniform moss coverage on walls, satisfying the needs of clients who want an aesthetically pleasing moss surface.

The irrigation system proposed in this report offers more benefits for a comparable price. This project takes moss surfaces a step closer to a product that is feasible, viable, and desirable for the stakeholders. By doing so, cities can be made cooler, therefore more climate resilient, even where space is scarce.

9.1 Recommendations

The proposed irrigation system still has several weaknesses and uncertainties that demand for additional tests and further development.

I recommend to first test the water distribution when the soaker hose is replaced by a drip hose. Next, repeat the water distribution tests for soaker hose, drip hose, and original nozzle on a concrete panel covered in moss gel, to observe if that significantly impacts the performance. After this, I recommend testing the pressure drop over long distances for a soaker hose and a drip hose. After investigating the small scale and large-scale water distribution performance, the best irrigation system can be installed at a pilot project.

Mould growth in the mat is a concern. I recommend searching for a material that slows mould growth. This could go together with ventilation gaps in the top of the profile, allowing the mat to dry in between irrigation cycles. Alternatively, additional tests can be done without a mat to see if it is essential or can be left out.

APPENDIX A – PROJECT BRIEF

Personal Project Brief – IDE Master Graduation Project

Name student Ruben van Briemen **Student number** 4,666,070

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT
Complete all fields, keep information clear, specific and concise

Project title Adaptable recirculating irrigation system for moss covered walls

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

Concrete and bricks retain heat, which causes the temperature to build up over time. As a result, the cities are several degrees warmer than non urban areas. This effect is called the urban heat island effect. In order to reduce the urban heat island effect cities should become greener.

A promising strategy is to cover concrete surfaces by moss. Moss by itself grows slow, but the growth can be accelerated by a bio-gel, which helps the moss to attach to the concrete, while providing it with nutrients. This offers a new method for making cities greener, more biodiverse and more resilient against the urban heat island effect. Besides that, moss absorbs (traffic) sound better than plain concrete does.

The TU Delft start-up Respyre is taking this opportunity and developing it into a product. The product entails applying a bio receptive concrete layer to a surface, applying a bio-enhancing gel to that concrete layer and finally letting moss grow on the surface (see figure 1). Their product (moss surfaces) is already in the pilot phase at some locations, but some elements are lacking.

space available for images / figures on next page

introduction (continued): space for images

image / figure 1 An example of Respyre's moss covered walls

image / figure 2

Personal Project Brief – IDE Master Graduation Project

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

Moss needs water to grow. By itself, moss grows very slow, which makes it unviable as a product. Clients want a green surface as soon as possible. Moss growth can be accelerated by the aforementioned bio-gel and by providing sufficient amounts of moisture. Respyre has an irrigation prototype, but it is inefficient; a lot of water is drained at the bottom of the green wall. Also, there are many different surface types (buildings, quay walls, sound barriers) of different sizes, at on-grid or sometimes off-grid locations (electricity to drive a pump for example). Finally, the cost of Respyre's prototype is too high.

A low-cost, water efficient, universal method for providing moss in this system with moisture is lacking. This is the missing piece to make moss a viable, desirable and feasable way to cool cities.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence) As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the ***green text format:***

Investigate the possibilities to provide moss on vertical surfaces with water in order to speed up moss growth and develop a promising possibility towards a prototype that can be applied at Respyre.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

The project will consist of the following steps (see Figure 2 for the planning of the next 5 months)

Concept phase:

Explore existing solutions, explore comparable solutions in other fields and generate new ideas or combine solutions. Choose the best solution concept for Respyre, based on existing literature, interviews with experts and possible results of test with prototypes.

Embodiment phase:

Make a detailed design by dimensioning the water flows, choosing materials. Estimate costs of production and use. Optimise for low cost and low environmental impact. Build a prototype and test the solution, installation and de-installation with installers.

Project planning and key moments

To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a ***kick-off meeting, mid-term evaluation meeting, green light meeting*** *and* ***graduation ceremony****. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	19 Dec 2023
Mid-term evaluation	16 Feb 2024
Green light meeting	23 Apr 2024
Graduation ceremony	23 May 2024

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	
For how many project weeks	
Number of project days per week	

Comments:

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

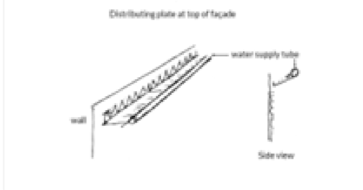
Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

My personal ambition was to focus on climate adaptation. I have done two design projects about green roofs before, which I found interesting because it is both technical/tangible (water management, material selection, roof force calculations) and one can apply an integral and creative IDE approach. Besides that, it has a goal I fully support: adapting cities to an expected warmer climate.

Well-known climate adaptive solutions like green roofs, a green environment and heat pumps are expensive, or require a lot of space. Either way, they seem inaccessible for low-income urban neighbourhoods. I think this an important and interesting direction for a graduation project. Respyre's product could be a sustainable and affordable solution to this, which makes me very motivated to help further develop it.

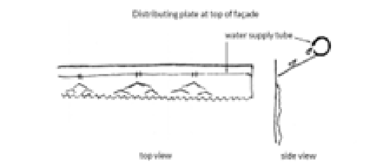
APPENDIX B – HARRIS PROFILE 1

A Harris profile is used twice. First to assess all brainstormed water distribution ideas and filter out the really unfeasible ones. They were considered unfeasible if the Harris profile pointed out that the idea failed to meet essential requirements. The reasoning for eliminating an idea is given in the table.



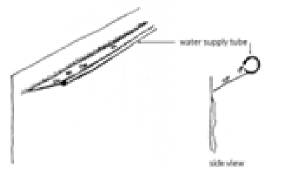
	--	-	+	++
Water is evenly spread over surface			▒	
Water gets to leaves			■	
The solution is scalable			■	■
The solution can work autonomously and requires little maintenance			■	■
Water losses to the surroundings are minimised			■	■
The solution is easy to install or deinstall			■	
The solution's unit price is minimised and at least low enough to compete			■	■
The solution's initial costs are minimised			■	■
No need for development of new parts. All parts are commercially available			■	
The solution's total environmental footprint is as low as possible			■	
The solution can be applied at different types of surfaces			■	■
The solution is suitable for both temporary and long term use		■		

Test



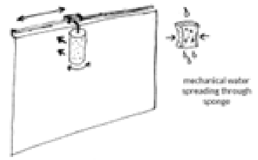
	--	-	+	++
Water is evenly spread over surface			▒	
Water gets to leaves			■	
The solution is scalable			■	
The solution can work autonomously and requires little maintenance			■	■
Water losses to the surroundings are minimised			■	■
The solution is easy to install or deinstall			■	
The solution's unit price is minimised and at least low enough to compete			■	■
The solution's initial costs are minimised			■	
No need for development of new parts. All parts are commercially available		■		
The solution's total environmental footprint is as low as possible			■	
The solution can be applied at different types of surfaces			■	■
The solution is suitable for both temporary and long term use		■		

Test



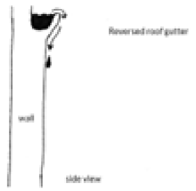
	--	-	+	++
Water is evenly spread over surface			▒	
Water gets to leaves			■	
The solution is scalable			■	■
The solution can work autonomously and requires little maintenance			■	■
Water losses to the surroundings are minimised			■	■
The solution is easy to install or deinstall			■	
The solution's unit price is minimised and at least low enough to compete			■	■
The solution's initial costs are minimised			■	■
No need for development of new parts. All parts are commercially available			■	
The solution's total environmental footprint is as low as possible			■	
The solution can be applied at different types of surfaces			■	■
The solution is suitable for both temporary and long term use		■		

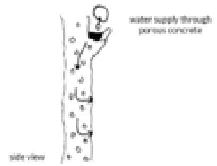
Combine with other ideas using a plank for water spreading.



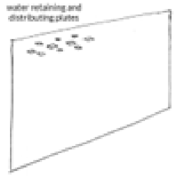
	--	-	+	++
Water is evenly spread over surface			▒	
Water gets to leaves			■	
The solution is scalable		■		
The solution can work autonomously and requires little maintenance		■		
Water losses to the surroundings are minimised		■		
The solution is easy to install or deinstall		■		
The solution's unit price is minimised and at least low enough to compete		■		
The solution's initial costs are minimised		■		
No need for development of new parts. All parts are commercially available	■	■		
The solution's total environmental footprint is as low as possible		■		
The solution can be applied at different types of surfaces	■	■		
The solution is suitable for both temporary and long term use	■	■		

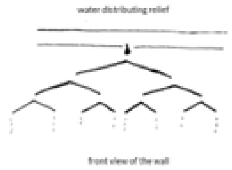
Unrealistic. Fails on almost every requirement.

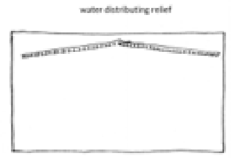


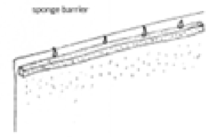


	- -	-	+	+ +	- -	-	+	+ +	- -	-	+	+ +	- -	-	+	+ +
Water is evenly spread over surface			░				░			░					░	
Water gets to leaves			■			■					■				■	
The solution is scalable		■				■			■	■				■		
The solution can work autonomously and requires little maintenance			■	■			■	■			■	■			■	■
Water losses to the surroundings are minimised			■	■			■	■			■	■			■	■
The solution is easy to install or deinstall		■				■					■	■			■	■
The solution's unit price is minimised and at least low enough to compete			■	■			■	■			■	■			■	
The solution's initial costs are minimised			■			■					■	■		■		
No need for development of new parts. All parts are commercially available			■			■					■	■		■		
The solution's total environmental footprint is as low as possible			■				■				■				■	
The solution can be applied at different types of surfaces		■					■		■	■					■	
The solution is suitable for both temporary and long term use			■				■				■	■			■	■
	Test				Not realistic, since we learnt from the literature and interviews that moss needs to absorb water through its leaves, not from underneath through its rhizoids.				Unrealistic. Not possible for majority of locations because we have to deal with existing walls that are vertical				Test			

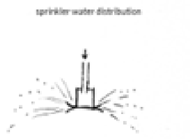
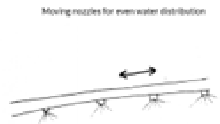
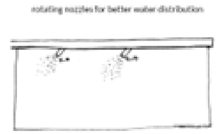


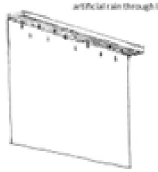
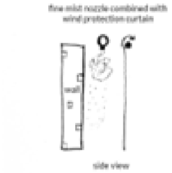
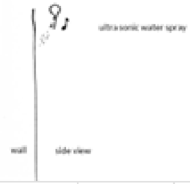
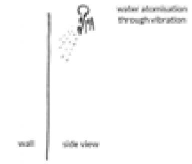


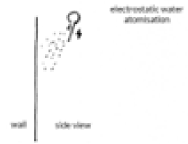


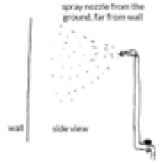


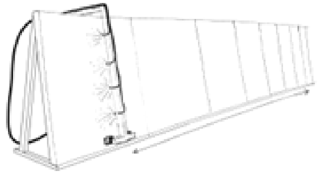
	--	-	+	++	--	-	+	++	--	-	+	++	--	-	+	++
Water is evenly spread over surface			▒				▒				▒				▒	
Water gets to leaves			■				■				■				■	
The solution is scalable		■					■				■				■	■
The solution can work autonomously and requires little maintenance			■	■			■	■			■	■			■	
Water losses to the surroundings are minimised			■	■			■	■			■	■			■	■
The solution is easy to install or deinstall		■					■				■				■	
The solution's unit price is minimised and at least low enough to compete			■				■				■				■	■
The solution's initial costs are minimised		■					■				■				■	■
No need for development of new parts. All parts are commercially available		■					■				■				■	
The solution's total environmental footprint is as low as possible			■				■				■				■	
The solution can be applied at different types of surfaces			■				■	■			■	■			■	■
The solution is suitable for both temporary and long term use			■	■			■	■			■	■			■	
	Adapt and test with similar pattern in concrete				Test				Test				Test with coconut fibre			

																
	- -	-	+	+ +	- -	-	+	+ +	- -	-	+	+ +	- -	-	+	+ +
Water is evenly spread over surface			▒				▒				▒				▒	
Water gets to leaves			■	■			■				■				■	■
The solution is scalable			■	■			■				■				■	
The solution can work autonomously and requires little maintenance			■	■			■				■				■	
Water losses to the surroundings are minimised		■				■				■			■	■		
The solution is easy to install or deinstall			■	■		■				■				■		
The solution's unit price is minimised and at least low enough to compete			■	■		■				■					■	
The solution's initial costs are minimised			■			■				■				■		
No need for development of new parts. All parts are commercially available			■		■	■			■	■				■		
The solution's total environmental footprint is as low as possible			■			■				■					■	
The solution can be applied at different types of surfaces			■				■				■				■	
The solution is suitable for both temporary and long term use			■	■			■	■			■	■			■	■
	several spray nozzles are tested				Unrealistic because it is a mechanically complex solution. This increases costs, need for maintenance, and makes it less suitable to scale up to large projects.				Unrealistic because it is a mechanically complex solution. This increases costs, need for maintenance, and makes it less suitable to scale up to large projects.				Unrealistic. The current spray nozzles already lose water to the wind. This idea is probably complex, water inefficient, and energy intensive			

																
	--	-	+	++	--	-	+	++	--	-	+	++	--	-	+	++
Water is evenly spread over surface																
Water gets to leaves																
The solution is scalable																
The solution can work autonomously and requires little maintenance																
Water losses to the surroundings are minimised																
The solution is easy to install or deinstall																
The solution's unit price is minimised and at least low enough to compete																
The solution's initial costs are minimised																
No need for development of new parts. All parts are commercially available																
The solution's total environmental footprint is as low as possible																
The solution can be applied at different types of surfaces																
The solution is suitable for both temporary and long term use																
	Test				Unrealistic. Fine mist spray with a protective shield has been tested by Respyre. The moss died soon after removing the protective shield.				Unrealistic, since most water will be blown away by wind. A protective shield has been tested before, but failed.				Unrealistic, since most water will be blown away by wind. A protective shield has been tested before, but failed.			

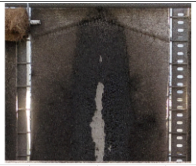
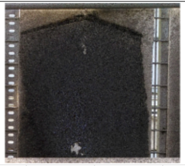
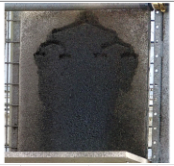


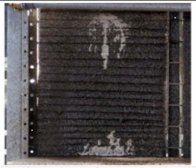
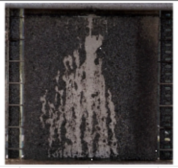
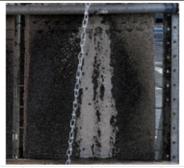




	- -	-	+	+ +	- -	-	+	+ +	- -	-	+	+ +
Water is evenly spread over surface			■				■				■	■
Water gets to leaves			■				■	■			■	■
The solution is scalable			■				■			■		
The solution can work autonomously and requires little maintenance			■				■			■		
Water losses to the surroundings are minimised		■			■	■					■	
The solution is easy to install or deinstall			■				■		■	■		
The solution's unit price is minimised and at least low enough to compete			■				■	■	■	■		
The solution's initial costs are minimised			■				■	■	■	■		
No need for development of new parts. All parts are commercially available							■	■	■	■		
The solution's total environmental footprint is as low as possible		■					■			■		
The solution can be applied at different types of surfaces			■			■			■	■		
The solution is suitable for both temporary and long term use			■	■		■			■	■		
	Unrealistic, since most water will be blown away by wind. A protective shield has been tested before, but failed.				Unrealistic, since most water will be blown away by wind if nozzle is placed so far.				Not suitable for buildings, which is an important target. Also, this system is mechanically complex, therefore needs a lot of R&D, thus not realistic for Respyre in its current phase.			

APPENDIX C – HARRIS PROFILE 2

		1: Coconut fibre mat				2: Pattern 1 with vertical indents				3: Pattern 1 without indents				4: Pattern 2			
	Note: concepts can either be installed on existing walls or on prefab walls. For requirements 5, 6, and 7 there is a different score for both cases.																
		--	-	+	++	--	-	+	++	--	-	+	++	--	-	+	++
1	Water is evenly spread over surface		■			■	■					■	■			■	■
2	The solution can work autonomously and requires little maintenance		■					■	■			■	■			■	■
3	Water losses to the surroundings are minimised			■	■			■	■			■	■			■	■
4	The solution requires a low water flow rate per metre			■	■			■				■				■	
5	The solution is easy to install or deinstall on existing walls			■		■	■					■		■	■		
	The solution is easy to install or deinstall on new walls			■		■	■				■			■	■		
6	The solution's unit price is minimised and at least low enough to compete (existing walls)			■		■	■					■		■	■		
	The solution's unit price is minimised and at least low enough to compete (new walls)			■				■				■				■	
7	The solution's initial costs are minimised (existing walls)			■			■					■			■		
	The solution's initial costs are minimised (new walls)			■		■	■				■			■	■		
8	The solution's initial costs are minimised (new walls)			■			■				■				■		
9	The solution's total environmental footprint is as low as possible		■					■				■				■	
10	The solution can be applied at different types of surfaces			■				■	■			■	■			■	■
11	The solution is suitable for both temporary and long term use		■					■	■			■	■			■	■
	ASSESSMENT:	**PROMISING**								**PROMISING**							
		Can be maintenance-intensive, since mould might grow in fibre. Requires a low water flow rate and almost no pressure to operate. Requires some labour when installing. Standard parts and acceptable amount of labour result in average unit price. Little development costs are needed since standard parts are used.				Very little maintenance expected. Requires a low water flow and pressure to operate. The vertical indents are extremely time consuming to carve into concrete, which increases variable costs, but not initial costs. In the case of pre-fab panels, it is complicated to implement in a mould, resulting in high initial costs, but the variable costs are acceptable once a mould is available. No new parts are needed, except for the mould.				Very little maintenance expected. Requires a low water flow and pressure to operate. The V-shaped pattern is easy to carve into concrete by hand, resulting in acceptable variable costs. Initial costs are low since no new parts are used. In the case of pre-fab panels, simple modifications are needed to the mould, resulting in higher initial costs, but the variable costs are acceptable once a mould is available. No new parts are needed, except for the mould.				Very little maintenance expected. Requires a low water flow and pressure to operate. The tree-pattern is time-consuming to carve into concrete by hand, resulting in high variable costs. Initial costs are low since no new parts are used. If a "stamp" is developed to imprint the pattern by hand, initial costs are a bit higher and variable costs slightly lower. In the case of pre-fab panels, complicated modifications are needed to the mould, resulting in high initial costs, but the variable costs are acceptable once a mould is available. No new parts are needed, except for the mould.			

		5: Textured				6: Single horizontal ditch 1				7: Triple horizontal ditch				8: Pattern 3			
	Note: concepts can either be installed on existing walls or on prefab walls. For requirements 5, 6, and 7 there is a different score for both cases.																
		--	-	+	++	--	-	+	++	--	-	+	++	--	-	+	++
1	Water is evenly spread over surface		■					■				■		■	■		
2	The solution can work autonomously and requires little maintenance			■	■			■	■			■	■			■	■
3	Water losses to the surroundings are minimised			■	■			■	■			■	■			■	■
4	The solution requires a low water flow rate per metre			■				■				■				■	
5	The solution is easy to install or deinstall on existing walls	■	■					■	■			■		■	■		
	The solution is easy to install or deinstall on new walls	■	■					■				■		■	■		
6	The solution's unit price is minimised and at least low enough to compete (existing walls)	■	■					■	■			■			■		
	The solution's unit price is minimised and at least low enough to compete (new walls)			■				■				■				■	
7	The solution's initial costs are minimised (existing walls)		■					■				■			■		
	The solution's initial costs are minimised (new walls)	■	■				■				■			■	■		
8	The solution's initial costs are minimised (new walls)		■					■	■			■			■		
9	The solution's total environmental footprint is as low as possible			■				■				■				■	
10	The solution can be applied at different types of surfaces			■	■			■	■			■	■			■	■
11	The solution is suitable for both temporary and long term use			■	■			■	■			■	■			■	■
	ASSESSMENT:					**PROMISING**											

5: Textured

Very little maintenance expected. Requires a low water flow and pressure to operate.
The ribbed pattern is extremely time-consuming to carve or imprint into concrete by hand, resulting in very high variable costs. Initial costs are low since no new parts are used, unless a "stamp" is developed for imprinting the ribs by hand. In the case of pre-fab panels, complicated modifications are needed to the mould, resulting in high initial costs, but the variable costs are acceptable once a mould is available.
No new parts are needed, except for the mould.

6: Single horizontal ditch 1

Very little maintenance expected. Requires a low water flow and pressure to operate.
The horizontal ditch is very easy to carve into concrete by hand, resulting in low variable costs. Initial costs are low since no new parts are used. In the case of pre-fab panels, simple modifications are needed to the mould, resulting in higher initial costs, but the variable costs are acceptable once a mould is available.
No new parts are needed, except for the mould.

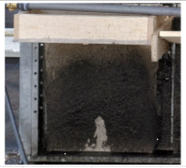
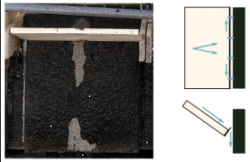
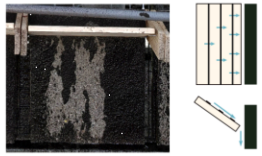
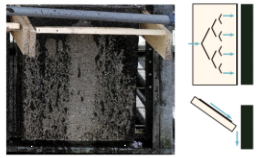
7: Triple horizontal ditch

Very little maintenance expected. Requires a low water flow and pressure to operate.
The horizontal ditches are very easy to carve into concrete by hand, resulting in low variable costs, but higher than a single ditch. Initial costs are low since no new parts are used. In the case of pre-fab panels, simple modifications are needed to the mould, resulting in higher initial costs, but the variable costs are acceptable once a mould is available.
No new parts are needed, except for the mould.

8: Pattern 3

Very little maintenance expected. Requires a low water flow and pressure to operate.
The carvings are very time-consuming to carve into concrete by hand, resulting in very high variable costs. Initial costs are low since no new parts are used. If a "stamp" is developed to imprint the pattern by hand, initial costs are a bit higher and variable costs slightly lower. In the case of pre-fab panels, complicated modifications are needed to the mould, resulting in high initial costs, but the variable costs are acceptable once a mould is available.
No new parts are needed, except for the mould.

Note: concepts can either be installed on existing walls or on prefab walls. For requirements 5, 6, and 7 there is a different score for both cases.

		9: Rain box				10: Gutter plank 1				11: Gutter plank 2				12: Gutter plank 3			
																	
		--	-	+	++	--	-	+	++	--	-	+	++	--	-	+	++
	Water is evenly spread over surface		■					■	■			■	■			■	■
2	The solution can work autonomously and requires little maintenance		■				■				■				■		
3	Water losses to the surroundings are minimised			■				■	■			■	■			■	■
4	The solution requires a low water flow rate per metre			■	■			■	■			■	■			■	■
5	The solution is easy to install or deinstall on existing walls		■				■				■				■		
	The solution is easy to install or deinstall on new walls		■				■				■				■		
6	The solution's unit price is minimised and at least low enough to compete (existing walls)	■	■				■				■			■	■		
	The solution's unit price is minimised and at least low enough to compete (new walls)	■	■				■				■			■	■		
7	The solution's initial costs are minimised (existing walls)	■	■				■			■	■			■	■		
	The solution's initial costs are minimised (new walls)	■	■				■			■	■			■	■		
8	The solution's initial costs are minimised (new walls)	■	■				■			■	■			■	■		
9	The solution's total environmental footprint is as low as possible		■				■				■				■		
10	The solution can be applied at different types of surfaces			■				■				■				■	
11	The solution is suitable for both temporary and long term use		■					■				■				■	
	ASSESSMENT:					Interesting											

9: Rain box

Quite some maintenance required since the box can get clogged by leaves, mould might grow or birds might nest in them.
Requires a low water flow and almost no pressure to operate, water dripping down from the exit hole is sufficient.
Requires relatively much labour to produce and fix to walls. Also requires more materials than other solutions. Therefore, variable costs are high.
Initial costs are high if a production line needs to be set up, however it's unknown yet if standard parts can be used for this solution.

10: Gutter plank 1

Quite some maintenance required since the plank can get clogged by leaves or birds might nest in them.
Requires a low water flow and almost no pressure to operate, water dripping down from the exit hole is sufficient.
Requires average amount of labour to produce and fix to walls. Also requires more materials than other solutions. Therefore, variable costs are high.
Initial costs are high if a production line needs to be set up, however it's unknown yet if standard parts can be used for this solution.

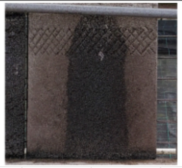
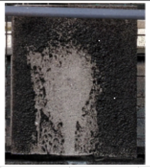
11: Gutter plank 2

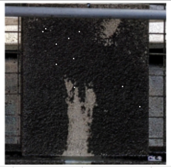
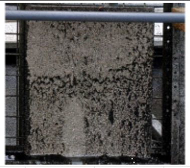
Quite some maintenance required since the plank can get clogged by leaves or birds might nest in them.
Requires a low water flow and almost no pressure to operate, water dripping down from the exit hole is sufficient.
Requires average amount of labour to produce and fix to walls. Also requires more materials than other solutions. Therefore, variable costs are high.
Initial costs are high if a production line needs to be set up, however it's unknown yet if standard parts can be used for this solution.

12: Gutter plank 3

Quite some maintenance required since the plank can get clogged by leaves or birds might nest in them.
Requires a low water flow and almost no pressure to operate, water dripping down from the exit hole is sufficient.
Requires average amount of labour to produce and fix to walls. Also requires more materials than other solutions. Therefore, variable costs are high.
Initial costs are high since a production line needs to be set up for making the pattern.

Note: concepts can either be installed on existing walls or on prefab walls. For requirements 5, 6, and 7 there is a different score for both cases.

		13: Gutter in concrete				14: Pattern 4				15: Single horizontal ditch 2				16: Spray nozzle 1 (current system)			
																	
		--	-	+	++	--	-	+	++	--	-	+	++	--	-	+	++
1	Water is evenly spread over surface			■	■	■	■					■				■	
2	The solution can work autonomously and requires little maintenance		■					■	■			■	■			■	
3	Water losses to the surroundings are minimised			■	■			■	■			■	■		■		
4	The solution requires a low water flow rate per metre			■				■				■			■		
5	The solution is easy to install or deinstall on existing walls	■	■			■	■					■	■			■	
	The solution is easy to install or deinstall on new walls	■	■			■	■					■				■	
6	The solution's unit price is minimised and at least low enough to compete (existing walls)		■			■	■					■	■			■	
	The solution's unit price is minimised and at least low enough to compete (new walls)		■					■				■				■	
7	The solution's initial costs are minimised (existing walls)		■				■					■				■	
	The solution's initial costs are minimised (new walls)		■			■	■				■					■	
8	The solution's initial costs are minimised (new walls)		■				■					■	■			■	■
9	The solution's total environmental footprint is as low as possible			■				■				■				■	
10	The solution can be applied at different types of surfaces			■				■	■			■	■			■	
11	The solution is suitable for both temporary and long term use			■	■			■	■			■	■			■	■
	ASSESSMENT:													BASELINE			
		Some maintenance required since the gutter might get clogged by leaves. Requires a low water flow and pressure to operate. The gutter is difficult to make, both for application to existing walls and for pre-fab. Therefore, very high variable costs are expected. Initial costs are expected to be low, unless a mould is made. No new parts are needed (unless a mould is used).				Very little maintenance expected. Requires a low water flow and pressure to operate. The grid-pattern is very time-consuming to carve into concrete by hand, resulting in very high variable costs. Initial costs are low since no new parts are used. If a "stamp" is developed to imprint the pattern by hand, initial costs are a bit higher and variable costs lower. In the case of pre-fab panels, complicated modifications are needed to the mould, resulting in high initial costs, but the variable costs are acceptable once a mould is available. No new parts are needed, except for				Very little maintenance expected. Requires a low water flow and pressure to operate. The horizontal ditch is very easy to carve into concrete by hand, resulting in low variable costs. Initial costs are low since no new parts are used. In the case of pre-fab panels, simple modifications are needed to the mould, resulting in higher initial costs, but the variable costs are acceptable once a mould is available. No new parts are needed, except for the mould.				Little maintenance needed, but sometimes nozzles need replacement. Nozzles require a higher water flow and pressure to operate. Some water is lost to the surroundings, especially in strong winds. Relatively easy to install, but screwing in the nozzles takes some time and effort. This results in acceptable variable costs. Initial costs are low since no new part need to be developed.			

		17: Spray nozzle 2				18: Spray nozzle 3			
	Note: concepts can either be installed on existing walls or on prefab walls. For requirements 5, 6, and 7 there is a different score for both cases.								
		--	-	+	++	--	-	+	++
	Water is evenly spread over surface			■				■	
2	The solution can work autonomously and requires little maintenance			■				■	
3	Water losses to the surroundings are minimised	■	■			■	■		
4	The solution requires a low water flow rate per metre		■				■		
5	The solution is easy to install or deinstall on existing walls			■				■	
	The solution is easy to install or deinstall on new walls			■				■	
6	The solution's unit price is minimised and at least low enough to compete (existing walls)			■				■	
	The solution's unit price is minimised and at least low enough to compete (new walls)			■				■	
7	The solution's initial costs are minimised (existing walls)			■				■	
	The solution's initial costs are minimised (new walls)			■				■	
8	The solution's initial costs are minimised (new walls)			■	■			■	■
9	The solution's total environmental footprint is as low as possible			■				■	
10	The solution can be applied at different types of surfaces			■				■	
11	The solution is suitable for both temporary and long term use			■	■			■	■
	ASSESSMENT:								
		Little maintenance needed, but sometimes nozzles need replacement. Nozzles require a higher water flow and pressure to operate. Some water is lost to the surroundings, especially in strong winds. Relatively easy to install, but screwing in the nozzles takes some time and effort. This results in acceptable variable costs. Initial costs are low since no new part need to be developed.				Little maintenance needed, but sometimes nozzles need replacement. Nozzles require a higher water flow and pressure to operate. Some water is lost to the surroundings, especially in strong winds. Relatively easy to install, but screwing in the nozzles takes some time and effort. This results in acceptable variable costs. Initial costs are low since no new part need to be developed.			

APPENDIX D – TEST RESULTS

Results experiment 2A

	Water collecting buckets [mL]																		
	1	2	3	4	5	6	7	8	9	10	Sum	Total	Time [s]	Q [L/u]	Q per nozzle	min/ max	max/ min ex. outlier	CV	CV ex. outlier
Spray nozzle	5,4	11,4	11,1	60	482,9	555,8	52,3	11,8	3,4	3,9	1198	1220,7	86	51,1				168%	
V-shaped indent	257,4	23,1	37,8	12,5	11,2	166,9	27,3	30	0	231,3	797,5	810,3	587	5,0				118%	
V-shaped indent with nozzle	662,7	106,3	371,9	224,6	390	218,8	142,5	48,6	162,1	672,6	3000,1	3317,9	270	44,2				70%	
Horizontal indent	0	0	0	5,1	609,3	642,5	10	0	0	0	1266,9	1265,9	109	41,8				197%	
Horizontal indent with nozzle	0	0,9	1,6	50	522,5	668,4	13,9	1,5	0	0	1258,8	1255,9	138	32,8				189%	
Gutter plank ribbed with edge	0	1,6	63,1	140,6	397,6	4,6	357,4	72	1	432,5	1470,4	1478,8	512	10,4				115%	
Soaker hose & mat	21,7	76,8	171,3	200	267	278,6	285,3	203,9	106,4	113,6	1724,6	1764,3	519	12,2		0,08	0,27	50%	39%

Results experiment 2B

	Water collecting buckets [mL]																		
	1	2	3	4	5	6	7	8	9	10	Sum	Total	Time [s]	Q [L/u]	Q per nozzle	min/ max	max/ min ex. outlier	CV	CV ex. outlier
Spray nozzle every 33 cm perpendicular	509,2	368,5	384,3	428,8	232,2	463,8	239,1	537,2	253,5	490,7	3907,3	3906,6	41	343,0	68,6	0,43		28%	
Soaker hose & mat (second measurement)	277,2	443,1	507,9	668,9	605,8	606,4	783,3	794,2	716,1	538,2	5941,1	5936,9	224	95,4		0,35	0,56	26%	18%

Results experiment 3

CV *: Average of the 5 CVs   CV **: CV of the 10 averages

	Water collecting buckets [mL]																			
	1	2	3	4	5	6	7	8	9	10		AVG	CV between buckets	Sum	Control value	Time [s]	Q [L/u]	Q per nozzle	min/ max
Soaker hose, mat & aluminium profile 1	299,1	380	255,6	242,5	366,9	316,3	391,9	371	302,1	302,7	→	323	15%	3228	3227	299	38,9	N/A	0,62
Soaker hose, mat & aluminium profile 2	277,7	332,2	268,3	274	263,9	331,9	287,9	347	276,9	276,6	→	294	10%	2936	2933	181	58,3	N/A	0,76
Soaker hose, mat & aluminium profile 3	258,7	338,9	282	234,7	312,7	304,7	318,6	323	288,9	276,5	→	294	10%	2939	2937	163	64,9	N/A	0,69
Soaker hose, mat & aluminium profile 4	210	285,2	233,2	190	278,5	229,1	273,3	282,1	230	230,7	→	244	13%	2442	2439	159	55,2	N/A	0,67
Soaker hose, mat & aluminium profile 5	245,6	330	266	230	314,5	247,2	381,1	292	283,1	263,6	→	285	15%	2853	2851	127	80,8	N/A	0,60
	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓		CV *:	13%	2879		186	59,6		0,67
Average per segment	258	333	261	234	307	286	331	323	276	270	→	**CV **:**	**11%**						
CV between measurements within segment	12%	9%	6%	11%	12%	14%	15%	10%	9%	9%									
Low flow nozzle every 33 cm 1	351,4	196,2	286,9	187,7	257,4	341	153,3	395,5	288,4	393	→	285	29%	2851	2843	80	127,9	25,6	0,39
Low flow nozzle every 33 cm 2	445,7	321,9	430,6	317	347,3	468,7	290,7	463,2	494,1	508,1	→	409	19%	4087	*1859*	105	140,1	28,0	0,57
Low flow nozzle every 33 cm 3	463,4	111,7	344,5	169,5	200	378,8	55,7	524,6	211,6	474,7	→	293	53%	2935	2943	95	111,5	22,3	0,11
Low flow nozzle every 33 cm 4	382,9	325,7	409	323,5	357,6	473,5	161,7	359,2	404,8	371,2	→	357	22%	3569	3566	96	133,7	26,7	0,34
Low flow nozzle every 33 cm 5	386,4	309	378,3	315,7	330,9	478,2	136,9	384,3	407,4	386,9	→	351	24%	3514	3512	101	125,2	25,0	0,29
	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓		CV *:	29%	3168		95	127,7	26	0,34
Average per segment	406	253	370	263	299	428	160	425	361	427	→	**CV **:**	**26%**						
CV between measurements within segment	10%	34%	14%	26%	20%	13%	47%	14%	28%	13%									

	Water collecting buckets [mL]																		
	1	2	3	4	5	6	7	8	9	10		AVG	CV between buckets	Sum	Control value	Time [s]	Q [L/u]	Q per nozzle	min/max
Original nozzle every 33 cm 1	330	286,9	389,1	365,4	417,2	377,3	340,6	537,2	340	360	→	374	17%	3744	N/A	50	269,5	53,9	0,53
Original nozzle every 33 cm 2	348,4	359,1	499	377,8	580,5	346,2	549,4	458,8	551,7	386,3	→	446	20%	4457	N/A	38	422,3	84,5	0,60
Original nozzle every 33 cm 3	466,1	366	418,5	448,7	432,1	495,6	358	608,6	413,8	425,5	→	443	15%	4433	N/A	60	266,0	53,2	0,59
Original nozzle every 33 cm 4	375,5	261	383	387,4	292,1	460	205,8	544,9	247,5	417,7	→	357	28%	3575	N/A	59	218,1	43,6	0,38
Original nozzle every 33 cm 5	440	322,2	407,8	416	388,9	476,4	301,7	582,7	370	430	→	414	18%	4136	N/A	57	261,2	52,2	0,52
	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓		CV *:	20%	4069		53	287,4	57	0,52
Average per segment (1-5)	392	319	419	399	422	431	351	546	385	404	→	**CV **:**	**14%**						
CV between measurements within segment	13%	13%	10%	7%	22%	14%	32%	9%	26%	7%									

Results experiment 4

11-12 metre soaker hose

		1 [mL]	2 [mL]	3 [mL]	4 [mL]	5 [mL]		Average [mL]	CV [-]	min/max [-]		CV [-]	min/max [-]
	→												
1		862	562	626				683	19%	0,65			
2	→	745	561	612	342			565	26%	0,46	avg:	24%	0,52
3	→	673	485	476	310			486	26%	0,46			
4	→	621	591	445	519	364	←	508	19%	0,59			

APPENDIX E – COST ESTIMATION

Assuming a wall 6 m tall 100 m long	Concept 1 Original nozzle		Concept 1b Low flow nozzle		Concept 2 Soaker hose & profile		Concept 3 V-shaped indent		Concept 3b V-shaped indent & nozzle		Concept 4 Single horizontal indent		Concept 4b Horizontal indent & nozzle		Concept 5 Gutter plank	
	Existing wall	*Prefab wall*	*Existing wall*	*Pre-fab wall*	*Existing wall*	*Pre-fab wall*	*Existing wall*	*Pre-fab wall*	*Existing wall*	*Pre-fab wall*	*Existing wall*	*Pre-fab wall*	*Existing wall*	*Pre-fab wall*	*Existing wall*	*Pre-fab wall*
FIXED COSTS	No extra tools needed for concepts 3 and 4, a regular plastering darby, used for spreading concrete, can also be used for making an indent. In case of pre-fab concrete panels: concepts 3 and 4 need small adjustments to the mould for making an indent in the panel, which requires some R&D, labour in factory and materials. This is a bit simpler for C4 than for C3 A production line for drilling holes in pipes is very comparable to that of concept 1, the holes are simply smaller. Concepts 2 and 5 are assumed to consist of an existing profile, so no extra R&D or investments are needed															
R&D								€ 2.400,00		€ 2.400,00		€ 2.000,00		€ 2.000,00		
Investment in tools	€ -	€ -			€ -	€ -	€ -	€ -		€ -	€ -	€ -		€ -		
Investment in production line						€ -	€ -	€ 1.100,00		€ 1.100,00		€ 780,00		€ 780,00		
Total fixed costs	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ 3.500,00	€ -	€ 3.500,00	€ -	€ 2.780,00	€ -	€ 2.780,00	€ -	€ -
VARIABLE COSTS *(per 100 m wall, 6 m tall)*																
Materials & off-shelf parts	Concrete, gel & moss is the same for all concepts. Concepts 2-5 require a lower minimum pressure and water flow than concept 1, allowing for smaller/fewer pumps, computer and reservoir. Concepts 3 and 4 need a little less material than 1 since the nozzles are eliminated.															
	The costs for C1 are based on the company's internal data for existing projects.		The costs for this variant are similar to C1, but the lower water usage allows for fewer sections, resulting in simpler plumbing, less/smaller reservoir, simpler computer and fewer valves. Water flow is assumed to be 3x lower (supplier claims 45 L/h compared to 140 for C1's nozzle)		Soakerhose costs €88,49 (https://www.wildkamp.nl/product/alfapore-zweetslang-rol-a-100-m/15094444). A mat from vreeken.nl costs €328 for 100 m. 100 m extruded profile is estimated at €677 (Zetwerkprofiel.nl (n.d.) for 25-25-25-25-35 mm profiles 2 m long 50 pieces) No nozzles are needed as in C1. Since concept 2 requires a much lower water flow (up to 12x less), fewer sections are needed, resulting in simpler plumbing, smaller computer, smaller or even no pump.		Since concept 3 requires a much lower water flow (up to 10x less), fewer sections are needed, resulting in a smaller computer, smaller or even no pump and reservoir. Also, it results in simpler plumbing, so less pipes and no nozzles		This variant requires the same plumbing as C1		Since concept 4 requires a much lower water flow (up to 10x less), fewer sections are needed, resulting in a smaller computer, smaller or even no pump and reservoir. Also, it results in simpler plumbing, so less pipes and no nozzles		This variant requires the same plumbing as C1		Since concept 5 requires a much lower water flow (up to 10x less), fewer sections are needed, resulting in a smaller computer, smaller or even no pump and reservoir. Also, it results in simpler plumbing, so less pipes and no nozzles. Since the plank is heavier that just a tube with nozzles, C5 needs more fixtures than C1, resulting in increased materials. Tubes, fixtures and plumbing materials are therefore estimated to be comparable to C1. The "plank" is estimated at €880 assuming an aluminium profile comparable to: https://www.aluminiumopmaat.nl/ongelijkzijdige-aluminium-hoekprofielen.html	
Water flow per nozzle/hole [L/h]	140		45		*No discrete exit holes, 2~4 L/h/m*		14		140		14		140		14	
Water flow total [L/h]	42000		13500		7000		4200		42000		4200		42000		4200	
# pump-reservoirs needed (7200 L/h cap.)	6		2		1		1		6		1		6		1	
Metres of pipes needed ø40mm	286		62		6		6		286		6		286		6	
Metres of pipes needed ø32mm	100		100		0		100		100		100		100		100	
Magnet valves + control (https://irritech.nl/rainbird-100-hv	€ 178,87		€ 61,11		€ 31,67		€ 31,67		€ 178,87		€ 31,67		€ 178,87		€ 31,67	
DAB Esybox pump+reservoir	€ 1.771,90		€ 1.771,90		€ 1.771,90		€ 1.771,90		€ 1.771,90		€ 1.771,90		€ 1.771,90		€ 1.771,90	
Computer for X sections + wifi module	€ 283,00		€ 268,00		€ 268,00		€ 268,00		€ 283,00		€ 268,00		€ 283,00		€ 268,00	
Pipes for X sections	€ 854,44		€ 266,21		€ 15,76		€ 119,16		€ 854,44		€ 119,16		€ 854,44		€ 119,16	
Fixtures & connections	€ 625,81		€ 255,29		€ 30,92		€ 157,67		€ 625,81		€ 157,67		€ 625,81		€ 157,67	
Nozzles	€ 237,00		€ 237,00						€ 237,00				€ 237,00			
Extra material (plank or profile)					€ 1.093,49										€ 880,00	
Subtotal estimation irrigation material:	€ 3.951,01		€ 2.859,51		€ 3.211,73		€ 2.348,39		€ 3.951,01		€ 2.348,39		€ 3.951,01		€ 3.228,39	
Concrete mixture (15 m^3, 33 tonnes)	€ 3.000,00	€ 42.000,00	€ 3.000,00	€ 42.000,00	€ 3.000,00	€ 42.000,00	€ 3.000,00	€ 42.000,00	€ 3.000,00	€ 42.000,00	€ 3.000,00	€ 42.000,00	€ 3.000,00	€ 42.000,00	€ 3.000,00	€ 42.000,00
Moss 600 m^2	€ 3.600,00	€ 3.600,00	€ 3.600,00	€ 3.600,00	€ 3.600,00	€ 3.600,00	€ 3.600,00	€ 3.600,00	€ 3.600,00	€ 3.600,00	€ 3.600,00	€ 3.600,00	€ 3.600,00	€ 3.600,00	€ 3.600,00	€ 3.600,00
Gel 600 m^2, 600 L	€ 3.000,00	€ 3.000,00	€ 3.000,00	€ 3.000,00	€ 3.000,00	€ 3.000,00	€ 3.000,00	€ 3.000,00	€ 3.000,00	€ 3.000,00	€ 3.000,00	€ 3.000,00	€ 3.000,00	€ 3.000,00	€ 3.000,00	€ 3.000,00
Renting boom lift or scaffold during construction		€ -			€ -	€ -	€ -	€ -			€ -	€ -			€ -	€ -
Sub total material costs	€ 13.551,01	€ 52.551,01	€ 12.459,51	€ 51.459,51	€ 12.811,73	€ 51.811,73	€ 11.948,39	€ 50.948,39	€ 13.551,01	€ 52.551,01	€ 11.948,39	€ 50.948,39	€ 13.551,01	€ 52.551,01	€ 12.828,39	€ 51.828,39
Labour	Preparing concrete, gel & moss is identical for all concepts. Applying the concrete layer and the moss gel to the wall, as well as installing the reservoir, pump and plumbing are comparable too. Due to lack of cost specifications, the labour costs for installing the irrigation is extrapolated from a 450m^2 project based on the material costs: assumed is that double the amount of equipment requires double the amount of labour.															
	The costs for C1 are based on the company's internal data for existing projects.		Simpler plumbing also reduces the labour of installation. The installation of the system along the wall is the same, however the supply between computer and the wall consists of fewer pipes since it has fewer sections.		Concept 2 requires a little more time for plastering, as the top 20 cm needs to be smoother than concept 1. 20 cm is 1/30th of the height, and it is estimated to cost 50% more time resulting 1,7% more time. A soaker hose must be inserted in the extruded profile, which are then together fixed to the wall. The simpler plumbing for concept 2 is estimated to outweigh the extra time for attaching the hose in the profile, resulting in slightly lower labour for installation.		Plastering is expected to take more time, as the V-shape must be pressed into the concrete. Since C3 needs lower water flow, it needs fewer sections, thus simpler plumbing, resulting in lower labour. A small increase in installation compexity because the tube's exit holes must be aligned to the point of the V-shape.		This variant requires the same plastering work as C3 and the same irrigation system as C1, resulting in more labour.		Plastering is expected to take a bit more time, as the indent must be pressed into the concrete, but it is simpler than the V-shape. Since C4 needs lower water flow, it needs fewer sections, thus simpler plumbing, resulting in lower labour.		This variant requires the same plastering work as C4 and the same irrigation system as C1, resulting in more labour.		Plastering is comparable to C1. Installation takes more time, since installing the plank, stronger fixtures and the tube on the plank are more steps than in C1. Since C5 needs a lower water flow, the plumbing is simpler, so installations costs are that much higher than C1.	
Preparing concrete	€ 3.000,00	€ 3.000,00	€ 3.000,00	€ 3.000,00	€ 3.000,00	€ 3.000,00	€ 3.000,00	€ 3.000,00	€ 3.000,00	€ 3.000,00	€ 3.000,00	€ 3.000,00	€ 3.000,00	€ 3.000,00	€ 3.000,00	€ 3.000,00
Preparing gel & moss	€ 600,00	€ 600,00	€ 600,00	€ 600,00	€ 600,00	€ 600,00	€ 600,00	€ 600,00	€ 600,00	€ 600,00	€ 600,00	€ 600,00	€ 600,00	€ 600,00	€ 600,00	€ 600,00
Plastering 600 m^2	€ 33.000,00	€ -	€ 33.000,00	€ -	€ 33.561,00	€ -	€ 34.650,00	€ -	€ 34.650,00	€ -	€ 33.660,00	€ -	€ 33.660,00	€ -	€ 33.000,00	€ -
Applying gel	€ 9.000,00	€ 9.000,00	€ 9.000,00	€ 9.000,00	€ 9.000,00	€ 9.000,00	€ 9.000,00	€ 9.000,00	€ 9.000,00	€ 9.000,00	€ 9.000,00	€ 9.000,00	€ 9.000,00	€ 9.000,00	€ 9.000,00	€ 9.000,00
Installing irrigation: reservoir, pump & plumbing	€ 6.325,86	€ 6.325,86	€ 4.578,28	€ 4.578,28	€ 5.142,22	€ 5.142,22	€ 3.759,95	€ 3.759,95	€ 6.325,86	€ 6.325,86	€ 3.759,95	€ 3.759,95	€ 6.325,86	€ 6.325,86	€ 5.168,89	€ 5.168,89
Sub total labour costs	€ 51.925,86	€ 18.925,86	€ 50.178,28	€ 17.178,28	€ 51.303,22	€ 17.742,22	€ 51.009,95	€ 16.359,95	€ 53.575,86	€ 18.925,86	€ 50.019,95	€ 16.359,95	€ 52.585,86	€ 18.925,86	€ 50.768,89	€ 17.768,89
Total variable costs	€ 65.476,87	€ 71.476,87	€ 62.637,79	€ 68.637,79	€ 64.114,95	€ 69.553,95	€ 62.958,34	€ 67.308,34	€ 67.126,87	€ 71.476,87	€ 61.968,34	€ 67.308,34	€ 66.136,87	€ 71.476,87	€ 63.597,28	€ 69.597,28

APPENDIX F – PROFILE LCA

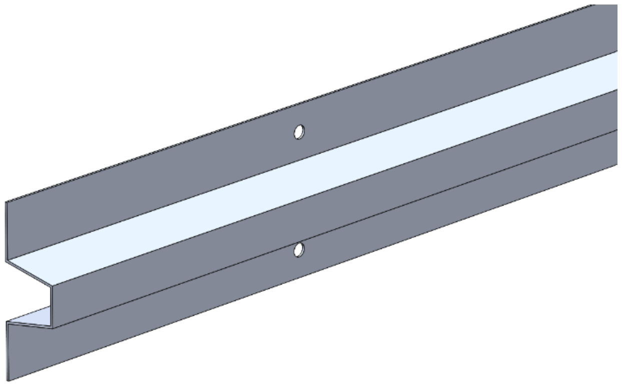


Figure 62: A Solidworks model of the profile.

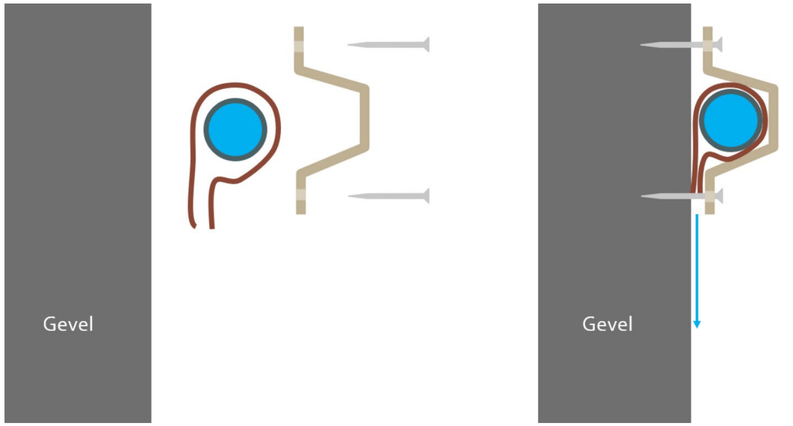
The LCA of the profile (Figure 62) is based on the following assumptions:

- The profile's mass is calculated from its volume, which is derived from its Solidworks model, and from its material density.
- Material thickness influences the mass:
    - The aluminium is 1 mm thick. The prototype consists of a 1 mm thick aluminium profile, which works fine.
    - The zinc's thickness is extrapolated from aluminium based on yield strength. The profile must not break; zinc's higher yield strength allows to make a thinner profile. The resulting material thickness is 0,75 mm.
    - The ABS is 2,5 mm thick, based on a standard polymer extrusion profile with the desired properties.
    - The thickness of PC, PVC, and PP is extrapolated based on yield strength, resulting in material thicknesses of 1,7 mm, 2,5 mm, and 4 mm respectively.
- The profile's length is 1 m. This is not the advised profile length, but for this comparison 1 m is chosen.
- The profile is extruded.
- The lifespan is one year. Reuse is possible and some materials might have a longer lifespan than others, resulting in a lower impact per functional unit. However, considering this product has not yet been tested in the field, we cannot assume it will be reused. After the first year, the profile likely needs some adjustments, making the first batch useless.
- The materials can be recycled at the end-of-life. Default recycling credits from the Idemat 2023 database are used.

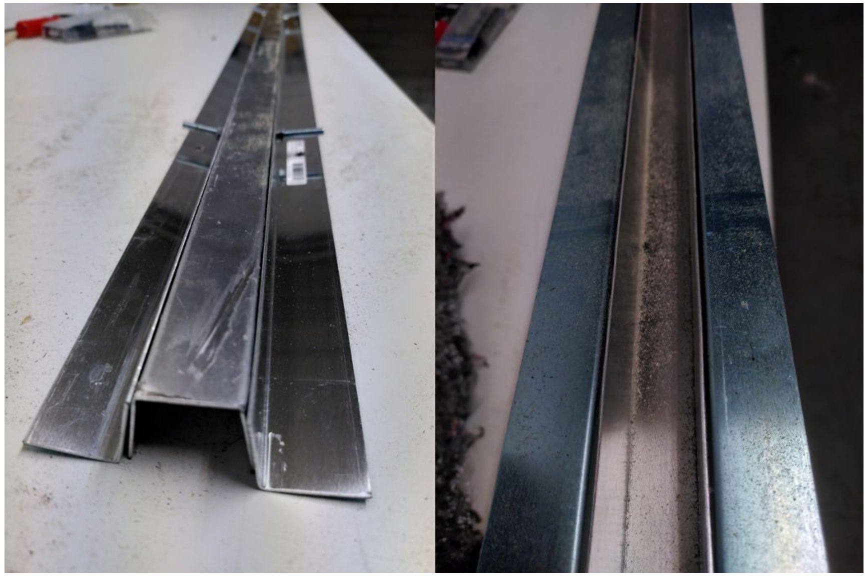
Material properties are based on Ansys GRANTA EduPack software (ANSYS, Inc., 2022). Impact data is based on the Idemat dataset (Idemat, 2023).

APPENDIX G – INSTALLERS’ FEEDBACK

The availability of installers was very limited, it was not possible to install the prototype together with them. Instead, the installation process is explained to them in photos and text. The following pictures and text are what was shared with them.



“The design consists of a soaker hose, with a growing mat wrapped around it. This together with an omega profile is pressed against the façade and fixed with screws. See cross section above (red = mat, yellow = profile).” – This figure was shared with one the installers, who was less familiar with Respyre’s old system.



“The system uses an omega profile. I made one using 3 separate profiles but it will be one profile in the end.”

“The growing mat is placed in the profile. The soaker hose is placed in there. Fold the mat.”

"The whole thing is screwed into the façade. In this case I used a mat that was way too big, but this can be ordered with a custom size. The profile is supposed to clamp around the soaker hose + mat, so they won't fall out while screwing the profile to the wall."

BIBLIOGRAPHY

Aceto, M., Abollino, O., Conca, R., Malandrino, M., Mentasti, E., & Sarzanini, C. (2003, January). The use of mosses as environmental metal pollution indicators. *Chemosphere*, *50*, 333–342. https://doi.org/10.1016/s0045-6535(02)00533-7

Ahrens, G. (2022, July). A closer look at French drains & how they compare with other methods - Armored Basement Waterproofing, LLC. *A closer look at French drains & how they compare with other methods - Armored Basement Waterproofing, LLC.* https://armoredbasement.com/a-closer-look-at-french-drains-how-they-compare-with-other-methods/

Akbari, H., & Rose, L. S. (2008, January). Urban surfaces and heat island mitigation potentials. *Journal of the human-environment system*, *11*, 85–101. https://doi.org/10.1618/jhes.11.85

Aktacir, M. A., Büyükalaca, O., & Yılmaz, T. (2010, February). A case study for influence of building thermal insulation on cooling load and air-conditioning system in the hot and humid regions. *Applied Energy*, *87*, 599–607. https://doi.org/10.1016/j.apenergy.2009.05.008

Alpert, P., Oliver, M. J., Black, M., & Pritchard, H. W. (2002, January). *Drying without dying.* https://doi.org/10.1079/9780851995342.0003

Ambius. (n.d.). How green walls work: Irrigation. *How green walls work: Irrigation.* https://www.ambius.com/plant-design/green-walls/irrigation

Anderson, A. (2023, June). Know a fire sprinkler, like a boss – Part 2. *Know a fire sprinkler, like a boss – Part 2.* https://www.warrenforensics.com/2023/01/09/know-a-fire-sprinkler-like-a-boss-part-2/

ANSYS, Inc. (2022). Ansys GRANTA EduPack software. *Ansys GRANTA EduPack software.* www.ansys.com/materials

Armitage, H. F., Britton, A. J., Van Der Wal, R., Pearce, I., Thompson, D. B., & Woodin, S. J. (2011, July). Nitrogen deposition enhances moss growth, but leads to an overall decline in habitat condition of mountain moss-sedge heath. *Global Change Biology*, *18*, 290–300. https://doi.org/10.1111/j.1365-2486.2011.02493.x

Atlas Leefomgeving. (2023, February). Stedelijk hitte-eiland effect (UHI). *Stedelijk hitte-eiland effect (UHI).* https://www.atlasleefomgeving.nl/stedelijk-hitte-eiland-effect-uhi

Bartok, J. (2016, October). Sprayers and spray application techniques. *Sprayers and spray application techniques.* https://ag.umass.edu/greenhouse-floriculture/fact-sheets/sprayers-spray-application-techniques

Berekenhet.nl. (n.d.). Inflatie berekening. *Inflatie berekening.* https://www.berekenhet.nl/modules/beleggen/inflatie.html#calctop

BETE Fog Nozzle. (2006). Flue gas desulphurization. *Flue gas desulphurization.* https://www.bete.com/PDFs/BETE_FGD_Techmanual.pdf

BETE Fog Nozzle. (2020). Spray nozzles, fabrications, and engineered systems. *Spray nozzles, fabrications, and engineered systems.* https://bete.com/wp-content/uploads/2022/01/BETE_0320_Metric_Catalog.pdf

Bowker, M. A., Doherty, K. D., Grover, H. S., Antoninka, A., Durham, R. A., & Ramsey, P. W. (2023, June). Moss establishment in restoration: The role of moss production method and short-term benefits of abscisic acid. *Land Degradation & Development*, *34*, 4320–4327. https://doi.org/10.1002/ldr.4779

Consultancy.nl. (2023, November). Nederlands consortium zet in op meer kunststofrecycling in de bouw. https://www.consultancy.nl/nieuws/50135/nederlands-consortium-zet-in-op-meer-kunststofrecycling-in-de-bouw

De Munck, C., Pigeon, G., Masson, V., Meunier, F., Bousquet, P., Tréméac, B., Merchat, M., Poeuf, P., & Marchadier, C. (2012, January). How much can air conditioning increase air temperatures for a city like Paris, France? *International Journal of Climatology*, *33*, 210–227. https://doi.org/10.1002/joc.3415

El-Salam, M. H. (2003). *Membrane techniques | applications of reverse osmosis* (2 ed.). Academic Press. https://doi.org/10.1016/b0-12-227055-x/00762-8

Florafelt Living Wall Systems. (n.d.). *Recirculating irrigation for living walls*. Retrieved January 2, 2024, from https://www.plantsonwalls.com/guides/recirculating-irrigation-living-walls/

Fritz, C., Lamers, L. P., Riaz, M., Van Den Berg, L. J., & Elzenga, J. T. (2014, January). Sphagnum Mosses - Masters of Efficient N-Uptake while Avoiding Intoxication. *PLOS ONE*, *9*, e79991. https://doi.org/10.1371/journal.pone.0079991

Furness, S. B., & Grime, J. P. (1982, July). Growth Rate and Temperature Responses in Bryophytes: II. A Comparative study of species of contrasted Ecology. *Journal of Ecology*, *70*, 525. https://doi.org/10.2307/2259920

Gemeente Amsterdam. (2023, September). *Begroting 2024*. Gemeente Amsterdam. https://www.amsterdam.nl/bestuur-organisatie/financien/begroting-2024/

Gemeente Rotterdam. (2023, July). Je kunt subsidie krijgen! *Je kunt subsidie krijgen!* https://rotterdamsweerwoord.nl/wie-betaalt-wat/

Gemeente Rotterdam. (n.d.). *Financiën*. https://watdoetdegemeente.rotterdam.nl/begroting2023/programmas/stedelijke-ontwikkeling2/7-financien/

Goffinet, B. (2008, October). *Bryophyte Biology*. Cambridge University Press.

Gong, G. Y., Kang, J. S., Jeong, K. J., Jeong, J. H., & Yun, J. G. (2019, February). Effect of several native moss plants on particulate matter, volatile organic compounds and air composition. *Journal of people, plants, and environment*, *22*, 31–38. https://doi.org/10.11628/ksppe.2019.22.1.031

Grimmond, S. (2007, March). Urbanization and Global Environmental Change: Local Effects of Urban Warming. *The Geographical Journal*, *173*, 83–88. http://www.jstor.org/stable/30113496

Hashemi, N., Fayaz, R., & Sarshar, M. (2010, October). Thermal behaviour of a ventilated double skin facade in hot arid climate. *Energy and Buildings*, *42*, 1823–1832. https://doi.org/10.1016/j.enbuild.2010.05.019

Haynes, A., Popek, R., Boles, M., Paton-Walsh, C., & Robinson, S. A. (2019, April). Roadside Moss Turfs in South East Australia Capture More Particulate Matter Along an Urban Gradient than a Common Native Tree Species. *Atmosphere*, *10*, 224. https://doi.org/10.3390/atmos10040224

Heidt, V., & Neef, M. (2008). *Benefits of urban green space for improving urban climate.* New York: Springer. https://doi.org/10.1007/978-0-387-71425-7{_6

Helmers, M. J., Isenhart, T. M., Dosskey, M. G., Dabney, S. M., & Strock, J. S. (2008, January). Buffers and Vegetative Filter Strips. *Final Report: Gulf Hypoxia and Local Water Quality Concerns Workshop*. https://doi.org/10.13031/2013.24243

Hendrawan, Y., & Murase, H. (2008, January). Water irrigation control for Sunagoke Moss using intelligent image analysis. *IFAC Proceedings Volumes*, *41*, 2956–2961. https://doi.org/10.3182/20080706-5-kr-1001.00497

HOERBIGER Motion Control GmbH. (n.d.). Piezoelectric ultrasonic atomizer. *Piezoelectric ultrasonic atomizer*. https://www.piezoproducts.com/products-solutions/ultrasonic-atomizers/

Idemat. (2023). *Idemat*. Stichting Sustainability Impact Metrics. https://www.ecocostsvalue.com/data-tools-books/

Irritech. (n.d.). *Drainagebuis kokos*. https://irritech.nl/drainage-kokos/

Ketav Consultant. (n.d.). *Cascade Aerator*. https://ketavconsultant.com/cascade-aerator/

Lee, A., & Maheswaran, R. (2010, September). The health benefits of urban green spaces: a review of the evidence. *Journal of Public Health*, *33*, 212–222. https://doi.org/10.1093/pubmed/fdq068

Metaalwinkel. (n.d.-a). *Aluminium L-profiel*. https://www.metaalwinkelonline.nl/aluminium-l-profiel.html

Metaalwinkel. (n.d.-b). *Aluminium matrijzen*. https://metaalwinkel-metalen.nl/aluminium_matrijzen.1.kw

Metaalwinkel. (n.d.-c). *Zink L-profiel (uit plaat gezet)*. https://www.metaalwinkelonline.nl/zink-l-profiel.html

Metaalwinkel. (n.d.-d). *Zoekresultaten voor: 'omega profiel'*. https://www.metaalwinkelonline.nl/catalogsearch/result/?q=omega+profiel

Michigan State University. (n.d.). *Silvery Thread Moss*. https://www.canr.msu.edu/ipm/diseases/silvery-thread-moss

Mohajerani, A., Bakaric, J., & Jeffrey-Bailey, T. (2017, July). The urban heat island effect, its causes, and mitigation, with reference to the thermal properties of asphalt concrete. *Journal of Environmental Management*, *197*, 522–538. https://doi.org/10.1016/j.jenvman.2017.03.095

Mwendwa, P., & Giliba, R. A. (2012, March). Benefits and challenges of urban green spaces. *Chinese Journal of Population Resources and Environment*, *10*, 73–79. https://doi.org/10.1080/10042857.2012.10685062

Myers, V. R. (2019, October). What is a dripline? *What is a dripline?* https://www.thespruce.com/dripline-3269491

National Academies of Sciences, Engineering, and Medicine. (2020). *Strategies for Legionella Control and Their Application in Building Water Systems*. Washington (DC): The National Academies Press. https://doi.org/10.17226/25474

Niachou, A., Papakonstantinou, K., Santamouris, M., Tsangrassoulis, A., & Mihalakakou, G. (2001, September). Analysis of the green roof thermal properties and investigation of its energy performance. *Energy and Buildings*, *33*, 719–729. https://doi.org/10.1016/s0378-7788(01)00062-7

Overheid.nl. (2023, May). Drinkwaterwet. *Drinkwaterwet*. https://wetten.overheid.nl/BWBR0026338/2023-05-05/0

Pepper, I. L., & Gerba, C. P. (2018, August). Risk of infection from Legionella associated with spray irrigation of reclaimed water. *Water Research*, *139*, 101–107. https://doi.org/10.1016/j.watres.2018.04.001

Proctor, M. (2008, October). *Physiological ecology* (2 ed.). Cambridge University Press.

Proctor, M. C. (1990, September). The physiological basis of bryophyte production. *Botanical Journal of the Linnean Society*, *104*, 61–77. https://doi.org/10.1111/j.1095-8339.1990.tb02211.x

PWN. (n.d.). *Waterbeluchting*. https://www.pwn.nl/api/cms/files/styles/large/public/beluchting_van_het_water_in_waterfabriek_heemskerk_0.jpg?itok=LzPqklAF

Raudenbush, Z., Keeley, S. J., & Basel, M. T. (2016, February). Effect of irrigation water pH and acidifying source on silvery-thread moss (Bryum argenteum Hedw.) establishment. *The Bryologist*, *119*, 1. https://doi.org/10.1639/0007-2745-119.1.001

Rijksdienst voor ondernemend Nederland. (2013, March). Menukaart Hitte in de gebouwde omgeving. *Menukaart Hitte in de gebouwde omgeving*. https://infographics.rvo.nl/klimaatadaptatie/menukaart-hitte/

Rijksoverheid. (2021, December). Taken van een waterschap. *Taken van een waterschap*. https://www.rijksoverheid.nl/onderwerpen/waterschappen/taken-waterschap

RWBNL B.V. (2021, September). Hydroblob Kopen - Voor zowel particulieren als professionals. *Hydroblob Kopen - Voor zowel particulieren als professionals*. https://www.regenwaterbuffer.nl/hydroblob/

Semananda, N. P., Ward, J., & Myers, B. (2018, September). A Semi-Systematic Review of Capillary Irrigation: the benefits, Limitations, and opportunities. *Horticulturae*, *4*, 23. https://doi.org/10.3390/horticulturae4030023

Sindayihebura, D., Cousin, J., & Dumouchel, C. (1997, April). Experimental and theoretical study of sprays produced by ultrasonic atomisers. *Particle & Particle Systems Characterization*, *14*, 93–101. https://doi.org/10.1002/ppsc.199700018

Stache, E., Schilperoort, B., Ottelé, M., & Jonkers, H. M. (2022, April). Comparative analysis in thermal behaviour of common urban building materials and vegetation and consequences for urban heat island effect. *Building and Environment*, *213*, 108489. https://doi.org/10.1016/j.buildenv.2021.108489

Stone, B., Hess, J., & Frumkin, H. (2010, October). Urban form and extreme heat events: Are sprawling cities more vulnerable to climate change than compact cities? *Environmental Health Perspectives*, *118*, 1425–1428. https://doi.org/10.1289/ehp.0901879

U.S. Department of Health & Human Services. (2022). Water treatment. *Water treatment*. https://www.cdc.gov/healthywater/drinking/public/water_treatment.html

Ultrasafe Fire Suppression. (n.d.). *How fire sprinklers work*. https://www.ultrasafe.org.uk/wp-content/uploads/2020/10/How-a-Fire-Sprinkler-Works-Guide-V2.pdf

Urban Greening. (2013). UK Guide to Green Walls. https://www.urbangreening.info/_files/ugd/c0a820_877fc4a9e779472c53296c58fdfb8d20.pdf

Varela, Z., Real, C., Branquinho, C., Paço, T. A., & De Carvalho, R. C. (2021, November). Optimising artificial moss growth for environmental studies in the Mediterranean area. *Plants*, *10*, 2523. https://doi.org/10.3390/plants10112523

Wallender, L. (2022, December). 12 DIY yard drainage Methods. *12 DIY yard drainage Methods*. https://www.thespruce.com/diy-yard-drainage-methods-5080419

Waterwall Park. (n.d.). https://uptown-houston.com/experience/parks/waterwall-park/

Whitmore, L. F. (2000). *Electrostatic charging and novel applications of atomised liquids.* University of Southampton.

Wildkamp. (n.d.). Drainagebuis. *Drainagebuis*. https://www.wildkamp.nl/product/drainagebuis-pe-pp-450-m-omhulling-60-mm-l-50-m/15184000%3Bpgid=iOm4XryJnQg000rkOjYptvf10000NvjqVx3h%3Bsid=ZYWGYh8iwqpXZHkISzOAXxUo-zVKr4GSqUhaV3Vu-zVKrw==

Williams, K., Lee, E., Sargent, L. D., Johnson, K. A., Rayner, J. P., Farrell, C., Miller, R., & Williams, N. S. (2019, August). Appraising the psychological benefits of green roofs for city residents and workers. *Urban Forestry & Urban Greening*, *44*, 126399. https://doi.org/10.1016/j.ufug.2019.126399

Yang, L., Qian, F., Song, D. X., & Zheng, K. J. (2016, January). Research on Urban Heat-Island Effect. *Procedia Engineering*, *169*, 11–18. https://doi.org/10.1016/j.proeng.2016.10.002

Zander, J. (2022, July). Close up of a soaker hose. *Close up of a soaker hose*. https://thisgardener.com/wp-content/uploads/2020/12/How-To-Set-Up-A-Soaker-Hose-System-Easily-2-1024x770.jpg?ezimgfmt=ng:webp/ngcb1

Zechmeister, H. G., Möslinger, L., Korjenić, A., Streit, E., Sulejmanovski, A., Frank, P. N., & Hummel, E. (2023, November). Viability of living moss for indoor green walls: A study on temperature, humidity, and irrigation. *Sustainability*, *15*, 15625. https://doi.org/10.3390/su152115625

Zetwerkprofiel.nl. (n.d.). *Bestellen*. https://shop.zetwerkprofiel.nl/bestellen