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Modularity of living wall systems

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Modularity of Living Wall Systems

Masters Thesis

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PREFACE

This Thesis is the product of a graduation project in the department of Building Technology within the faculty of Architecture and the Built Environment of the Delft University of Technology. This Thesis contains a literature research of the concept of modularity as well as research of living wall systems. An analysis has been conducted of eight different living wall systems. This research will unfold itself into a new design for a living wall system. It should be noted that the analysis of the living wall systems (chapter 6 of this Thesis) was conducted along with M.A.J. Kok, BSc., BBA. The author would like to express his sincere gratitude to her.

The author would also like to express his gratitude to the supervisors of this graduation project: Prof.dr.ir. A.A.J.F. van den Dobbelsteen, Dr. ir. M. Ottelé, Ir. A.M. Bergsma and Dr. N.M. Biloria.

The eight living wall systems that are analyzed in this Thesis are products from eight different companies. Again, the author would like to express his gratitude to the following companies for providing information and insight into their products:

- Copijn
- Green Fortune Nederland B.V.
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- Allface Befestigungs- technologie GmbH & Co KG
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- Rotterdam Science Tower
- Stadsarchief Rotterdam
- Stichting Dakpark Rotterdam
- Tuincentrum Soontiëns
- Wallflore Systems N.V.

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ABSTRACT

Living wall systems are not applied on a large scale, even though they offer multiple benefits to buildings. They are able to improve the air quality, the insulation values or social and psychological benefits. The aim of this Thesis is to increase the application of living wall systems by designing a living wall system with the principles of modularity, which should decrease the two biggest disadvantages of living wall systems: the high production cost and the high amount of maintenance.

To reach this goal it is important to channel both knowledge about modularity and vertical green. For modularity this means understanding the principles: designing with repeating components, designing for prefabrication, designing for disassembly and designing for a catalogue. In the next step various connections are listed which can be used when designing for disassembly, along with types of façades and building references which apply the use of the principles of modularity.

As for vertical green, a clear typology can be seen. Vertical green can be divided into green façades, wall vegetation and living wall systems. Living wall systems can be based on planter boxes, panel systems (of which some use mineral wool) and on felt layers. A history is provided of vertical green, along with a detailed explanation about the advantages and disadvantages of placing of vertical green on a building. All of these advantages are researched to find out if they can be improved with the means of modularity. These advantages are a first step into the world of innovations that could be used when designing a new living wall system, together with an insight into new innovations regarding modularity.

The main research of this report is an analysis of all the living wall systems on the current Dutch market. These systems are explained in their way of working and are separated into components and materials. A conclusion is made about the separability and reusability of the components, as well as the circularity of the materials, along with general data, such as weight, water consumption and lifespan. This information is later used in a Harris profile that defines the type of living wall system that's best for the design requirements. The design requirements have been determined by researching the context of a location where this living wall system can be installed; the Europoint-complex in Rotterdam. The Harris profile makes clear that planter box can best be used due to their low water consumption, high lifespan and their fit for circular design.

In the end a planter box system is designed which can easily be removed from the building skin and replaced by means of modularity, which decreases the maintenance. It has even been adapted so it can be transported by drones, so no persons have to climb up a building. Planter boxes that are recovered from the building can be reused or recycled thanks to the circular design. By designing the system in such a way that it can function as the outer layer of a building, it also decreases the building costs. Finally, the system receives three add-ons, which use innovations to increase the effect certain benefits of living wall systems. These add-ons are part of a design catalogue, which helps the system to be applicable on other locations than the Europoint-complex, depending on the design problems at hand.

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1. INTRODUCTION

Over the years, vertical green has increased in popularity in the building industry. Many architects and building engineers, as well as companies, are aware of the effects of climate change and how to fight these problems within the building industry. Vegetation is one of the many answers that come along with a great deal of benefits, like improving the biodiversity and improving various social and psychological factors. Unfortunately, urban areas do not seem to have enough space to gain from these benefits - unless we start painting the city green by the means of green walls and green roofs.

As soon as the interest in solutions for vegetation in urban areas grew, companies started popping up and they released their ideas for green roofs and green walls onto the public market. The green roof has evolved into a well-known product, and many companies use the same system. But when it comes to vertical green, a lot of companies seem to be divided on what seems to be the ideal solution. After all, many plants do not naturally grow on vertical surfaces. This means that a system should be designed with the best scenario for the plants in mind. Eventually this has led to many different systems for vertical green that are all high in maintenance cost. This seems to be the ultimate reason for vertical green to be implemented so little in the building industry.

This Thesis tries to solve this problem by reviewing the living wall system, the most intensive type of vertical green, from a building engineering perspective. When designing such a system, cost and maintenance could be decreased by using several ideas of modularity. It is also important to review the living wall systems that are currently on the market, so that all of the ideas we currently have about the life of plants on a vertical surface will not go to waste. Lastly we will take into account if this living wall system is able to be a circular design made from circular materials, so that the living wall system becomes a green product itself.

2. RESEARCH OUTLINE

2.1 Background and relevance

2.1.1 Designing with modularity

Designing with modular elements is the response of modern architecture to the mass production of commercial products. Whenever a building requires many repetitive elements that are exactly the same, it could benefit from a modular design. Modular elements could be created in a factory setting, which would increase their quality and reduce their production time and cost. When they are designed to be easily disassembled, broken elements can easily be replaced and materials can easily be recycled. These are all factors that are currently important issues for green façades and living wall systems.

Although green façades and living wall systems are developed as modular elements, they cope with problem such as high costs, maintenance to elements and they improve the sustainability of the elements. By making modularity play a bigger part in the design process of a green façade or a living wall system, these problems could be resolved, which would lead to a bigger and better implementation of green façades and living wall systems.

2.1.2 Popularity of living wall systems

Green façades have been around for a long time, and thanks to the benefits green façades have to offer they have become more popular in the last few decades. A green façade or living wall system can improve air quality, it can provide shading to a building and increase the biodiversity, just to name a few benefits (Peck & Callaghan, 1999). Slowly, green façades have developed into living wall systems which are suitable for a wider range of plant species than green façades and are better in addressing the function of green walls (Mir, 2011). However, living wall systems are not implemented in the building industry on a large scale. This is mostly due to the lack of implementation guidelines and incentive programs (Köhler, 2008). Furthermore, living wall systems are not as well-known as green roofs, even though they offer similar benefits (Köhler, 2008).Green façades and living wall systems even offer a few advantages over green roofs, for example; buildings in general have a bigger façade area than roof area (Salejova, 2015). Another benefit of green façades is that greenery can be seen from street level, which is not always the case with green roofs. Knowing all of these benefits, it has become clear that living wall systems are not used to their full potential.

There are various options to make the living wall system more popular for use within the world of building design. Firstly, more value could be added to a living wall system by adding more functions that have a positive effect on the users and/or the environment. Another solution would be the removal or decrease of one or more of the disadvantages of living wall systems, like the cost, weight or maintenance. A third option would be to make the living wall system more accessible to design by offering a living wall system that can be easily adapted for a certain function, location and/or aesthetic. These become an easy-to-implement solution for certain architectural design processes. These last two solutions can be reflected in a modular living wall system, which will be the further focus of this Thesis.

2.1.3 Implementation in vacant utility buildings

The modular living wall systems will be implemented on the existing vacant utility buildings. Three quarters of the dwellings in 2050 are buildings that exist today (Ravetz, 2008). Over 90% of this stock of existing buildings is affected by energy performance requirements (European Climate Foundation, 2013). Possible solutions to this are to refurbish or to reskin these buildings. For this reason a modular living wall system should be designed with these existing buildings in mind.

The utility sector accounts for 25% of the total building stock in Europe when looking at the floor area(Economidou, 2011). In Holland alone, 6.74 million square meters of entirely occupied work space exists in high-rise towers as of 2011 (Designersparty, 2011). This is why a vacant high-rise office building will be chosen as the context for designing this modular living wall system.

2.1.4 Design for disassembly using compostable or recyclable materials

Since the implementation of a living wall system should be seen as a sustainable solution, the design of a modular living wall system should take sustainability into account. One way of doing this is by making sure all the materials of the façade element are retrievable and need to return into a technical or biological cycle once the lifespan of the building or façade element has ended. This means the façade element should be designed while keeping the possibility of disassembly in mind.

2.1.5 Designing with new innovations

Currently there are "modular" living wall systems on the market, but only types in which a singular façade element can be repeated. Most companies offer a singular product that can be used in the entire façade. However, modularity can be much more than that. A different way to view modularity is to offer a single product that can adapt to the design questions by optimizing it for a specific function or location. Secondly, all current living wall systems on the market only seem to function as the outer layer of the façade; there is no fully modular façade system with vertical green. This is what will be the aim of this Thesis. The Thesis starts by researching modularity in façades as well as living wall systems. The next step is to look into new innovations of modular design, as these innovations could be implemented in the design for a modular living wall system.

2.2 Problem statement

Now that the background information and the relevance of a modular system are clear, a proper problem statement can be formulated. This problem statement will clarify the objective of this Thesis.

The main problem statement can be formulated as follows:

Living wall systems aren't implemented on a big scale, even though they offer multiple benefits to both the user as the environment, and can't be easily used on the existing utility sector, due to the lack of a fully modular living wall system façade element.

Possible sub problems include the need for existing buildings to fulfill energy performance requirements and the demand for a sustainable green façade element -which indirectly is a demand for a green façade element that is fully demountable and composed out of recyclable and compostable materials. Taking these problems into account, an objective can be formed.

2.3 Objective

2.3.1 Objectives

The general objective of this Thesis follows from the problem statement. The general objective of this Thesis is as follows:

To design a demountable and fully modular living wall system façade out of recyclable and compostable materials

The sub-objectives are as follows:

- To research the principles of modularity and disassembly
- To research materials used in living wall systems on composability/recyclability
- To research living wall systems currently on the market
- To research new innovations within modularity
- To design a modular living wall system façade element

2.3.2 Final products

To fulfill these objectives, various products will be produced:

- A design for a modular living wall system façade
- A small mock-up of this modular LWS façade design
- A Thesis including:
    - Research on modularity and disassembly
    - Research on LWS
    - System analysis of current available LWS systems and their materials
    - Design explanation

2.3.3 Boundary conditions

Within the design of a modular LWS system, the following boundary conditions will be taking into account:

1. The modular LWS façade will be designed for an existing vacant utility building.
2. The connections between components and between the element and the structure will be taken into account.
3. The main construction of this building will not be taken into account.

2.4 Research questions

By using the problem statement and objective, research questions can be formulated. The main research question of this Thesis goes as follows:

How to design a fully modular living wall system façade for existing utility buildings that can be fully disassembled and which is made out of recyclable and/or compostable materials.

This can be divided into the following sub-questions and background questions:

- What are the principles of modular building?
  - How do typical modular façade elements work?
  - How do connections in modular elements work?
  - How can living wall systems be designed for disassembly?
  - Are there any new innovations in modular building?
- What are the principles of designing with green façades and living wall systems?
  - What types of vertical green currently exist?
  - What are the benefits of green façades and living wall systems?
    - Can these benefits be optimized in a single element?
- What is the current offer in living wall systems on the market and how do they work?
  - What are the important components living walls systems are made of?
  - Are there any demountable living wall systems and how do they work?
  - Which façade building materials are compostable?
  - Which façade building materials are recyclable?

2.5 Approach and methodology

To answer all these research questions, an organized approach is needed, which will be explained in this paragraph.

Firstly, in Chapter 3, this Thesis will look into modularity, explaining the principles of modularity and looking into existing modular façade elements, materials and connections. This explanation is backed up by literature research.

The second step is to look into vertical green, explaining what types of vertical green exist, what benefits they offer and how these benefits could be optimized for modular design. This will be explained in Chapter 4. This explanation will also be backed up by literature research.

Now that the general knowledge is clear, Chapter 5 will looks into innovations regarding modularity, which could be used for design. Literature research helps to aid this process.

The next step is to provide a system analysis. Chapter 6 will display the living wall systems currently on the market and elaborate on how they work. An overview of all the components and materials is compiled to show if these components can be recycled, reused or biodegraded.

Now that the literature and system analysis is complete, the design process can begin in Chapter 7. By drawing, modeling and building, the design will slowly evolve. This will be the final product of the Thesis. The design process will also be evaluated.

3. DESIGNING WITH MODULARITY

3.1 Introduction

A modular design has several advantages. By focusing on a small element that gets implemented on a large scale, it can be easily prefabricated in a factory before it gets installed on-site. This means a shorter construction time, lower costs and more detail of precision in the element. The overall implementation of an element also becomes easier. The better the modular design, the more opportunities it has for implementation. When a modular design is designed for disassembly, it uses the advantage that modular elements can be replaced easily. This is the case with certain living wall systems. Living wall systems are usually modular and demountable, so elements which lose their performance over time can be replaced without much effort.

This chapter will look into modular design by discussing its principles. Once the principles of modularity are clear, several types of connections are researched on their ability to be disassembled. This chapter will look into various types of façades and their relation with modularity. This paragraph explains the research of three buildings with a modular façade, which will function as precedents for the design process. This will give a proper insight on how to design for modularity.

3.2 Definition and principles of modular design

Before starting to design with modularity, the definition and principles of modularity have to be made understandable. This begins with determining the definition of a module:

A module is a basic dimension of a unit from which all other measurements can be derived. (Blanc, 2014)

The term "module" comes from the Latin *modulus*, which means small measure. There is now an internationally agreed basic modular dimension of 100 mm, which means the dimensions of a module should be 100 mm or a multiplication thereof.

Modularity is the degree in which a system's bundle of repeating components, that are produced en masse prior to installation, may be separated and recombined(Baldwin & Clark, 2000; Schilling, 2000).

Through existing literature and the description of modularity, four main principles of designing with modularity have been established. The principles of modular design are as follows:

1. Design with repeating components
2. Design for prefabrication
3. Design for disassembly
4. Design for a catalogue

The principles are in a clear order, meaning that designing with repeating components is more important than designing for a catalogue. This also means a modular design does not necessarily have to stay true to all the principles. When a modular design cannot be disassembled it can still be a modular design. However, to create a modular design with the optimal use of all advantages, all principles need to be applied.

3.2.1 Design with repeating components

Instead of designing a whole façade, one can design a fraction of the façade and extrapolate it over the whole area: this is the main principle of modularity. One single piece of the façade will be designed and repeated of the entire façade area. Within façade design, modularity can be divided into two types: modular façade elements with the load bearing structure integrated and modular elements without the load bearing structure integrated.

Building blocks can be seen as modular façade elements with the load bearing structure integrated. No additional structure is needed to support the modular elements. However, this type of modularity has one big disadvantage. Since all modular elements work together to create a load bearing structure, a single element cannot be removed without the structure collapsing. This problem does not appear with modular elements without the load bearing structure integrated.

Façade modules can also be mounted onto an existing structure. For example, façade panels can be fixated on slabs of the building. The load bearing structure is not integrated within the module, which makes it easy to replace a single element when it is broken.

Figure 1: The Qbiss One modular façade system shows repeating elements. The elements have no integrated load-bearing structure, but hang on steel columns. (Trimo d.d., 2011)

3.2.2 Design for prefabrication

By using one element that keeps repeating itself, the construction time and cost could be reduced while precision could be increased. This is due to the fact that all the modules can be prefabricated. A single module can be repeatedly created inside a factory environment, which could then be transported to the construction site and mounted on the slabs. It is important to take prefabrication into account in the design process to make sure no time-consuming or on-site construction processes, such a pouring concrete, have to be done.

3.2.3 Design for disassembly

Designing for disassembly can take place on multiple scales. If the entire façade can be disassembled without affecting the structure of the building, it offers the possibility for a building to be refurbished. For a modular façade it is important to work on a smaller scale, so that every module can be mounted on the façade and be removed from the façade without destroying any of the components or connections. This way, a single element can be removed, so that it can be replaced when broken. This also makes it possible for modules to be rearranged if there are various types of modules.

3.2.4 Design for a catalogue

It is possible to create a modular façade out of one repeating module, but there is also the possibility of creating a set of different modules that all focus on a specific function. For example, one could design a non-transparent panel as a modular façade element along with a transparent one. The transparent module would only be placed on locations on the façade that need a window. Although these modules differ, they use the same connections as the other modules to attach to the building structure. By offering a variety of modules that work with the same principle, a catalogue of modules can be made. This expands the functionality of the façade and helps a modular façade to act upon a specific design question.

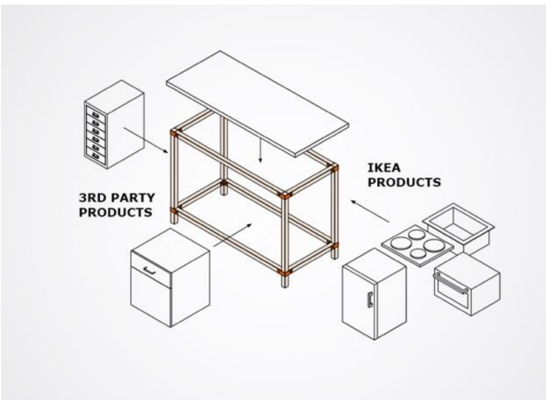


Figure 2 (left): The IKEA HACKA Toolbox is an example of catalogue design

Figure 3 (right): Objects with different functions fit into the same system

3.3 Types of connections

Connections are the most important components to look into when designing for modularity. That is why this paragraph will look into types of connections. Connections can be divided into three types: direct connection using the form and shape of components, indirect connections using extra objects and material connections (Meijs & Knaack, 2010). The use of these types of connections is clear for wood and plastic materials. Steel and concrete connections have some exceptions in the way they work, so this chapter will elaborate on them shortly.

3.3.1 Direct connections using form and shape

This type of connection helps to shape all of the components that need to be connected by removing material, until they fit together. The shapes of the components define how they fit together, just like Lego blocks. Various types of connections that fit under this category are tongue and groove connections and dovetail joints, but many types are possible. These types of connections are easily disassembled, but they do have some disadvantages. The connection might loosen due to components changing in size because of temperature differences. Another problem is that material is removed at the location where the highest stresses appear, making the connection unsuitable for load bearing elements.

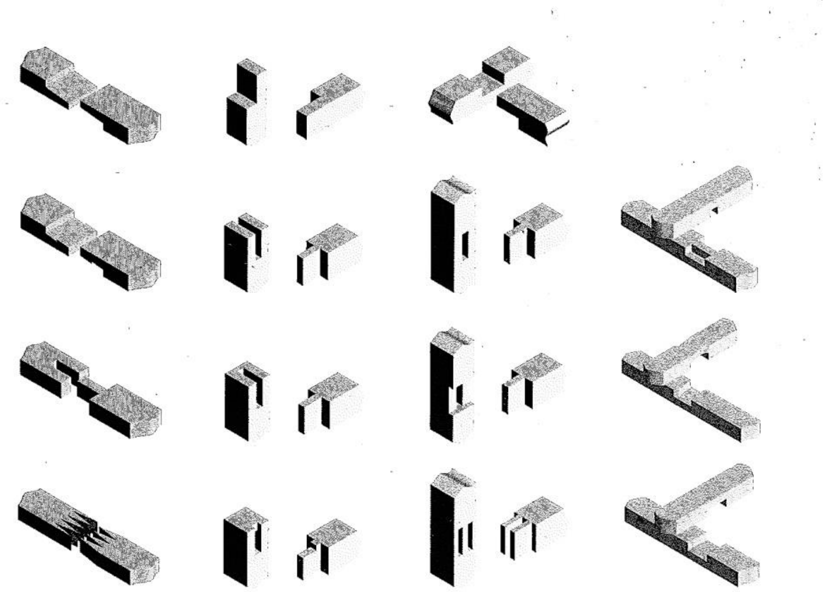


Figure 4: Direct connections (Meijs & Knaack, 2010)

Direct connections using form and shape (bold means generally demountable and reusable):

Birdsmouth joint
Bridle joint
Butt joint
Cross lap
Dado joint
Dovetail joint
Dowel joint
Finger joint
Groove joint
Mitre joint
Mortise and tenon
(Over)lap joint
Splice joint

3.3.2 Indirect connections using objects

Instead of using the shape of a component, an extra object can be used to connect two components, for example by using nails, bolts or hook and loop fasteners. It is possible to disassemble this type of connection, but it does not necessarily have to be done using rivets or staples, for example. Material is removed just like the direct connections, but in lesser quantities. However, this type of connection requires more components in general, which makes it more complex. This also results in more and different kinds of components that have to be removed when disassembling the connection. All these components have to be recycled differently, resulting into more labour.

Indirect connections using objects (bold means generally demountable and reusable):

Anchor Bolt
Batten
Biscuit
Brass fastener
Buckle
Button
Cable tie
Captive fastener
Clamp
Clasp
Clecko
Clip
Clutch
Dowel joint
Drawing pin
Flange
Frog
Grommet
Hook and loop fastener
Hook-and-eye closure
Latch
Nail
Peg
PEM nut
Pin
Retaining ring
Rivet
Rubber band
Screw anchor
Snap fastener
Staple
Stitches
Strap
Threaded fastener
Tie
Toggle bolt
Treasury tag
Twist tie
Wedge anchor
Zipper

Figure 5 (left): Indirect connections (Evans, 2013)

Figure 6 (right): Material connections (Hill, 2013)

3.3.3 Material connections

Material connections directly connect two components by the means of melting two components together or by using adhesives. Large elements with little errors can be made using this technique. However, in most cases, the elements are not demountable. New innovations offer adhesives that lose their connecting power when an electrical current passes through. This technique is not fully implemented yet in the building world and is quite expensive at the moment.

Material connections (bold means generally demountable and reusable):

Adhesives	Cementing	Welding
Brazing	Soldering	

3.3.4 Connections in steel

Direct connections are a possibility in steel connections, usually using the force of gravity to stay in place. Think of hooks in the case of a clothes hanger for example. Much more popular are the indirect connections using nuts and bolts, which can transfer much more stress. Material connections in steel are usually done by welding or soldering, but these types of connections aren't demountable. Welding as much as possible should be dedicated by the factory, since it causes difficulties on site.

3.3.5 Connections in concrete

Concrete connections can be divided into wet connections and dry connections. The dry connections are no different than the connections mentioned before. An example of direct connections could be a concrete block with a Lego block like shape, stacked on top of each other. Within a concrete structure, nuts and bolts can also be used which would be an indirect connection. The steel reinforcement of two concrete components can be welded together to connect them. This can be seen as a material connection, although it does not really connect to the primary material.

Wet connections are perhaps a better example of material connections in concrete. Two concrete components can be attached to each other by pouring concrete between the two components. An additional mold might be needed for this process. In this scenario, the concrete itself can act as the adhesive. However, this type of connection is, just like most of the material connections, non-demountable.

3.3.6 What connections to use for a demountable design?

To create a modular design, demountable joints need to be used to make sure the element can easily be disassembled. The previous chapter makes it clear that this mostly means making use of direct connections using form and shape and indirect connections using objects. The latter is the stronger connection of the two. Material connections will not be demountable and therefore not interesting in a modular design.

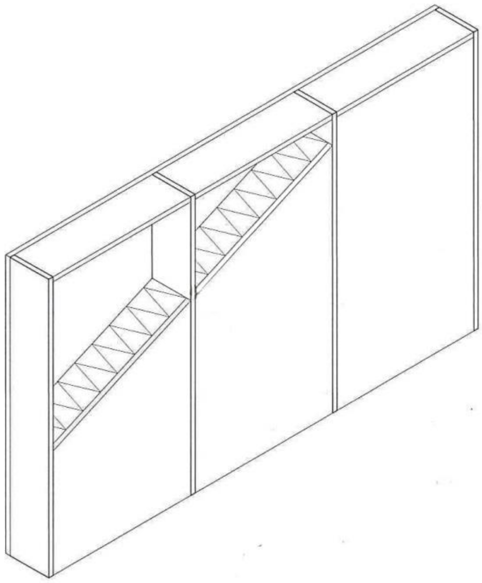
3.4 Types of façades

This paragraph will look into various existing façade types and how they perform within the concept of modularity. By understanding how these façades are constructed, insight is gained on how to constructively design a new façade. This paragraph will also explain some terms that are used when describing the precedents in the next paragraph.

3.4.1 Skeletal structure and balloon frame

One of the oldest methods of constructing a façade that also functions as construction of the building is by means of a skeletal structure. The structural part of the façade is made out of vertical elements, or a skeleton. This skeleton is covered by the façade material. Both the skeleton and the covering material have to be fairly light.

A specific American principle of this type of façade is called the balloon frame. A wooden skeleton made out of vertical components spans two stories. The structure is filled with insulation material and covered with wooden plates. In general, this façade is not a modular façade, since an element cannot be removed without the building collapsing.



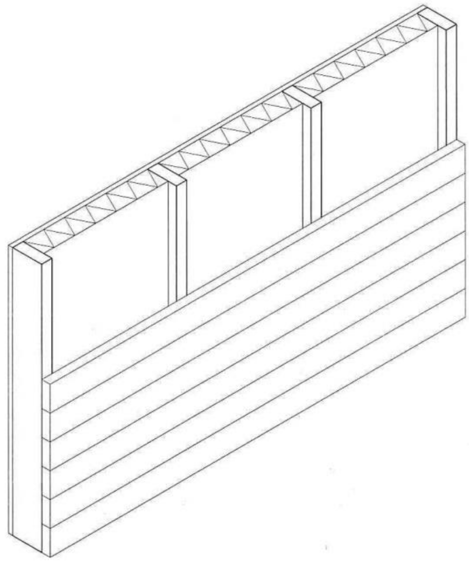


Figure 7: Skeletal structure (left) (Knaack, Klein, Bilow, & Auer, 2014)

Figure 8: Balloon frame (right) (Knaack et al., 2014)

3.4.2 Post-and-beam façade

Over time the construction of a building removed itself as a function of the façade. This led to new ways of building a façade. Façade elements could now cover a single story with vertical components, or posts. These vertical components are then connected with horizontal components, such as beams, to leave rectangular openings. These openings could be covered to close the façade, but inserting windows could also be a possibility. Again this façade type is not usually modular; however, it could be designed as such.

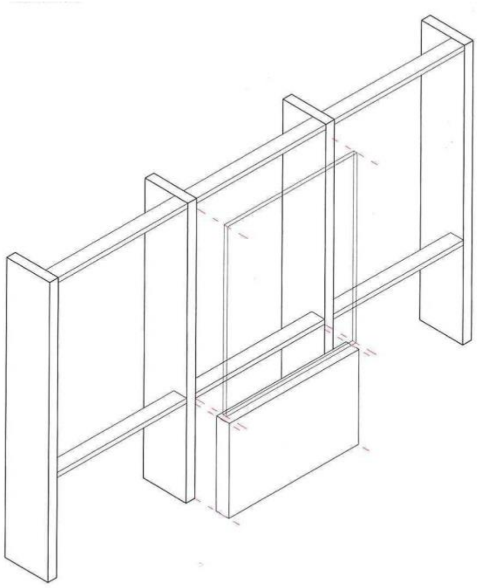
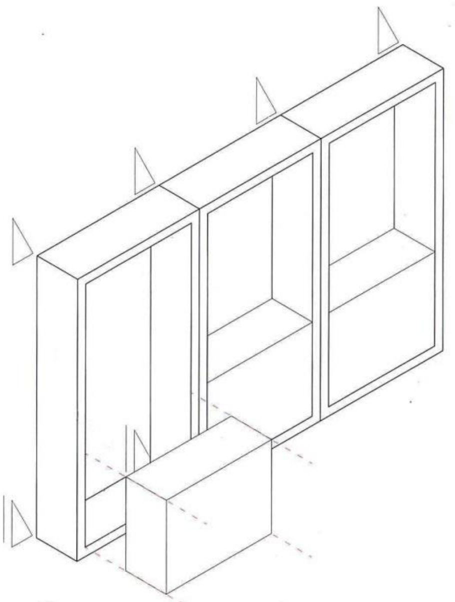


Figure 9: Post-and-beam façade (Knaack et al., 2014)

3.4.3 Curtain wall and systems façade

For more freedom in the façade design, the façade could also hang from the roof or the upper floor, like a curtain. This would be known as a curtain wall. The façade is usually connected to the construction of the building at every floor, so stresses can easily be led to the construction. There is also the possibility of adding special constructing elements so that bigger spans are able to be created.

A specific type of curtain wall is the unit systems façade. This type of façade is made out of repeating modules, which are placed and connected on location. The modules itself are usually prefabricated. This is a primary example of a modular façade.



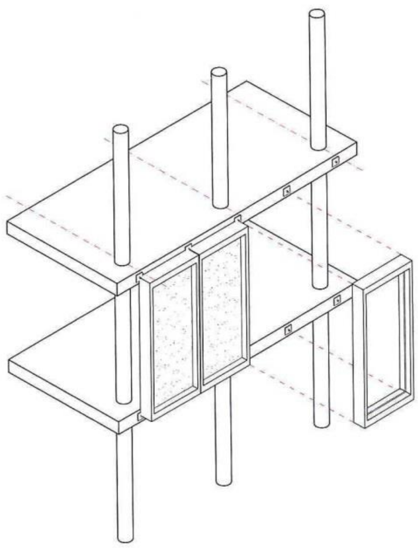


Figure 10: Curtain wall (left) (Knaack et al., 2014)

Figure 11: Systems façade (right) (Knaack et al., 2014)

3.4.4 Double façade

A fairly new development actually suggests moving ventilation from the inside of a building to the façade of the building. This means the façade will receive an extra layer, resulting in a double skin. This has the various advantages for acclimatizing the building, for example, solar heat could heat up the air of a building and also provide sound insulation. There are various types of double skin façades, such as second skin façades, corridor façades, shaft-box façades, hybrid façades and integrated façades, which all differ in the way they acclimatize the air.

3.4.5 Construction

In any scenario in which the façade is not part of the primary construction of the building it should be properly connected to it. There are various ways to do this. A façade element could either be hanging from the upper floors or standing on the lower floors. In both scenarios it is important that the façade element is able to expand due to temperature influences. Illustration 12 shows various options for a secondary construction, which is then connected to the primary construction. This can be done with a secondary structure without posts (a), or without beams (b), a secondary structure with small partitions (c), a secondary structure consisting of lateral tie rods (d), a half-timbered structure (e) and a cable-mesh structure (f).

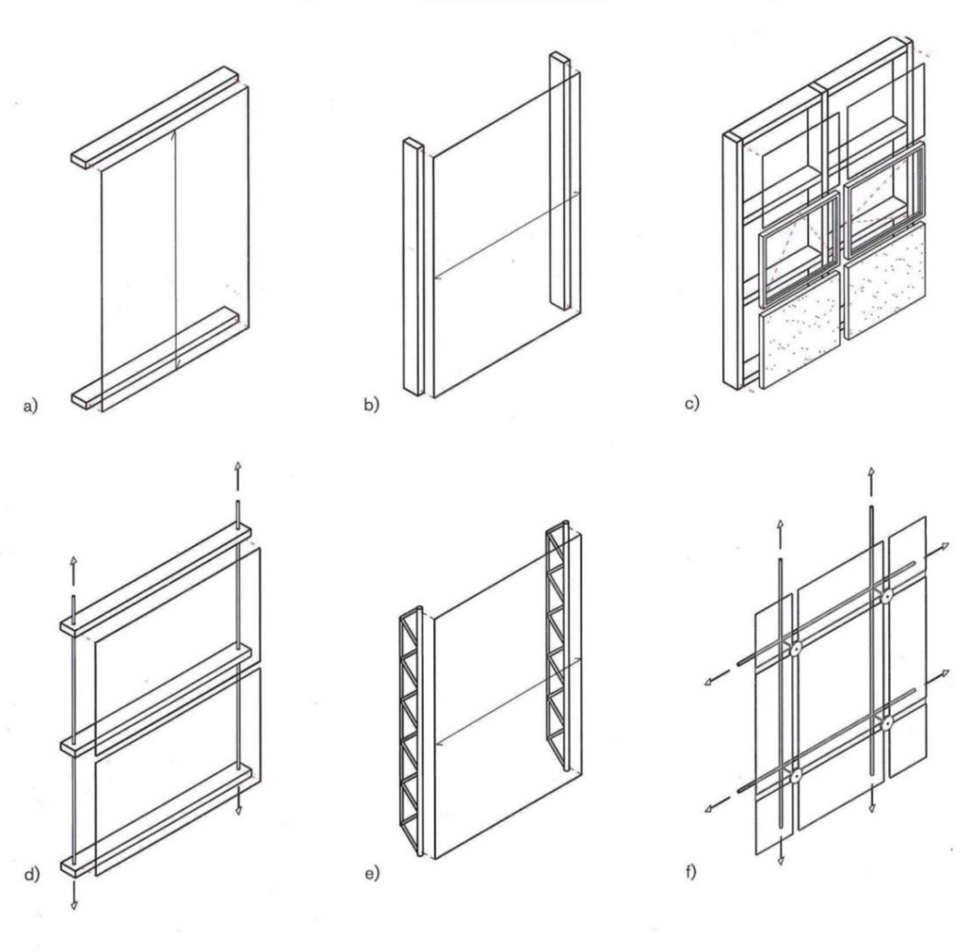


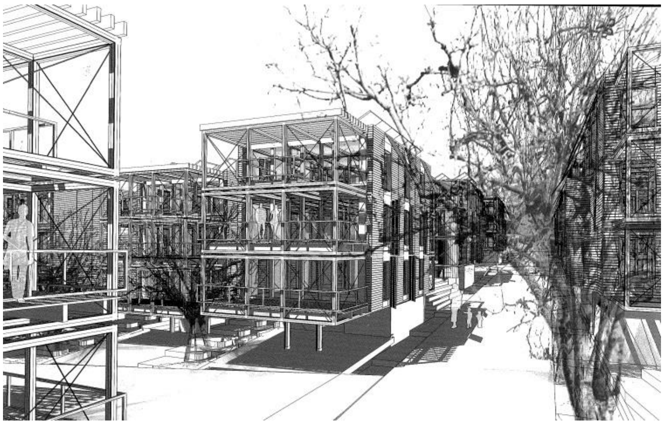
Figure 12: Loadbearing systems (Knaack et al., 2014)

3.5 Research of existing modular façades

To gain insights into modular façades, it is a good idea to research some modular façades of existing buildings. This paragraph will look into the façades of three case studies; the organic urban living field in Charlottesville, the LifeCycle Tower ONE in Dornbirn and the Debitel Headquarters in Stuttgart. When researching these buildings it is not only important to look at the façade element itself, but also how it connects to the structure of the building and how it connects to adjacent elements. Transport and building process are also taken into account.

3.5.1 Organic Urban Living Field

The Organic Urban Living Field is an urban living landscape in Charlottesville, Virginia. The landscape contains modular three story homes for three families. The construction is made out of a steel frame with structural insulated panels (SIP) acting as walls, floors and roofs. Each floor has a construction made out of two halves that can be transported by truck. The halves are bolted together to create a floor. Then they are stacked on top of each other using a crane before all the façade elements are attached. (Anderson & Anderson, 2007)



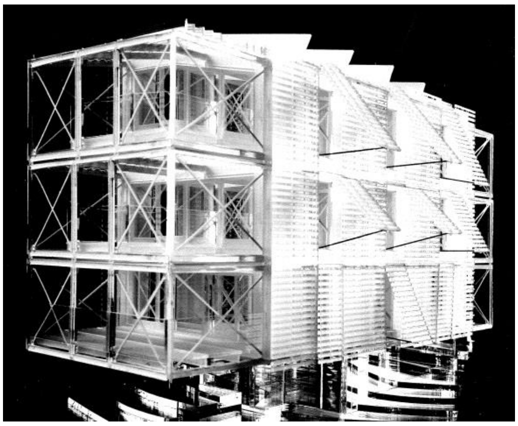


Figure 13 (left): Rendered exterior view (Anderson & Anderson, 2007)

Figure 14 (right): Scale model (Anderson & Anderson, 2007)

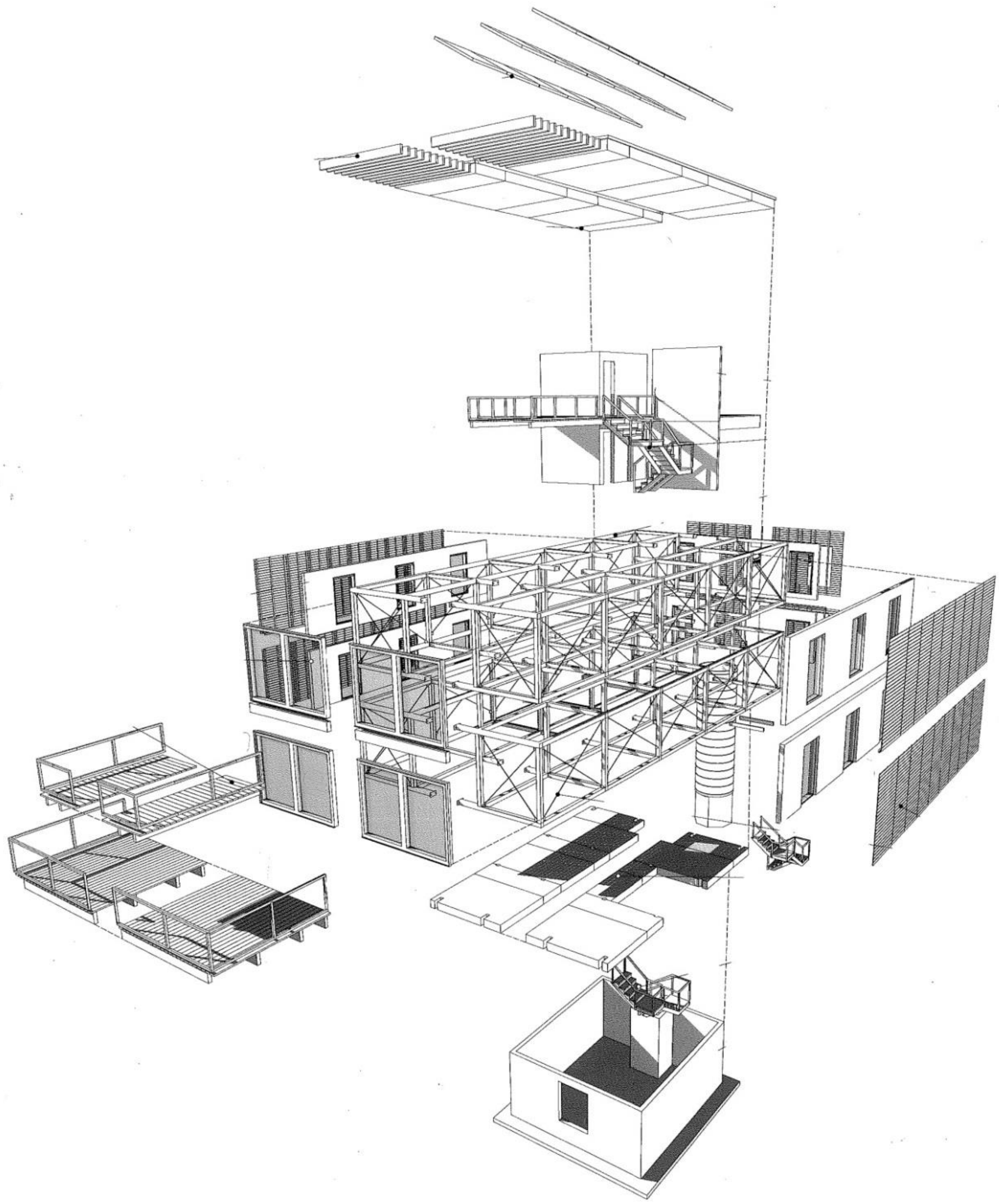
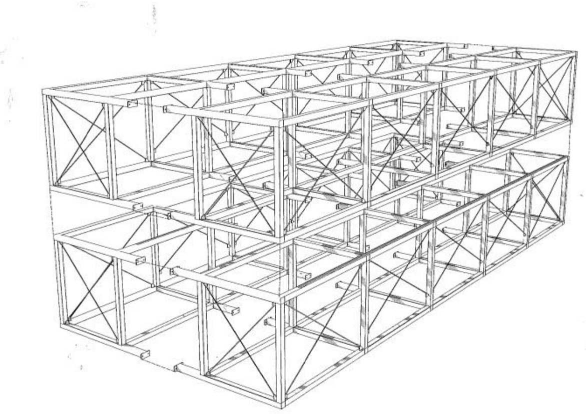


Figure 15: Complete assembly of elements (Anderson & Anderson, 2007)

The structural insulated panels are placed on the steel structure with steel wall spacers in between them. Then they are connected using bolts with a diameter of 0.5 inches. The SIBs could contain windows, but there is also the possibility to cover a steel frame module with a prefabricated window element so that the entire panel is transparent. The SIBs are covered with wooden slat siding supported by a hollow steel tube with a width of 1 inch. The hollow steel tubes are fixed to the SIBs. If the SIB contains a window, it is covered with an operable vertical swinging louvered window shutting system, made out of the same wooden slats.



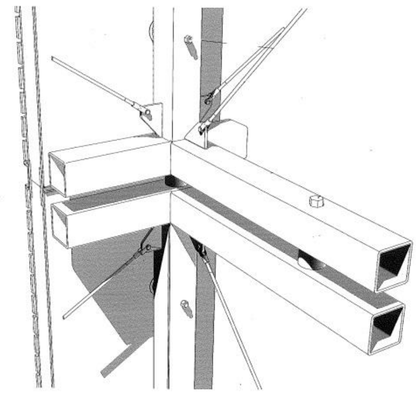
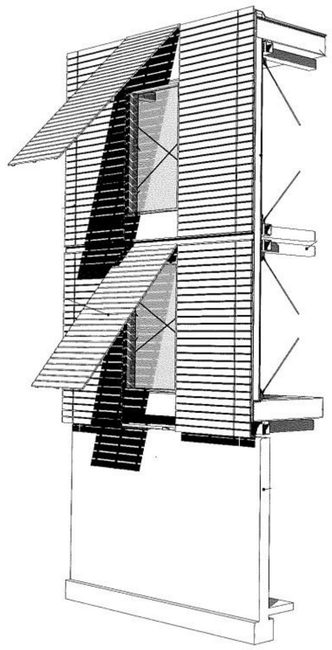


Figure 16 (left): Exploded view of structural frame (Anderson & Anderson, 2007)

Figure 17 (right): Module frame connection detail (Anderson & Anderson, 2007)



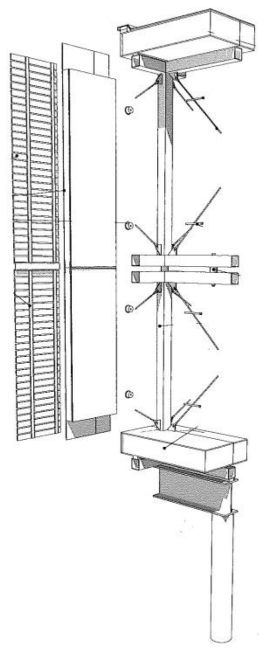


Figure 18 (left): Wall section detail (Anderson & Anderson, 2007)

Figure 19 (right): Exploded view of corner detail (Anderson & Anderson, 2007)

The SIPs are sandwich elements made out of two layers of wood with foam in between, acting as an insulation layer. For openings in the elements, extra wooden framing can be added. The panels fit together using a connection based on shape. There is room on the side of a panel between the layers to fit in wooden strips. These strips are attached with common nails and a sealant, which is not a demountable connection, but this could also work with bolts. The insulation layers between the two panels have a notch for expanded foam sealant.

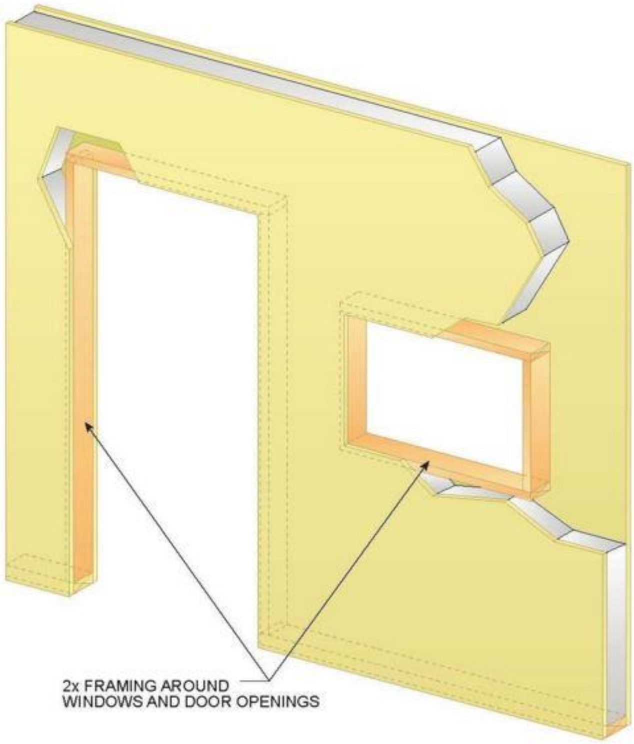


Figure 20: Build-up of a structural insulated panel (SIB) (Structural Insulated Panel Association, 2016)

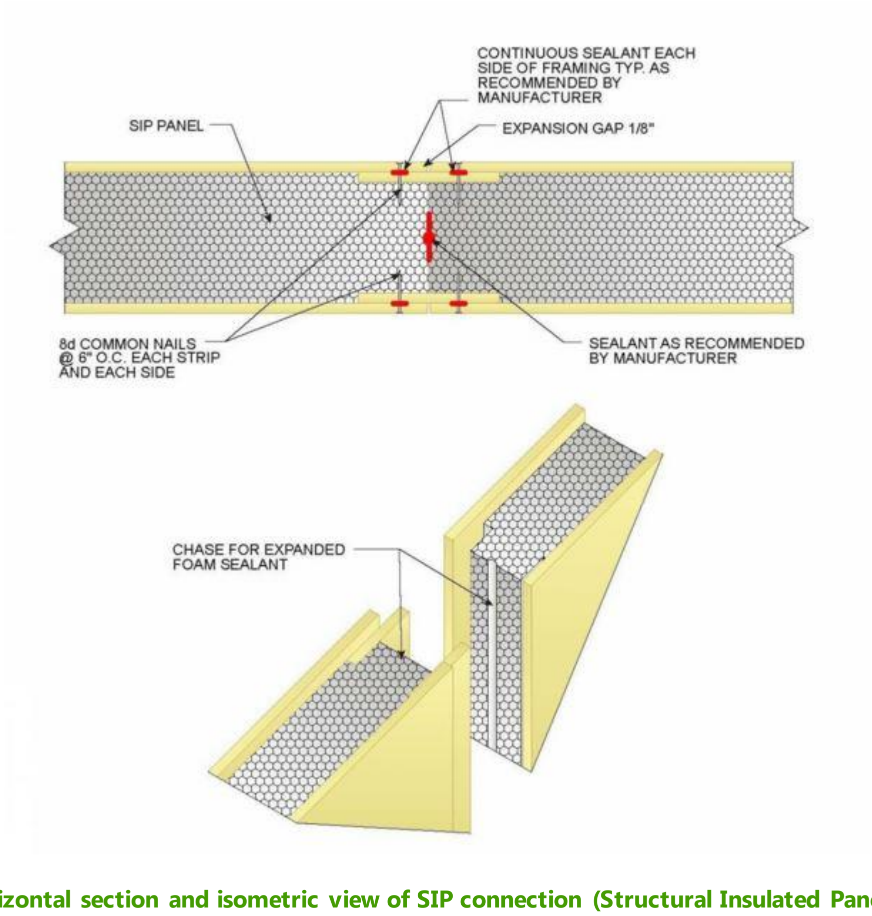


Figure 21: Horizontal section and isometric view of SIP connection (Structural Insulated Panel Association, 2016)

3.5.2 The LifeCycle Tower ONE

The LifeCycle Tower is a prefabricated building system for high-rise buildings that uses a timber based construction. The LifeCycle Tower ONE is a specific building using this system located in Dornbirn, Austria as a research project of the LifeCycle Tower system. The choice for wood was easily made, because it is a renewable resource. The amount of wood used for the main building materials for a 30-story LifeCycle Tower regrows in the United States forests within 3.5 minutes. However, some timber elements are combined with concrete elements for more structural strength, which cannot be recovered when recycling the element.

The building has a total of eight stories. A core that serves as the stiffening element of the building contains technical services such as elevators. It is made out of concrete, but could potentially be made out of wood. The lower stories are built out of conventional reinforced concrete. The floor slabs above the ground floor already contain mounting points for the LCT system. The floors are hybrid slabs made out of timber and concrete. They are connected to the building core on one side and on the outer side they rest on double wooden columns. The hybrid slabs are prevented and the columns from separating through the use of mortise and tenon joints. Curtain wall façade elements are connected to these wooden columns.

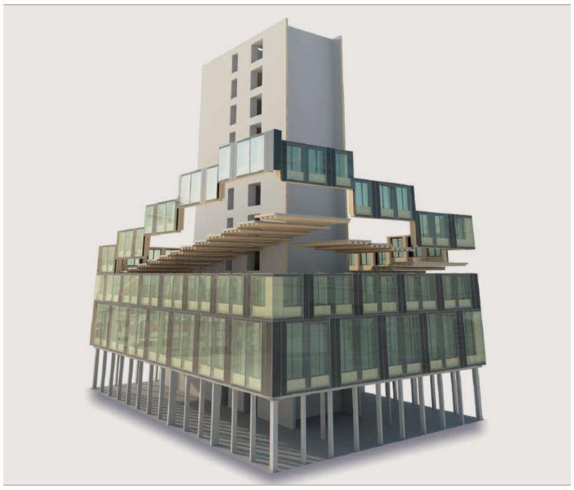


Figure 22: LifeCycle Tower One in Dornbirn (left) (WoodSolutions, 2013)

Figure 23: Construction of the LifeCycle Tower (right) (Cree GmbH, 2010)

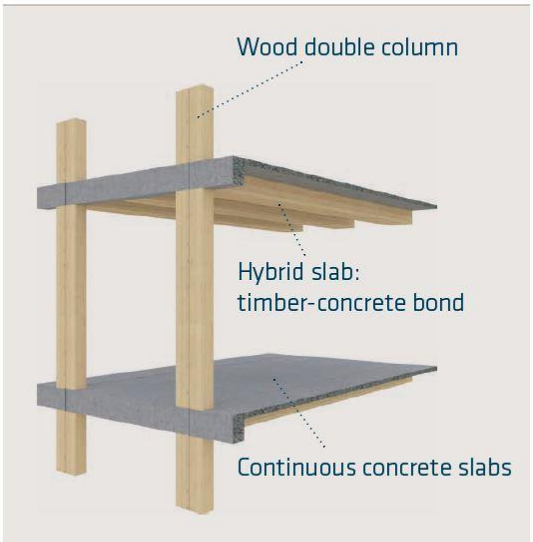


Figure 24: Hybrid slabs resting on wood double columns (left) (Cree GmbH, 2010)

Figure 25: Façade element connected to column (right) (Tahan, 2012)

Figure 26: Placement of hybrid slabs on columns of façade elements (Tahan, 2012)

The curtain wall façade elements for the LifeCycle Tower ONE are simple sandwich elements made out of wood panels and insulation in between. Sections of the façade can be found in appendix A. The elements are one story high and three modules in width, so they can be transported by truck. They include sheathing and windows with taped joints. The wooden columns are already connected to the façade elements, so the façade and floors have to be built from the ground up. This means the façade is load bearing and therefore a single element cannot be removed without taking the building apart. This could be changed by designing the wooden columns with demountable joints, such as bolts, and connecting it to the façade elements.

Figure 27: Façade element being lifted into place (left) (Tahan, 2012)

Figure 28: Façade elements installed on floor (right) (Tahan, 2012)

3.5.3 Debitel Headquarters

The headquarters of the telecommunications company Debitel is a 16 story building connected to a six story building with a glass corridor. The building is located in Stuttgart and is special in the way building services are integrated. For example, the high-rise building has a solar chimney which functions as a natural exhaust for used air, which means the building is able to use natural ventilation.

Figure 29: Debitel Headquarters in Stuttgart (left) (Knaack et al., 2014)

Figure 30: Façade of Debitel Headquarters high-rise (right) (Knaack et al., 2014)

The main building has a façade covered with panels of natural stone, but the façade of the high-rise is made out of system elements to allow a fast and easy assembly. The elements are comprised of alternating box windows and ventilations wings with fixed sun protection. The box windows have internal double glazing and external single glazing in an aluminum load bearing frame with venetian blinds between the glass panes. Each element has a casement on top, which can be opened for cleaning purposes. Above the casements there are steel mounting fixtures in the header area of the façade element, which are attached to the concrete slabs of the building structure.

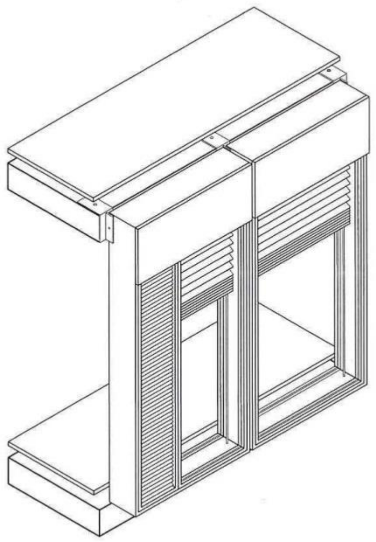
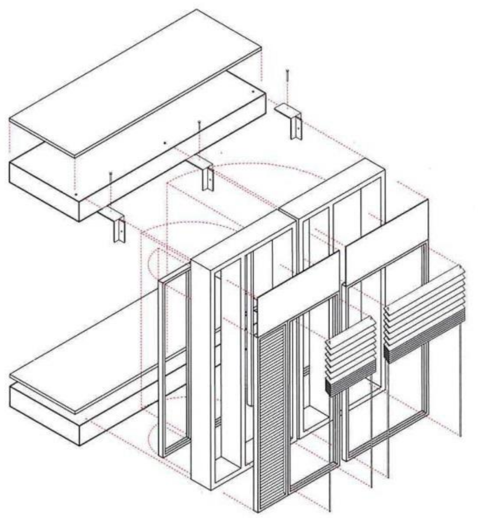
 

Figure 31: Isometric view of façade element (left) (Knaack et al., 2014)

Figure 32: Exploded view of façade element (right) (Knaack et al., 2014)

The element is built up in the following layers, starting from the exterior: Single glazing with laminated safety glass, the main aluminum loadbearing section, plastic spacers carrying the inner frame (which provide thermal separation from the internal space) and finally the internal double glazing within the window casement. The window casement is sealed with three sealing lips. Adjacent elements connect to each other with three rubber continues profiles connected to the aluminum load bearing frame.

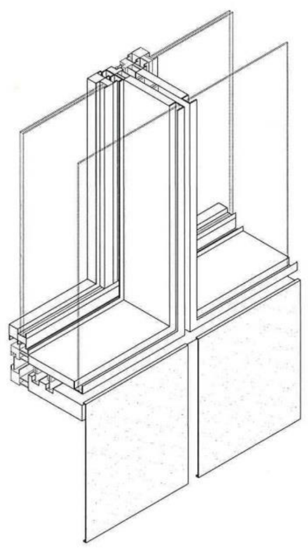
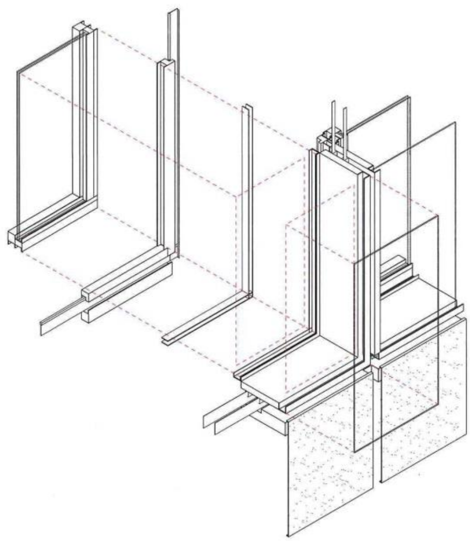
 

Figure 33: Isometric view of elemental joint (left) (Knaack et al., 2014)

Figure 34: Exploded view of elemental joint (right) (Knaack et al., 2014)

3.6 Conclusion

This chapter started off by establishing the principles of modular design. These principles have a clear order of importance, starting with the most important principle. The principles of modular design go as follows:

1. Design with repeating components
2. Design for prefabrication
3. Design for disassembly
4. Design for a catalogue

Designing with repeating components is the main idea of modular design (one design -a single module, which is then repeated over and over). By prefabricating this module the quality of the element improves and the cost is lowered. By designing for disassembly, a module can easily be replaced and reused. However, to make this a possibility, the module must be created with demountable joints. This chapter has shown that direct connections using form and shape and indirect connections using objects can be used as demountable joint. Material connections are usually not demountable. The last principle, designing for a catalogue, explains how you can improve a design for individuals by creating additional components and selling these separately.

This chapter makes clear that curtain walls and system façades are examples of modular façade design. These façade types evolved from the skeletal frame and the post-and-beam façade. This chapter concludes by researching three buildings on their modularity; The Organic Urban Living Field in Charlottesville, The Lifecycle Tower One in Dornbirn and the Debitel Headquarters in Stuttgart.

4. GREEN FAÇADES AND LIVING WALL SYSTEMS

4.1 Introduction of green façades and living wall systems

The collective noun for green façades and living wall systems is *vertical green*. The following definition is given:

"Vertical green is the result of greening surfaces with plants, either rooted into the ground, in the wall material itself or in planter boxes attached to the wall in order to cover buildings in vegetation." (Ottelé, 2011)

This definition given by Ottelé already shows the various ways green façades and living wall systems might work. Ottelé also divides vertical greening systems in such a manner. The first one is based on this description:

- Vertical green rooted into the ground
- Vertical green rooted in artificial substrates or potting soil (which would include systems with plants rooted into the wall, planter boxes or potting soil)

Another way of classifying vertical greening systems mentioned by Ottelé is by dividing them into two groups: direct greening and indirect greening. With direct greening, plants are placed directly onto the wall structure, which usually guides the plants to grow upwards. There is also the possibility to separate the wall structure and the plants with an air cavity, this is indirect greening. They air cavity in this scenario could be created by a supporting structure, spacers, planter boxes or modular substrate systems (Ottelé, 2011).

Up until now, this Thesis has been referring to vertical green as green façades and living wall systems (LWS). However, living wall systems are distinct from green façades in that they support vegetation that is rooted in substrate attached to the wall itself, rather than being rooted at the base of the wall. Living wall systems or green walls are constructed from modular panels, each containing its own soil or other artificial growing mediums like felt, foam and mineral wool, using balanced nutrient solutions to provide all or part of the plant's food and water requirements (Dunnett & Kingsbury, 2004; Mir, 2011). The word "modular" shows why it is relevant to this Thesis to divide vertical greening into separate categories of living wall systems and green façades, since the main difference between the two is that living wall systems are modular whereas green façades are not. Considering this, only indirect living wall systems are a possibility. Later on in this Thesis it will be discussed what modular living wall systems actually are.

Next to providing modularity, living wall systems are suitable for a wider range of plant species. The effect of this is that specific function of vegetated walls can be addressed better (Mir, 2011). For example, when a building would need vertical green to improve the air quality it is best to use a plant that is exceptionally good in filtering air. This plant might not be suitable for a green façade - perhaps due to its inability to root itself into a wall or grow a certain height - but would be suitable for a living wall system. This way of designing for a specific function adds to the concept of modularity.

LWS systems do not require the plants to grow along the full height of a wall, which gives them a short realization time in comparison to green façades. It usually takes around one year to grow (Mir, 2011). However, LWS systems are more expensive than green façades (Ottelé, 2011). It should also be noted that the suitability for a bigger range of plants causes a larger need for maintenance since a larger plant variety needs more attention: a larger variety of plants each require their own conditions that need to be met. Since LWS systems already provide the plants with (a part of) their food and water requirements, LWS systems are also feasible indoors unlike green façades.

Apart from green façades and living wall systems, there is also a third category: wall vegetation. Wall vegetation uses the wall itself as a substrate, which means that plants root directly into the wall. This category can be divided into natural and artificial wall vegetation. Natural wall vegetation has no human intervention involved. The plants appear naturally. With artificial wall vegetation, plant growth is stimulated.

Figure X shows an overview of various types of vertical green and how they could be categorized.

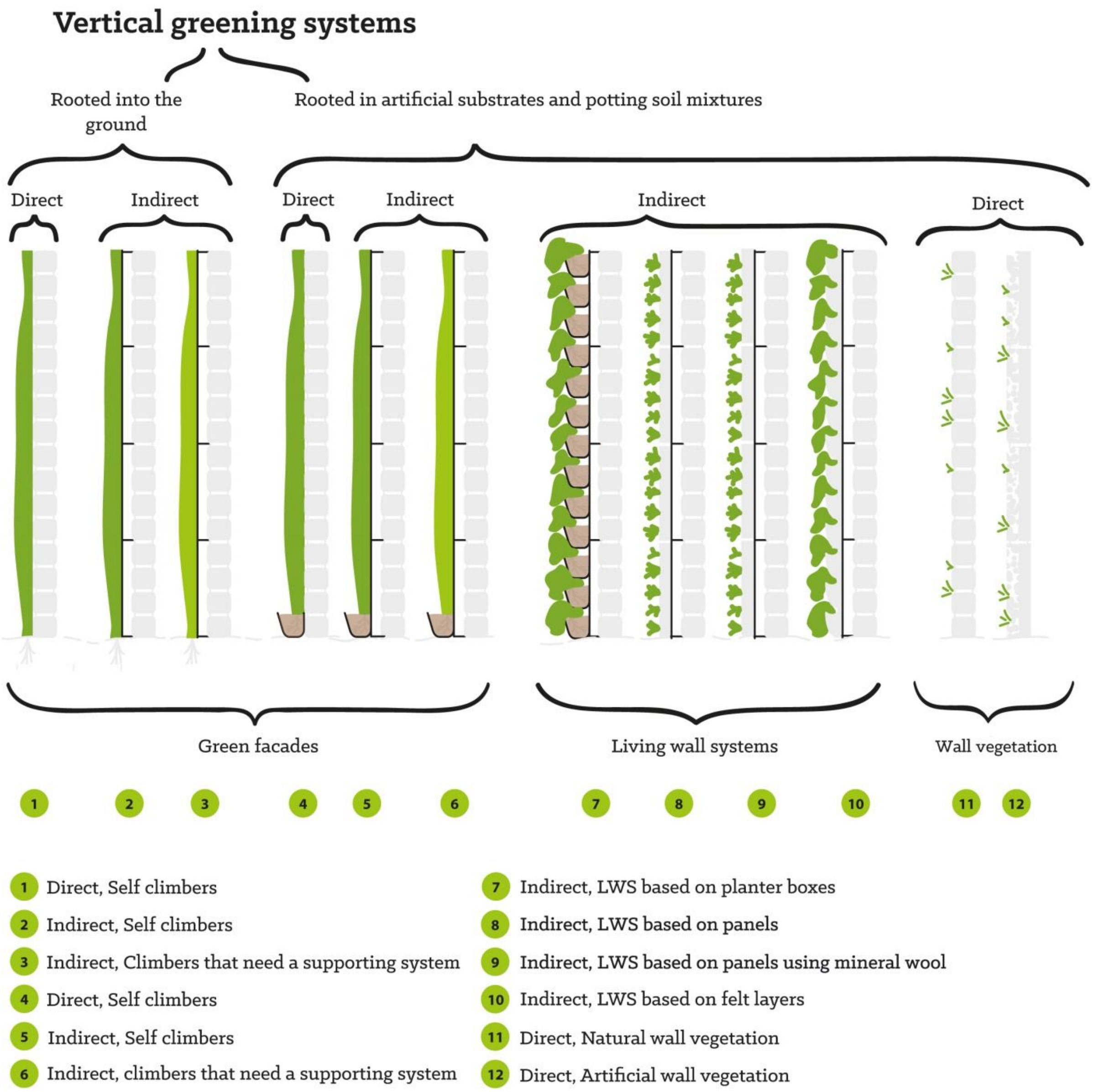


Figure 35: Categorization of vertical greening systems

Since this Thesis deals with the modularity of vertical green, it focuses on living wall systems. As seen in the image above, there are already a few systems known:

1. Living wall systems based on planter boxes.
2. Living wall systems based on panels
3. Living wall systems based on panels using mineral wool
4. Living wall systems based on felt layers.

In the next paragraphs, these systems will be elaborated.

4.1.1 Living wall systems based on planter boxes

As the name implies, this systems contains planter boxes to hold plants. The planter boxes are fixed above each other on a supporting structure. With this system, around 30 plants can be implemented per square meter (Mir, 2011). The life expectancy of such a system is over 50 years (Ottelé, 2011).

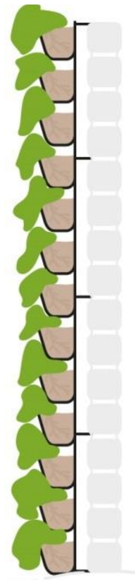


Figure 36 (left): The Bin Fen planter box system (O'Hara, 2012)

Figure 37 (right): A schematic planter box LWS system

4.1.2 Living wall systems based on panels (using mineral wool)

This system uses panels of mineral wool or other types of substrates. Mineral wool is the most common substrate for panels because it is not a loose substrate and can stand on itself. Other substrates are collected in a bag, cassette or other structural element. The plants are rooted into this substrate, usually before they panels are installed onto the building. This is why they are already slightly grown. This also makes panels easy to install and have a direct effect on the environment.

Foam is also a suitable substrate for a wide arrange of plants that can be used as a panel, as it offers a pH neutral growing substrate. Around 22-25 plants per square meter can be implemented, which is around 27 for mineral wool based systems (Mir, 2011). However, panel systems using a foam substrate are rarely used.

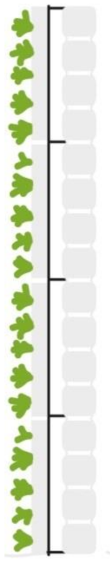


Figure 38 (left): The framepanel system from Sempergreen (Sempergreen, 2015)

Figure 39 (right): A schematic panel based LWS system

4.1.3 Living wall systems based on felt layers

The LWS based on felt layers uses different layers of fabric in which pockets are made. In these pockets there is room for a small amount of soil and plants with short roots. However, the life expectancy of this system is much shorter and is around 10 years. Over time, panels have to be replaced due to degraded substrate or torn layers (Mir, 2011).

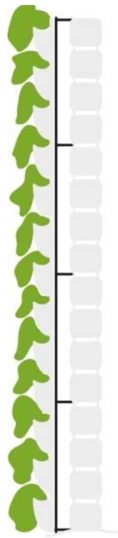


Figure 40 (left): The felt based panel from Dutch Impressive Green (Dutch Impressive Green, 2013)

Figure 41 (middle): The felt based panel from Dutch Impressive Green without plants (Dutch Impressive Green, 2013)

Figure 42 (right): A schematic mineral wool based LWS system

4.2 History of vertical green and living wall systems

Vertical green has been around for a long time. Many sources point back to the hanging gardens of Babylon, which were built ca. 600 BCE. One could say that the hanging gardens of Babylon were built for the social or psychological benefit of plant life. The Babylonian king Nebuchadnezzar ordered to build these gardens which consisted of artificial knolls, hills and watercourses planted with exotic trees, shrubs and trailing vines. This was done so that his Median queen would not feel homesick to her native mountains (Clayton & Price, 2013; Foster, 1998). However, the hanging gardens of Babylon consisted mostly of roof gardens instead of green walls and there is no archeological evidence for the existence of the hanging gardens of Babylon.

Figure 43: The Hanging Gardens of Babylon by Dutch painter Maarten van Heemskerck (Stolk, 2010)

The first archeological evidence of vertical green comes from the Romans, who grew climbing plants on garden's colonnades, walls or trellis screens to provide shade and therefore they were able to use the cooling effect of vertical green. Popular choices for plants were the grapevine (Vitis vinifera), the morning glory (Ipomoea species), the evergreen smilax (Smilax aspera) and the ivy (Hedera species). Archeological evidence of the Roman era also shows the first use of planter boxes. Climbing plants were grown in terracotta pots set underground. These pots were tilted in the direction the plants were meant to grow. For example: in the scenario a plant was to be trained to a column, the terracotta pot was tilted in the direction of the column. Other excavations have uncovered nail holes in garden walls that were used to support climbing plants and can be seen as the first supporting structure for vertical green (Bowe, 2004).

The vertical garden keeps its appearance through the ages. In the Renaissance, fruit walls became popular among European estate owners and monastery gardens. Warm sheltered façades formed a perfect habitat for the growing process of new and exotic fruits. The highlight of fruit walls in history has to be the construction of the palace gardens of Louis XIV at Versailles around 1680 (Ottelé, 2011).

The importance of greenery within rural areas became a topic of discussion again when a garden city movement from the British and Americas appeared in the 1920s. Integration of garden features and plants, for example by using pergolas, trellis structures and self-climbing plants, was encouraged by this movement (Walsh, 2012).

In the 1930s, a cooperation of well-known architects such as Burle Marx, Lucio Costa and Le Corbusier led to one of the first large scale uses of a living wall concept. They designed and created a hanging garden with no access to natural soil for the Ministry of health and education in Rio de Janeiro (Lambertini, Leenhardt, & Ciampi, 2007; Ottelé, 2011).

Figure 44 (left): Palace gardens of Louis XIV at Versailles (L'Atelier Vert, 2001)

Figure 45 (right): Ministry of health and education in Rio de Janeiro (Raggett, 2014)

The importance of ecological enhancements of cities peaked in the 1980s due to the growing interest in environmental issues. This led to studies on the benefits of plants on façades, since the variety of benefits from vertical green could tackle multiple problems at once. Insulating and cooling effects along with the ability of plants to mitigate dust improved the popularity of green façades and living wall systems (Köhler, 2008).

Over the course of the last century, new technologies have appeared on the market that are present in various green façades and living wall systems. In the 1990s cable and wire rope net systems and modular trellis panel systems add to the idea of modular vertical greening systems (Walsh, 2012). Although vertical green is now considered a well-known topic in Europe, it does not mean designs are optimized. Looking into a specific benefit of living wall systems, one might be able to improve the performance of a living wall system element.

4.3 Effects of vertical green

Installing a green façade or living wall system on a building has various benefits. As mentioned earlier, vertical green does not excel in any of these benefits; it just offers a variety of them. This chapter will go over these advantages and even some disadvantages to show why it might be a good idea to install a green façade or a living wall system and how this could help the modularity.

There are several studies that show the advantages of vertical green. These advantages can be separated into benefits regarding the acclimatization of temperature and other benefits. These are listed as follows:

Benefits regarding the acclimatization of temperature:

1. Reduce the urban heat island effect (Mir, 2011)
2. External shading (McPherson, Herrington, & Heisler, 1988; Mir, 2011)
3. Create a microclimate (Alexandri & Jones, 2008; Mir, 2011)
4. Improve insulation properties (Mir, 2011; Stec, Van Paassen, & Maziarz, 2005)

Other benefits:

1. Improving air quality (Mir, 2011; Pope III, Ezzati, & Dockery, 2009)
2. Provide sound insulation (Mir, 2011; Wong, Tan, Tan, Chiang, & Wong, 2010)
3. Increase biodiversity (Köhler et al., 1993; Ottelé, 2011)
4. Aesthetical effects (Peck & Callaghan, 1999)
5. Social and psychological benefits (Westphal, 2003)

4.3.1 Reduce the urban heat island effect

There is not much vegetation in cities, and there is a lot of heat storing in materials such as concrete and asphalt. These materials absorb heat in the daytime and store it until nighttime, when they will release the heat. This effect - along with added heat from things such as air conditioning, vehicles and factories- cause urban areas to be much warmer than rural areas. This effect is called the urban heat island (UHI) (Mir, 2011).

Vegetation can fight this problem. First of all, vegetation covers areas and shades them from the sun, therefore preventing materials such as concrete and asphalt from collecting more heat. Secondly, vegetation can reduce heat by means of evapotranspiration cooling. This means evaporation and plant transpiration take place at the same time. Plants collect evaporated water and turn solar radiation into latent heat, which does not cause temperature to rise (McPherson, 1994).

There is no real way to optimize this effect other than making a modular façade element that not only houses vertical green, but also small bodies of water. Therefore, this benefit is not an ideal scenario for a modular LWS element focusing on a single benefit.

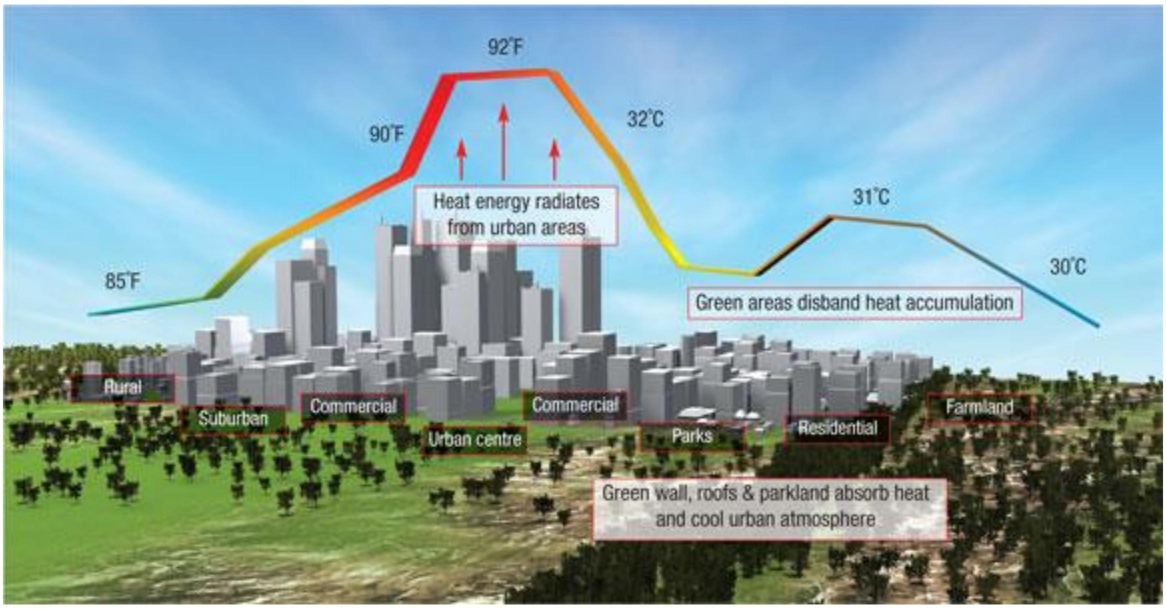


Figure 46: The urban heat island effect (Mehmood, 2014)

4.3.2 External shading

The Romans already used plants for their shading (Bowe, 2004). Nowadays, vertical green can still help control the indoor climate of a building through shading. With vertical green, the active heat absorbing surface are the leaves, instead of the building envelope (McPherson et al., 1988). Ideally, plants are used that wither in the winter, so that the building envelope will get heat provided by sunlight in the colder months.

Providing passive heating and cooling through façade elements is quite common; there are already various technologies like double façades (von Grabe, 2002) and trombe walls (Gan, 1998). Perhaps combining (parts of) these ideas with living wall systems will result in a modular living wall system element that is ideal for passively heating or cooling a building.

4.3.3 Creating a microclimate

A green façade or living wall system has quite a big impact on solar irradiation and air flow, but also influences air temperature, humidity and long wave radiation. This means that a vertical green element alters the micro-climate of the built environment. This could affect the thermal performance of the building in a positive way.

Combining the effect of a vegetated wall with that of a green roof and green open spaces can even affect the topo-climate of towns. However, a single modular element will not have that much effect, only in combination with other elements in a specific way. The micro-climate is dependable on factors of a larger scale, such a s urban geometry and climate characteristics (Alexandri & Jones, 2008). This benefit would not really be suitable to look into when looking at the matter of modularity.

4.3.4 Improve insulation properties

Better insulation causes a more constant climate in the building, because there is less heat exchange between inside and outside temperature. In the summertime, insulation with a lower thermal resistance offers less heat transfer from the outside to the inside, meaning there is not much need for cooling. In the wintertime this means the heat will be kept inside, meaning the need for heating is lower. This will save energy.

Adding a green façade or a living wall system improves the insulation properties by adding an extra layer to the building, sometimes with a cavity in between the layers. This cavity contains air moving at a very slow speed and therefore is a good insulation layer. The substrate in living wall systems and even the plants can act as an extra insulation layer (Stec et al., 2005).

The insulating effect of vertical gardens could be optimized with a single element. By letting all elements connect without any thermal leakage - such as openings - and by choosing an indirect system with a high insulation value, the insulation could be improved much more than by picking a random green wall system. When this is the case, this specific system could become a solution for old city buildings with low insulation properties.

4.3.5 Improving air quality

Plants improve the air quality in a variety of ways. First of all, they convert gaseous pollutants such as CO_2 and NO_X during the daytime (Berry & Downton, 1982; Ottelé, 2011). Secondly, plants are able to filter out particulate matter (PM_X) by adhering it to the outside of the plant (Minko & Witter, 1983; Ottelé, 2011). Fine dust in high concentrations can lead to various health risks, such as decreasing lung functions, increased respiratory problems and increased cardiovascular events (Brook et al., 2002; Pope III et al., 2009). The smaller the particles are, the more dangerous they are for human health.

The efficiency of a plant's ability to collect fine dust particles can be influenced by a variety of factors, such as the type and amount of leaf surface, electrical charge of the vegetation (Oosterbaan, Tonneijck, & De Vries, 2006) and the contact between pollution and leaves. For example, air movement can improve the efficiency of a plant to collect fine dust. The dust particles are eventually washed of by rainfall, except for fine and ultra-fine particles (Ottelé, 2011). Considering all these factors that influence particle matter collection, one might be able to tweak these factors and design a living wall system element that is optimized for the improvement of air quality.

It must also be noted that this particular benefit is not merely a benefit from urban green, but also becomes more effective when used in vertical green. Vertical green can circulate the pollution from the air better and earlier than trees, because trees might block the street canyon (Mir, 2011) as seen in figure 47.

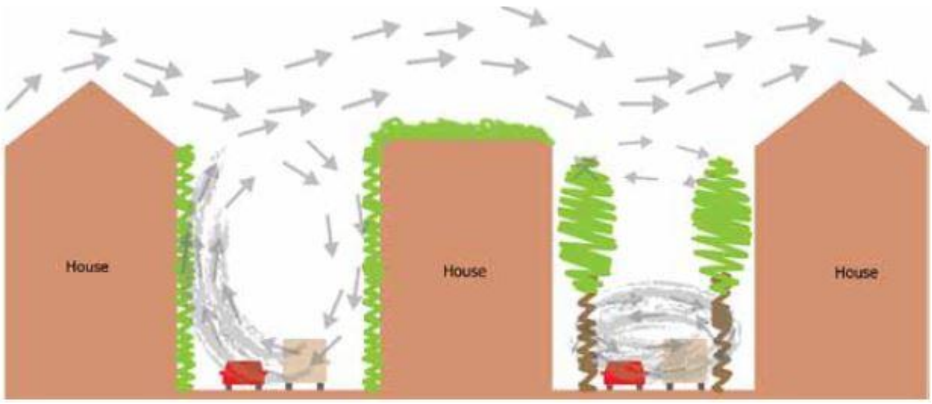


Figure 47: Trees blocking the circulation of air (Ottelé, 2011)

4.3.6 Provide sound insulation

Within urban areas, sound can be a big problem. Vehicles and persons can create a lot of sound pollution. Vertical green can address this noise pollution, as plants can absorb, reflect and diffract noise (Wong et al., 2010). Plant type, plant density, location and frequency are important factors of the efficiency (Rutgers, 2011). However, the plants themselves mostly affect noises of a high frequency, while noises of low to middle frequency are mostly affected by the substrate (Wong et al., 2010). For the substrate, factors such as the depth of the growing media and the materials used influence the noise reduction (Cook & VanHaverbeke, 1971).

Knowing this, it is possible to create a living wall system element that is optimized for reducing sound pollution by picking the correct plant, the correct substrate and the correct materials. For example, the texture of the planter boxes or the felt or mineral wool layer could also reduce noise.

4.3.7 Increase biodiversity

Biodiversity can be increased by offering ecological habitats using vertical green, for example (Ottelé, 2011). Vertical gardens can offer breeding and resting habitats for birds, such as house sparrows, blackbirds and greenfinches (Köhler et al., 1993). Apart from a habitat, a vertical garden can act as a food source by housing insects. Mainly beetles, flies and spiders can be found in green façades, but bees are also possible. Note that the increase in insects due to the installation of a vertical garden can also be seen as a disadvantage by the client.

However, watching animals can function as a source of pleasure by locals. By providing nesting locations, such as artificial nest boxes, and plants that offer food in the wintertime, a design can increase the biodiversity, or perhaps increase the growth of a rare or endangered species. Modularity could go hand in hand with this concept by offering a specific type of green wall that can be optimized for a certain species of birds or bats. The green façades or living wall systems need to be placed at certain locations and need to be able to withstand the damage done by animals.

4.3.8 Aesthetical effects

Designing with nature and plant textures can contribute to the aesthetic environment (Peck & Callaghan, 1999). For the building owner that is considering to install this green façade or living wall system, this is a very important aspect and has been noted as the main selling point of green façades and living wall systems. There seems to be a preference in systems where the entire surface of a system is covered with plants and nothing of the actual system can be seen. This seems to be the main reason why clients tend to choose for panel based systems instead of systems based on planter boxes.

Apart from the aesthetic effect given by the plants, a vertical garden also protects a wall from vandalism and graffiti. Large uncovered surfaces of façades are attractive for graffiti. By placing a vertical garden on a façade, this specific area can't be reached by a graffiti artist.

A modular living wall system element focusing on aesthetics could be a possibility, but it would not make a lot of sense. Various products with plants arranged by color or texture could be produced, but the highest aesthetical value would be reached by giving as much artistic freedom as possible. This allows for the designer to design something just the way he or she wants is, instead of picking a fully predesigned product from a catalogue.

Figure 48: Van Gogh's painting Wheat Field with Cypresses depicted into vertical green by ANS (Young, 2011)

4.3.9 Social and psychological benefits

Urban greening does not only improve the environmental quality of an area, they can sometimes have an impact on critical social issues such as health care, education, crime and safety, economic development, and social disenfranchisement (Westphal, 2003). Green can reduce stress factors (R. S. Ulrich et al., 1991) and improve the human health and mental well-being in general (Hermy, Schauvliege, & Tijskens, 2005; R. Ulrich, 1984).

Unfortunately, these effects are more aimed at human interaction and this would mean it is an almost impossible design tool to work with. Large groups of people will not be affected by a single element of a vertical garden, so this specific benefit of vertical green would not be an important aspect of modularity.

4.4 Disadvantages of vertical green

Before designing a new living wall system, it is important to be aware of the current problems on the market. What are the disadvantages of vertical green? What is the reason a person would not want a living wall system on their façade? By taking these disadvantages into account, their effects can be minimalized, increasing the value of the product.

4.4.1 Cost

The installation of a living wall system can have a high construction cost. The initial costs of a vertical greening system based on a living wall system can be between 300 and 1200 euro per square meter façade (Mir, 2011; Ottelé, 2011; Perini, Ottelé, Fraaij, Haas, & Raiteri, 2011). This cost only grows when the high maintenance is taken into account (see the next paragraph), since this has to cover irrigation, manual labor, renting a boom lift, replacing plants and replacing panels.

However, the shading and insulating effects of vertical green lower the energy usage needed for heating a building. On a larger scale this works for the urban heat island effect. Implementing a lot of green lowers the urban heat island effect and reduces the need for cooling in the winter, which leads to saving energy. The installation of a living wall system could be seen as an investment.

4.4.2 Maintenance

As mentioned earlier, green façades and living wall systems need a lot of maintenance. Apa rt from natural wall vegetation, all plants need additional water and nutrients to survive. This can be added to the plants using an irrigation system. An irrigation system can be very energy consuming, especially when it is fully automated with a water management system. In this scenario it completely monitors the moisture levels of the soil, resulting in the release of the appropriate levels of water and nutrients.

Dead plants need to be replaced, preferably at least twice a year. This needs manual labor and a boom lift for high-to-reach places. Sometimes not only plants, but entire elements need to be replaced. Felt systems, for example, could rip. Pruning (long term maintenance) for plants is recommended. Various companies selling and installing green façades and living wall systems also provide maintenance and check-ups.

4.4.3 Insects

Wall vegetation increases the biodiversity and sequentially the amount of insects. People tend to see this as a disadvantage, since they are annoyed or frightened by insects (Mir, 2011). This effect is increased by the soil temperature. The soil temperature of vertical green is much warmer in the summertime than soil in the ground. This makes the soil more attractive for insects, which can lead to negative effects, such as the destruction of plants (Bruck & Donahue, 2007).

One example is the vine weevil, or the *Otiorhynchus sulcatus*. The vine weevil usually targets plants in containers. The adult vine weevil usually eats the outer edges of leaves, which is not a problem for the plants. However, the grubs target the roots of the plants, which could cause severe damage or the death of the plant. For plants in containers there is a higher chance of severe damage, because the root length is restricted.

4.4.4 Cold temperatures

The soil temperature of vertical green is much more dynamic than the soil temperature of the earth, which means it is not only warmer in the summer, but also colder in the winter. This means plants in vertical green are much more vulnerable to cold temperatures than plants in the ground. This could lead to plant death (Kaspar & Bland, 1992). Systems with a thin substrate, such as certain panel based systems or felt systems, leave the roots more vulnerable to temperature. This is why retailers prefer to use systems using soil, such as planter boxes.

4.5 Conclusion

Placing green façades or living wall systems in cities has various benefits for the building, the locals and the urban environment. Vertical green can improve the air quality, reduce the urban heat island effect, provide sound insulation, act as external shading, create a microclimate around the building, provide biodiversity, improve insulation properties, create aesthetical effects and improves the mental well-being of the local people. Some of these benefits could be optimized within a single living wall system element, such as improving the air quality, in which in element captures as much particulate matter as possible. Reducing noise pollution can be improved by combining a living wall systems element with various noise reducing materials and textures. The effect of external shading can also be combined with new techniques of shading and cooling a building. An element could be optimized for providing biodiversity by paying extra attention to the needs of local wildlife and offering food and shelter to these animals. Insulation properties could be improved by focusing on the air cavity and the insulating effects of the soil and reducing the amount of thermal leaks. The other benefits of vertical green aren't suitable for optimization or modular design. Table 1 gives an overview of all the benefits of vertical green of every system and if the benefit is suitable for modular design.

Green façades and living wall systems also have a set of disadvantages. High costs and maintenance are needed for the vertical green and the plants are more vulnerable to the cold air than when placed into soil in the ground. Vertical green also increases the amount of insects, which can be considered to be an annoyance by some people, and certain species can also damage the plants. It is important that the disadvantages will be taken into account into the design process.

1. Direct, Self climbers
2. Indirect, Self climbers
3. Indirect, Climbers that need a supporting system
4. Direct, Self climbers
5. Indirect, Self climbers
6. Indirect, climbers that need a supporting system
7. Indirect, LWS based on planter boxes
8. Indirect, LWS based on panels
9. Indirect, LWS based on panels using mineral wool
10. Indirect, LWS based on felt layers
11. Direct, Natural wall vegetation
12. Direct, Artificial wall vegetation

Vertical green type		Rooted into the ground			Rooted in artificial substrates and potting soil mixtures								
type		**Green façade**						**Living wall system**				**Wall vegetation**	
direct or indirect		direct	indirect	indirect	direct	indirect	indirect	indirect	indirect	indirect	indirect	direct	direct
Effects	Can be optimized for modular desing (Y/N)	1	2	3	4	5	6	7	8	9	10	11	12
Reduce the urban heat island effect	N	+	+	+	+	+	+	++	++	++	++	-	-
External shading	Y	+	+	+	+	+	+	++	++	++	++	-	+
Create a microclimate	N	+	+	+	+	+	+	+	+	+	+	-	-
Improve insulation properties	Y	-	-	-	-	-	-	+	+	+	+	--	--
Improving air quality	Y	+	+	+	+	+	+	++	++	++	++	-	-
Provide sound insulation	Y	+	+	+	+	+	+	++	++	++	++	-	+
Increase biodiversity	Y	+	+	+	+	+	+	+	+	+	+	-	-
Aestetical effects	N	+	+	+	+	+	+	+	++	++	++	--	-
Social and psychological benefits	N	+	+	+	+	+	+	+	++	++	++	-	-

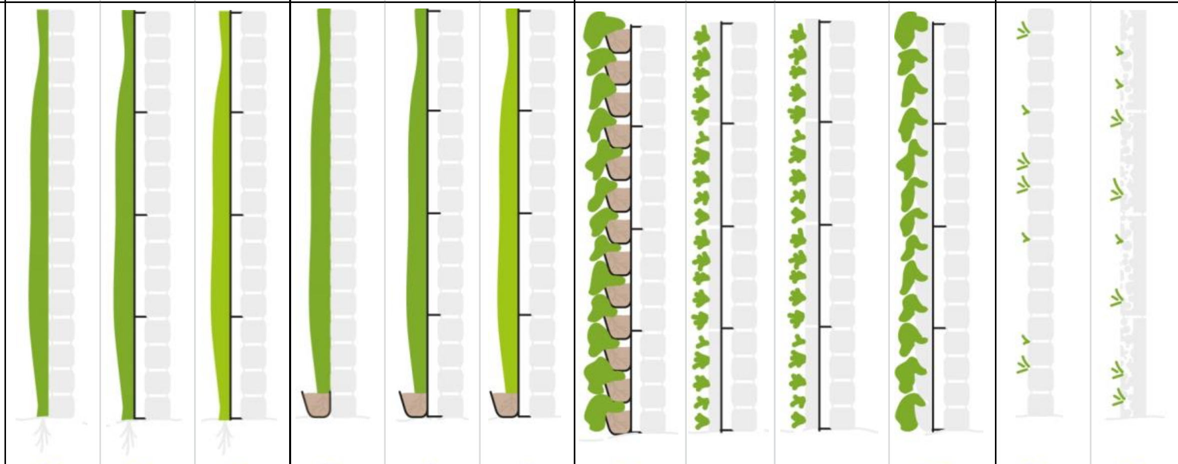


Table 1: : Advantages of various vertical greening systems (Mir, 2011)

5. INNOVATIONS

5.1 Introduction on innovation

For a design to truly stand out and evolve from what's currently already available on the market, innovation is needed. This chapter functions as a literature research that looks into various innovative ideas about modularity and other concepts that share the same benefit as vertical green. These innovations do not offer a direct solution to the design problem, but might be a base for the concept that will result in the solution to the design problem. Some of these concepts might even seem too vague to implement, but they can still act as a stepping stone towards the correct design solution.

The upcoming paragraph explains various innovations regarding modular façades. Perhaps the general modularity of a vertical green façade can be improved by learning from these ideas. The paragraph after that will not look into modularity as a general concept for façade design, but will look into connections that could be used in designing for modularity.

Not only innovations of modularity will be discussed, but also innovations that share the same benefits as vertical green, such as acclimatizing temperatures, improving the air quality and improving the insulation. By looking into these concepts, ideas to improve a living wall system for a certain benefit might appear. Innovations regarding sound insulation and increasing the biodiversity haven't surfaced, so these will not be mentioned.

Every concept that is discussed in this chapter will not only be explained, but also reviewed for the possible combination of the ideas and vertical green. Some will not offer any real benefits and some will. Potential problems that might appear will also be mentioned.

"If you look at history, innovation does not come just from giving people incentives; it comes from creating environments where their ideas can connect."

- Steven Johnson, author

5.2 Innovations regarding modular façades

5.2.1 Tri-material cubes façade

Cubes form the modular elements of a façade. They are strong enough to function as the load-bearing structure of the wall. The cubes are made out of three materials; one material for every two opposite sides. In this case, the cubes can be rotated so that a particular cubes faces the inside and the outside, adapting the wall to local conditions.

Only a singular element needs to be produced, but it can have multiple effects that are all dependent on how the element is positioned. However, the wall cannot be easily changed, because the modules are also load bearing structures. A singular element cannot be removed from the wall. It is not an interesting technique for vertical green, since plants always need to receive sunlight. This is not the case when the cubes are rotated to be opaque.

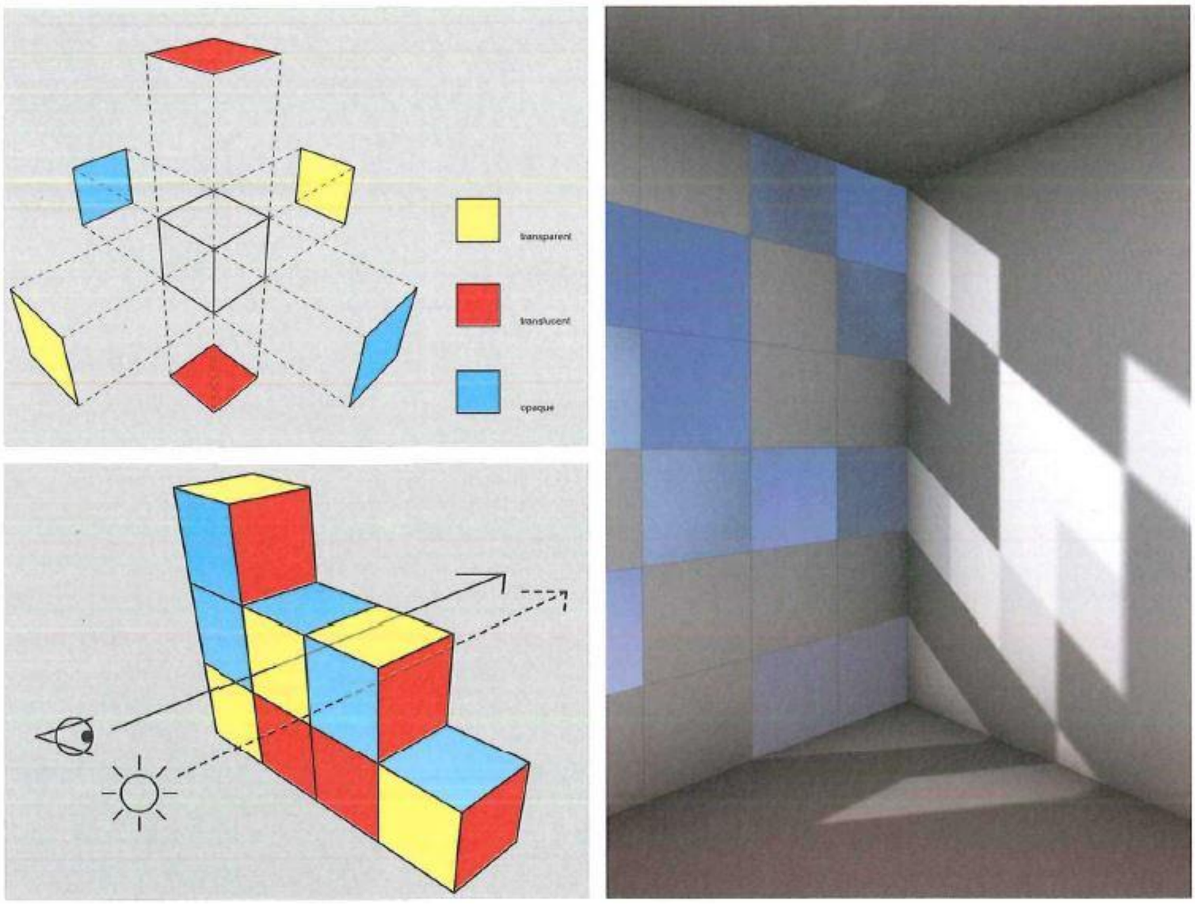


Figure 49: A façade made out of tri-material cubes (Knaack, Klein, & Bilow, 2011a)

5.2.2 Honeycomb façades

This façade has a separate load bearing structure made out of hexagons. Modules also have a hexagonal shape and can fit inside or on this structure. Various hexagons perform different functions. The hexagonal shape is chosen, because it is the optimum shape for a load-bearing structure with a minimum size. This is an example from nature where hexagons can be found honeycomb structures. These contain the minimum amount of beeswax, but the maximum amount of honey.

A hexagonal green façade might be a new and interesting concept within modular vertical gardens. A hexagon could contain plants or other functions, such as a semi-permeable membrane for natural ventilation or perhaps a birdhouse to increase biodiversity. When a hexagon loses its function (for example when the plants die), they entire hexagon could be replaced. The non-functioning hexagon could then properly be disassembled and recycled in a factory environment. A problem that might appear when green façades take a hexagonal shape is that the irrigation pipes also need to adapt to this shape, which probably increases their length.

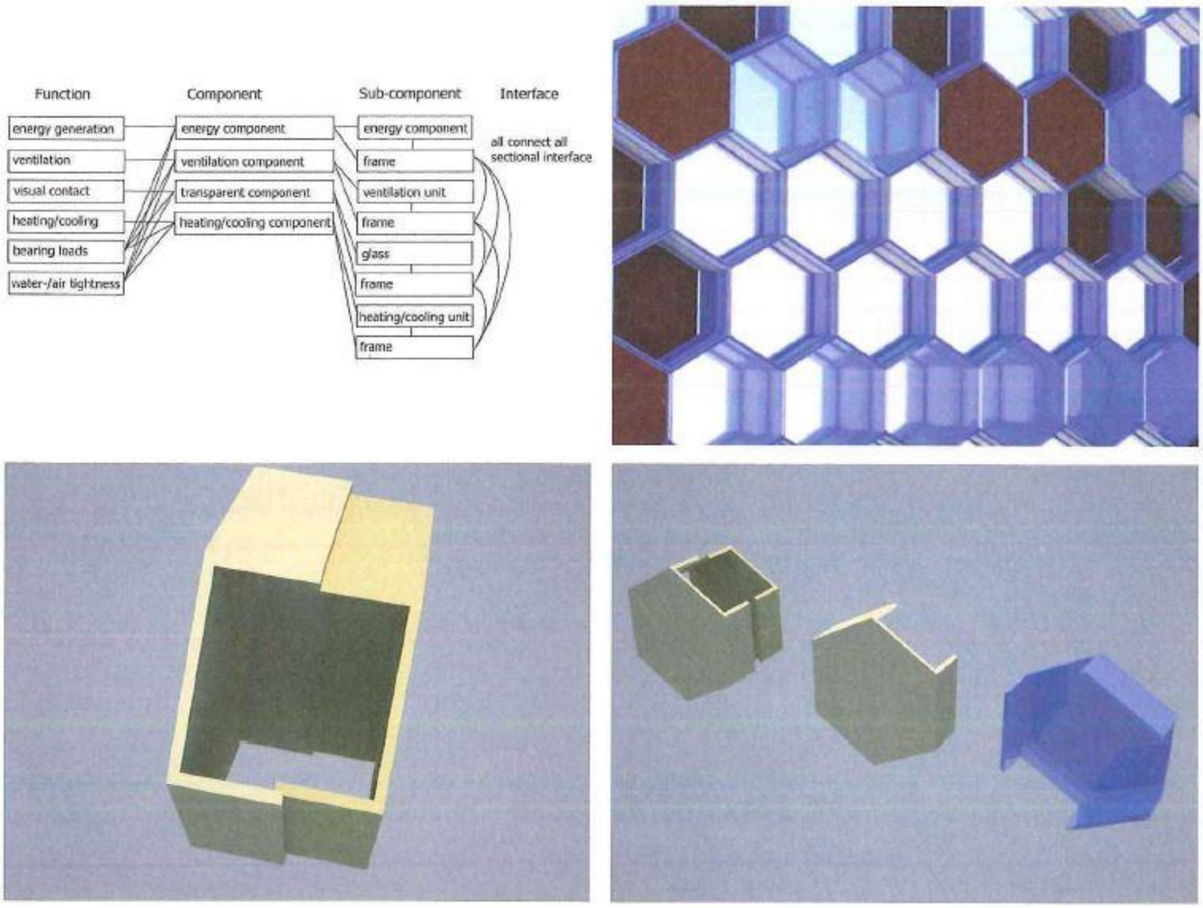


Figure 50: The honeycomb façade (Knaack et al., 2011a)

5.2.3 Deflated glass hexahedron façade

This façade is an example of a honeycomb façade. It contains a frame made out of hexahedrons and tetrahedrons, which have a deflated air cavity providing thermal and sound insulation. Although a façade made out of hexagons is ideal for load bearing, the glass has to be quite thick to take up bending moments.

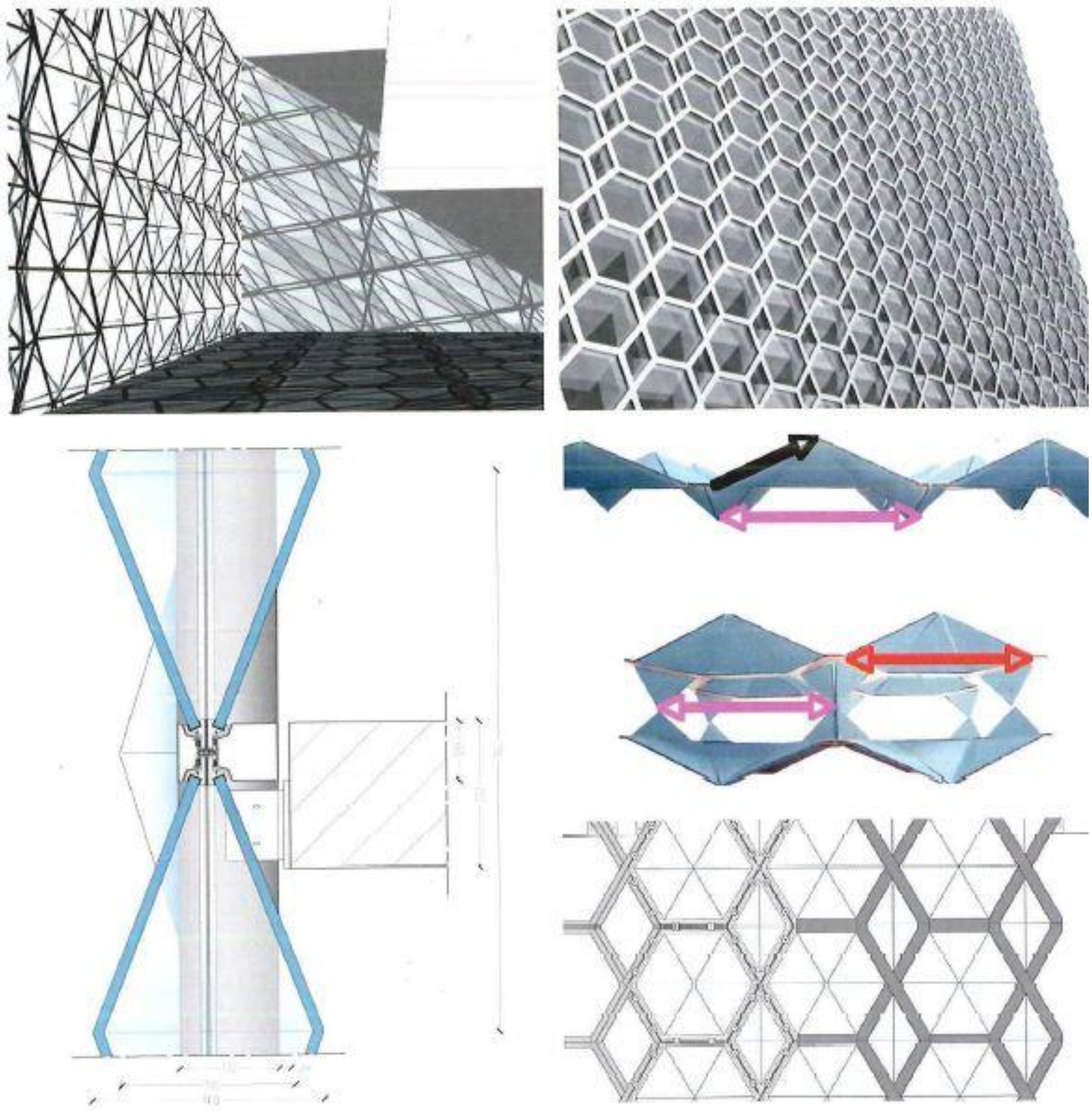


Figure 51: The deflated glass hexahedron façade (Knaack, Klein, & Bilow, 2008)

5.2.4 Matrix façades

The Matrix façades start from a future façade in which installations are integrated. A modular façade could provide various climate functions, such as ventilation, heating or cooling. A media matrix collects information of the climate, energy and water supply from all modules in a single computer and then shares the information with all modules. The façade becomes a living organism, which constantly adapts to the user needs and the environment.

This innovation seems to already exist within living wall systems, but on a smaller scale. The irrigation of plants can be fully automated, with sensors checking if the plants receive the correct amount of water and nutrients. If they do not, more water and/or nutrients will be applied. Perhaps this automated irrigation could be combined with other modular elements that provide other functions.

5.2.5 Rolled wall

This is system really easy to install, since the wall can be rolled up until it is filled with concrete. It consists of a core insulation of soft mineral insulation with textile layers on the outside. To control deformation when pouring concrete, the fabric layers are connected with nylon strings. The outer textile layers will not let water penetrate.

Although it is easy to install and available in separate elements, it is not completely modular, because the structural element (the concrete) has to be poured on-site. Secondly, the concrete cannot be recycled. Therefore, this concept is not interesting for modular building.

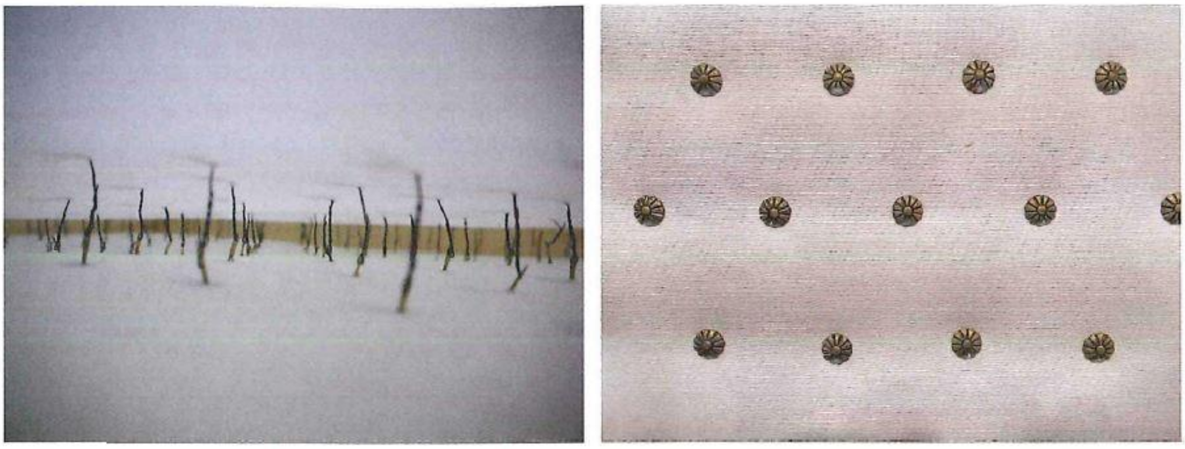


Figure 52: Cavity and outer layer of a rolled wall (Knaack, Klein, & Bilow, 2015)

5.2.6 Solid unitized wall

Normal sandwich elements do not provide any structural strength, but this does not necessarily have to be that way. This system inserts aerated concrete element into prefabricated elements, in which everything is glued together. A finishing layer can still be added, so what if this was a vertical green element?

However, there is one problem. The concrete cannot be recycled, but perhaps this component could be replaced with another recyclable material.

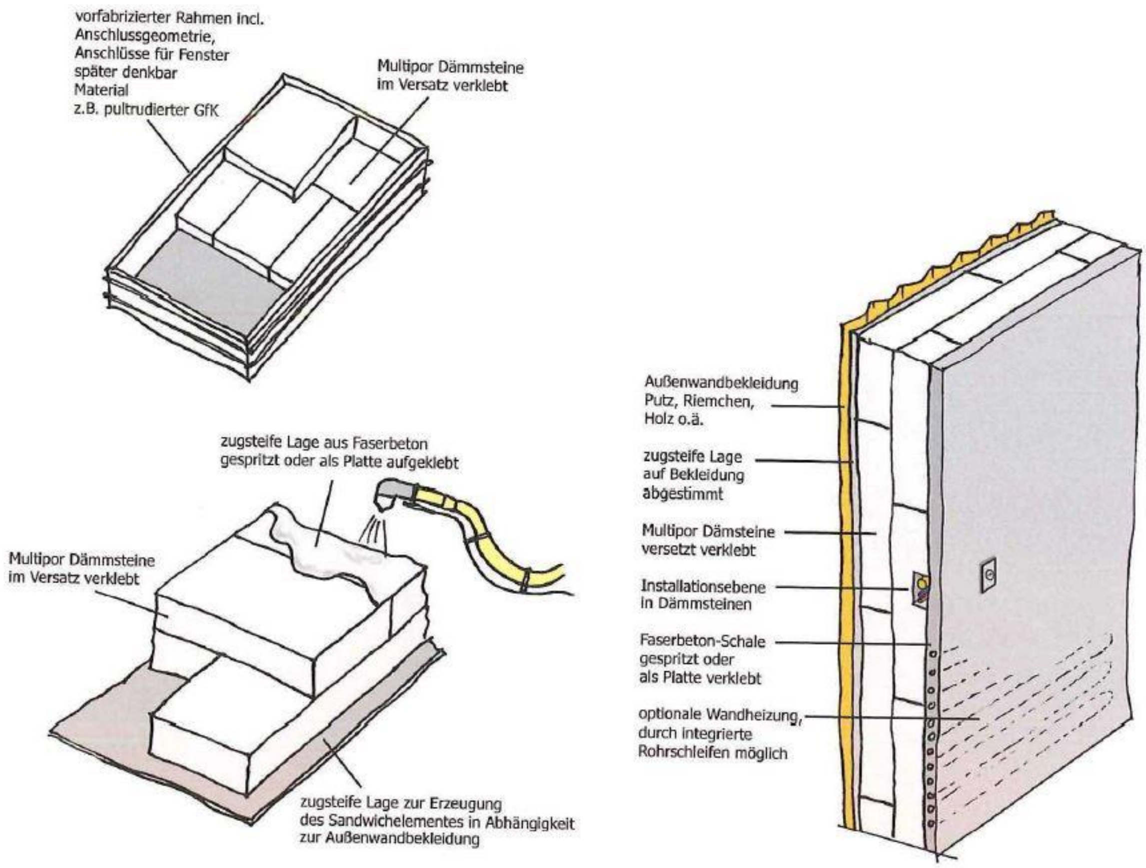


Figure 53: Principle of a solid unitized wall (Knaack et al., 2011a)

5.3 Innovations regarding modular connections

5.3.1 Snap joints

Snap joints are connections based on the "snap and lock" principle. These joints are indirect connections that can be disassembled, but still offer the provided strength. If a module would be light enough, it could even be mounted by a single person, when these joints are the only connections that are applied. The most common examples of these joints are made out of polymers. These joints could improve the construction time of modular living wall systems.

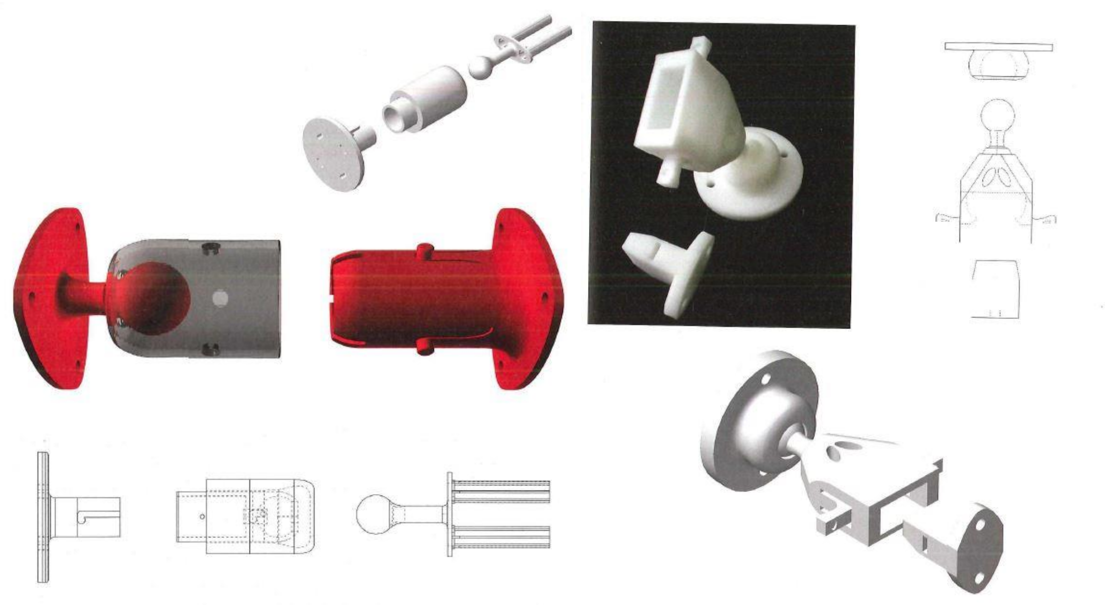


Figure 54: Various snap joints (Knaack, Klein, & Bilow, 2010)

5.3.2 Deflatable connections

Deflatable joints are designed connections that can easily be disassembled. There are two possible ways in which this could work. In the first one, two elements are fixed together and a small component made out of an expendable material receives air, grows in size and fixates the elements. The second scenario has a connection element tightening, because it is inside a vacuum.

The second scenario is not very interesting for designing with vertical green. Plants need air, so creating a vacuum inside the façade will make it too complex. The first option might be possible, but it does not sound very durable, which is very important for a connection.

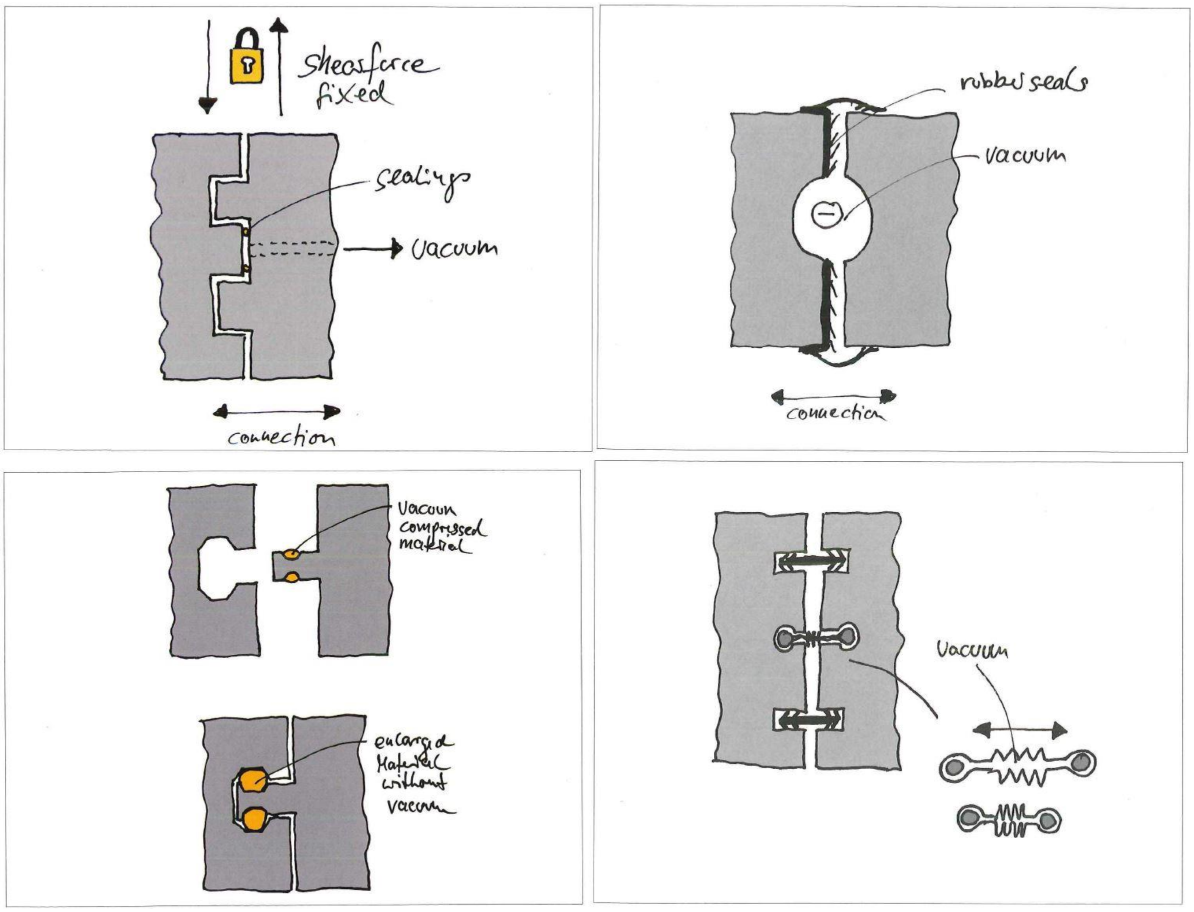


Figure 55: Various deflatable connections (Knaack et al., 2008)

5.3.3 Tango point holders

Tango points holders are moving connections for double skin façades. These connections are able to open or close the space between the two skins, regulating the insulation value of the skin. This way, the skin can adapt to different conditions. This connection could also be used on living wall systems, changing the size of the cavity for various conditions. In summertime on a windy day, the cavity could become bigger to catch more wind and cool down the building. If there is no wind, the connection retracts, making the cavity smaller, creating a lower insulation value. The microclimate around the building will become manageable.

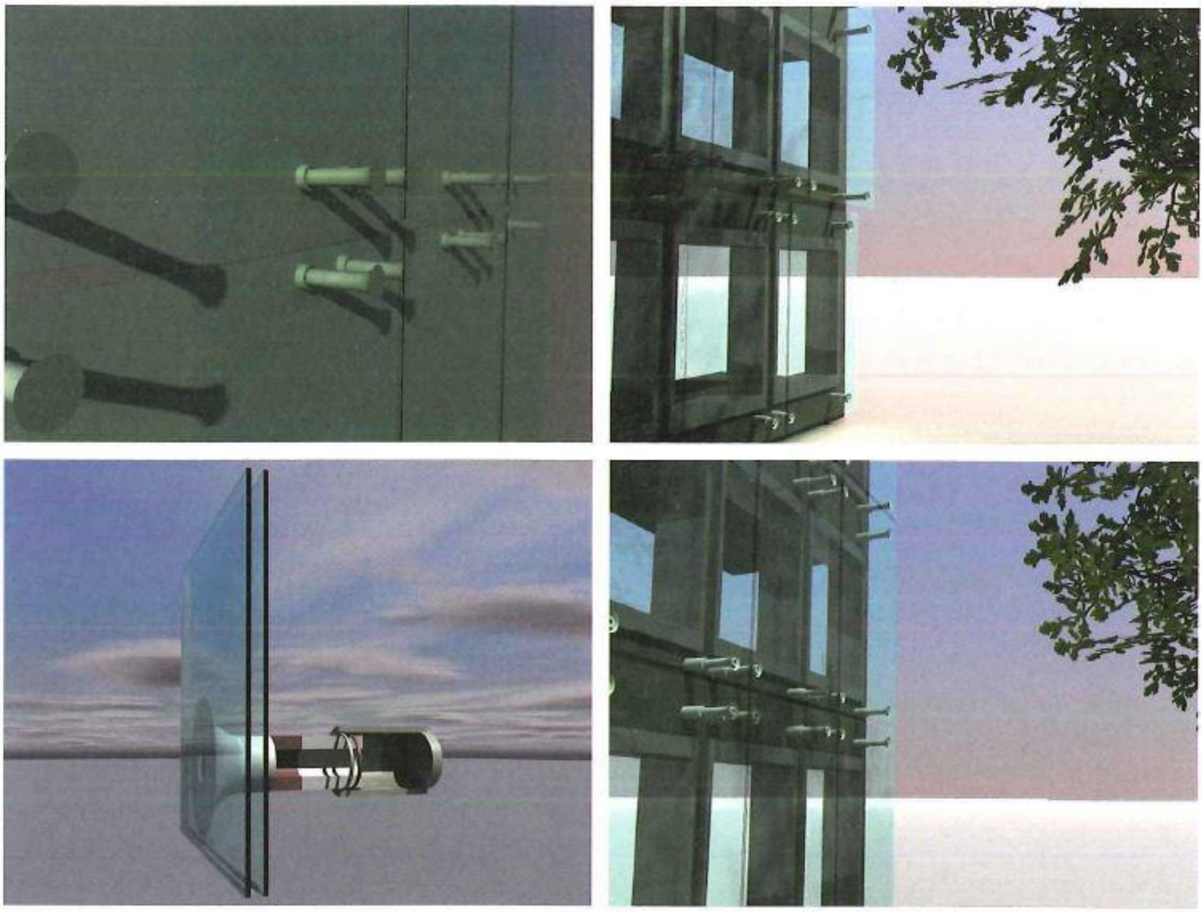


Figure 56: Principle of tango point holders (Knaack et al., 2010)

5.4 Innovations regarding the acclimatization of temperature

5.4.1 Trombe wall

The trombe wall is a fairly popular technology using indirect solar heating. It consists of three layers, a glass layer, an air gap with an air flow and a wall with a high thermal capacity. Sunlight enters the building through the glass layer. The radiation is absorbed by the wall with a high thermal capacity. The solar energy is conducted to the inner side of the wall or is conveyed by the air flow that is running through the air gap. This way, solar radiation is an indirect gain. This technology is especially useful for areas that receive inconsistent solar radiation.

Unfortunately, vertical gardens need sunlight themselves. There is a possibility to replace the glass layer with a green layer. Sunlight that penetrates the green layer is absorbed by the green wall, but cannot escape. However, since a vertical garden is not transparent, not a lot of sunlight will reach the trombe wall, decreasing the effect. Therefore, a trombe wall does not seem like a good idea to combine with a vertical garden.

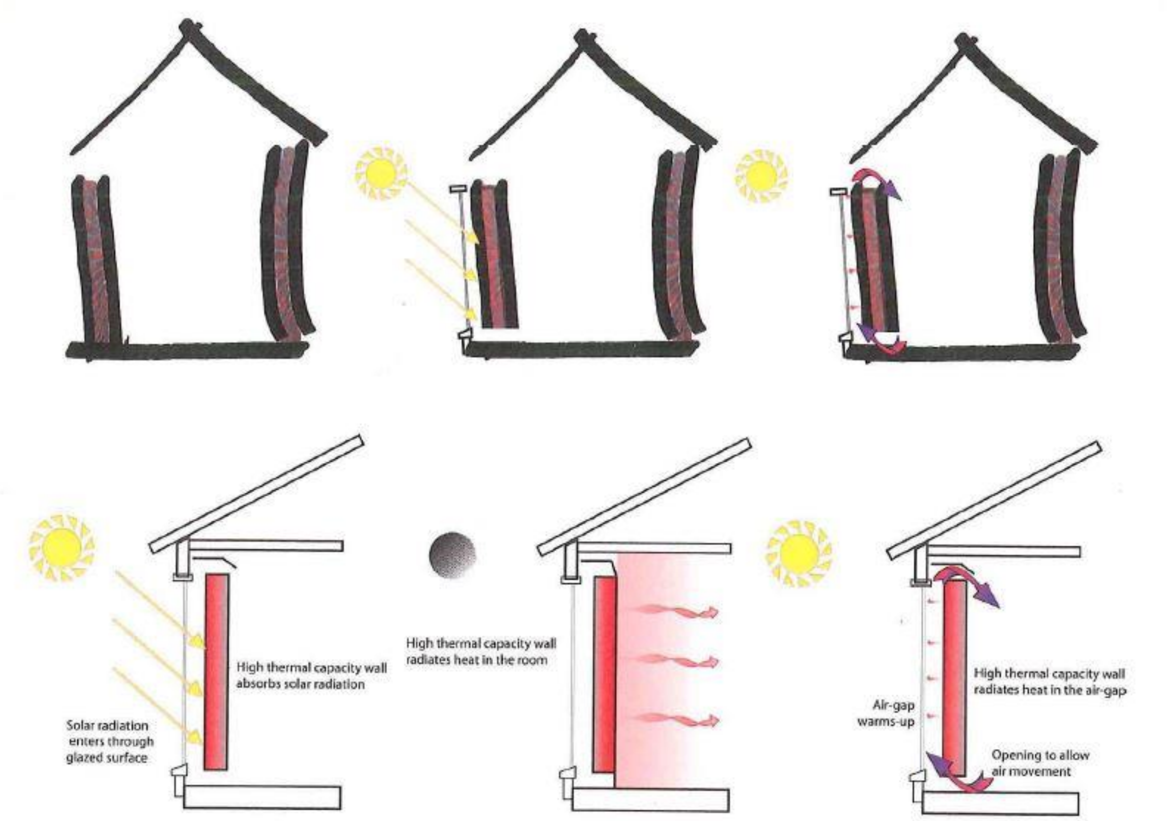


Figure 57: Principle of a trombe wall (Knaack, 2012)

5.4.2 Humidity driven ground water cooling

This system makes use of a wet wall which causes cooling effects inside a building. By placing a building in an excavation with circulating ground water, the walls soak up the water and cool down the inside. This means no waterproofing layer has to be installed. However, bulkheads need to be installed to dry out the basement in winter, to prevent mold.

This idea might go hand in hand with vertical green. Since the walls contain water, it could also provide irrigation for mosses or plants rooted into the wall. The moss or plants improve the cooling effect by offering shading. Ideally, these plants would wither in the wintertime, so that the shading is gone in the winter. This idea, however, could decrease the strength of the wall.

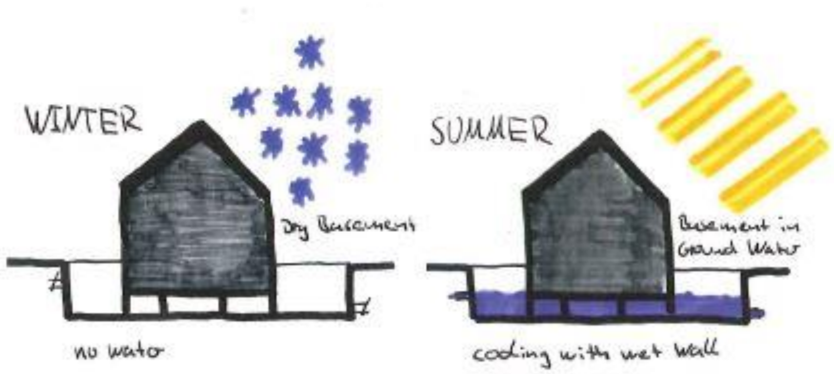


Figure 58: Principle of humidity driven ground water cooling (Knaack et al., 2015)

5.4.3 Rammed salt wall

Kitchen salt, or sodium chloride, has hygroscopic properties meaning it draws water. A wall made out of salts can dehumidify a room. A concept idea shows a perforated salts wall with a glass panel with an air gap as an outside layer. The sun heats up the air in the gap, which flows upwards into the building and through the salt wall. Inside the wall it can be used as a cooled dehumidified air supply or as a heated humidified exhaust.

Again, sunlight is used to heat up air inside an air cavity, just like a trombe wall. Vertical green block sunlight and also humidify the air, so combining this idea with vertical green would not be helpful.

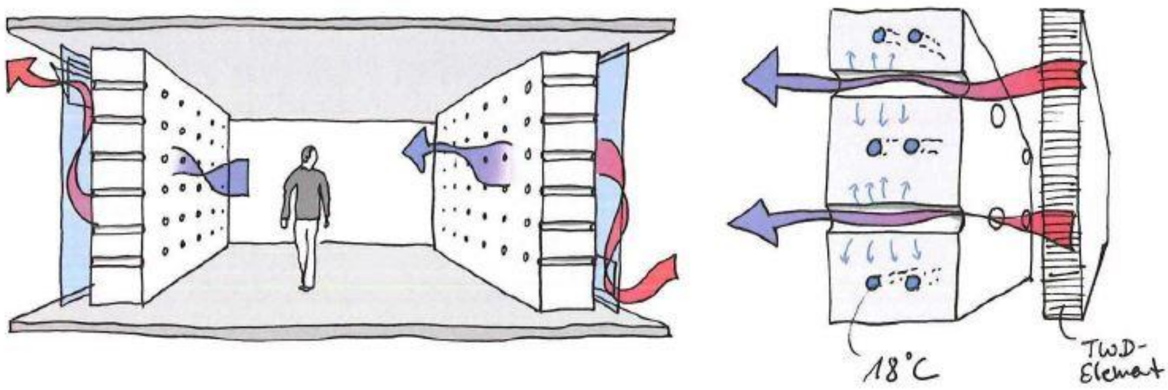


Figure 59: Schematization of a rammed salt wall (Knaack et al., 2011a)

5.5 Innovations regarding improving the air quality

5.5.1 Breathing concrete and natural ventilation

The idea of breathing concrete is based on natural ventilation through a concrete wall. The concrete itself offers structural support, but it also has a fine mesh of ventilation pores. The ultra-fine Three-dimensional structure offers a natural air flow, but keeps water out. Because concrete has a lot of mass, it can transfer heating and cooling to the air due to concrete core conditioning.

As mentioned earlier, concrete is not an interesting material for modular design. However, natural ventilation in a structural wall might improve a vertical garden. The plants can protect the wall from rain that might enter the building. Because plants have an air improving effect, clean air can easily enter the building, while air with high CO_2 levels exit the building near the plants.

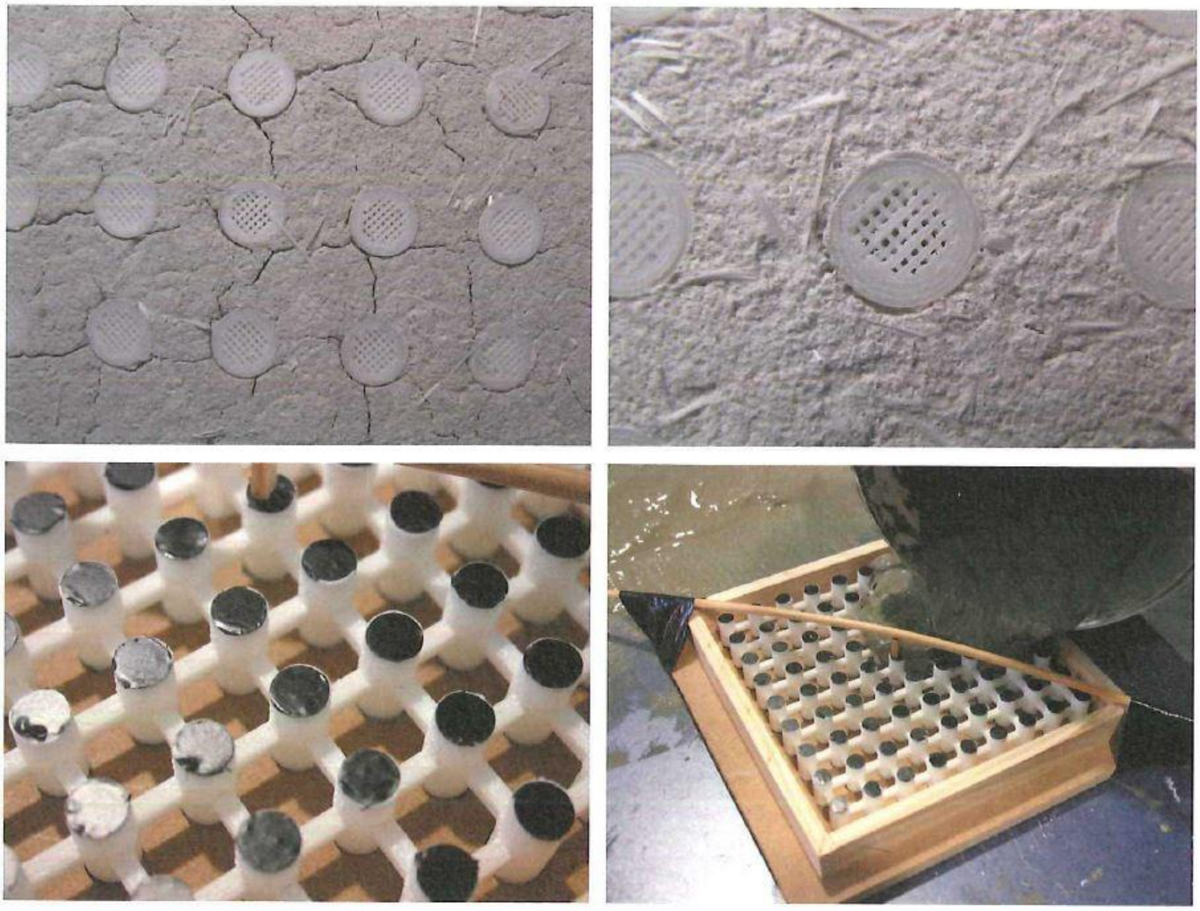


Figure 60: A breathing concrete wall and how it is made (Knaack et al., 2011a)

5.5.2 Micro-shingles

Micro-shingles is a concept based on a pinecone, which opens and closes its *shingles* based on the weather conditions. When it is sunny, the pinecone is open and air is able to flow through and disperse seeds. When it is rainy, the pinecone closes and is water tight. If a building structure could do the same, it could have natural ventilation with sunny weather, while being closed when it is raining outside.

Various plants have cones that work in the same way as the pinecone, such as the blue spruce (*Picea pungens*). However, a vertical garden containing these plants would not create the same effect, unless all the plants function in a very specific way. Therefore, this idea seems not practical.

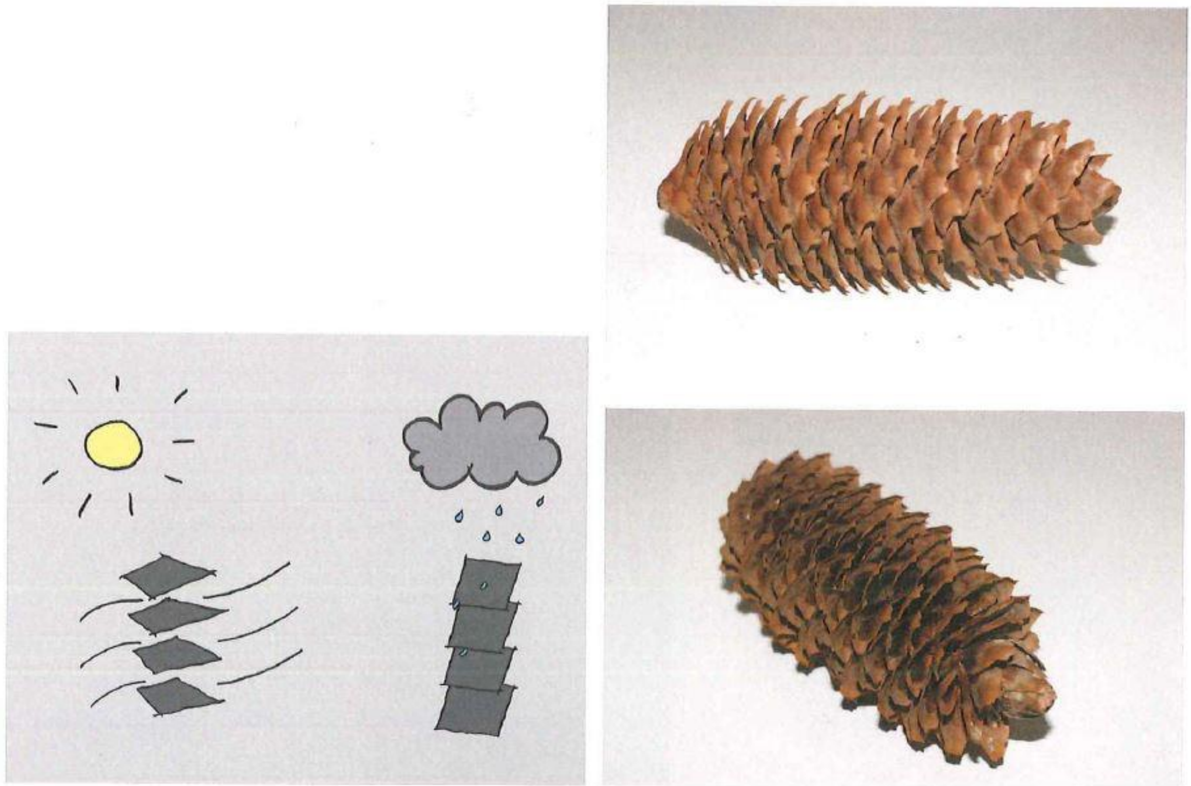


Figure 61: Principe of a façade made out of micro-shingles (Knaack et al., 2011a)

5.5.3 Titanium dioxide coating

Titanium dioxide (TiO_2) is commonly used as pigment and has received a reputation for its self-cleaning and germicidal qualities. A new technology uses the nano-photovoltaic version of this titanium dioxide coating, which breaks down and neutralizes NOx (nitrogen oxides) and VOCs (volatile organic compounds) into harmless amounts of carbon dioxide and water when positioned near pollution sources. To do this, the coating requires small amounts of naturally occurring UV light and humidity.

The superfine coating is used on modular tiles with a high surface area, optimizing the technology and capturing omni-directional light, where light is dense or scarce. These modules are made out of a lightweight thermoformed fire-rated ABS-plastic shell with standard steel fixings. An example of a building where these modules are used as façade cladding is the Torre de Especialidades, a hospital in Mexico City. (elegant embellishments limited, 2014)

This technology seems ideal to function along with living wall systems. First of all because it strengthens the air quality and secondly because this technology requires a humidity which could be provided by nearby plants. Lastly, the titanium dioxide coating releases carbon dioxide, which could then function as a supplement for plants. This carbon dioxide is then turned into oxygen by these plants.

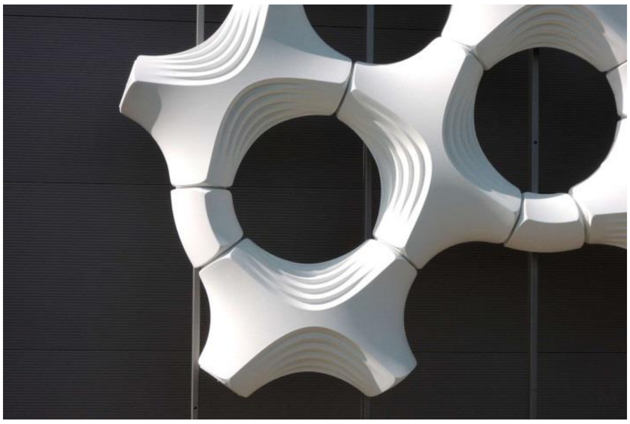


Figure 62: Façade of the Torre de Especialidades in Mexico City (Cartagena, 2013)

Figure 63: Titanium dioxide coated modules (Cartagena, 2013)

5.6 Innovations regarding insulation properties

5.6.1 Active insulation

Instead of having solid insulation, the insulation of your house could retract and extend in the summer- and wintertime. This could be done with printed microstructures. Mounting vertical green on the façade would make the structure a lot heavier, which would become quite the challenge. For this idea to work together with vertical green, soil would act as the insulation layer, making the challenge even harder. It is possible, but these ideas will probably offer more disadvantages than advantages.

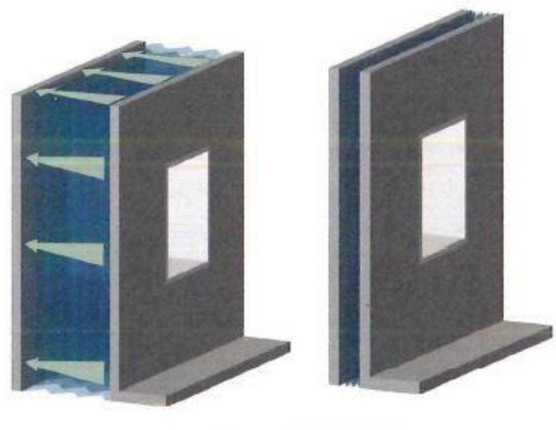


Figure 64: Principle of active insulation (Knaack, Klein, & Bilow, 2011b)

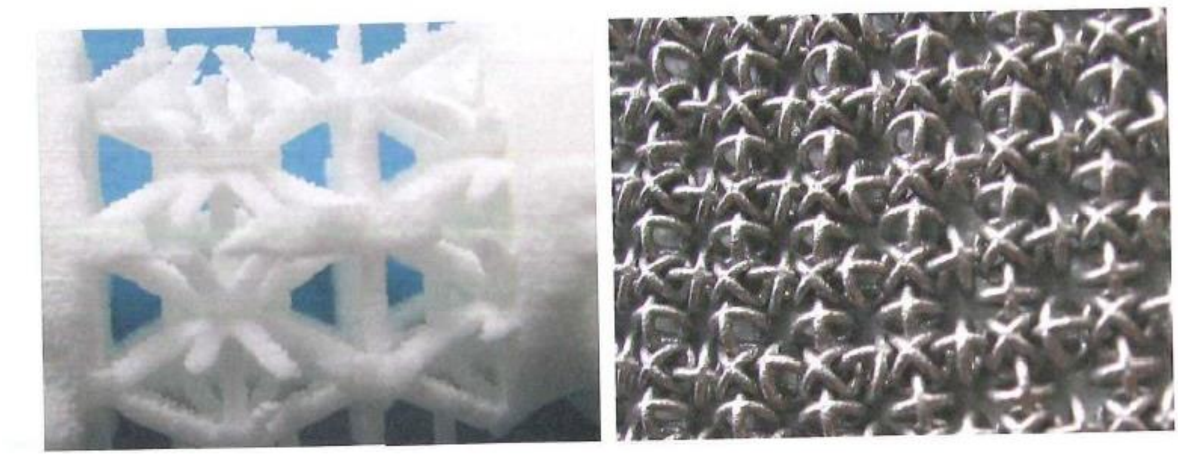


Figure 65: Microstructures that could be used as a material for active insulation (Knaack et al., 2011b)

5.6.2 Suspended cavity

A bulky façade element with an air cavity has no spacers. Instead the cavity is filled with a vacuum, which works as an insulation layer. The vacuum creates a tension, but this is absorbed by the outside construction.

Façades with vacuums and plants do not mix well together, but perhaps it could works as two different layers. The bulky shape of this façade element makes for an interesting vertical garden.

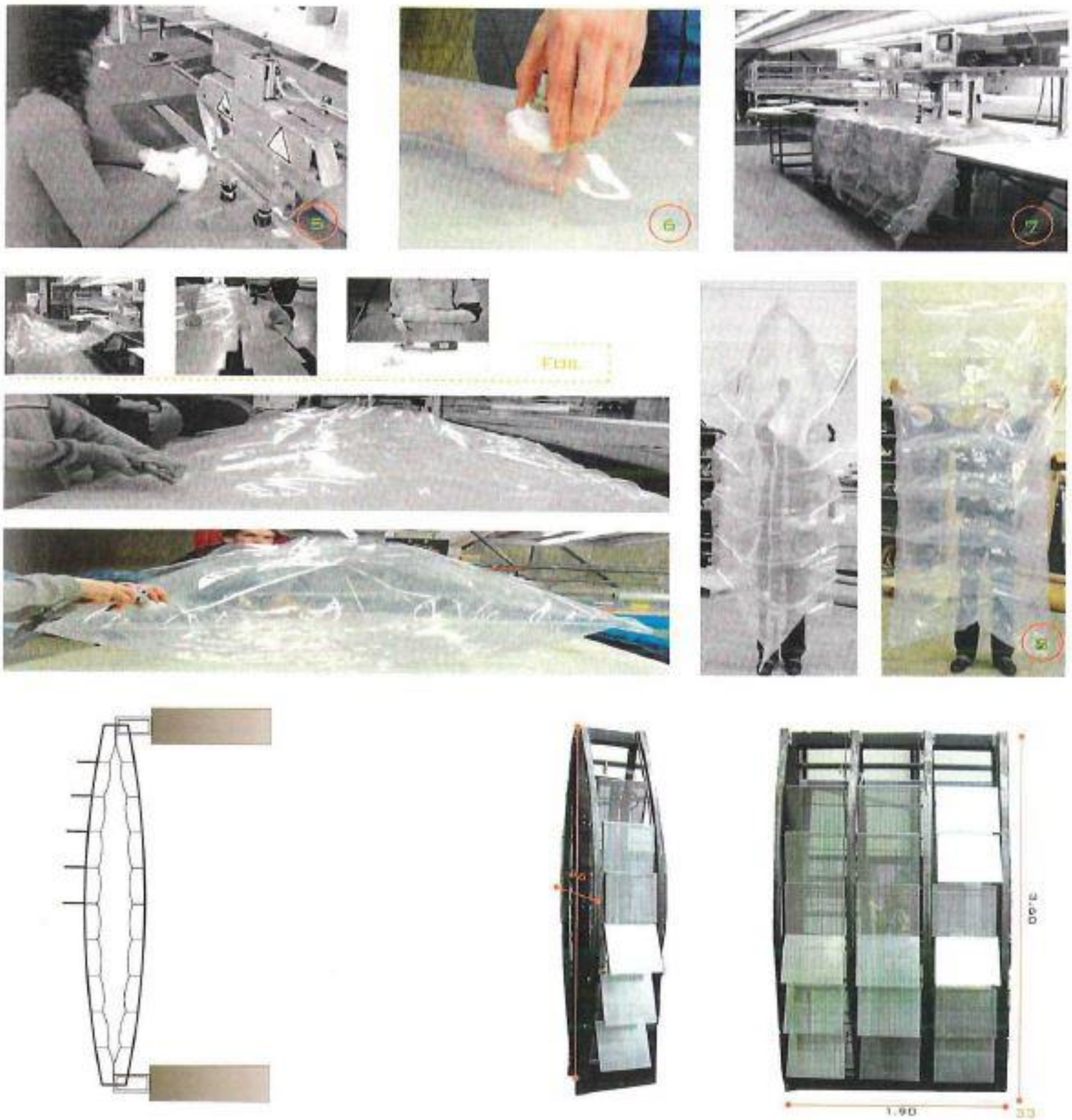


Figure 66: A suspended cavity façade and how it is made (Knaack et al., 2008)

5.6.3 Vacu-bam

This type of façade is very simplistic, one of its strong points. It consists of just vertical bamboo columns with two layers of transparent foil on the outside. In between the foils, a vacuum is created for insulation.

The bamboo seems like a nice component to use with vertical green. However, again the vacuum is an important part of the design. A vertical garden could be placed on the outside, but the construction would probably be too heavy.

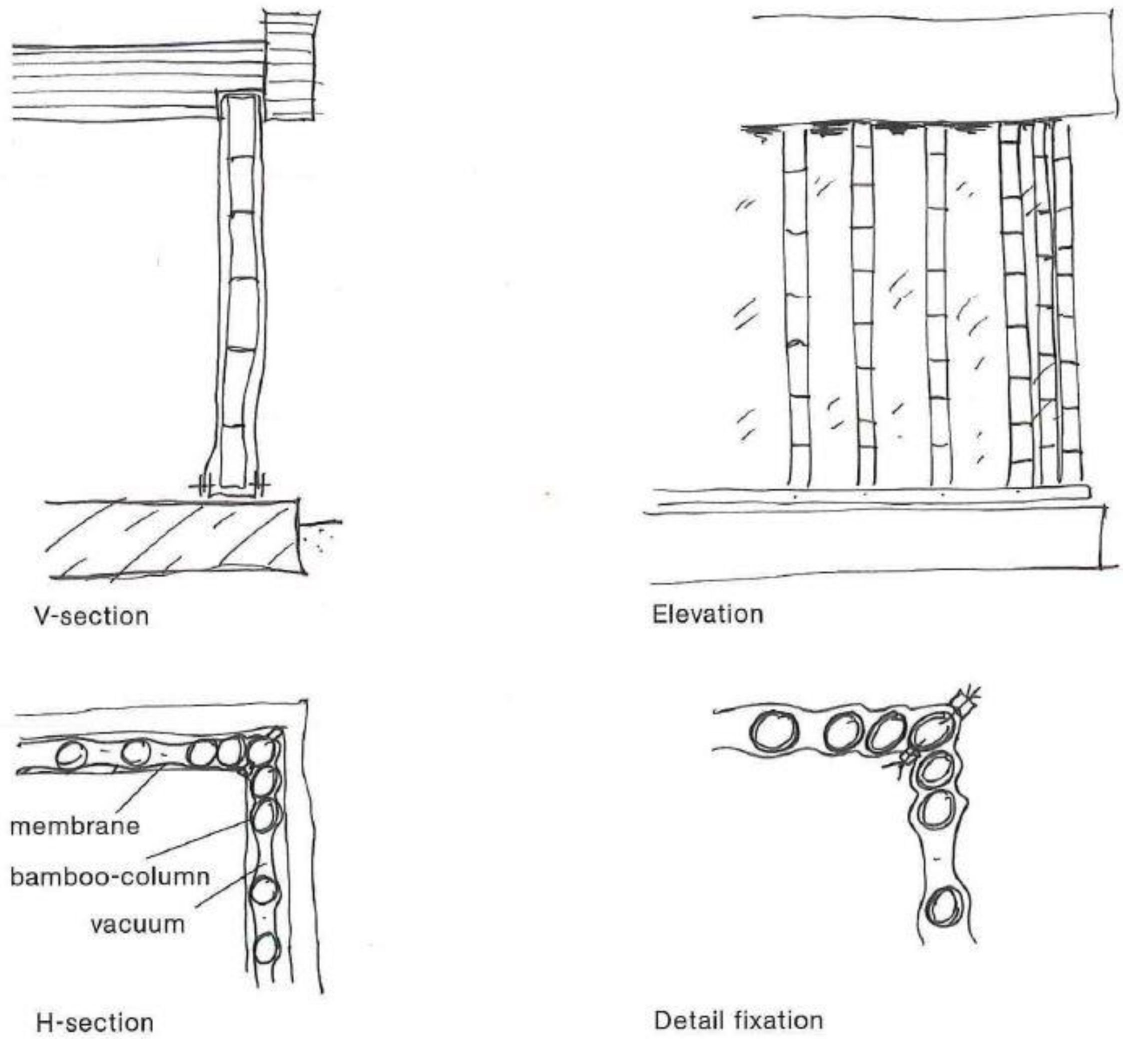


Figure 67: Principle of a vacu-bam façade (Knaack et al., 2008)

5.7 Conclusion and useful innovations

This chapter reviewed a set of innovations that extended modularity or benefitted from living wall systems. The workings of these innovations have been explained along with if these innovations could be used in combination with living wall systems. To conclude this chapter, all useful innovations will be listed that could be used in the design process. The following innovations are marked as useful:

Useful innovations regarding modular façades:

- Honeycomb façades
- Deflated glass hexahedron façade
- Matrix façade
- Solid unitized wall

Useful innovations regarding modular connections:

- Snap joints
- Tango point holders

Useful innovations regarding the acclimatization of temperature:

- Humidity driven ground water cooling

Useful innovations regarding improving air quality:

- Breathing concrete and natural ventilation
- Titanium dioxide coating

Useful innovations regarding insulation properties:

- Suspended cavity

These innovations will eventually be an important part of the design process, in which some of these innovations will be used to create fully modular living wall system. However, the first steps of the design process will be made using conclusion of researching the current living wall systems on the market. This research is explained in chapter 6.

6. SYSTEM ANALYSIS

6.1 Introduction on the system analysis of living wall systems

In this chapter a system analysis is made of the Living wall systems available on the Dutch market. By researching living wall systems that are currently on the market, various things can be learned. What are common materials used for building living wall systems? How do these systems function in their modularity? What is currently lacking in the vertical green market? These questions cannot be answered with literature research and that's why a system analysis is needed.

Another important aspect of this chapter is the insight in what sustainable materials to use when designing a living wall system. In most cases, when a building receives vertical green, it is because sustainability is an important aspect of the building design. A living wall system that is not sustainable is not interesting to implement. Therefore, sustainability on a material level is researched in this chapter.

For each system type one or two living wall systems are investigated on the elemental level, component level and material level in terms of material properties and material connections. This is done using the method of Circular Design. Circularity implies that a material or product should be:

- Of high quality (functional performance)
- Of sustainable origin (mining method, mining close to use, production method)
- Non-harmful (healthy for people and the environment)
- Recyclable and/or biodegradable.

The conditions mentioned above are the intrinsic properties of the material or product (Geldermans & Rosen Jacobson, 2015). Beside this one, it can be separated into three relational properties which indicate the relation between the products/materials and affect the serviceability and reusability of the material/product. According to the Municipality of Rotterdam, 2015 (p. 15) these relational properties are:

- Dimensions (possibilities of customization)
- Connections (demountability & separability)
- Performance time (lifespan)

The elements will be checked for dimensions, demountability and lifespan. All elements will be divided in various components (the bearing structure, the substrate and if present, the protection layer and water retaining layer). These components will be checked for reusability and separability in materials. All materials will be checked for harmfulness and possibility to be recycled and or biodegraded.

Drawn from the literature, a few deviations will be made in this Thesis:

1. The quality of the materials is not considered here, but only the materials used are mentioned. In this case it is assumed that the quality of the materials/products already fulfill the requirements needed for its function as the products are already on the market. For now the lifespan communicated by the supplier will be used as an indication of the products serviceability and thus overall material endurance and functional performance. In the design phase the material/product quality will be examined further, as the chosen quality depends among others on the dimensions, functional properties and styling of the final design.
2. The materials/products sustainable origin is omitted, although it is an important property, it would be a project in itself to identify materials of a sustainable origin. In the further developments this should be addressed.
3. The performance time (lifespan) discussed in this Thesis will only be related to the product on elemental level, as this is often mentioned by the supplier as a certain guarantee of life expectancy. The lifespan on material level and therefore component level are dependent on different factors such as the exposure to different media in relation to the location and fatigue. Even within the Netherlands the environmental circumstances vary a lot. Therefore lifespan on material/component level could only be taken into account if a case study is used, but this does not fall within the context of this Thesis.

A few Living wall systems, at least one of every type, will be explained in detail. The general properties of a LWS will be stated. The LWS will be separated into different components. All the materials of a component are listed and the will be tested on their harmfulness as well as their circular flow. The following icons will be used to explain the circularity of the materials:

H = Healthy. The material is not harmful to either people or the environment.

H = Not healthy. The material is harmful to either people or the environment, or in the worst case scenario both.

F = Can return into material flow. The material is either recyclable or biodegradable. It can return to the technical cycle or the material cycle.

F = Cannot return into material flow. The material is neither recyclable nor biodegradable. It cannot return to either the technical cycle or the material cycle.

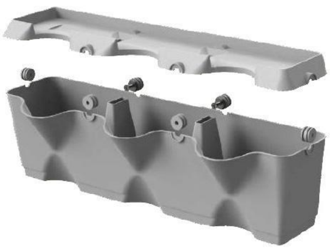
Finally, a detailed description of the LWS will be given, in which extra attention is given in how the system is build.

The chapter concludes with a comparison of the systems that have been researched in detail in both general properties as well as circularity.

6.2 System analysis

6.2.1 Minigarden by Minigarden

System type: Planter boxes
System warranty[1]: 3 years
Expected lifespan[2]: 20 years
Dry weight[3]: 31 kg/m²
Saturated weight[4]: 43 kg/m²
Indicative water consumption indoor[5]: ~
Indicative water consumption outdoor[5]: ~
Average yearly plant losses[5]: ~



Components	*Material 1*
1. Minigarden vertical module	Polypropylene Moplen (UV-resistant) (7,82 kg/m²) (0,09 m³/m²) *
2. Substrate	Potting soil (23,22 kg/m²) (0,08 m³/m²)

* Harmful to aquatic organisms when dumped in water

1 (Minigarden, 2016)
2 The expected lifespan of the system is based on the material with the shortest lifespan, in this case the polypropylene. See appendix K: Material list. In the determination of the expected lifespan, the substrate is not taken into account.
3 This value is based on a module size of 646x200mm (LxH)). Weight is incl. Minigarden vertical module and dry substrate consisting of 100% potting soil. Weight is excl. Plants, gutter (Minigarden baseplate), drainage pipe, irrigation system, irrigation lines, supporting system (wall support and wall fixers) and edge finishing (Minigarden, 2016).
See for detailed calculations appendix C: Calculations Minigarden.
4 Weight is dry weight incl. saturation of 50% of the potting soil (assumed saturation).
See for detailed calculations appendix C: Calculations Minigarden.
5 Can vary, depending on care taken by the private owner, type of plants and positioning (e.g. north, east, south, west).

The Minigarden is a system based on planter boxes, aimed towards the private user. However, it is also suitable for commercial use. The main element is actually similar to that of a normal planter box, but it has an additional lid on top. You can buy them in a set of 1, 3 or 8 planter boxes with a corresponding baseplate. As one module can be bought separately, a combination of modules can also be made of 1, 2, 3, 4 and so on. When positioned on the ground the modules can be stacked on top of each other to a maximum of ten. This is about 2 meter high and thus lower than the difference between two floors, this can be increased by adding wall supports. The standard module (a single planter box) is 200 mm high, 190 mm deep and 646 mm wide.

The planter boxes have notches on the front, back and sides. These notches can fit into mounting clips, which are made out of the same material as the planter boxes, and are used to connect the container to the top plate (see the picture of component 3). The mounting clips have a hole, in which bolts, nails, other connection elements or the dripping line fit. The mounting clips at the back can be used to fixate the planter boxes to the wall by means of wall fixers. So the planter boxes will not tip over. These wall fixers need to be applied when stacking more than five modules, if so the modules need to be attached by these wall fixers for every other module. The wall fixers themselves can be attached with screws, nails or double-sided tape. The mounting clips on the side can be used for a dripping line to enter and exit. An irrigation system is offered separately by the Minigarden Company, but other irrigation systems can also be used.

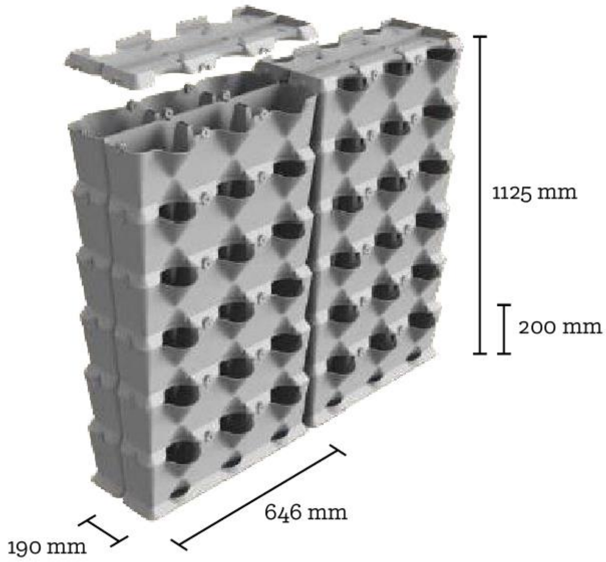
The modules are mounted to the back wall by means of wall supports. One support per baseplate can only carry four vertical modules or if one baseplate is supported by two wall supports a max of nine can be stacked. The wall brackets are not fixed to the elements, but only support them. Ofcourse another supporting structure can also be applied.

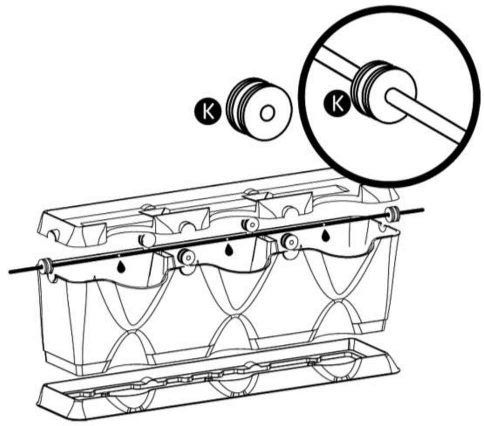
The element (Minigarden module) is made out of one material: polypropylene Moplen with UV-protection. The wall fixers and the wall support are also made out of this same material. Polypropylene is fully technically recyclable and not harmful to people and the environment. Only the bolts, nails or other connection elements that are needed for the connection to the wall are made out of another material.

The baseplate has to be placed on a flat surface and is not properly designed to drain excess water. When standing on the ground it will be difficult to empty the water basin, since the weight of the modules is on the baseplate. To prevent water rise at the bottom planter box, it is advised to use hydro grains for optimal drainage. A drainage layer is recommended in all the boxes by Minigarden anyhow. Because the system is designed for private use, the Minigarden Company only offers a three year guarantee.

Both components are completely separable. However, the substrate is not reusable, which takes account for a large portion of the weight. The only two materials used are polypropylene, which is recyclable, and potting soil, which is biodegradable. Therefore, this system is completely made out of circular materials.





1125 mm
200 mm
646 mm
190 mm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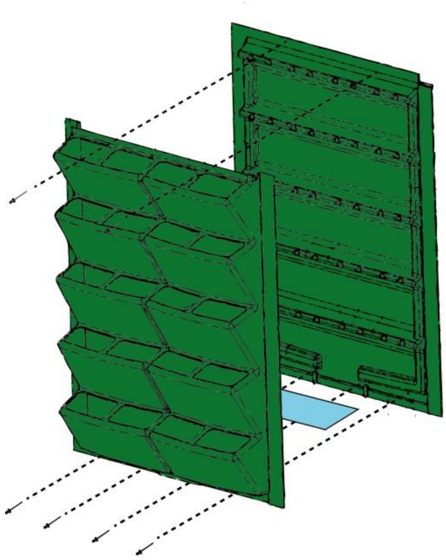
6.2.2 Modulogreen by Mostert de Winter



System type:	Planter boxes
System warranty[1]:	10 years
Expected lifespan[2]:	+20 years
Dry weight[3]:	29 kg/m²
Saturated weight[4]:	39 kg/m²
Indicative water consumption indoor[5]:	0.3 Liter / m² / day
Indicative water consumption outdoor[5]:	0.6 Liter / m² / day
Average yearly plant losses:	5%

Components	*Material 1*	*Material 2*	*Material 3*	*Material 4*	*Material 5*	*Material 6*
1. Modulo-green module	PP GF30 (9,62 kg/m²) (8,44 * 10^{-3} m³/m²) * H F	Geotextile (0,03 kg/m²) (2,94 * 10^{-4} m³/m²) H F	EPDM (0,12 kg/m²) (1,35 * 10^{-4} m³/m²) * H F			
2. Substrate	Sunterra Reg. Peat (1,43 kg/m²) (3,57* 10^{-3} m³/m²) H F	Coarse Peat (0,48 kg/m²) (1,19* 10^{-3} m³/m²) H F	Lignocell Coco Chip (0,19 kg/m²) (1,19* 10^{-3} m³/m²) H F	Perlite (0,11 kg/m²) (1,19* 10^{-3} m³/m²) H F	Pumice (3,05 kg/m²) (4,76 * 10^{-3} m³/m²) H F	Red Scoria (volcanic rocks) (14,28 kg/m²) (1,19* 10^{-2} m³/m²) H F

* Harmful to aquatic organisms

1 (Mostert de Winter, 2016a, 2016b)
2 The expected lifespan of the system is based on the material with the shortest lifespan, in this case the geotextile. See appendix K: Material list. In the determination of the expected lifespan, the substrate is not taken into account.
3 This value is based on a module size of 807x900mm (LxH)). Weight is incl. Modulogreen module and dry substrate consisting of 5% Coarse Peat, 5% Lignocell Coco Chip, 5% Perlite, 20% Pumice, 50% Red Scoria and 15% Sunterra reg. peat. Weight is excl.: Plants, gutter, drainage pipe, irrigation system, irrigation lines, supporting system and edge finishing (ByNature, 2015). See for detailed calculations appendix D: Calculations Modulogreen.
4 Weight is dry weight incl. saturation of the water absorption of the substrate (max saturation) (ByNature, 2015). See for detailed calculations appendix D: Calculations Modulogreen.
5 (ByNature, 2015)

Modulogreen is a planter box system made from reinforced polypropylene (30% glass fibre). The rectangular modules are available in widths of 300mm, 600mm and 900mm (containing 1, 3 or 4 planter boxes in a row), which are common building measurements. The height of the module can also vary and is available in 237 mm, 427 mm or 807 mm (containing 1, 2 or 4 planter boxes in the column). The depth of a module is always 178 mm. The modules are repetitive and overlap each other only in the vertical direction, so excess water can flow to the ground.

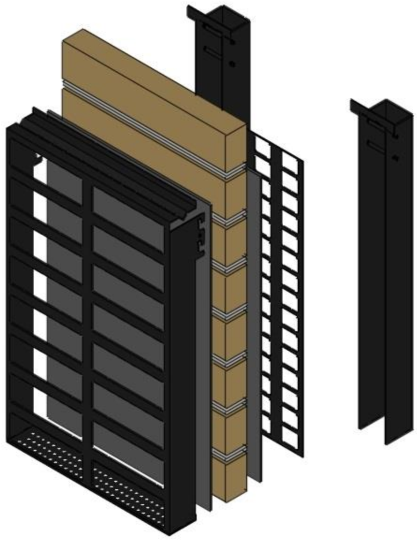
The modules are mounted on the back wall via an aluminum or wooden supporting structure (aluminum profiles or timber studs) on which they are attached to by means of stainless steel screws with an EPDM gasket.

The modules themselves are made out of two sheets of polypropylene reinforced with 30% glass fibre (PP-R). These sheets are fitted together with rivets at the sides. The sides are sealed off by an EPDM rubber, so water cannot exit the planter box panels at the flanks. The rivets are made out of the same material as the modules (PP-R). Because of the rivets this component (the module) is not demountable, as the EPDM cannot be removed without tearing apart the PP-R panels. However the two different materials (PP-R and EPDM) can both be recycled, for this the whole module will be shredded separating the EPDM and PP-R afterwards.

Irrigation is done by a dripping line, which fits into a notch at the top of the planter box modules. A dripline connector can be placed between the modules, to make sure the dripping line is connected thoroughly. This option is not a necessity. Thanks to the shape of the planter boxes, water is guided from the top of the element, through multiple planter boxes, before leaving it at the bottom of the element. A filter layer, a geotextile is placed into the planter box at the bottom of each module in order to prevent fine pieces of the substrate from clogging the system. Additional water will flow to a steel gutter. In addition granules can be added at the bottom for proper drainage.

The substrate recommended by the company is fairly light, making this a system with an overall low weight. Additionally, the system has a Cradle to Cradle silver certification, which complies with the circular design ideals. However, the Modulogreen module is not demountable and therefore not reusable. The Modulogreen module also contains a geotextile, which is very unlikely to be recyclable. However, this geotextile just takes up a small fraction of the total weight. The substrate also contains various materials that are not able to return into the material flow.

6.2.3 CultiWall by Saint-Gobain Cultilene B.V.



System type:	Panel system: mineral wool
System warranty[1]:	5 years
Expected lifespan[2]:	+10 years
Dry weight[3]:	16 kg/m²
Saturated weight[4]:	22 kg/m²
Indicative water consumption indoor:	~
Indicative water consumption outdoor[5]:	1.7 L/m² /day
Average yearly plant losses:	2-3%

Components	*Material 1*	
1. Cassette (front & rear plate)	Powder coated steel ($13,17\ kg/m^2$) ($1,67 * 10^{-3}\ m^3/m^2$) H F	Stainless steel ($0,03\ kg/m^2$) ($3,18 * 10^{-6}\ m^3/m^2$) H F
2. Substrate protection	Geotextile ($0,34\ kg/m^2$) ($3,80 * 10^{-3}\ m^3/m^2$) H F	
3. Interlayer	Recycled foam (polyurethane) ($0,13\ kg/m^2$) ($4,74 * 10^{-3}\ m^3/m^2$) H F	
4. Substrate	Stonewool ($2,25\ kg/m^2$) ($6,30 * 10^{-2}\ m^3/m^2$) H F	

1 This is the warranty on the module only; warranty on the irrigation system is 2 years.
2 The expected lifespan of the system is based on the material with the shortest lifespan, in this case the wet stonewool. See appendix K: Material list. In the determination of the expected lifespan, the substrate is not taken into account.
3 This value is based on a module size of 600x1,000mm (LxH)). Weight is incl. cassette, protection layer, water retention layer and dry substrate consisting of 100% stonewool. Weight is excl.: Plants, gutter, drainage pipe, irrigation system, irrigation lines, supporting system and edge finishing. See for detailed calculations appendix E: Calculations CultiWall.
4 Weight is dry weight incl. water absorption by the stonewool and recycled foam. See for detailed calculations appendix E: Calculations CultiWall.
5 This value is an average of the default irrigation settings and one case study reference. At the default irrigation settings the irrigation system delivers 1.4 L/m²/day, a reference case in London consumes 2 L/m²/day (outdoor LWS). The actual water consumption will vary per LWS, depending on type of plants, season, location and positioning (e.g. north, east, south, west).

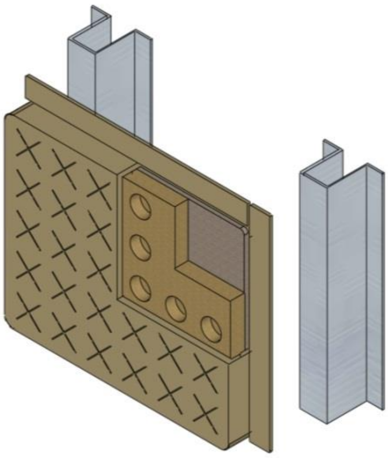
The main principle of the Cultiwall is steel cassettes with stonewool inside them, which makes it a system based on mineral wool. Stonewool is chosen, since water can easily be controlled when flowing through it. The stonewool has cylindrical holes to contain plants along with a bit of soil. The soil functions as the starting substrate for the plants, but eventually they will root into the stonewool. The stonewool consists of 8 blocks stacked vertically, between every two blocks an interlayer of recycled cloth is placed (7 in total). In front and at the back of the stonewool and interlayers a geotextile is placed to prevent the water from leaking out of the cassette. The cassettes are 250, 500, 750 or 1000 mm in height, 300 or 600 mm in width and 135mm in depth. They are hung onto rails of the same steel materials.

The stonewool and the geotextiles aren't connected in any way, but they're held together by the steel cassette. The steel cassette consists of two parts, the actual cassette in which the stonewool and geotextiles can be placed and a back plate, which closes the system. To close the cassette, two stainless steel screws are fixed at the sides of the cassettes (per 25 cm), which makes this system very easy to separate.

Every cassette has fixations at the top to place a dripping line for irrigation. The water that is distributed is slowed down when flowing through the stonewool, due to interlayers between every row of plants. These interlayers make sure the water does not fall down too fast, so that plants can take their optimal amount of water and there is almost no drainage water. However, a gutter still has to be placed. Cultilene uses a web based irrigation system. As soon as the outdoor temperature drops below 0.5° C, air is forced through the drainage pipes on high pressure to clean them. This way, the drainage pipes aren't able to freeze. The entire irrigation process is monitored by the company.

Due to the use of these steel cassettes, the structure is fairly heavy for a mineral wool based system. This also decreases the flexibility of the system. However, it does show potential to evolve into a fully self-supporting system. All components are fully separable and only the substrate is not reusable. There is a non-circular material used, the geotextile, but this material is only a small portion of the total weight.

6.2.4 Flexipanel by Sempergreen



System type:	Panel system: mineral wool
System warranty:	10 years
Expected lifespan[1]:	+10 years
Dry weight[2]:	9 kg/m²
Saturated weight[3]:	28 kg/m²
Indicative water consumption indoor:	1.5 Liter / m² / day
Indicative water consumption outdoor:	1.5 Liter / m² / day
Average yearly plant losses:	4%

Components	*Material 1*	*Material 2*
1. Rear plate	TPO (2,59 kg/m^2) (2,77 * 10^{-3} m^3/m^2) *	
2. Substrate bag	Polypropylene (UV-resistant) * (3,29 kg/m^2) (3,65 * 10^{-3} m^3/m^2)	Polyamide * (2,45 * 10^{-2} kg/m^2) (2,17 * 10^{-5} m^3/m^2)
3. Capillary layer	Recycled cloth (0,55 kg/m^2) (8,34 * 10^{-3} m^3/m^2)	
4. Substrate	Stonewool (2,23 kg/m^2) (5,58 * 10^{-2} m^3/m^2)	

* Harmful to aquatic organisms when dumped in water

[1] The expected lifespan of the system is based on the material with the shortest lifespan, in this case the polyamide. See appendix K: Material list. In the determination of the expected lifespan, the substrate is not taken into account.
[2] This value is based on a module size of 600x500mm (LxH)). Weight is incl. rear plate, protection layer, water retention layer and dry substrate consisting of 100% stonewool. Weight is excl.: Plants, gutter, drainage pipe, irrigation system, irrigation lines, supporting system (aluminium omega profiles) and edge finishing. See for detailed calculations appendix F: Calculations Flexipanel.
[3] Weight is dry weight incl. water absorption by the stonewool and recycled cloth. See for detailed calculations appendix F: Calculations Flexipanel.

Sempergreen is a panel system based on a mineral wool substrate. The element exists of a substrate bag sewed to a TPO rear plate. The element has fixed dimensions, of which the TPO rear plate is 720mm wide and 620mm tall. The substrate bag is 620 mm wide, 520 mm tall and 60 mm thick. The elements overlap each other both horizontally and vertically. A smaller panel can be custom made.

The TPO rear plate has four holes for fixation by means of stainless steel bolts (M8x30) to the supporting system: aluminum omega profiles (center to center 620mm). The aluminum styles facilitate an air cavity of 300 mm, if a drainage pipe needs to be placed behind the panels this can be bigger.

The substrate bag is made from UV-resistant polypropylene (lifespan 20 years) sewed together with nylon yarn. This nylon yarn is also used to fix the substrate bag to the rear plate. In the bag thirty cut-outs have been made to insert the plants: Five vertically and six horizontally. The plants are inserted with a bit of soil still on the roots. The plants will obtain their nutrients from the irrigation that flows at the backside of the element through a water absorbing layer made from recycled cloth. The recycled cloth encases a stonewool substrate, which is designed not to saturate with water. It keeps the plants in place. All materials are recyclable except for the nylon yarn.

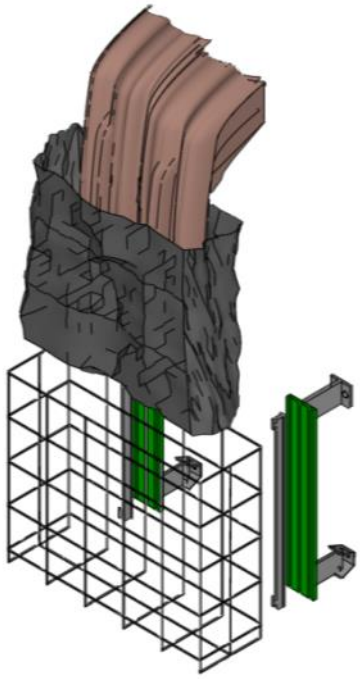
The panels are irrigated by means of a web based irrigation systems, which will be aerated during winter time. The dripline is located between the capillary layer and the substrate bag. Only the capillary layer is moistened, thus the water is not directed through the stonewool. The substrate bag is also made as such that water cannot enter the stonewool substrate, so the indoor environment of the panel can be fully controlled.

The Flexipanel is the only panel which can be used on curved walls. The TPO rear plate is flexible and bendable. Although it seems likely that felt layer systems could be applied on curved walls as well, they have a rigid rear plate. Therefore they need to be customized for application on curved walls.

In addition it is tested that the Flexipanel will have a sound reduction of 5 dB indoors and the element has fire prevention class B-S2, D0. Where B means difficult to ignite, S2 means limited smoke production and d0 means no droplets. This means that with regard to fire safety, the Flexipanel can be placed everywhere inside or outside a building, there are no restrictions.

The Flexipanel is very flexible and light, because of its materials. Due to the use of a lot of materials such as cloth and wool, only the rear plate is a reusable component. However, all the components are separable and the system only contains circular materials.

6.2.5 90 Green by The Vertical Green Company



System type:	Panel system: other
System warranty:	10 years
Expected lifespan[1]:	+20 years
Dry weight[2]:	27 kg/m^2
Saturated weight[3]:	37 kg/m^2
Indicative water consumption indoor:	~
Indicative water consumption outdoor[4]:	2.7 L /m^2 /day
Average yearly plant losses:	~

Components	*Material 1*	*Material 2*
1. Wire basket	Stainless steel (2,88 kg/m^2) (3,64 * 10^{-4} m^3/m^2)	
2. Substrate bag	Polyethylene (2,10 kg/m^2) (2,22 * 10^{-3} m^3/m^2) *	Polyester (9,42 * 10^{-3} kg/m^2) (7,73 * 10^{-5} m^3/m^2) *
3. Substrate	Urea – formaldehyde polymer (0,75 kg/m^2) (3,73 * 10^{-2} m^3/m^2)	Potting soil (20,78 kg/m^2) (6,93 * 10^{-2} m^3/m^2)

* Harmful to aquatic organisms when dumped in water

[1] The expected lifespan of the system is based on the material with the shortest lifespan, in this case the polyethylene. See appendix K: Material list. In the determination of the expected lifespan, the substrate is not taken into account.
[2] This value is based on a module size of 500x430mm (LxH)). Weight is incl. wire basket, protection layer and dry substrate consisting of 65% potting soil and 35% urea-formaldehyde polymer. Weight is excl. Plants, gutter, drainage pipe, irrigation system, irrigation lines, supporting system and edge finishing. See for detailed calculations appendix G: Calculations 90Green.
[3] Weight is dry weight incl. saturation of 75% of the urea–formaldehyde polymer (max saturation) and saturation of 50% of the potting soil (assumed saturation). See for detailed calculations appendix G: Calculations 90Green.
[4] This value is based on one reference. The actual water consumption will vary per LWS, depending on type of plants, season, location and positioning (e.g. north, east, south, west).

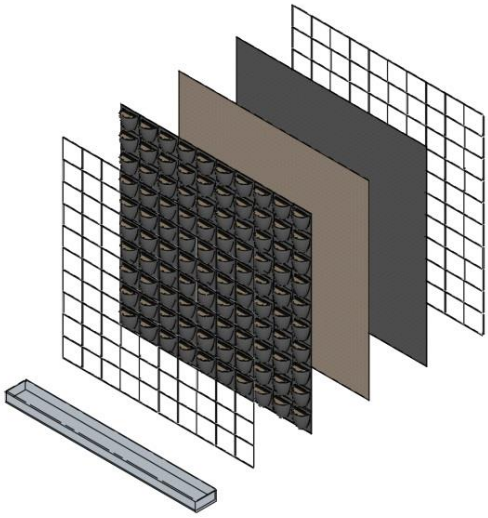
The 90 Green system used to be a fully foam based system with plants growing into a foam substrate block. This evolved over time into a system in which plants grow into a substrate of soil mixed with foam granules, as it appeared to be difficult to remove plants and thus maintain the wall when the roots got intertwined with the foam block. The mixed substrate is held together by a bag which is positioned in a wire frame basket. The entire element is 505 mm long, 15 mm deep and 430 mm high (which are the dimensions of the wire frame basket). The shape of the system provides good aesthetics in terms of plant coverage.

The basket is fixed with four hanging rails with wedge-shaped hooks to the back wall. These hanging rails are made out of stainless steel. Irrigation is provided with dripping lines placed on top of the substrate bags.

The substrate bag is made out of polyethylene sewed together with polyester threads and the wire frame basket is made out of stainless steel. The substrate is a mixture of potting soil and a foam called Fytocell. It is made out of Ureum – Aminoplast, which is much lighter than potting soil. A substrate made out of only foam granules is also possible, but as Fytocell does not offer any nutrients for the plants, supplementary feeding will be needed. A maximum concentration of 35% fytocell is advised however, for optimal plant growth.

The strength of this system lies in the substrate. Fytocell makes the total weight of the systems much lighter. The substrate can also be bought separately so it can be used in other systems. It should be noted that the Fytocell releases formaldehyde, which is irritating to the eyes, skin and respiratory tract. Another material that should be prevented from using is the polyester thread, since it cannot return to the material flow. However in this system, the polyester only takes up a small portion of the total weight. The separability and reusability are also not optimal, since the substrate bag cannot be separated and only the iron basket can be reused.

6.2.6 Muurtuin by Muurtuin



System type:	Felt layers
System warranty:	10 years
Expected lifespan[1]:	+10 years
Dry weight[2]:	20 kg/m²
Saturated weight[3]:	50 kg/m²
Indicative water consumption indoor:	0.6 L /m² /day
Indicative water consumption outdoor:	2.5 L /m² /day
Average yearly plant losses:	10%

Components	*Material 1*	*Material 2*
1. Frame	Iron (5,81 kg/m^2) (7,54 * 10^{-4} m^3/m^2) H F	
2. Textile	Geotextile (0,45 kg/m^2) (5,00 * 10^{-3} m^3/m^2) H F	
3. Water detention layer	Stonewool (0,20 kg/m^2) (5,00 * 10^{-3} m^3/m^2) H F	
4. Substrate	Humus (4,18 kg/m^2) (7,42 * 10^{-3} m^3/m^2) H F	Red Scoria (volcanic rocks) (8,91 kg/m^2) (7,42 * 10^{-3} m^3/m^2) H F

* Harmful to aquatic organisms when dumped in water

[1] The expected lifespan of the system is based on the material with the shortest lifespan, in this case the wet stonewool. See appendix K: Material list. In the determination of the expected lifespan, the substrate is not taken into account.
[2] This value is based on a module size of 600x600mm (LxH)). Weight is incl. frame, protection layer and water retention layer and dry substrate consisting of 50% humus and 50% volcanic rock. Weight is excl.: Plants, gutter, drainage pipe, irrigation system, irrigation lines, supporting system and edge finishing. See for detailed calculations appendix H: Calculations Muurtuin.
[3] Weight is dry weight incl. water absorption by the stonewool, saturation of 50% of the humus (assumed saturation) and saturation of 70% of the volcanic rock (assumed saturation). See for detailed calculations appendix H: Calculations Muurtuin.

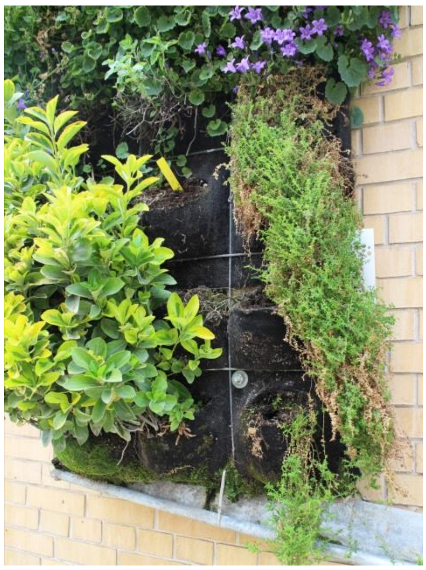
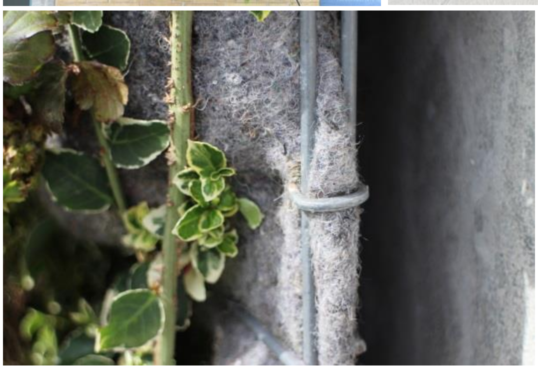
The Muurtuin system is a felt system that also uses mineral wool. The plants are still placed with the substrate inside pockets of a textile layer. There are two textile layers, which form a bag. In this bag, a layer of mineral wool is placed, but this one is purely for the distribution of water. In some cases, the mineral wool is replaced with X. There is an iron grating which functions as the structural layer at both the front and the back of the textile bag.

Muurtuin has two different systems; hanging and free standing. In this analysis the hanging facade is examined. The hanging systems have modules available with a width of 600 mm or 1200 mm. The height is always 2000 mm and the thickness is always 30 mm. The textile layer contains pockets of 200 mm x 200 mm.

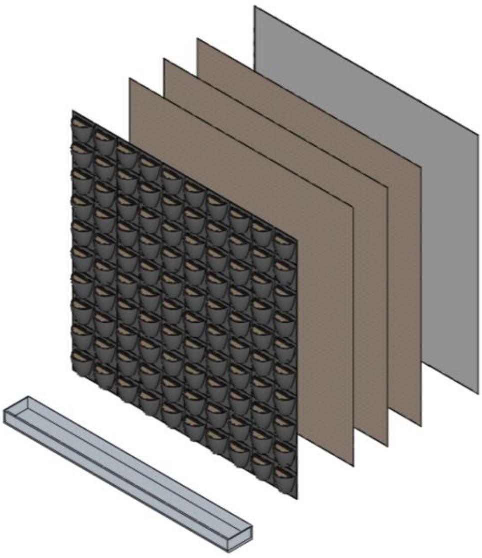
The Muurtuin system is flexible, much like the other felt systems. Installation can even be done by the consumer himself to save on costs. Modules can fitted onto the back wall by using plugs and bolts that are sloped downwards in such a way that water flows towards the module and not the back wall. A dripping line is placed on top of the module and a gutter is placed at the bottom.

The textile layer is made out of geotextile, which is commonly not recyclable. This is unfortunate, because it is one of the main materials used in this element. Another problem is the substrate. The type of substrate can vary according to the plants used, but with the Muurtuin system it commonly contains pumice and /or red scorcia, which both are not recyclable. However, both materials are very durable and reusable in their current shape, so the recyclability of these materials will not be of great concern. All components are completely separable. The iron frame is the only component that is reusable.



6.2.7 Plantwall by Green Fortune



System type:	Felt layers
System warranty:	2 years
Expected lifespan[1]:	+10 years
Dry weight[2]:	24 kg/m^2
Saturated weight[3]:	41 kg/m^2
Indicative water consumption indoor:	3.0 L /m^2 /day
Indicative water consumption outdoor:	1.4 L /m^2 /day
Average yearly plant losses[4]:	5%

Components	*Material 1*	*Material 2*
1. Rear plate[5]	Aluminum * (2,71 kg/m^2) (1,00 * 10^{-3} m^3/m^2)	Polyethylene * (2,37 kg/m^2) (2,50 * 10^{-3} m^3/m^2)
2. Textile	Polyester (including yarn) (12,21 kg/m^2) (1,00 * 10^{-2} m^3/m^2)*	
3. Water detention layer	Recycled cloth (1,97 kg/m^2) (3,00 * 10^{-2} m^3/m^2)	
4. Substrate	Potting soil (4,40 kg/m^2) (1,47 * 10^{-2} m^3/m^2)	

* Harmful to aquatic organisms when dumped in water

[1] The expected lifespan of the system is based on the material with the shortest lifespan, in this case the wet recycled cloth. See appendix K: Material list. In the determination of the expected lifespan, the substrate is not taken into account.

[2] This value is based on 1m^2 Plantwall. Weight is incl. rear plate, protection layer, water retention layer and dry substrate consisting of 100% potting soil. Weight is excl.: Plants, gutter, drainage pipe, irrigation system, irrigation lines, supporting system and edge finishing. See for detailed calculations appendix I: Calculations Plantwall.

[3] Weight is dry weight incl. water absorption by the recycled cloth and saturation of 50% of the potting soil (assumed saturation). See for detailed calculations appendix I: Calculations Plantwall.

[4] In the determination of the average yearly plant losses, the destruction by the vine weevil is not taken into account. Plant losses due to the vine weevil are prevented nowadays by using a different type of plant species.

[5] Alucobond® composite panel (two layers of aluminium and one layer of polyethylene, type LDPE in between). PVC foam is also used, but mainly indoors.

The Plantwall from Green Fortune is a felt system. This particular system has four layers of which three layers are made out of recycled clothing and the outer layer is made out of polyester. The outer layer of recycled cloth and the outer polyester layer has pockets which contain the plants and soil. The felt layers have a maximum width of 1500 mm and a maximum height of 3000 mm. These layers have pockets with a width of 205 mm and a height of 180 mm. The system has a total thickness of 43,5 mm.

The textile layers are stitched together and nailed and screwed onto the rear plate. For outdoor application this rear plate is an Alucobond® composite panel, which is a sandwich element that has two aluminum outer layers and a core of low density polyethylene (LDPE). For indoor application a PVC foam plate is used as rear plate. The whole element is then screwed onto the supporting structure.

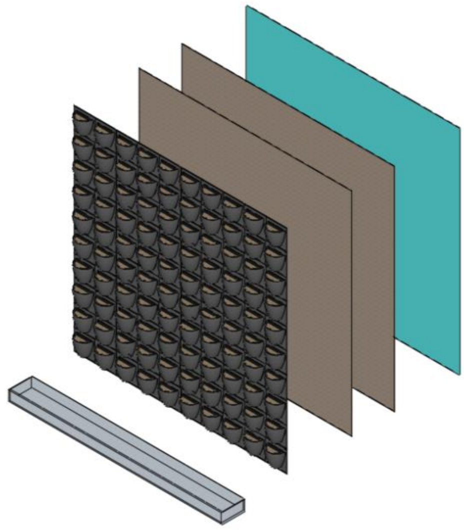
Irrigation pipes with a diameter of 12 mm are placed underneath the polyester layer. The pipes dispense water with nutrients for the plants. The substrate used in the Plantwall consists of potting soil, coco peat, perlite and ceramic substrate. This substrate is lighter than normal soil, but it is mainly used because of its high retention of water. Excess water is caught by the gutter placed beneath the system, made out of stainless steel.

Although the Plantwall uses prefabricated modular mats, it is not an actual prefabricated system. Most of the work is done on-site, which does make this system very flexible. However, the textile layers and the gutter are prefabricated. The polyester and the gutter can be recycled after they have been used as a living wall system, while the recycled textiles cannot. The recycled cloth in addition is equipped with layers of unidentified plastic (presumably PET), also other plastics are interwoven. It is unclear how these materials can be recycled. The Alucobond® composite panel can be recycled, by delaminating the layers. The separate materials can then be refined and melted into new products; however the process will lead to residues of glues and paints.

The Alucobond® panel is the only component that is reusable. All other components do not have this ability, but they can all be separated into materials. The only non-circular material is polyester, but it takes up a large part of the total weight.



6.2.8 Wonderwall by Copijn



System type: Felt layers
System warranty: 10
Expected lifespan[1]: +10 years
Dry weight[2]: 11 kg/m²
Saturated weight[3]: 19 kg/m²
Indicative water consumption indoor: ~
Indicative water consumption outdoor[4]: 5.0 L /m² /day
Average yearly plant losses[5]: 5-10%

Components	*Material 1*	
1. Rear plate	PVC foam * H F (4,00 kg/m^2) (1,00 * 10^{-2} m^3/m^2)	
2. Textile	Polypropyleen * H F (1,35 kg/m^2) (1,50 * 10^{-3} m^3/m^2)	Stainless steel * H F (4,96 * 10^{-4} kg/m^2) (6,27 * 10^{-8} m^3/m^2)
3. Water detention layer	Recycled cloth H F (0,79 kg/m^2) (1,20 * 10^{-2} m^3/m^2)	
4. Substrate	Potting soil H F (4,40 kg/m^2) (1,47 * 10^{-2} m^3/m^2)	

* Harmful to aquatic organisms when dumped in water

The Wonderwall of Copijn is a felt layer system, from synthetic felt. The maximum dimensions for the felt are 3000 mm by 1200 mm, which is only limited by its production. However, the patches can overlap both vertically as horizontally to cover any area needed. The pocket size is 150 mm in both width and height. The total thickness of the system is 27,

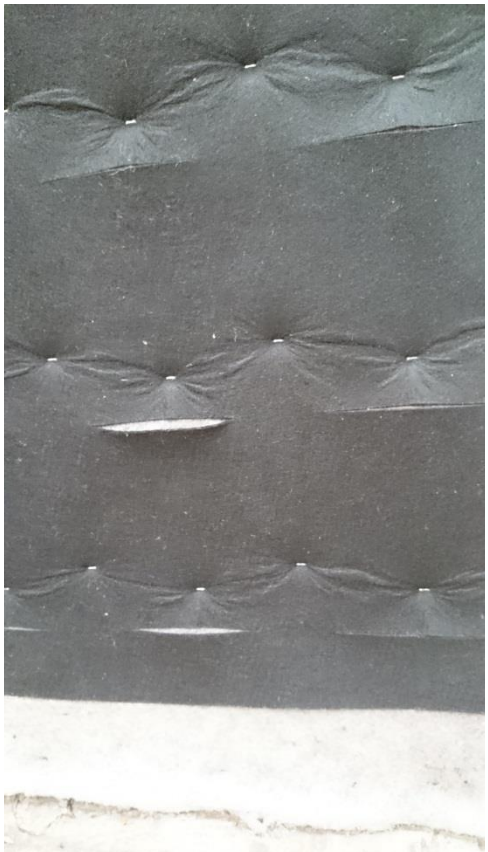
[1] The expected lifespan of the system is based on the material with the shortest lifespan, in this case the wet recycled cloth. See appendix K: Material list. In the determination of the expected lifespan, the substrate is not taken into account.
[2] This value is based on 1m² Wonderwall. Weight is incl. rear plate, protection layer, water retention layer and dry substrate consisting of 100% potting soil. Weight is excl.: Plants, gutter, drainage pipe, irrigation system, irrigation lines, supporting system and edge finishing. See for detailed calculations appendix J. Calculations Wonderwall.
[3] Weight is dry weight incl. water absorption by the recycled cloth and saturation of 50% of the potting soil (assumed saturation). See for detailed calculations appendix J. Calculations Wonderwall.
[4] This value is an average of the irrigation in summer and winter. During summer (25 degrees Celsius) the irrigation system delivers 8 L/m²/day, while in winter the irrigation system delivers 2 L/m²/day (this is above freezing point). The actual water consumption will vary per LWS, depending on type of plants, season, location and positioning (e.g. north, east, south, west).
[5] This value is strongly dependent on the type of winter: a very cold winter can lead to plant losses of 15%, whereas the last couple of years the losses were only 3-5%.

5 mm. The benefit of felt layers is that they are easy to adapt to any size/form needed at the building site.

In a case of a brick wall the felt system is mounted on profiled steel plates (stainless steel, galvanized or powder coated) which are attached to the bearing wall. If mounted on concrete a vapour barrier is placed on the wall on which wooden boards are attached, the felt system is then mounted to these wooden plates.

The pocket system consists of three layers. The two inner layers are made from recycled cloth (some plastics seem to be intertwined) and the outer layer is made from Polypropylene. The black outer layer is UV-resistant. The felt layers are stapled to a 3,4 mm foam plate made from PVC. The staples are estimated to be made out of stainless steel.

The panels of Copijn are prefabricated, by doing so the pocket sizes can be dimensioned consistently. But the major advantage is that the system still allows freedom of form at the building site itself. All materials used and assumed are healthy for people and the environment and they are all recyclable or biodegradable. However, the rear plate is only component that is entirely reusable when the system is removed.



6.3 Conclusion system analysis

The conclusion is split up into four parts. In the first part, the researched systems will be compared on various measurable factors such as circularity, weight and water consumption. This can be seen as the product of quantitative research. The second part will show all the materials used in the researched living wall systems and presents what materials could be used in the design process. Thirdly, the systems will be compared on the dimensions of a single module, which gives an idea of what dimensions to use in the design process. Lastly, other general findings will be presented. These general findings are the results of communicating with various manufacturers of LWS and can be seen as the products of qualitative research.

6.3.1 Comparison systems

This part of the chapter compares the LWS on measurable factors and forms a conclusion out of these comparisons. The systems will be compared on factors that are deemed the most important for the design phase, namely circularity, weight, water consumption, price and lifespan. Results can be found in table 2.

Element		Minigarden	Modulogreen	Cultiwall	Flexipanel	90 Green	Muurtuin	Plantwall	Wonderwall
System type		Planter boxes		Panel system (mineral wool)		Panel system (other)	Felt layers		
Guarantee	[Years]	3	10	5	10	10	10	2	10
Expected lifespan	[Years]	20+	20+	10+	10+	20+	10+	10+	10+
Dry weight	[kg/m2]	31	29	16	9	27	20	24	11
Saturated weight	[kg/m2]	43	39	22	28	37	50	41	19
Indicative water consumption indoor	[L/m2/day]	~	0.3	~	1.5	~	0.6	3.0	~
Indicative water consumption outdoor*	[L/m2/day]	~	0.6	1.7	1.5	2.7	2.5	1.4	5.0
Average yearly plant loses	[%]	~	5	2-3	4	~	10	5	5-10

Table 2: Comparison on general properties of living wall systems

*Water consumption at temperatures below 0° was not taken into account, no water is distributed at these temperatures.

Modularity

Since all elements have been divided into components and materials, it is now clear how many components are separable, how many are reusable and how many materials are circular. In graph 3 the results have been converted to percentage, which gives an idea of the modularity of the system.

The graph makes clear that planter boxes have the highest percentage of reusable components. This is due to the fact that planter boxes do not have the need for cloth or mineral wool for the plants to be rooted in, which cannot be reused. There is no system that reaches a 100% with reusability, because all systems use a substrate and substrates can never be reused. The same goes for water detention layers, which are present in mineral wool systems and felt layers. For this reason, felt layer systems have the lowest score in reusability.

All systems that use a single type of substrate score a 100% on separability. The Modulogreen, 90 Green and Muurtuin systems, because they all have a substrate made out of multiple materials. The Modulogreen system and the 90 Green system also have two other components that cannot be separated, the Modulogreen module and the substrate bag respectively.

The Minigarden system has the best overall score, mainly because it is made out of a low number of different materials. Due to the simplicity of its design, it has the best score.

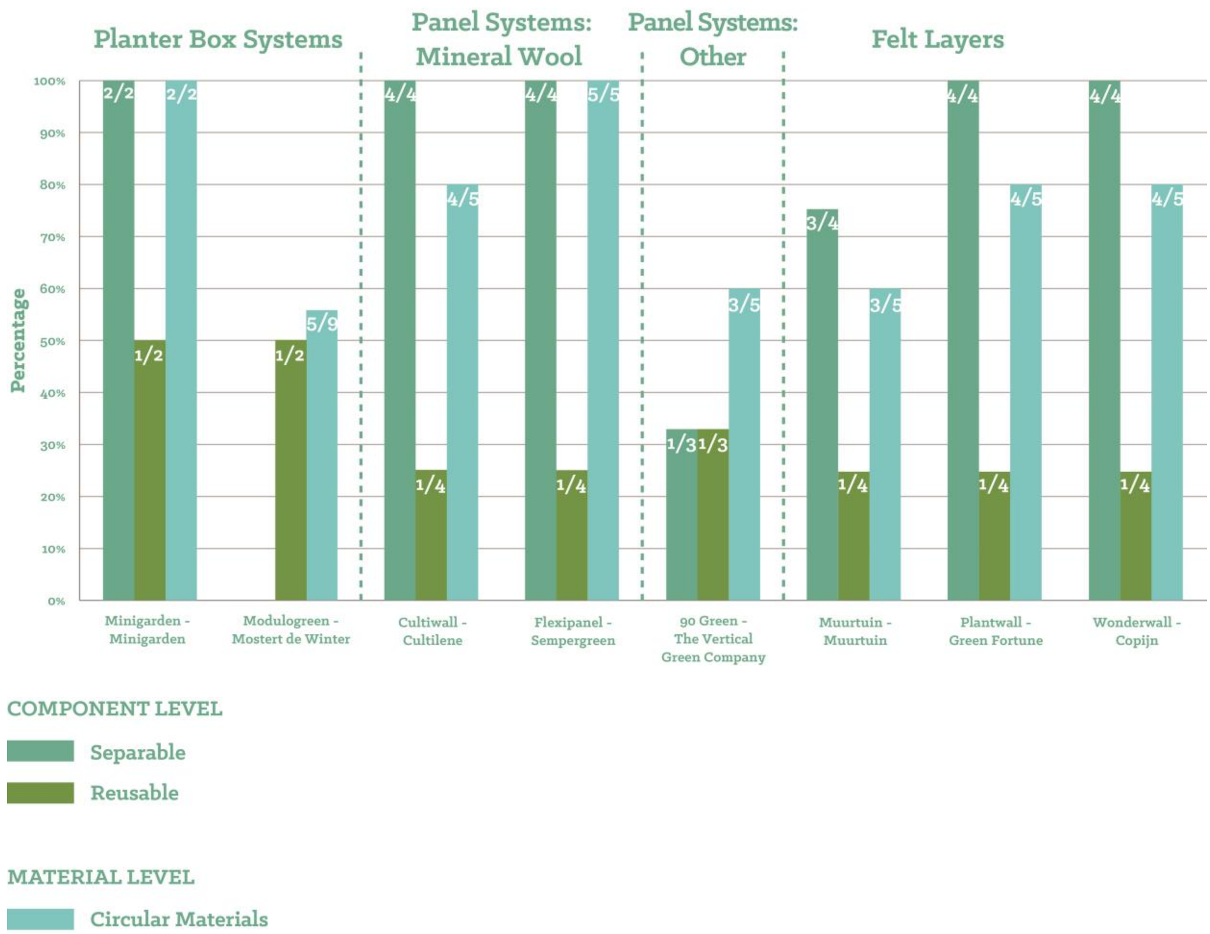


Table 3: Comparison on circularity

Circularity

To make an a clear point about circularity, all systems will be compared on the same factors as modularity, but the weight of the materials used per m^2 will be taken into account. In the previous graph, the circular materials used in a system would be presented as a percentage of the total amount of materials. In graph 4, the weight of circular materials is presented as a percentage of the total weight. If a system uses a non-circular material, but is only a small portion of the weight, it will still receive a high score in circular materials. According to NIBE classification, the weight is a guiding factor in circularity since the weight of a non-circular material defines: the energy needed for processing the material, the energy needed for transportation and the energy needed to process potential waste (Haas, 1996). The same calculation will be used to present the weight of the separable and reusable components as a percentage of the total weight.

In this graph we can see that Cultiwall has the highest reusability. The only non-reusable material is the mineral wool, which has a light weight. The separability has not changed much when compared to the previous graph.

Three systems score very low on circular materials; Modulogreen, Muurtuin and Plantwall. Modulogreen and Muurtuin both use Red Scorcia or volcanic rock in their substrate, which is a non-circular material which accounts for a lot of the weight. Modulogreen also uses pumice, which is roughly the same material. Plantwall has a low score because the structural pocket layer is made out of polyester.

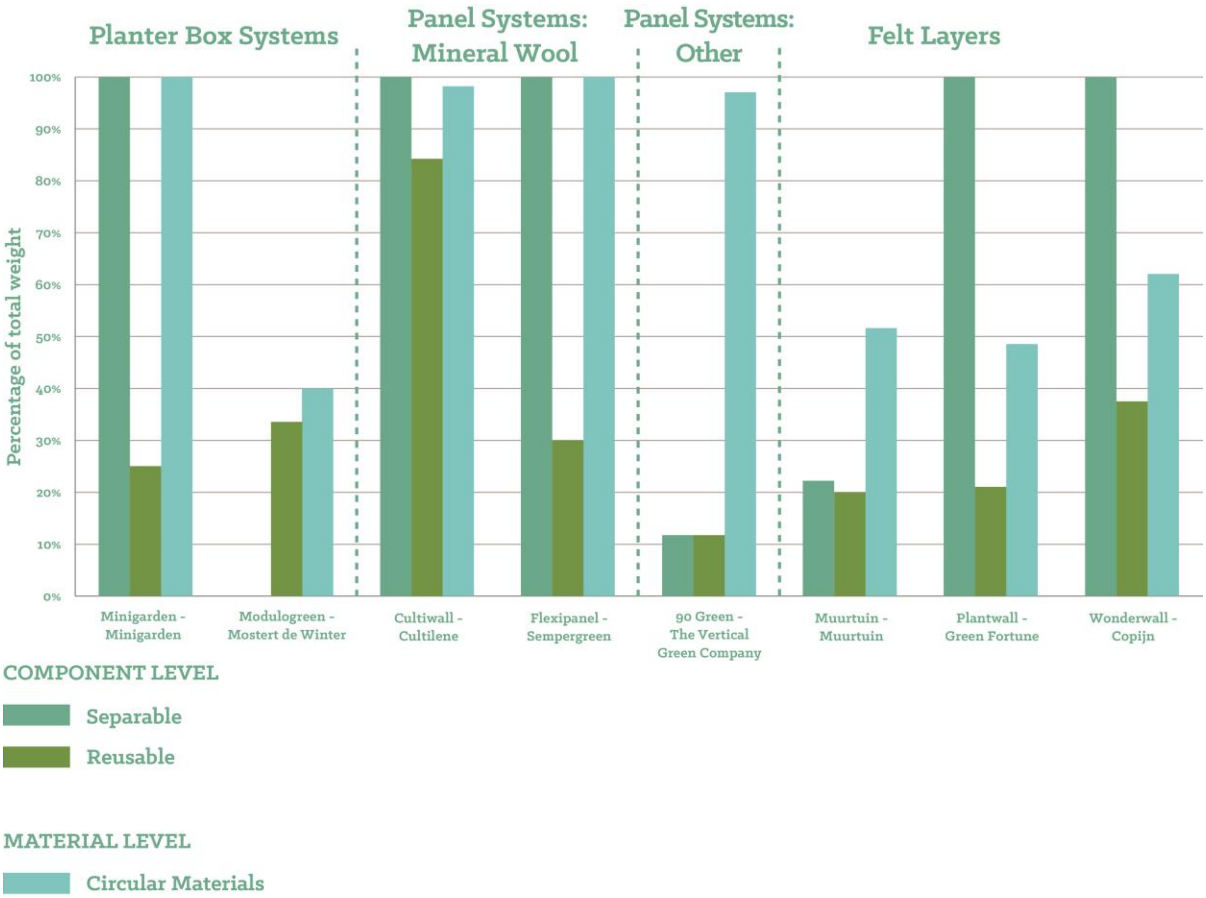


Table 4: Comparison on circularity

Weight

Weight is an important factor for façade systems. Heavy façade cladding perhaps couldn't be mounted on a wooden façade structure, as this would create stresses in the wood that would destroy the structure. However, all systems can be placed on a concrete structure.

When looking at graph 5, we can see a ranking in weight in the four different types of systems. Felt systems and mineral wool based systems are the lightest. Planter boxes and panel systems that do not use mineral wool are heavier, because all systems in these categories use a lot of soil. The type of substrate used is indicative of the total weight.

Felt systems are fairly light unless they're saturated, due to cloth and wool absorbing a lot of the water in the systems. The exception is the Wonderwall, which is one of the lightest systems. This is because the Wonderwall system has no heavy structural elements made out of steel and uses only two layers of recycled cloth.

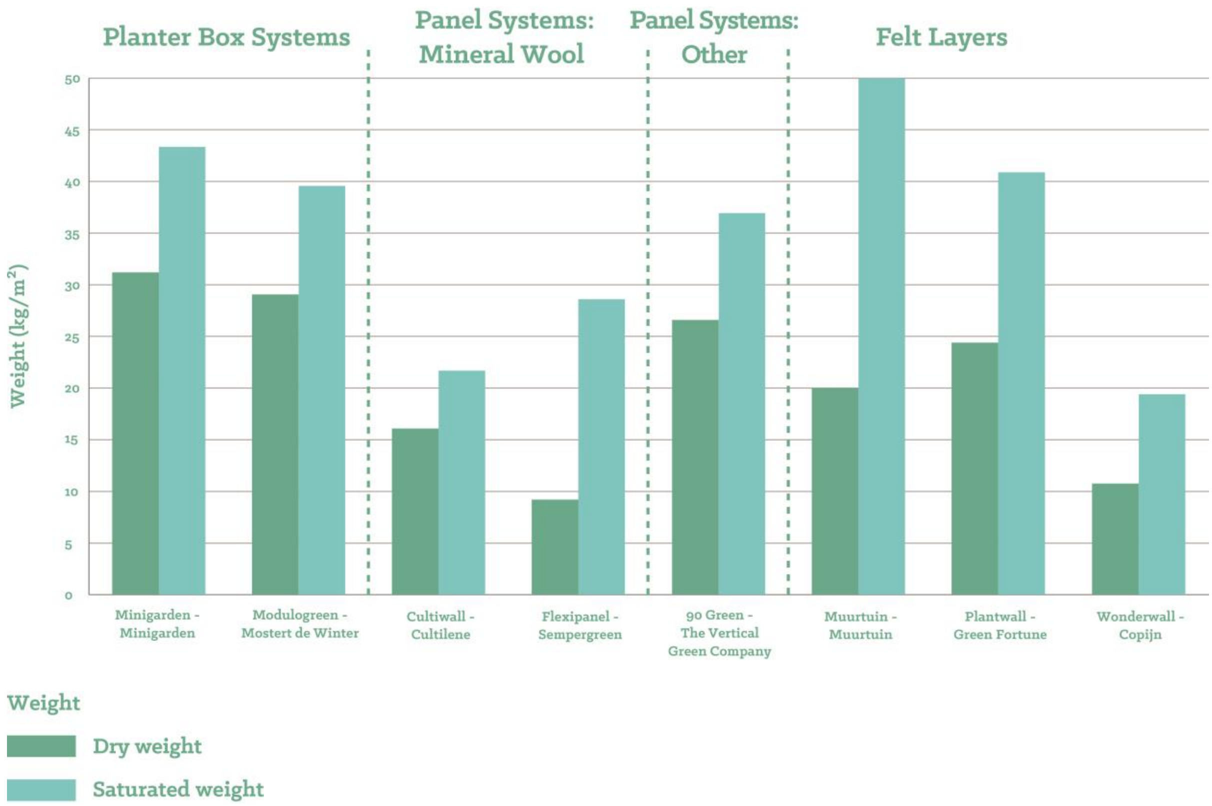


Table 5: Comparison on weight

Water consumption
The water consumption is also an important factor of a living wall system. After all, the less water a system needs, the better this will be for the environment and the user. There is a clear ranking in water consumption of the various systems noticeable in graph 6. Unfortunately, there is not enough data available to compare all the systems, especially on indoor water consumption. For this reason the outdoor water consumption will be the focus. In this scenario, the planter boxes systems have the lowest water consumption, followed by panel systems using mineral wool and lastly the other panel system and the felt layers systems.

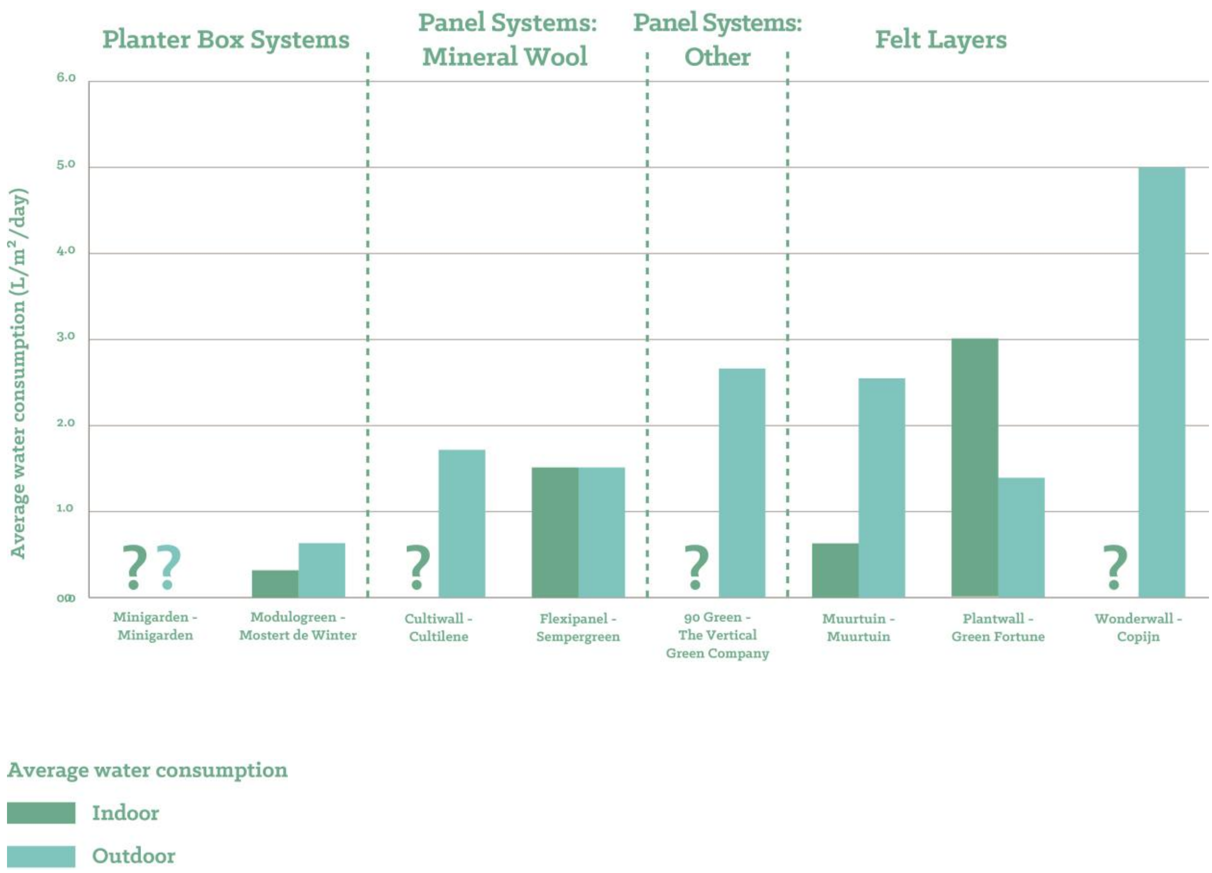


Table 6: Comparison on water consumption

Lifespan
It is also notable that felt layer systems have a slightly lower lifespan than all the other system types. The lifespan is lower, because the felt layer systems use a lot of cloth, which has a fairly low lifespan. The same goes for the Flexipanel system. These systems have a suspected lifespan which is higher than 10 years. Al other systems have a suspected lifespan higher than 20 years.

6.3.2 Materials

This paragraph will classify all materials used in the researched LWS. These materials will be categorized into materials that can easily be used, materials that should be used with caution and materials that should be avoided in the design process. This is done by checking the materials on harmfulness and their material flow. A complete list of all materials and their harmfulness and material flow can be found in appendix K: Material list.

Materials to use

These materials in living wall systems cause no harm to both people and they environment and are able to return in either the biological or technical cycle. Therefore, these materials are recommended to design with.

Metals

Iron
Steel (Galvanized)
Steel (powder coated)
Steel (stainless)

Substrates

Humus
Lignocell coco chip
Peat
Potting soil
Stonewool

Textiles

Recycled cloth (painter fleece)

Plastics

None

Materials to use with caution

These materials in living wall systems need to be used in caution. All of these materials are either toxic to aquatic organisms or could harm aquatic organism due to their inability to biodegrade. Therefore, when using these materials, supervision is needed to make sure these materials return to their technical lifecycle and are not accidentally discarded into the ocean.

Metals

Aluminum
Aluminum (coated)
Copper

Substrates

None

Textiles

None

Plastics

EPDM
Polyamide (PA)
Polybutylene (PB-1)
Polyethylene (PE)
Polypropylene (PP)
Polypropylene (PP) (glass fibre reinforced)
Recycled foam (polyurethane)
TPO

Materials not to use

These materials that are used in living wall systems either harm people or the environment or are in no way able to return to their material flow. It is recommended to refrain from using these materials. If there is no alternative to using these materials, the usage should be kept to an absolute minimum.

Metals

None

Substrates

Perlite
Pumice
Red scoria (volcanic rocks)
Urea - Formaldehyde Polymer

Textiles

Geotextiles

Plastics

Polyester
PVC foam

6.3.3 Dimensions of modular elements

An important aspect of modular design is the dimensions of a single modular element. The dimensions should be designed in such a way that a single element is applicable in as many scenarios as possible. This means the element should be as small as possible. At the same time, a smaller element could also lead to more connections, materials or connecting elements, which would have a negative effect on the price of an element. Therefore it is important to research the dimensions of the living wall systems on the current market.

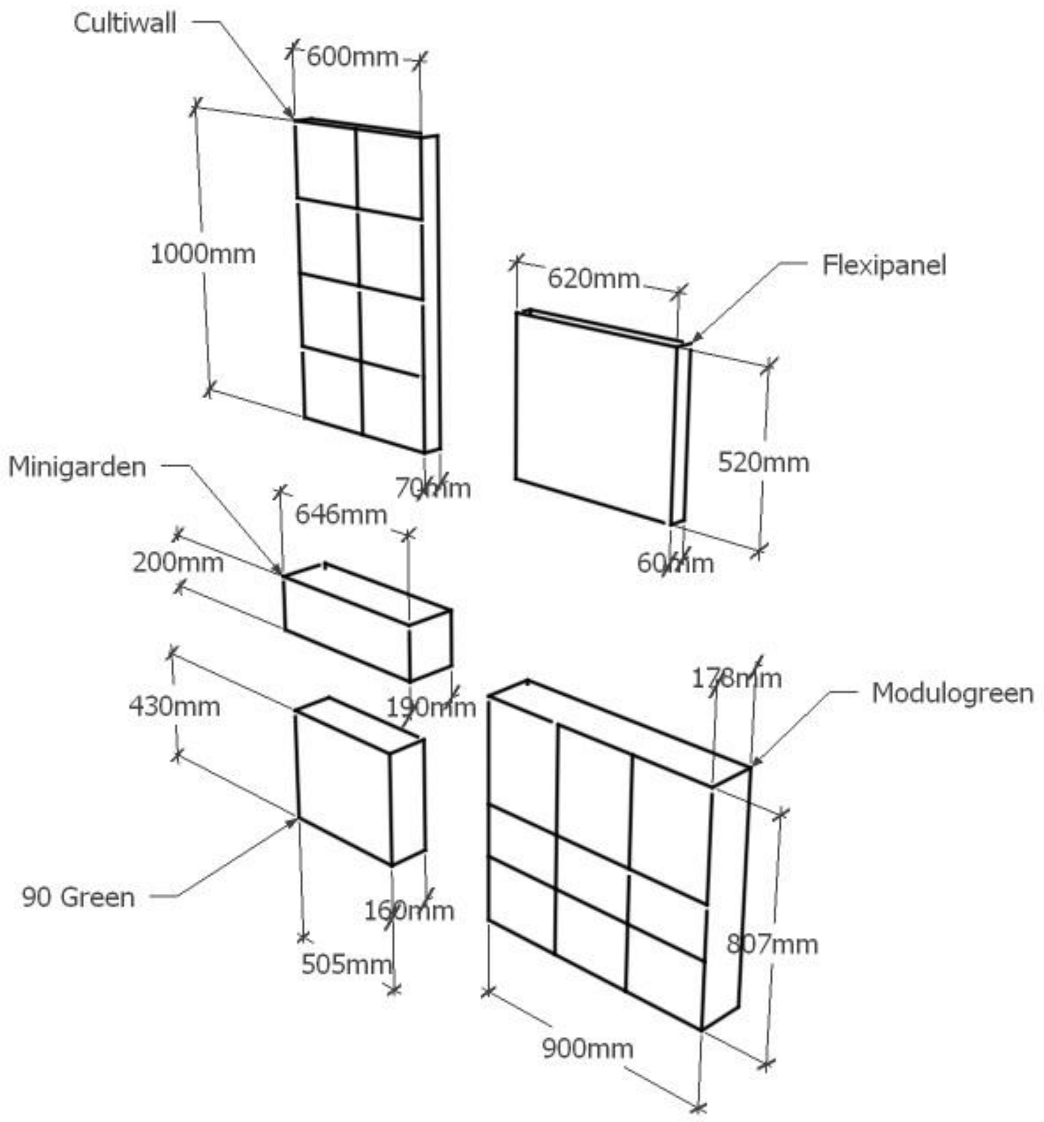


Figure 68: Dimensions of modular LWS elements (excluding felt systems)

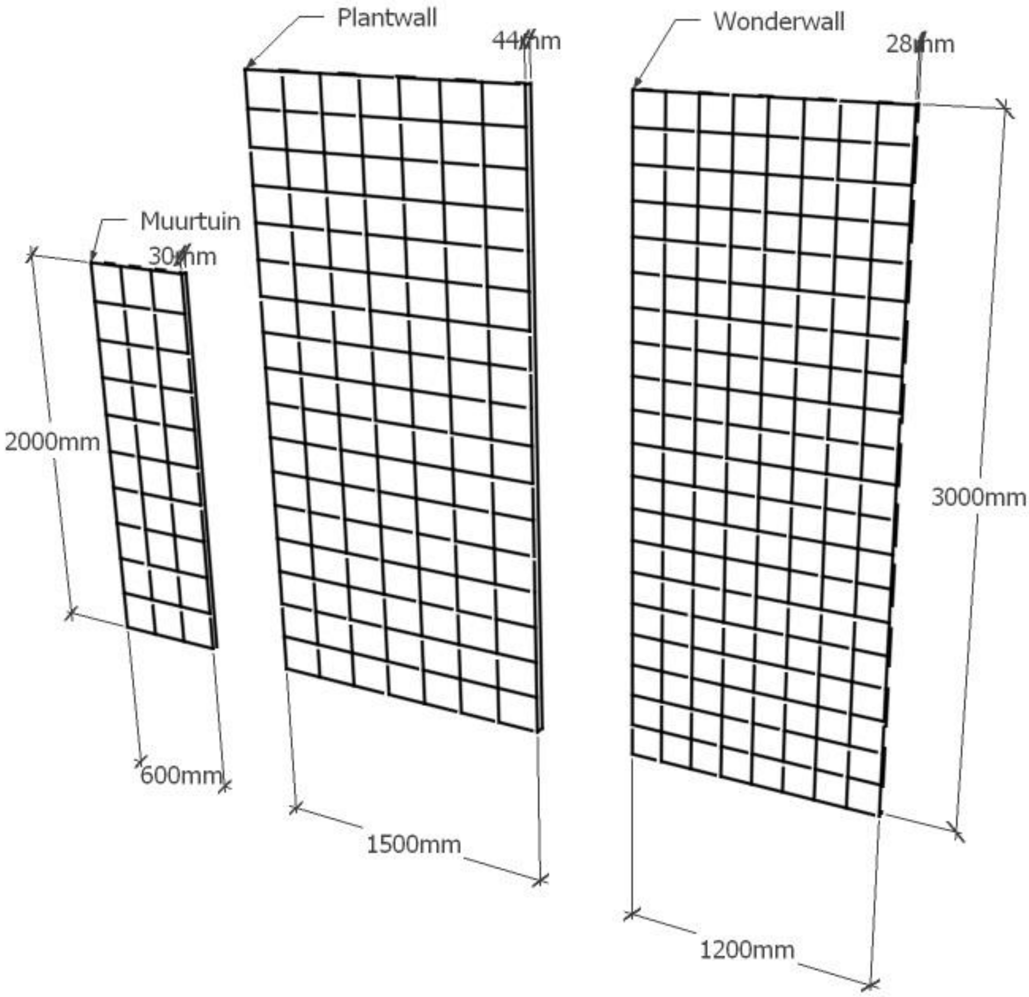


Figure 69: Dimensions of modular LWS elements (felt systems)

As can be seen on the images above, felt systems have much bigger dimensions than other systems. This is due to the fact that felt systems are much easier to edit. Pieces of cloth can easily be cut away when they are not needed. An exception is the Muurtuin system, which is a lot smaller. This system is limited in its flexibility, because it contains an iron frame in its design.

All other elements have a width between 500 and 900 mm, with a width of 600 mm being the most common. The depth of mineral wool systems is between 60 and 70 mm, while the other three systems have a depth between 160 and 190 mm. The height is varying a lot between these systems and ranges from 200 mm to 1000 mm.

When creating a modular element, it should be noted that in Europe the basic module for dimensional coordination is 100mm, which means every module should be 100 mm or a multiplication thereof (Blanc, 2014). Preferred multiplications are 3x, 6x and 12x 100 mm (Herzog, Krippner, & Lang, 2004). However, office buildings are usually based on a grid of 1,35 m, because this size allows for efficient furbishing (Knaack et al., 2014).

6.3.4 Other general findings

While performing the system analysis and discussing living wall systems with the companies providing vertical green, several general findings came up. These findings are not necessarily the conclusion of this research, but are helpful when designing a living wall system, which will be the second part of this Thesis. The general findings are as follows:

Aesthetics is the main reason to buy a LWS

Many clients see aesthetic as the main reason to purchase a LWS. Any of the other benefits are regarded as secondary. A LWS functions as a billboard for the company that is using the building. Therefore, they want to have a LWS with a high aesthetical value. In many cases this means the façade area entirely being covered with living plants. There should be no underlying structure or dead plants visible.

At the same time, a LWS also functions as a billboard for the company selling the LWS. For this reason all companies in vertical green want to take care of maintaining the LWS themselves, which is why an LWS is normally sold with a maintenance contract. This maintenance contract is usually within the price of the LWS system itself, which is why placing a LWS can be seen as a form of façade leasing.

A viable LWS needs proper monitoring, plant maintenance and plant selection.

Even though this has a focus on the LWS as a building element, it should be noted that monitoring, maintenance and plant selection are crucial for a proper living wall system. Even a perfectly installed LWS has no value when the maintenance is done poorly. In the ideal situation, plants would also need a buffer with extra water and nutrients when the monitoring and/or irrigation system breaks down. For this reason some companies prefer the use of soil above mineral wool, because the soil can offer these nutrients whereas mineral wool cannot.

The price range varies between €400,- and €1000,- per m²

As far as price goes, all systems are roughly in the same category, although the price of the Minigarden and is far lower than the others. The Minigarden system is designed for private use. There are no installation costs or maintenance costs, because the consumer is expected to take care of this. All the other companies have a price range between € 400,- and € 1000,-, depending on various factors. Some companies include installation, irrigation and lightning in their price, while others do not. The price per square meter also becomes cheaper the larger the area that is covered with a living wall system.

7. DESIGN

7.1 Context

The design for a new modular façade will be placed inside an existing context. The context chosen for this design will be the Europoint-complex in Rotterdam. These buildings have been chosen for a variety of reasons. First of all, the buildings have a large façade area consisting of repetitive elements. This is ideal for a modular façade. Secondly, the complex is struggling with empty office spaces, which is main problem tackled by this Thesis. One of the towers is currently empty, since the municipality of Rotterdam moved to another building. Lastly, the location of the complex, the Merwe-Vierhavens, is an area that is currently being transformed. It is also a possible location for the World Expo of 2025, which makes it an interesting location for new architectural elements, such as a large living wall façade.

7.1.1 The location

The Europoint-complex is located near the edge of the Merwe-Vierhavens, an old harbor area in Rotterdam. This harbor used to contain a fruit and vegetable storage. Within the city of Rotterdam, industrial harbor and commercial/residential area are entangled. The municipality of Rotterdam slowly wants to transform these harbor areas into educational, commercial and residential areas. The same goes for the Merwe-Vierhavens. For this reason, the area received a long roof park. The Merwe-Vierhavens is also a possible location for the World Expo in 2025. To transform the Europoint-complex, a visual landmark, into a building with a green façade would extend upon these ideas.

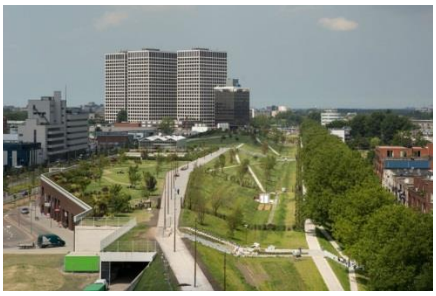


Figure 70 (left): Merwe-Vierhavens (Breit, 2014)

Figure 71 (right): Roof park of Merwe-Vierhavens (Schellekens, 2015)

A large four lane road with a tramline, the Schiedamseweg, acts as a border of the Merwe-Vierhavens and is located at the north side of the Europoint-complex. This road, along with the Vierhavenstraat, has a stroke of greenery, which eventually leads to the roof park. At the northeast side of the complex, a subway station is located. This means the complex has a good connection to the public transport. Visitors of the building that arrive with their car can park it in the parking garage on the west side of the complex. Figure 72 shows an analysis of the infrastructure and the urban green of the area, while figure 73 shows the sun diagram of the Europoint complex. This last diagram makes clear that the west and east façade receive very little sun in wintertime, while the south façade receives sunlight throughout the whole year.

Figure 72: Analysis of infrastructure and urban green of the Merwe-Vierhavens

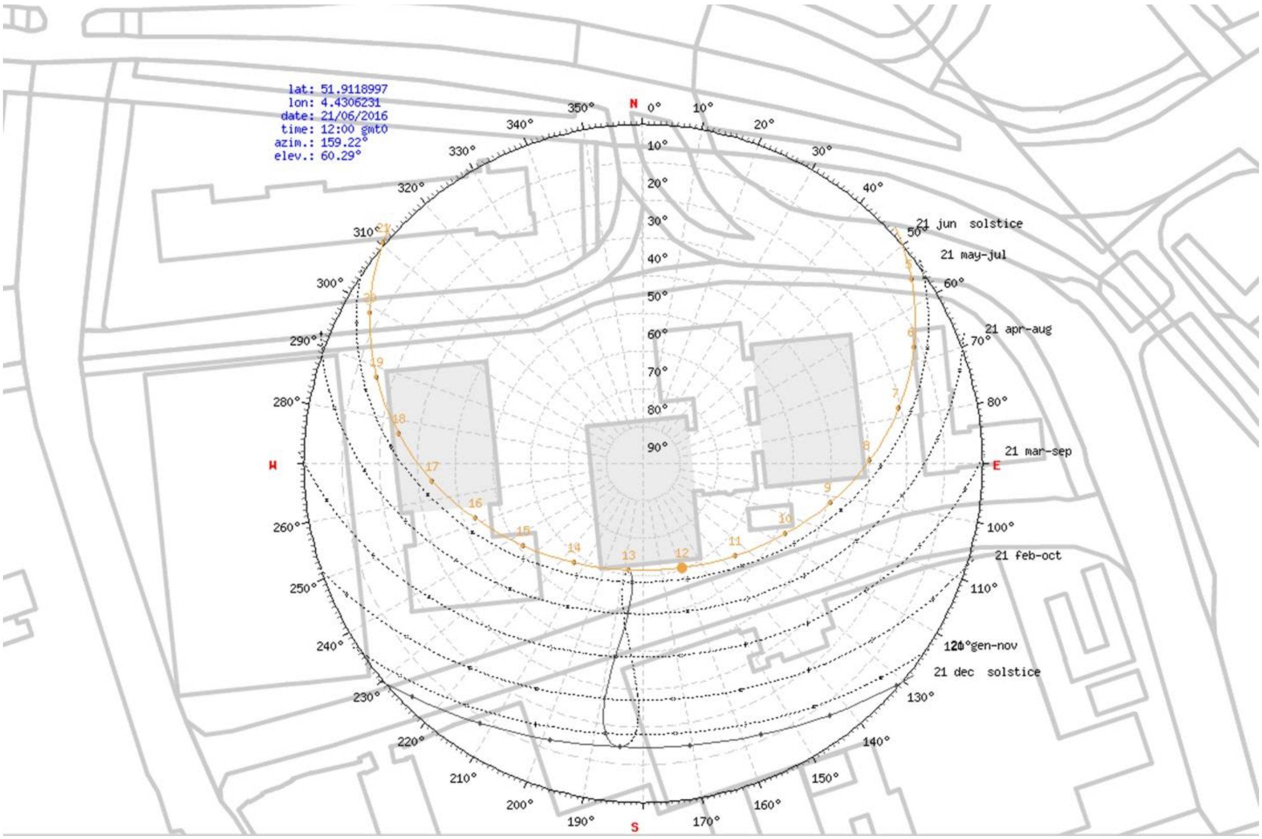


Figure 73: Sun diagram of the Europoint-complex

One of the biggest factors in transforming the Merwe Vierhavens into educational, commercial and residential areas is improving the urban living environment. Residential areas will be located very close to industrial harbour areas, which means residents might experience nuisance due to sound or bad air quality coming from this industrial harbor area. As mentioned earlier, both of these problems can potentially be solved with a LWS.

The main source of the sound received by the Merwe-Vierhavens is the harbor across the river, the Waal-Eemhaven. This harbour is producing a total of 55 dB, which reaches the Europoint-complex on the south façade. In the graph below, the blue line represents the 55 dB contour form the Waal-Eemhaven. Everything above the blue line will receive 50-55 dB. Everything beneath the blue line will receive 55-60 dB.

Figure 74: Sound analysis Merwe-Vierhavens. Left is the situation in 2007 and right is the current situation with some industrial harbour removed. (Projectbureau Stadshavens Rotterdam, 2009)

7.1.2 The building

The design for the Europoint complex started in 1973 as a design for a World trade Centre in the city center of Rotterdam. Eventually the design was slightly modified and realized in 1975 as a three-tower complex on the Marconiplein. On this location, the towers really stand out, since they're much higher than the surrounding buildings. They are an iconic landmark. The towers are 95m high and even have a perspective correction. Each story is just a few centimeters wider than the story below (Groenendijk & Vollaard, 2006).

Figure 75 (left): The Europoint-complex (SmartCityStudio, 2014)

Figure 76 (right): Interior wideslab precast concrete floor spanning structural core and façade columns

The Europoint-complex is a typical example that shows the problem of empty offices. For a long time, the municipality occupied one of these towers, but unfortunately they moved out, leaving one of the buildings, a total of 31.000 m² empty. This has led to various interventions on the building, such as using the towers as billboards or the creation of redesigns that were never realized. This is also one of the reasons a redesign of the façade is suggested.

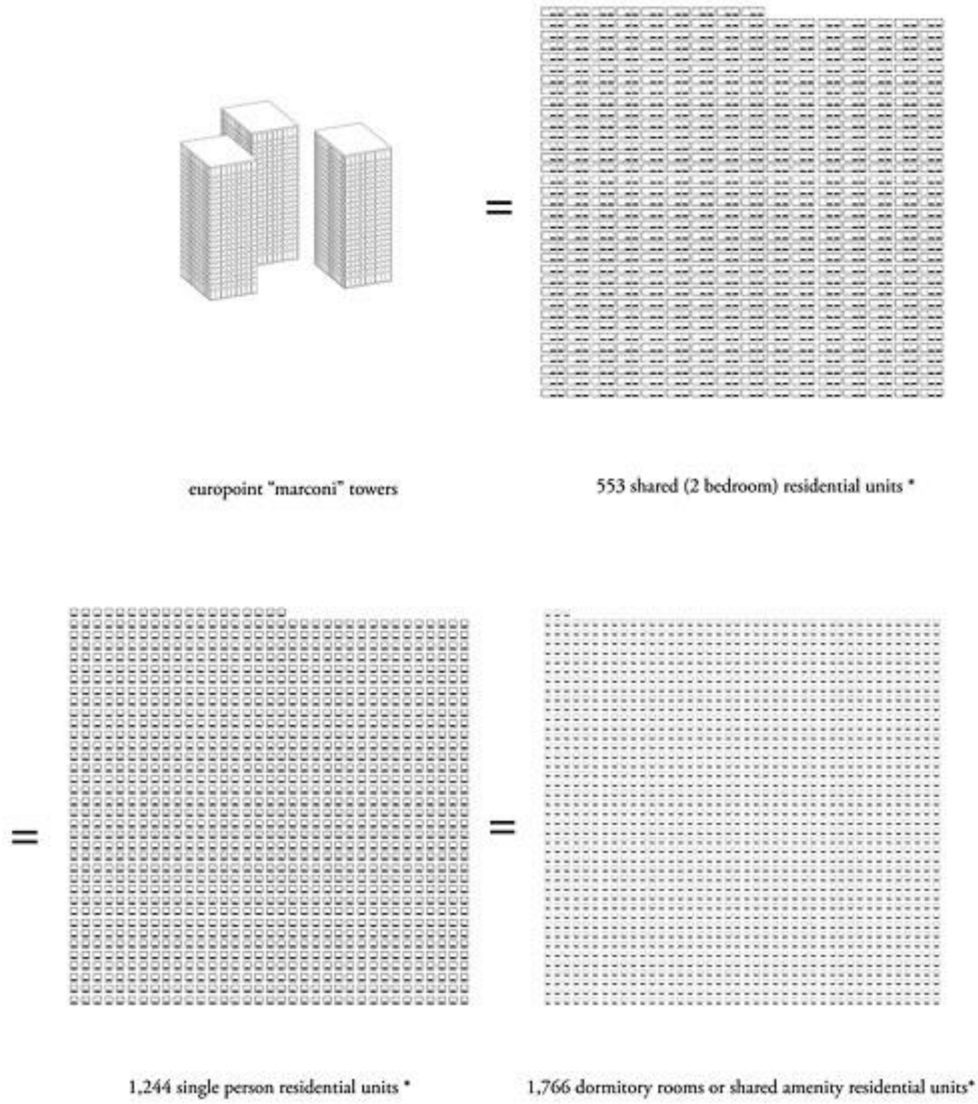


Figure 77: Floor area analysis of the Europoint Marconi towers (Designersparty, 2011)

Figure 78 (left): The googly eyes campaign on the towers to increase safety (de Vries, 2012)

Figure 79 (right): Redesign of the Europoint Marconi towers (RE-NL, 2013)

The buildings have a structural core, which includes lifts, stairs, toilets and technical rooms. This structural core is connected with prefabricated beams to the structural framework that is the façade. This means there are no columns in the office spaces. The floors are wideslab precast concrete floors that span the core and the façade. (Aronsohn raadgevend ingenieurs, 2005). The structural framework of the façade is made out of concrete columns. These columns carry window façade elements.

Dimensions building	33,50 x 47,90 m
Highest point	102,36 m +NAP
Stories	22 (21 office floors + ground floor)
Total amount of poles	347 pieces, Vibro Casing
Dimensions foundation blocks	35,40 x 50,45 x 2,80 m
Dimensions core	14,50 x 21,70 m
Dimensions columns	560 x 820; 560 x 700; 560 x 640 mm, center to center 3600 mm
Dimensions façade beams	560 x 900 mm
Story height	3750 mm
Construction height	650 mm
Maximum floor span	12.900 mm
Total amount of concrete	18.000 m^3 (5000 m^3 for foundation)
Total amount of rebar	2000 tons (445 tons for foundation)
Total amount of rebar per m^3 concrete	120 kg in building, 90 kg in foundation

(Overmars, 1974)

7.1.3 The façade

The façade of the building is made oud of white travertine cladding, which is fixed onto the concrete columns with a simple demountable connection using bolts. The window frames, however, seem to be glued to the structure. The window frames bronze-colored anodized aluminum frames with bronze-tinted plate-glass. The frame extends into the cavity between the concrete and travertine on all sides, where they are glued to the concrete columns or floors. The edges have been closed with sealant. Appendix B shows all the details in the façade on a 1:2 scale.

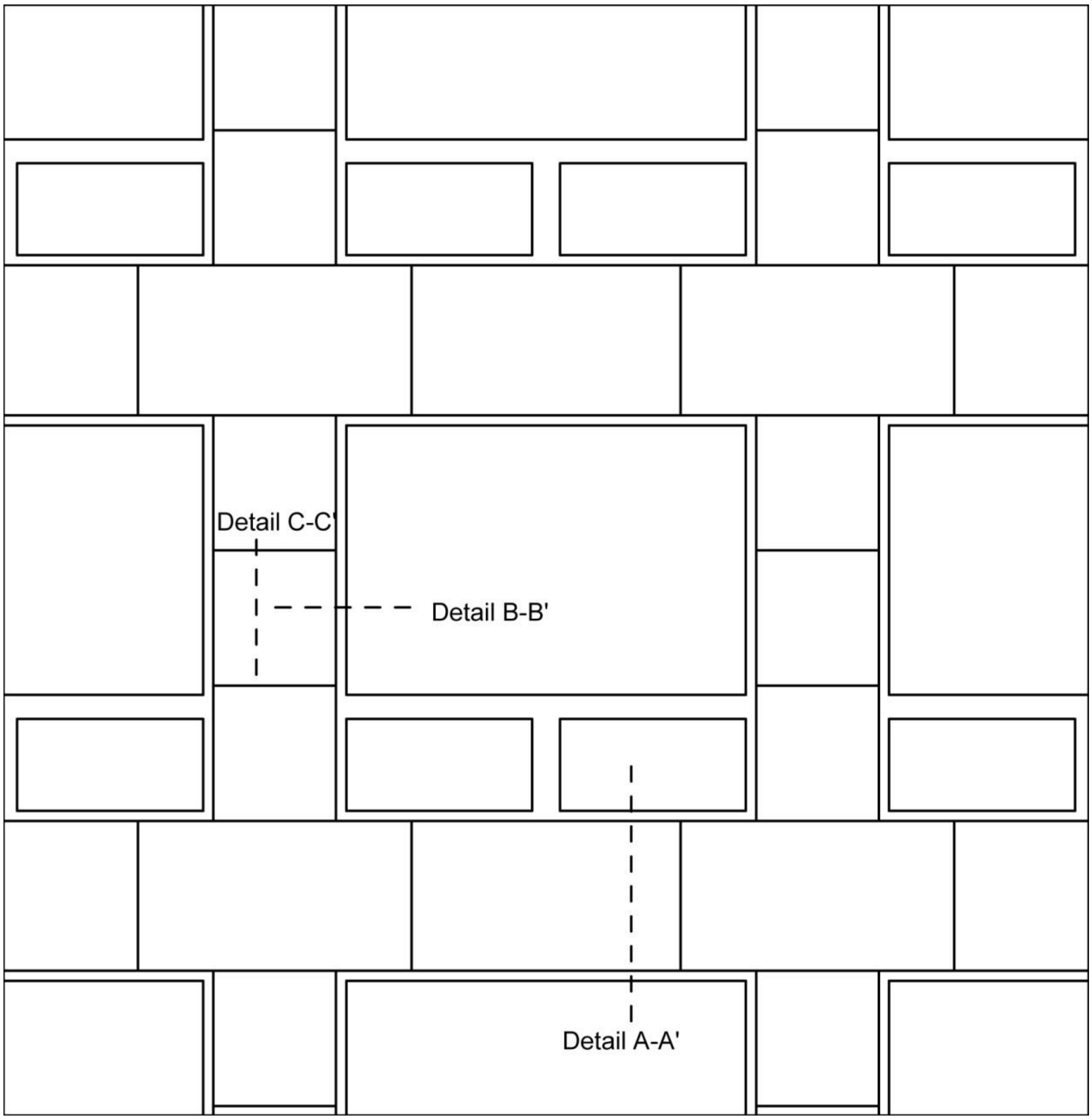


Figure 80: Window element 1:50

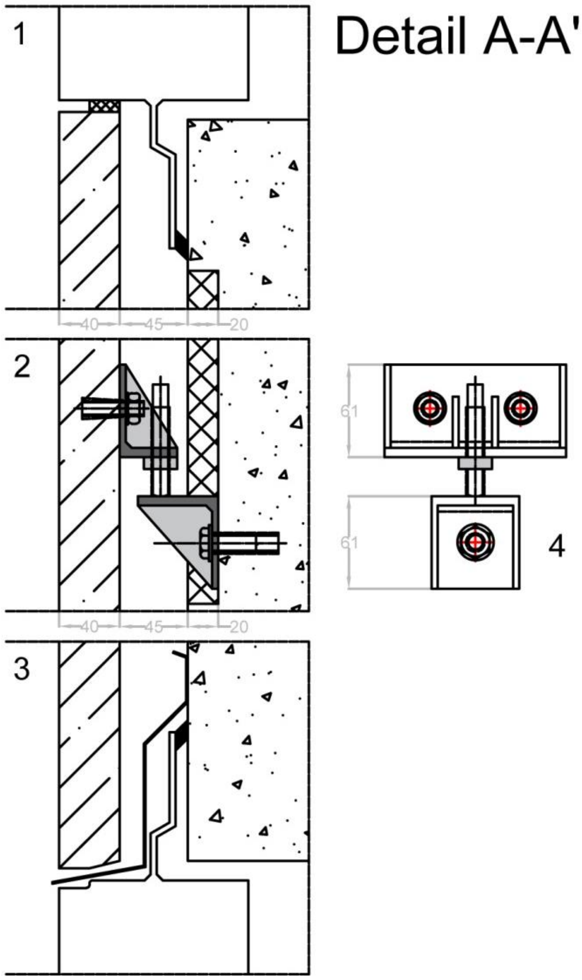


Figure 81: Details section A-A' 1:5

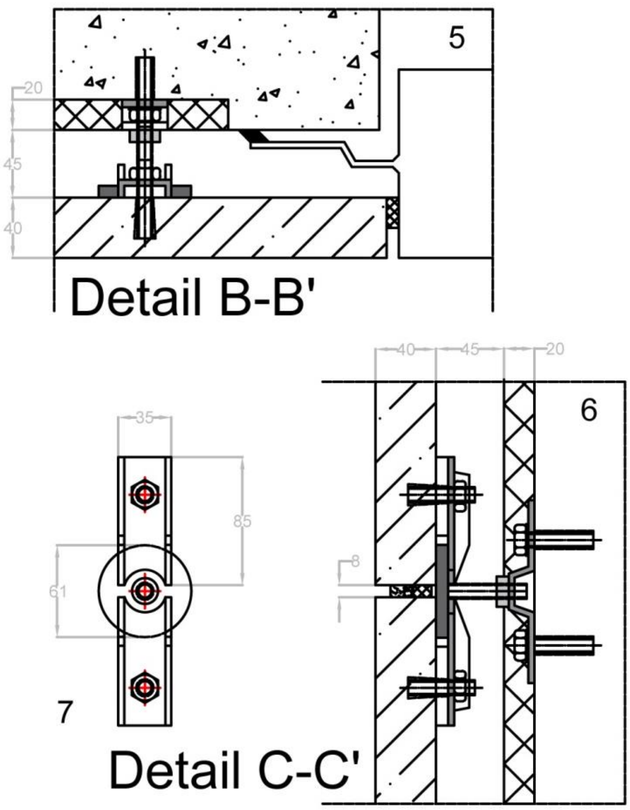


Figure 82: Details section B-B' and C-C' 1:5

The north and south façade have nine windows per story, while the east and west façade have thirteen windows per story. The ground floor has higher windows. The highest floor has no windows, because they are replaced with grates for ventilation purposes. The 21 floors in between have the standard windows, which means a single tower has a total of (9+13+9+13) x 21 = 924 window elements.

7.2 Design boundaries and requirements

Designing is a step by step process in which the product slowly gains its shape. Before stepping in the design process, the boundaries and requirements need to be clear. In this paragraph this step will be undertaken by setting the design requirements, determining the shape and LWS type, choosing the main materials and looking at how maintenance should be performed.

7.2.1 Design requirements

The first step towards a design is setting the design requirements for the design. The design requirements for the LWS design will be explained in this chapter and follow from the context.

Modularity design requirements

As we've seen in Chapter 3, to make a good modular design it should be prefabricated, designed for disassembly and designed for a catalogue. To make sure it can be prefabricated, the systems should easily be transported by truck and able to be installed on site. The installation on site needs to be done quick and easily, so the installation process should not take more than 2 people. The elements also need to be demountable, so they can easily be removed at the end of their lifespan. This process should not need more than two people. Elements can then be transported by truck back to the factory so all materials can be recycled.

For a catalogue design, the element needs to be available in various types. As we've seen from the location of the Europoint-complex, there are various environmental factors that are working on the building. First of all, on the north side of the complex, a large road is located, which is causing pollution. Secondly, the towers are most of its sunlight on the south façade. Lastly, a fairly new roof garden is located east of the complex, which has its own biodiversity that has no further connection with the city of Rotterdam. These three problems can be solved with a living wall system, and each façade could have panels with a different optimization. The façade will be divided as seen in figure 83.

Figure 83: Focus different façade designs

Which means the following requirements can be stated for the modularity of the design:

- The LWS is able to be transported by truck, which means a single element needs to fit within a container of 2,55 m x 4,00 m x 12,00 m.
- The LWS can be installed and removed easily and quickly by a single person, which means as single element cannot weigh more than 10 kg when dry.
- The LWS can be disassembled.
- There will be 3 LWS types:
    - One is optimized to increase the local biodiversity
    - One is optimized to improve the air quality
    - One is optimized to provide energy for the building

LWS Design requirements
As far as the LWS requirements goes, the product is limited by the fact that it is placed on a building with a height of 102m. First of all, the weight should be taken into account. The LWS needs to be supported by the structure of the building. Currently the building is cladded with travertine marble panels with a thickness of 40 mm. This means the façade has a weight of 108 kg/m². The LWS should be below this weight when fully saturated.
Secondly, the water consumption of plants increases with the height, because air is much dryer on higher altitudes. To be able to maintain the elements, the water consumption needs to be as low as possible by decreasing the amount of water that goes to waste.

Lastly, the price and the lifespan are taken into account. To make sure the product can actually be realized, it should be done for a price that is not higher than what's available on the market right now. Another way to make sure the product has a decent price is to make sure it can be used as long as possible before it needs to be replaced. This is why the lifespan is taken into account. The lifespan should at least exceed 20 years.

Circularity design requirements
When comparing the systems on circularity, various systems appeared to be 100% separable and 100% made out of circular materials. This means all materials can be retrieved at the end of the lifespan of an element and the materials can either be recycled or biodegraded. However, the reusability of the various systems never reaches 100%, mainly because the substrate can never be reused. Nevertheless, the product will be designed for circularity, so the product is aimed to be as reusable as possible. Other than that, it needs to be fully separable and made out of circular materials

7.2.2 LWS type
This paragraph will define the shape and the LWS type of the design. This will be done by comparing various options on the requirements stated in the previous paragraph.

To define what type of LWS to use, a Harris profile will be used based on all the defined requirements. A Harris profile is a graphic representation of a design choice, which uses a four-scale scoring to define the strength and weaknesses of these design choices. The LWS types will receive a score of -2, -1, +1 or +2, in which -2 means bad and +2 means good. In table 7 we can see the Harris profile for determining the LWS type. It shows that an LWS based on planter boxes would be the best option for this scenario. Extra attention could be given to decrease the weight of the LWS.

	Planter boxes				Panel: wool				Panel: other				Felt layers			
	-2	-1	+1	+2	-2	-1	+1	+2	-2	-1	+1	+2	-2	-1	+1	+2
Properties																
Price																
Weight																
Water consumption																
Lifespan																
Circularity																
Separability																
Reusability																
Circular materials																
Benefits																
Improving air quality																
Increase biodiversity																
Total			11				9				6				1	

Table 7: Comparison LWS types on design requirements

7.2.3 Shape and structure

Much like the LWS type was chosen by using a Harris profile, so will the shape of the design be chosen. For the redesign of the façade of the Europoint-complex, two scenarios are created. In the first scenario, the entire façade will be redone, including the windows and window frames. In the second scenario, the façade will remain mostly intact, but only a portion of the façade will be replaced by LWS. This Harris profile will determine the shape of the coverage of the LWS in the second scenario.

There are various options in how to clad the building with LWS. A total of 7 options have been created:

- Shape 1: Cladding the columns completely
- Shape 2: Cladding the floors completely
- Shape 3: Cladding the columns next to the windows
- Shape 4: Cladding the floors below the windows
- Shape 5: Cladding around the windows
- Shape 6: Cladding replacing the windows
- Shape 7: Cladding the entire façade, but the windows

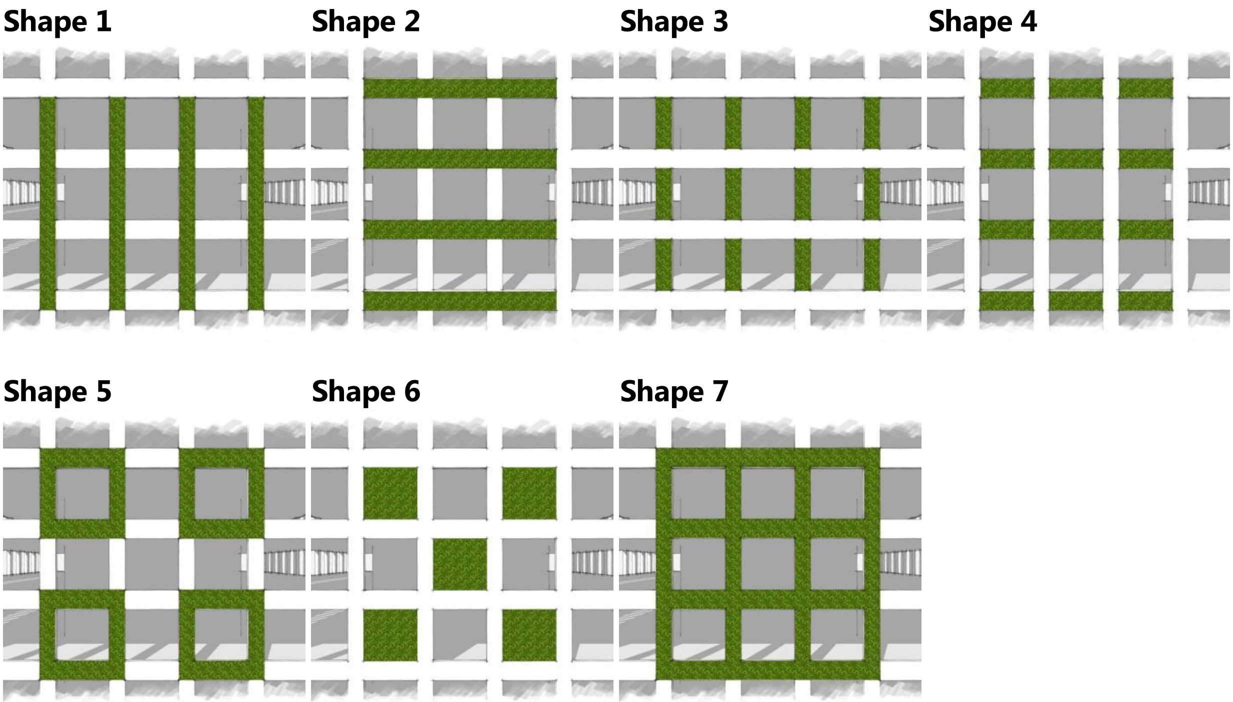


Figure 84: Concepts for shapes of the LWS cladding

The shapes will be compared on the following factors:

- Ease of installation

Some shapes are easier to install than others, which would improve the modularity of the design. A higher score is given to shapes which are easier to install.

- Coverage

A higher score is given to shapes which cover more area.

- Division in smaller modular elements

Can the shape be divided in smaller elements? Could these elements be the same shape? A higher score is given to shapes which do not use a lot of different element shapes.

- Placement of irrigation pipes

Does the irrigation have to make weird turns or can it be placed easily around the building. A higher score is given to shapes which have an easier projection of the irrigation.

- Placement of gutter

Does every level need a gutter? Does every level have a long connected gutter, or small gutters? How many drainage pipes are needed? A higher score is given to shapes which use the low amount of gutters and drainage pipes.

These factors have led to the following Harris profile:

	Shape 1				Shape 2				Shape 3				Shape 4				Shape 5				Shape 6				Shape 7			
	-2	-1	+1	+2	-2	-1	+1	+2	-2	-1	+1	+2	-2	-1	+1	+2	-2	-1	+1	+2	-2	-1	+1	+2	-2	-1	+1	+2
Properties																												
Ease of installation																												
Coverage																												
Division in smaller modular elements																												
Placement of irrigation pipes																												
Placement of gutter																												
Total score			4				6				1				4				-4				4				-6	

Table 8: Comparison of shapes on design requirements using Harris profile

We can see that shape 2 received the highest score and would be the best shape of the design for this scenario. It is fairly easy to install and can easily be converted into smaller elements. The coverage is not optimal, but every level could use one ongoing irrigation pipe per façade. Every level would still need its own gutter, but they can all be connected to each other and use a single drainage pipe per façade. Therefore, shape 2 will be used as the basis for the design process.

The next step after deciding the shape of the coverage of the LWS and the LWS type, is deciding the structure of the LWS. Again, 6 types have been created out of which a solution can be picked.

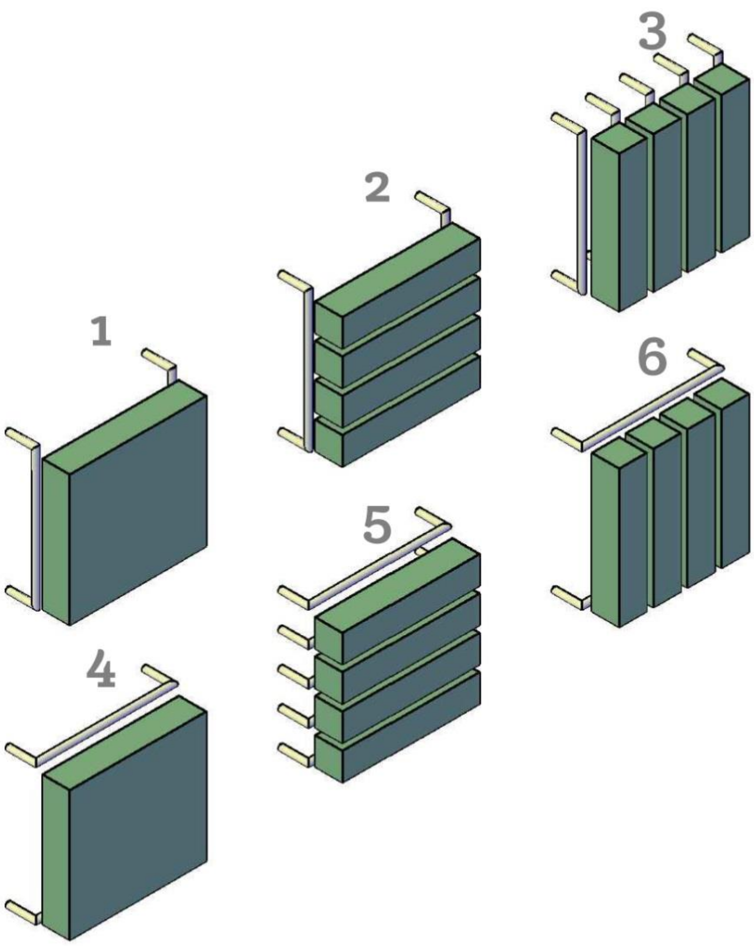


Figure 85: Different types of structure (isometric view)

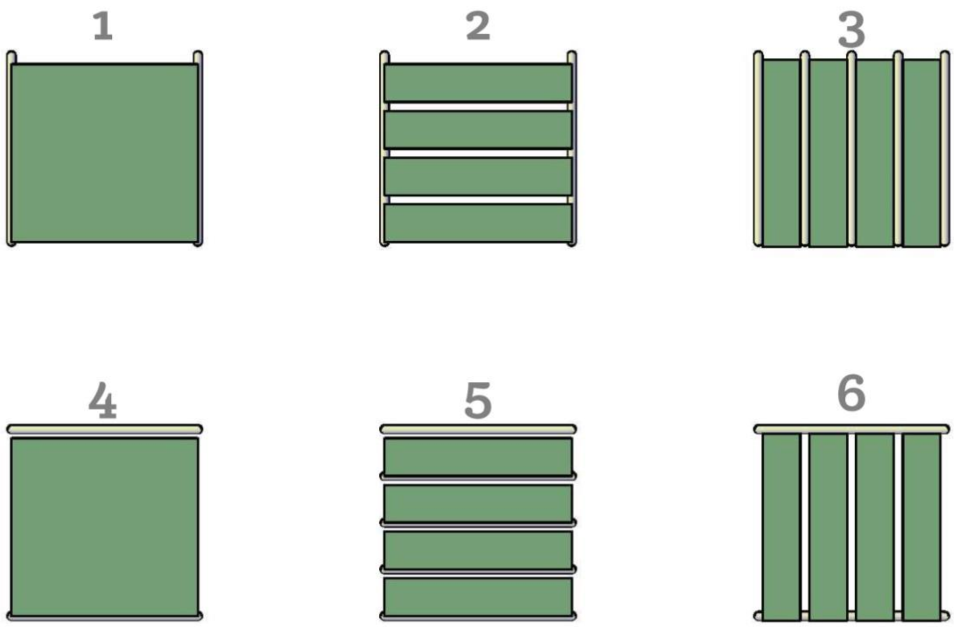


Figure 86: Different types of structure (front view)

In these drawings the silver beam elements represent the structure whereas the green boxes represent the planter boxes. In the design phase, it could happen that these elements appear as a single component, in which a planter box provides its own structure. For now, the elements have been separated to make the idea more clear.

Type 3 and 5 are not very interesting, since there are too many structural elements needed to hang up the LWS. This will affect the cost and installation time negatively. Type 1 and 4 are also not ideal for this situation as the elements have a large size which in turn will affect the weight. Earlier, when creating the design requirements, it has been mentioned that the weight has to be kept to a low, so the elements can be retrieved easily. This will lower the maintenance time. Therefore, types 2 and 6 are the only viable options for this design project. Type 2 has been chosen, because the planter box has a horizontal shape which can easily be used as a planter box at home by private consumers.

7.2.4 Materials

In chapter 6.3.2 a list of materials is given that are consider circular, non-circular, or should be used with caution. In the best case scenario, only circular materials would be used. However, for design reasons it might be a better idea to switch to a material that should be used with caution. For example, the structural layer could be made out of stainless steel, a circular material. The design, on the other hand, needs to be lightweight, which makes aluminum more preferable. Since aluminum is a lighter material, it is easier to transport, which is not only more preferable for the design, but also decreases the energy needed for transportation and is more sustainable. It should be noted that aluminum is toxic to aquatic organisms, so extra care is needed to make sure the element is recycled and not dumped into the ocean. Explanation for the design choice is needed for materials that should be used with caution. Materials that are considered non-circular are out of the question.

7.2.5 Maintenance

A very important aspect of this living wall system is the maintenance. By making the system low in weight, demountable and transportable by truck, a single element can be easily retrieved and replaced with another. Due to the design by modularity and circularity, this means a replacement for an element that needs maintenance can already be created in a factory setting. On site, this element can easily be replaced, while the broken element can be returned to the factory for recycling.

Nevertheless it is a good idea to look into the retrieving of this element from the façade. Currently a lot of the façade maintenance is done with building maintenance units and this is an important aspect that should be taken into account for the design. There is a variety of building maintenance units available. They can be split up into mobile building maintenance units and permanent buildings maintenance units:

Mobile building maintenance units:

- Ladders
- Truck mounted platforms such as boom lifts and scissor lifts

Permanent building maintenance units:

- Façade ladders
- Work bridges
- Semiautomatic façade elevators
- Fully automatic façade elevators with wall conduction
- Fully automatic façade elevators without wall conduction

Permanent building maintenance units are usually fixed on the façade or the roof, whereas mobile building maintenance units are not attached to the building and can be stored elsewhere. However, mobile building maintenance units are only available to reach heights of around 50m. When a building is higher, a permanent building maintenance unit is recommended. Secondly, it is important for mobile building maintenance units that the entire area around the building is easily reachable with these units; otherwise these units will not be able to reach the façade. Table 9 shows a comparison of some of these building maintenance units in speed of the façade maintenance (in this case the speed of window cleaning), described in m^2 per hour. The most frequent type of façade maintenance is window cleaning, which is why this will be used as the main example.

Capacity by window cleaner in m^2 / hour	Type of façade			
Type of installation	Masonry and concrete 30% glass	All glass in sealant	90-95% glass in profiles	Powder coated metal in one plane
Façade elevator (fully automatic with wall conduction)	54	53	50	40
Façade elevator (fully automatic without wall conduction)	54	66	63	50
Façade elevator (semiautomatic)	49	60	56	45
Façade ladder (mobile with platform)	39	48	45	35
Free standing ladder	41	51	47	35

Table 9: Comparison of building maintenance units in capacity (Reijmers, 2015).

In this graph we can see that using a fully automatic façade elevator without wall conduction is the fastest way to clean a façade. However, these face elevators tend to be quite expensive. Fortunately, in the scenario of the Europoint-complex, all three of the towers have been equipped with this type of building maintenance unit. This solves the problem for this specific design scenario. On the other hand this designed living wall systems needs to be a system that is applicable everywhere. Therefore it is important to look for a design solution that reduces the maintenance of this living wall system on both high-rise and low-rise buildings.

In the ideal scenario, façade element could receive maintenance without sending a person up the façade. Façade elements could transport themselves to the ground floor where they can be handles more easily and properly, because a person does not have to force himself into an uncomfortable position. This futuristic idea might not be so far off. Various companies already use drones, a type of flying robots equipped with cameras, for window cleaning.

Figure 87: Window cleaning drone (Robinson, 2016).

These drones are usually used for transporting packages from companies to households and can take up quite some weight. Drones that are available on the market right now for personal use can lift up to 8 kg. With this in mind, it is possible to design a living wall system, which can be transported from the façade towards ground level or vice versa by a set of drones. The requirements to make this happen are the weight for the living wall system and the availability for a component to which a drone can connect. This will decrease the maintenance of the system and will make the system futureproof.

7.3 Design: the Plug 'n Plant system

7.3.1 Introduction of the design and design process

Using the literature, research and design requirements we can finally create a design. This is an intensive process in which it is not uncommon to take a few step backwards and review the design. This chapter will not only explain the design, but also the design process. This will make clear why certain decisions have been made, which is part of understanding the design. Any weak points become clear almost directly, as well as what future technologies could be used to improve the design.

7.3.2 The concept and design process

The first step in a design process is a concept design, which is a rough sketch, showing the idea and rough shape of a product. The first sketch of this design started as a side view of the living wall system, roughly based on the Modulogreen system. The shape was chosen for an ideal water flow, but also because it has two diagnoal surfaces. Plantes are rooted into the top surface, but the bottom surface could function for any of the other benefits like cleaning the air. The sketch on the right shows how air hits the bottom surface from below and returns outwards into the sky.

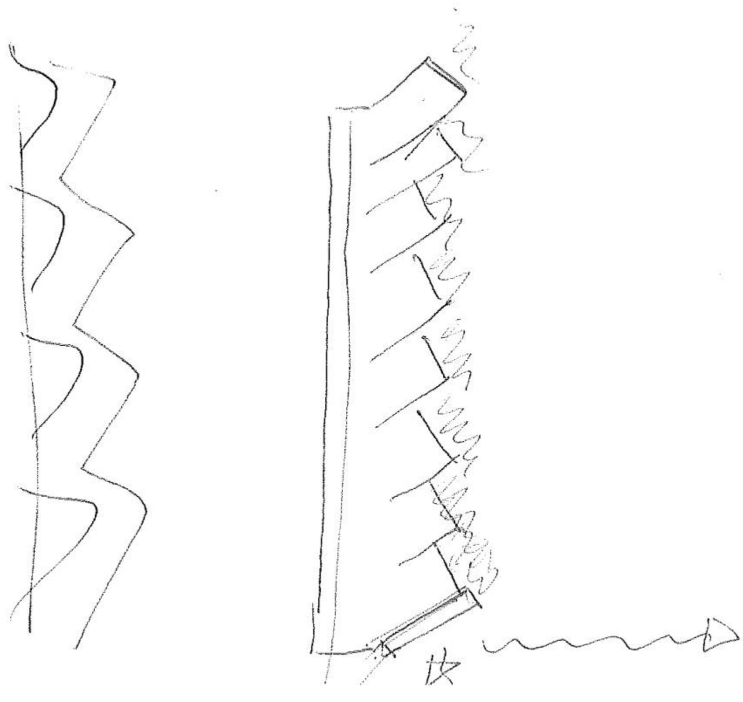


Figure 88: First concept sketches defining shape.

The main problem with this concept, however, was the size and weight. Here we see a set of planter boxes combined as one big panel, which has a lot of weight. This makes maintenance a lot harder. It also affects the lifespan. If one planter box is broken, the entire panel has to be replaced.

The next concept creates a division between two parts. The structure on the back is supposed to have a bigger lifespan than the planter boxes in front, so the structure does not have to be replaced as often. The planter boxes need to be removed easily so maintenance of the plants is easier.

In this sketch we can see a panel functioning as back wall structure. Planter boxes can be placed into the panel. The planter boxes still have the same shape as before, with the top surface being used for plants and the bottom surface being used for additional benefits.

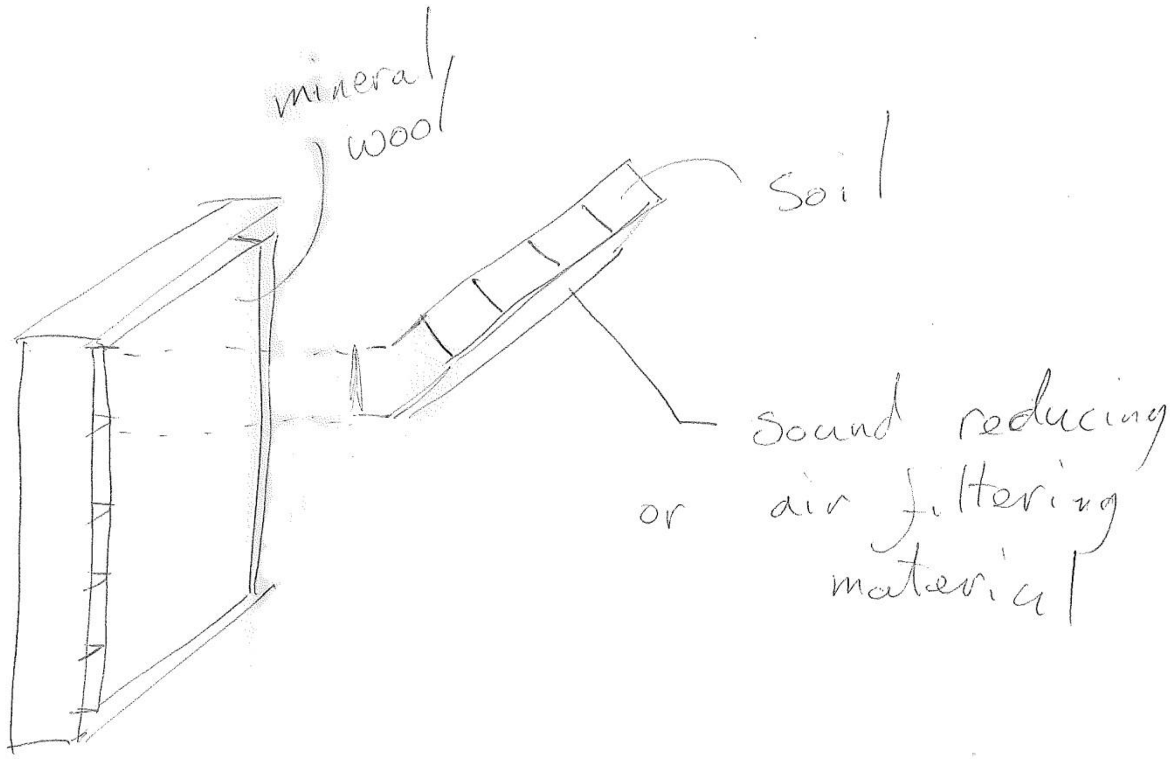


Figure 89: Sketch of concept dividing elements into components based on lifespan.

The structural components are still quite large in this design. It also has a large panel of mineral wool inside of it, which could function as the substrate of the plants, with soil for additional nutrients in the planter boxes. This idea would use the best of both substrates, but the planter boxes couldn't be removed if the plants were rooted into the back structure. In the next step of the design process, it would perhaps be better to stop designing with the structural component as a starting point. First, the planter boxes would need to be designed with an optimal shape for plants and their maintenance.

The shape of a single planter box was redefined by using the shape of the Modulogreen system, but separating it in single planter boxes, roughly the size of the Minigarden system. This means the planter boxes can be used as a regular planter box inside your own home and have a low weight, but still uses a shape that is optimal for the plants to take in water. The bottom of a planter box would also be filled with recycled polyurethane foam, as seen in the Cultiwall system. This holds the water for a little longer, so plants have more time to absorb the water.

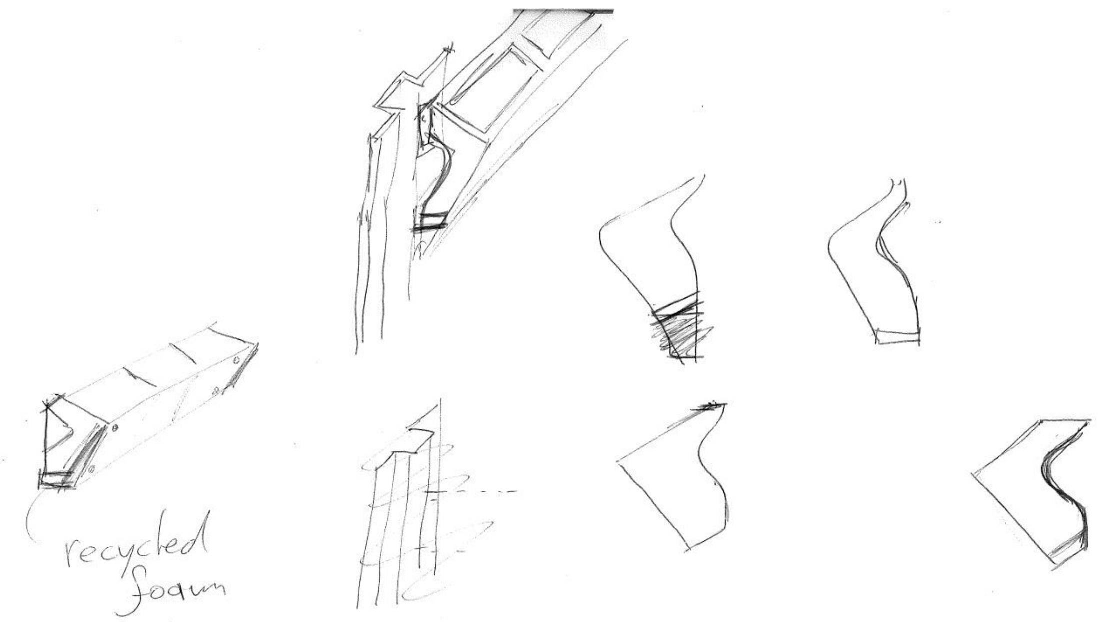


Figure 90: Designing the shape of the planter box.

Now that the shape of the planter box has been defined, it is time to think of the back structure. Three options have been researched; a structure made out of a steel frame, a structure made out of a full panel (made out of Alucobond, for example) and a structure made out of aluminium profiles.

Again the weight was a defining factor for choosing the structural components, but another important aspect was how to connect the planter boxes to it. For example, planter boxes could simple be hung onto a steel frame. It should also be noted that either the structural layer or the planter boxes should function as a water retaining layer, so water cannot reach the layers behind the living wall system. By doing this, the living wall structure does not have to be placed on top of the outer layer of a façade, but function as this layer itself.

Eventually the aluminium profiles have been chosen. They are the most lightweight structure, but also allow easy connections such as a hanging rail. The structural layer is not completely closed for water, so the planter boxes have to be designed in such a way that water cannot infiltrate the inner layer.

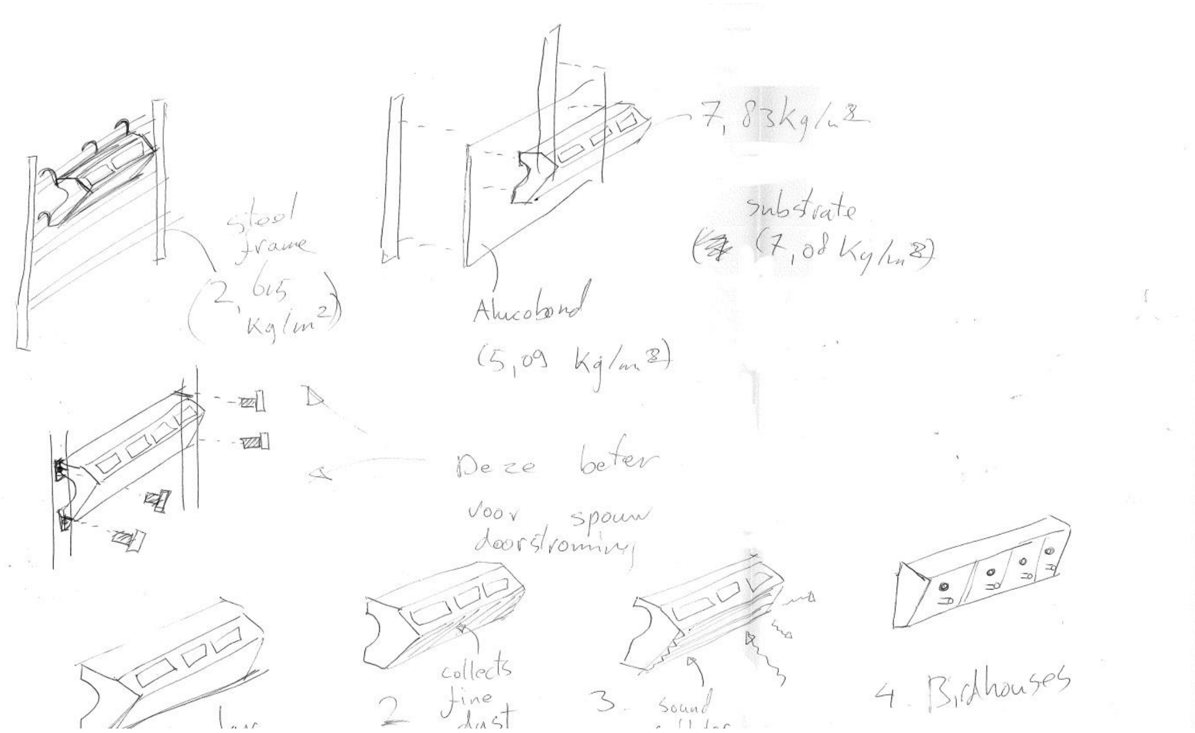


Figure 91: Comparing structural components and designing additions.

In the final step, ideas for various additions to the planter box took shape. In this sketch we can see the bottom surface of the planter box functioning as a collector of fine dust or a surface that reflects sound. The idea for planter boxes to reflect sound was not strong enough and eventually scrapped. We can also see a way to transform the planter boxes into birdhouses to improve biodiversity.

One major improvement that was needed for the final design is the inclusion of components for placing irrigation and drainage. Since this system needs to be designed for modularity, all important elements of a living wall system should be able to be implemented in some way in this design. By including ways to connect the irrigation and drainage to this living wall system, the system can function as a whole and the user does not need to add additional components in the design.

7.3.3 Final design: The Plug 'n Plant system

The main element of this living wall system is a green planter box with a height of 250 mm and a width of 600 mm. The measurement of 600 mm and other multiplications of 300 mm are common in the researched living wall systems, as seen in 6.3.3. The height of 250 mm is a division of 1000 mm, which is not only another common modular length in living wall systems, but also the height of the strokes on the Marconi Towers that need to be covered with green.

The planter box is equipped with various components to improve its applicability and modularity. Sheets at the back are made, so planter boxes can above and below can overlap each other, to create a water retaining layer. The front of the planter box has holes and snap joints for additional components to connect to that improve the benefits of this living wall system even further. Finally, the planter box has two handles at the top. These handles make sure it is easy to carry around, but also give the possibility for a drone to grab the planter box for easy maintenance.

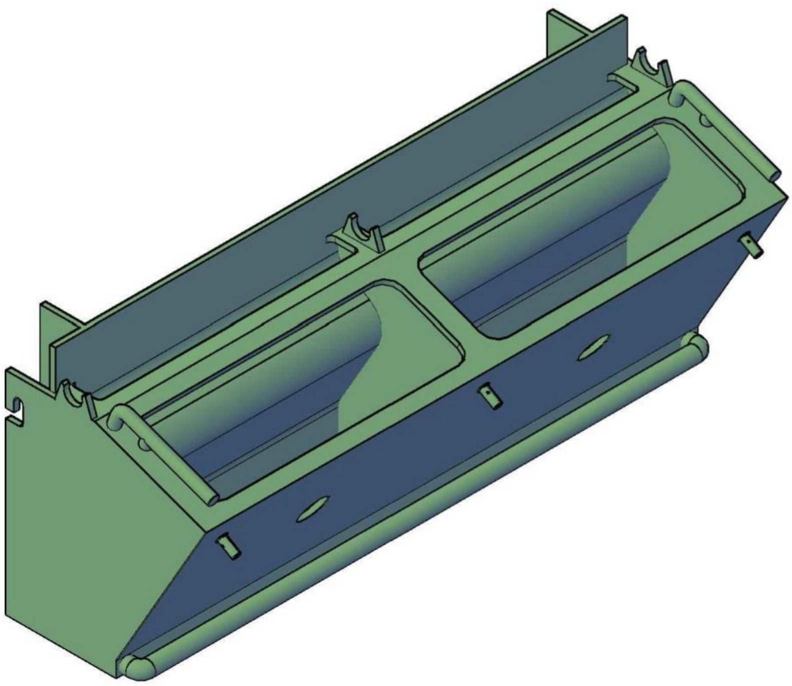


Figure 92: Single planter box

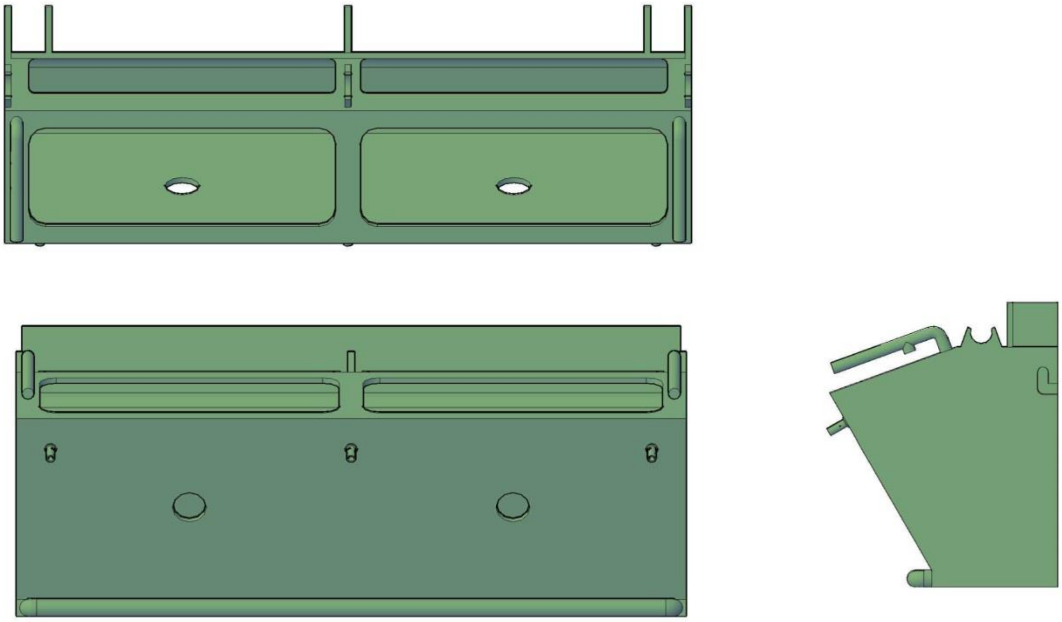


Figure 93: Top, front and side view of single planter box

The planter box is made out of polypropylene formed by the means of injection molding. HDPP was chosen, because it is a lightweight and durable material with a fairly low cost. The processability is always very high in terms of moldability and weldability (Ashby, 2016). Polypropylene has a lot of factors in common with polyethylene. This material was also taken into consideration, but polypropylene was chosen due to its better resistance to chemicals, organic solvents and cracking, and it being lighter in weight (Hinsley, 2016).

The planter boxes are filled with regular potting soil, which seems to be preferred by certain companies selling living wall systems, since the potting soil acts as a reserve supply of nutrients for the plants. The soil could be made lighter by mixing it with various other substrates, but this would affect the separatability. Therefore this design just uses regular potting soil.

At the backside of the planter boxes, extra sheets of HDPP appear that can overlap the sheets of other elements above and below. This makes sure the connections between elements are waterproof. Other PP elements attached to the planter box are: snap joints which are used to connect add-ons, and a plastic cylinder at the bottom on which a gutter can connect.

The design above is the standard size and colour of a planter box, but different sizes and colours are possible too. HDPP is available in every color (even transparent). The bending moment and deflection of a single planter box filled with saturated soil and plants was also calculated and it shows a planter box can have a total length of 1200 mm. Using this size , however, does mean the maintenance has to be done with more people or it takes more effort. For this reason, and because modularity advices providing a catalogue of items, three different sizes were made; 600 mm, 900 mm and 1200 mm.

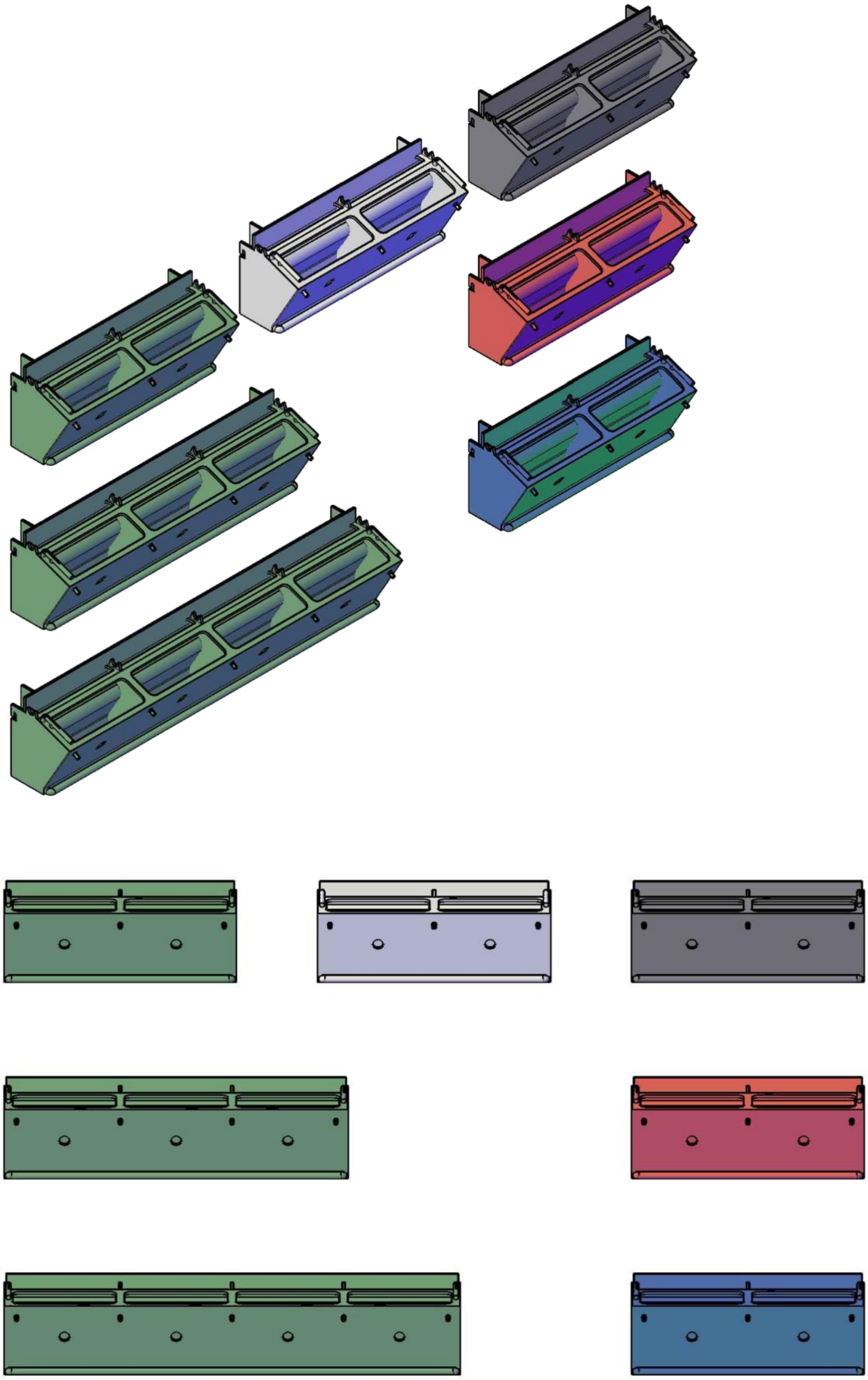


Figure 94: Different sizes and colours for the Plug 'n Plant system, isometric view and front view

The planter boxes use the same shape as the Modulogreen system so the water flow is ideal for plant roots to take up the water. The water enters the planter box through a dripping line in the top box and flows downwards. The shape of the element pushes the water towards the plant roots. On the bottom of each box there is a layer of polyurethane foam, much like the Cultiwall system. The foam holds the water for a longer period of time, so plants have more time to substract the water they need, before it flows out of the bottom of the planter box to the next planter box.

The planter boxes are hung onto horizontal aluminum profiles, based on a system for hanging up metal façade cladding from the company Allface. The profiles have small segments of the profile inside, which can be screwed on the larger profile to stay in place. This segment holds the metal cylinder on which the plater box can hang, but also functions as a drainage pipe. The aluminum profile can be connected to the structure of the building by using aluminum wall mounts. The wall mounts have adjustment holes to take up any deviations.

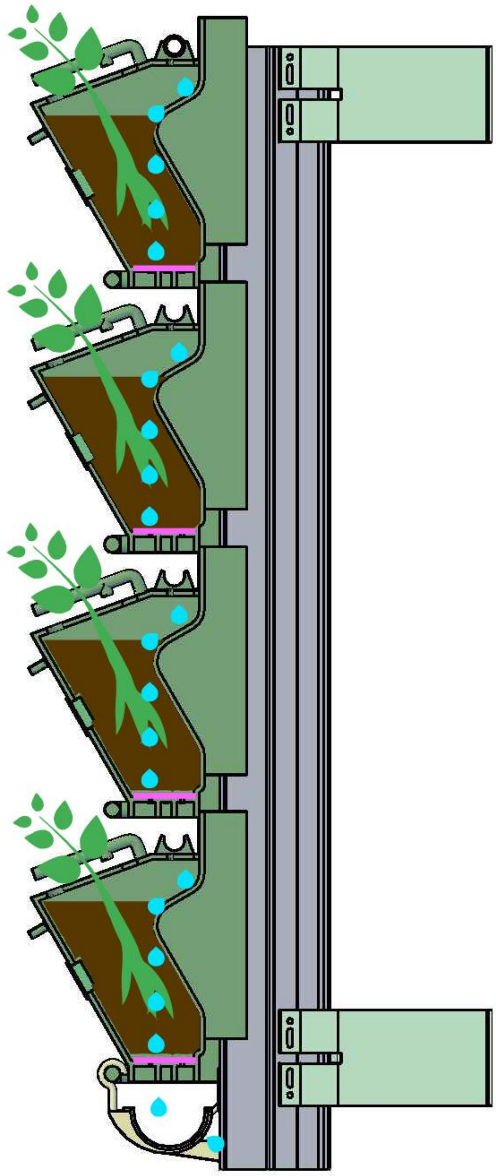


Figure 95: Diagram of water flow

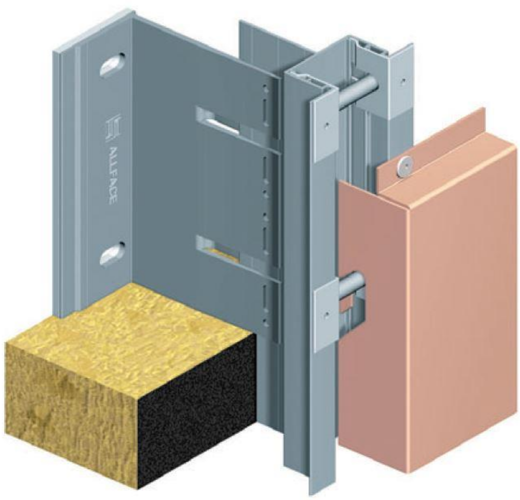


Figure 96: F1.50 Allface system for metal façade cladding

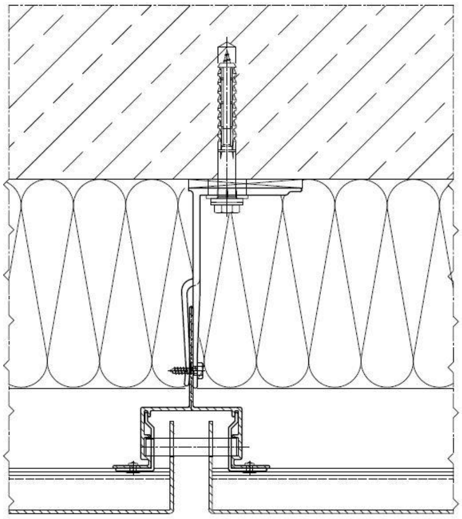


Figure 97: Horizontal section F1.50 Allface systen

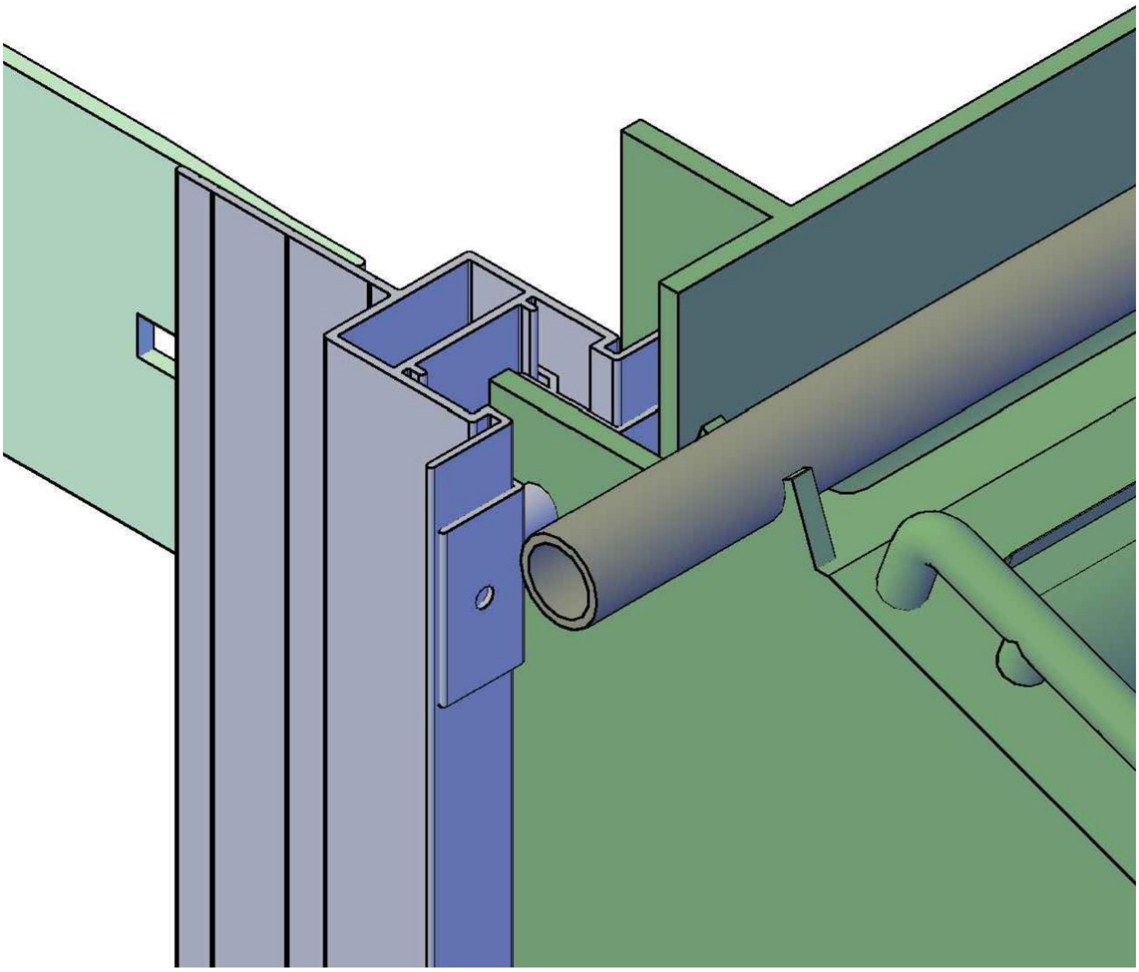


Figure 98: Plug 'n Plant Hanging system with irrigation pipe

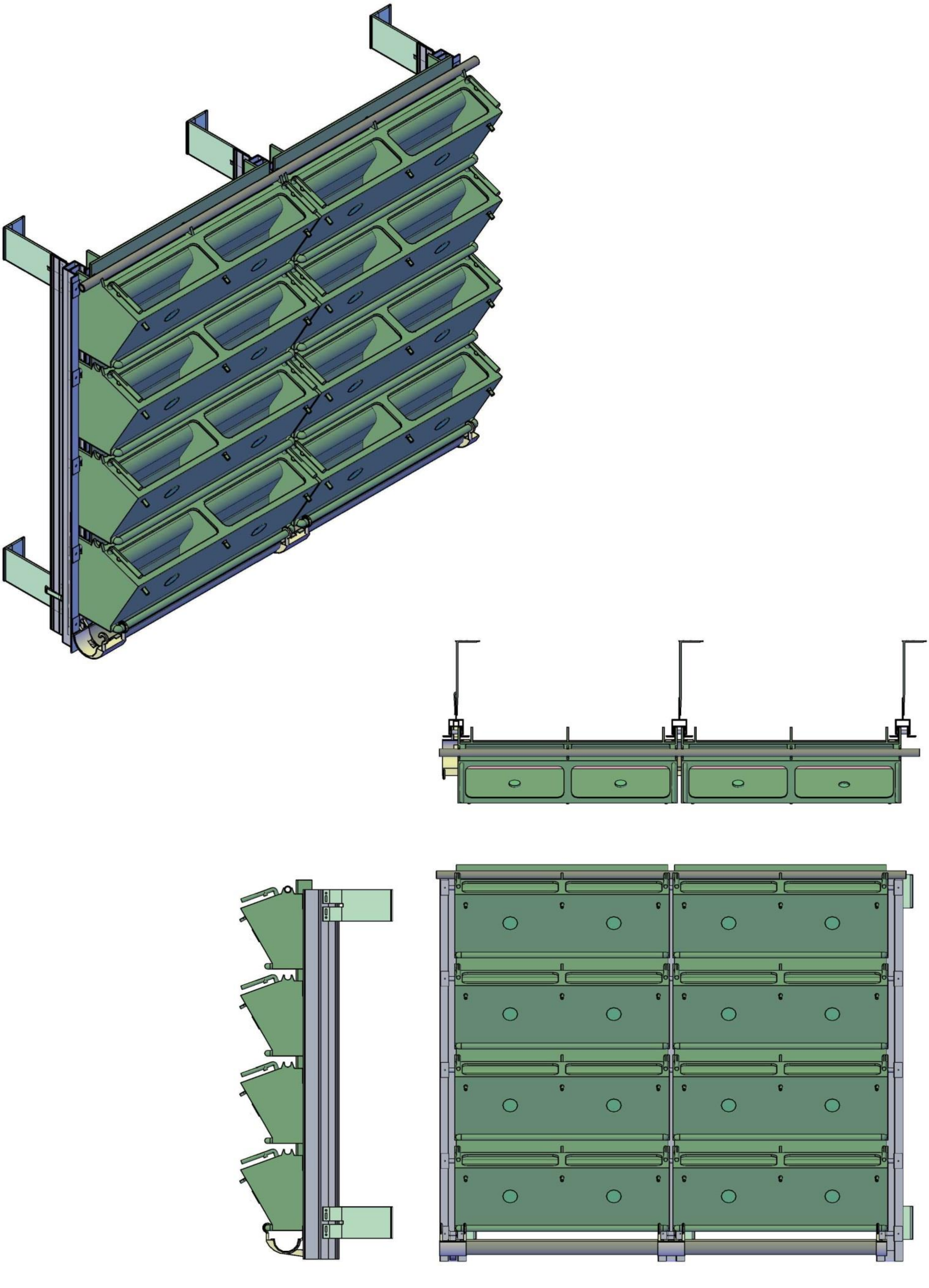


Figure 99: Plug 'n Plant system, isometric view, top view, front view and side view

The first step for setting up the Plug 'n Plant system is attaching the anchors to the rear wall. To these anchors, the aluminium profiles can be hung with the inner profiles already connected on the correct position. Once this is complete, the planter boxes (filled with soil and plants) can be hung up to the inner profile. Now, the gutter can be hung unto the bottom planter box. Additional elements can be attached to the planter boxes. These attachments will be discussed in paragraph 7.3.5, 7.3.6 and 7.3.7.

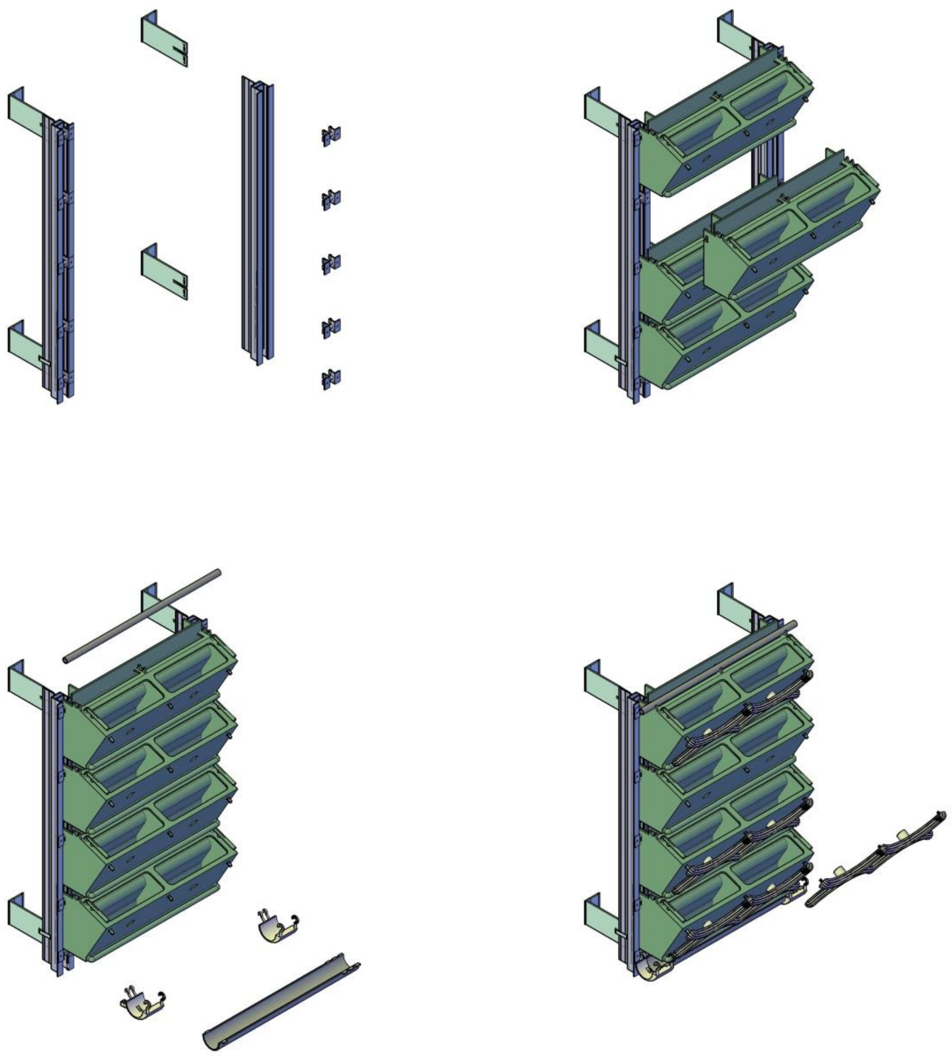


Figure 100: Step by step building process

7.3.4 The gutter

The gutter is the hardest part of the design, because it needs to have a slope, which is hard to work with in a modular element. The solution to this is to make it possible to change the various heights of the connections to the structure. The inner profiles of the aluminum structure can be varied on height before being fixed to the outer profile. This makes for an ideal connecting element between the gutter and the structure. HDPP elements can be hung onto this inner profile on one end and hung onto the planter boxes on the other end. PVC gutters can be placed between these hanging HDPP elements. PVC is a recyclable material, which has not been researched because it is not present in any of the researched living wall systems. However, it is often used as drainage or gutter and since the material is recyclable it is considered a circular element.

The hanging HDPP elements come in various forms. The first type hangs on two planter boxes. The second type hangs on a single planter box and acts at the end of the gutter. A third type hangs on two planter boxes and has an opening in between which leads the drainage water towards the drainage in the aluminum profile. The hooks attached to these HDPP elements can be rotated so they become longer or shorter. This is another way in which the height of the gutter can be changed.

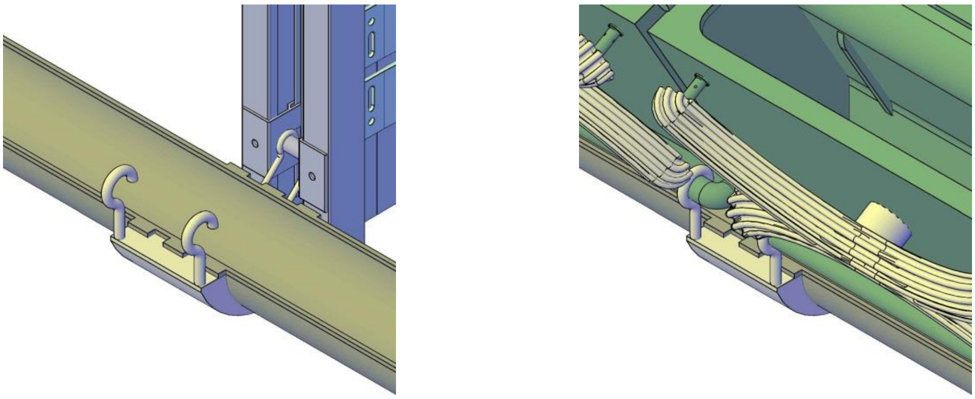


Figure 101: First type of gutter hanging elements

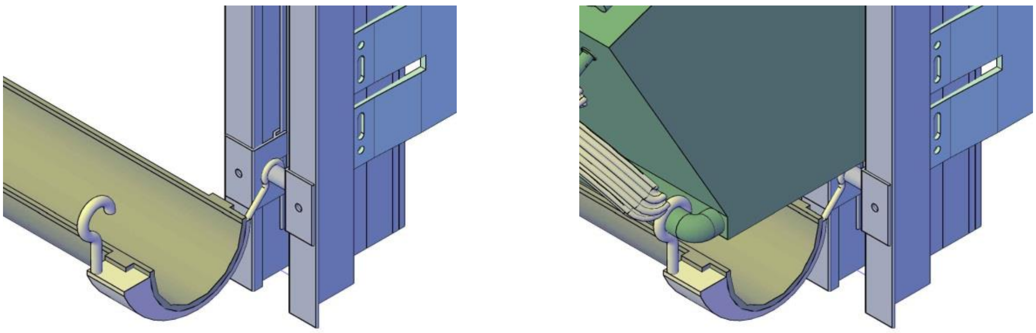


Figure 102: Second type of gutter hanging element at the end of a gutter

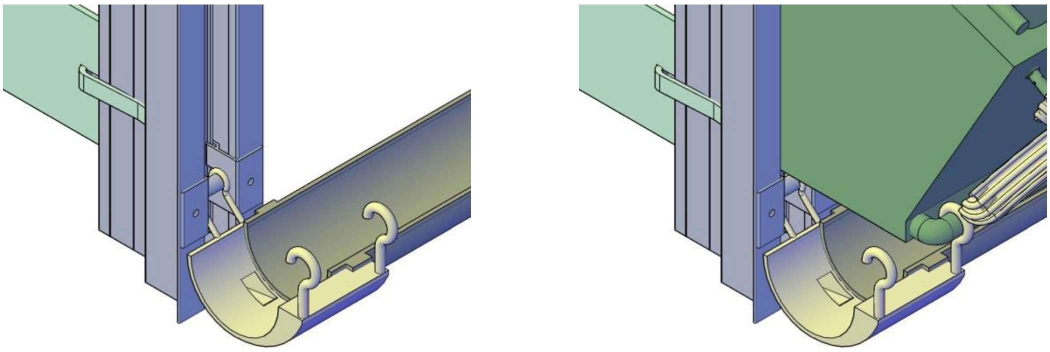


Figure 103: Third type of gutter hanging element, guiding water to the drainage pipes

7.3.5 Add-on for improving air-quality

One of the guidelines of designing for modularity is designing for a catalogue. The consumer could just buy the living wall system, but by designing for a catalogue, he might be able to purchase add-ons to improve his system according to the context of the building. The same design technique was used for the Plug 'n Plant system and three add-ons have been designed. The first one focusses on improving the air quality and is based on the innovation described in paragraph 5.5.3; the titanium dioxide façade.

By cladding a façade with elements with titanium dioxide coating it can improve the air quality. The titanium dioxide turns volatile organic compounds, NOx and SO_2 into harmless products like CO_2 and H_2O. The plants on their turn process the CO_2 and release it as O_2. This would be an ideal solution for the northern façade of the Marconi towers where pollution from the busy roads appears.

The add-on elements are made from polypropylene, just like the planter boxes themselves. The elements are coated with a titanium dioxide coating. To maximize the air filtering effect, the surface area of the elements has been increased by giving the elements a lot of corrugations. The elements are attached to the planter boxes using the hole in the middle of each planter boxes and the snap joints.

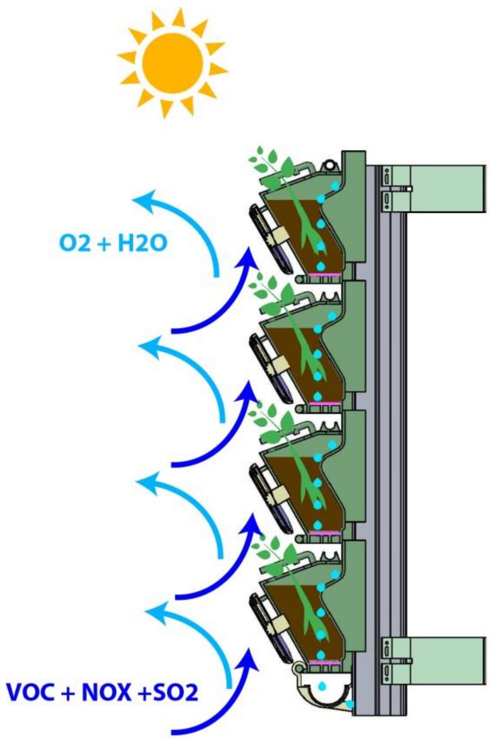


Figure 104: Scheme of air filtering process

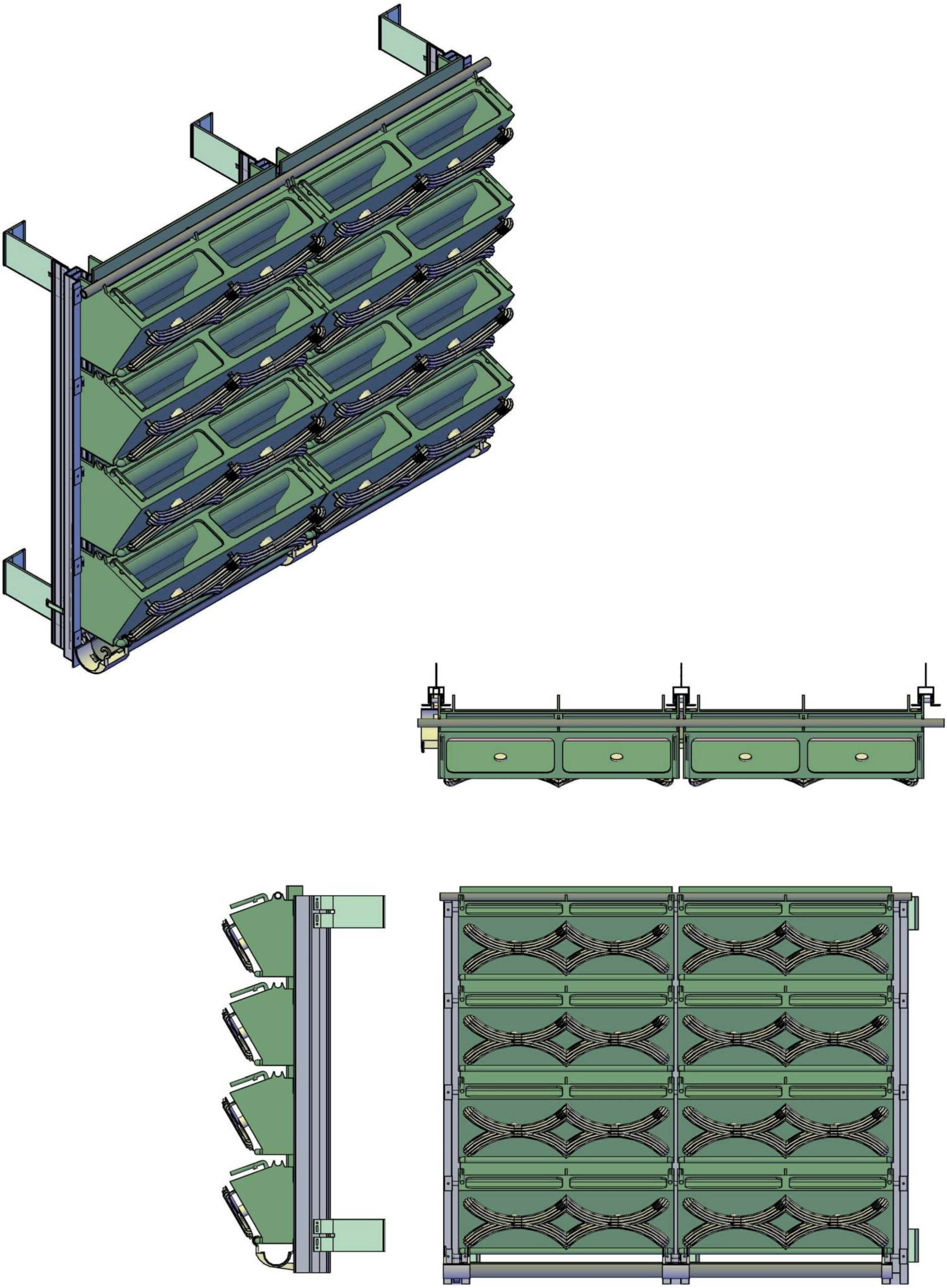


Figure 105: Plug 'n Plant system with air improving add-on, isometric view, top view, front view and side view

7.3.6 Add-on for improving the local biodiversity

The second add-on for the Plug 'n Plant living wall system focusses on increasing the biodiversity. It does this by making it possible to transform various planter boxes into birdhouses or insects cabinets. The hole in front of the planter box is simply left open and the boxes will not be filled with soil, polyurethane foam and plants. Instead, a lid is placed in the opening on the top surface of the planter box. The lids are made from polypropylene, just like the planter boxes themselves. The snap joints are not used when transforming the element into a nest site, but additional bird feeder components are created that are able to connect to these snap joints.

Improving biodiversity is and objective the roof garden next to the Marconi towers is trying to achieve. For this reason the community placed insect cabinets in the roof garden. The living wall system can act on this goal by helping to improve the biodiversity. Various birds have been recorded in the roof garden, namely the blackbird, the robin, various types of gulls and pigeons and even the threatened house sparrow. The Dutch BirdLife association is currently taking measures for protecting the house sparrow by creating nest sites (Vogelbescherming Nederland, 2016). These birdhouses could help with this problem.

Another creature that has been spotted near the roof garden is the pipistrelle bat. The birdhouses can also function as nest sites for bats.

The blackbird

The robin

The herring gull

The feral pigeon

The house sparrow

The pipistrelle bat

Table 10: Fauna near the Marconi towers

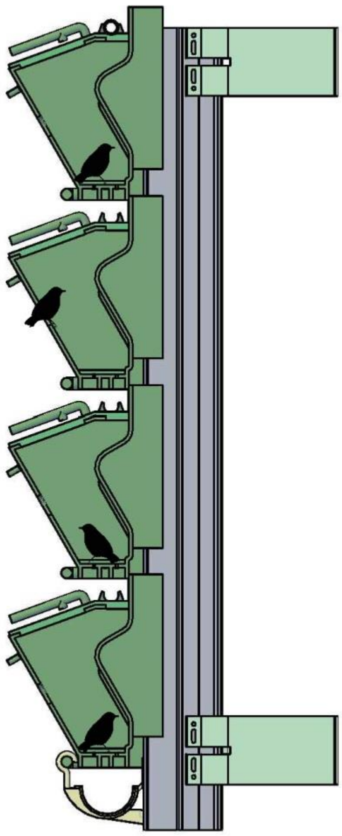


Figure 106: Scheme of biodiversity improving process

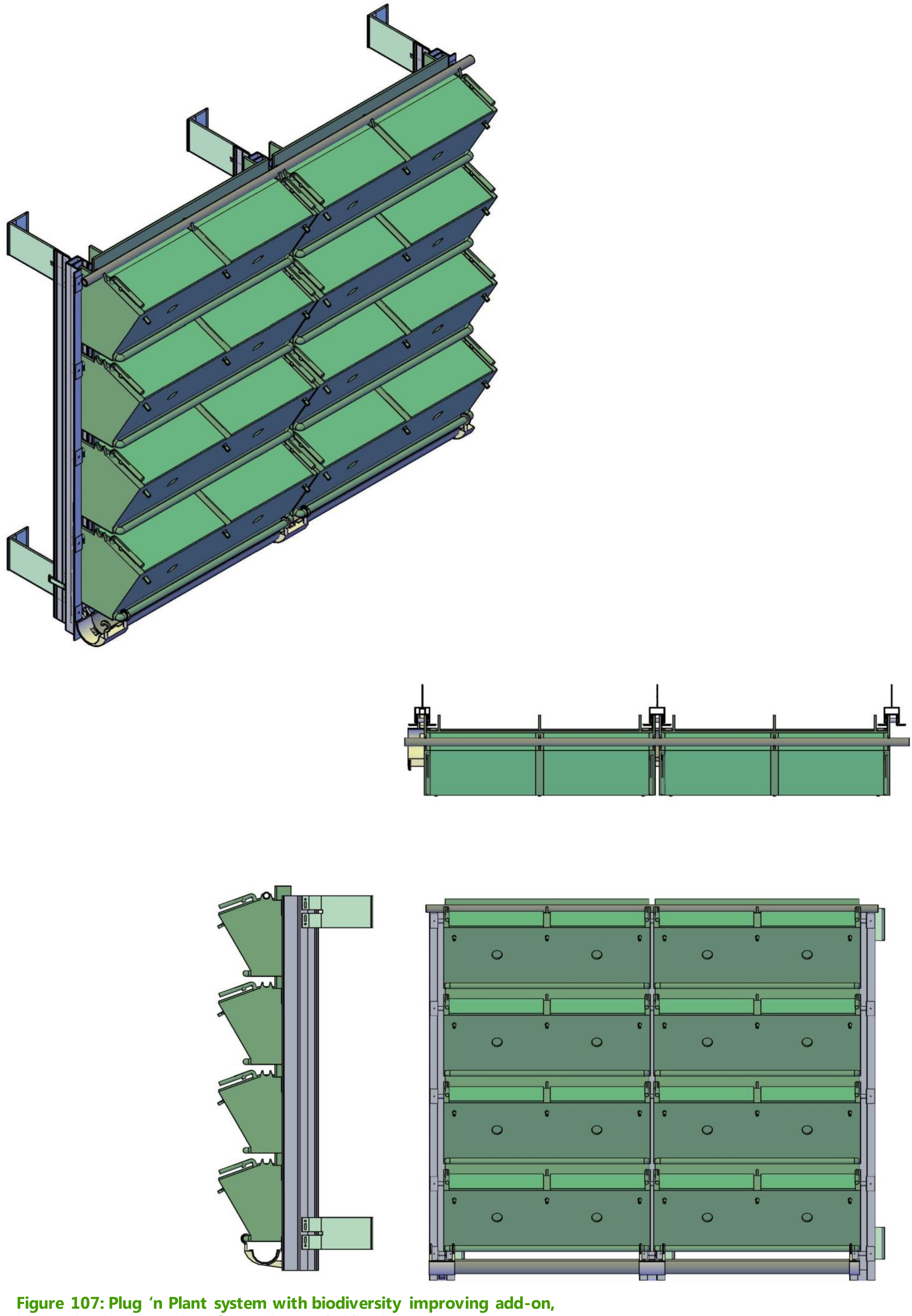


Figure 107: Plug 'n Plant system with biodiversity improving add-on, isometric view, top view, front view and side view

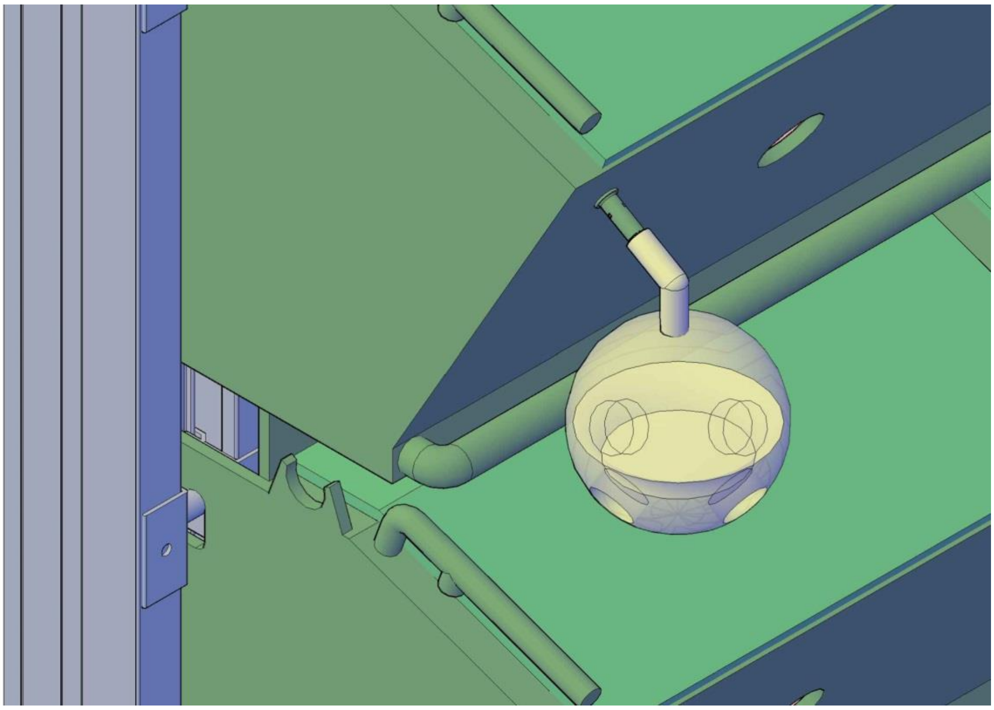


Figure 108: Bird feeder components can be connected to the snap joints

Figure 109: Bird feeder components

7.3.7 Add-on for collecting energy

The third and final add-on for the Plug 'n Plant living wall system is an add-on for collecting energy. Collecting energy is not necessarily an improved benefit of a living wall system, but living wall systems can reduce the energy consumption of a building. Therefore this add-on does seem a logical addition to the living wall system.

The add-on elements are made from transparent polypropylene. The elements contain solar cells on a 35 degree angle, which is the standard optimal angle for collecting solar energy globally. Sunlight that is not collected by the solar cells passes the transparent element and is collected by the plants. The same goes for indirect sunlight and sunlight from a lower angle, which appears in the morning and evening. For the full effect, these add-ons should be placed on a southwards facing façade. The elements are attached to the planter boxes using the hole in the middle of each planter boxes and the snap joints.

Every planter box has roughly 0,04 m^2 of solar cells. An average solar cell can generate roughly 1000 W per square meter and has an efficiency around 0,2. This means a single planter box could generate 0,04 x 1000 x 0,2 = 8 Watts. Cladding the south façade of the Marconi towers would generate around 4620 Watts.

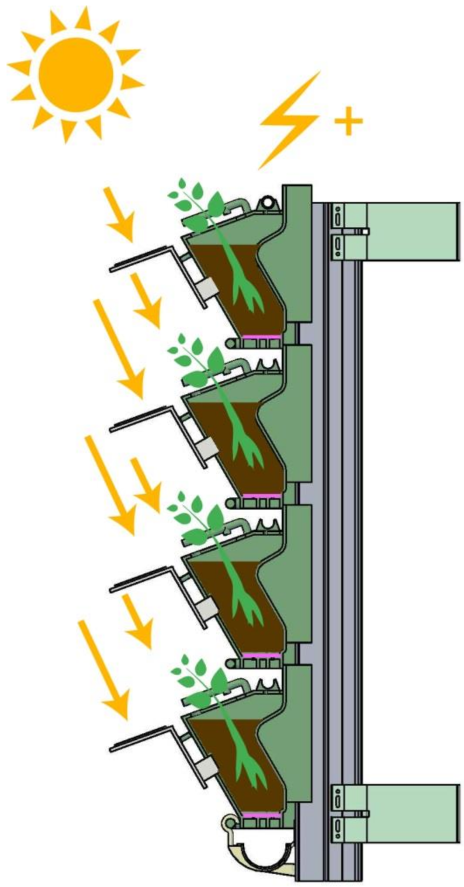


Figure 110: Scheme of energy collecting process

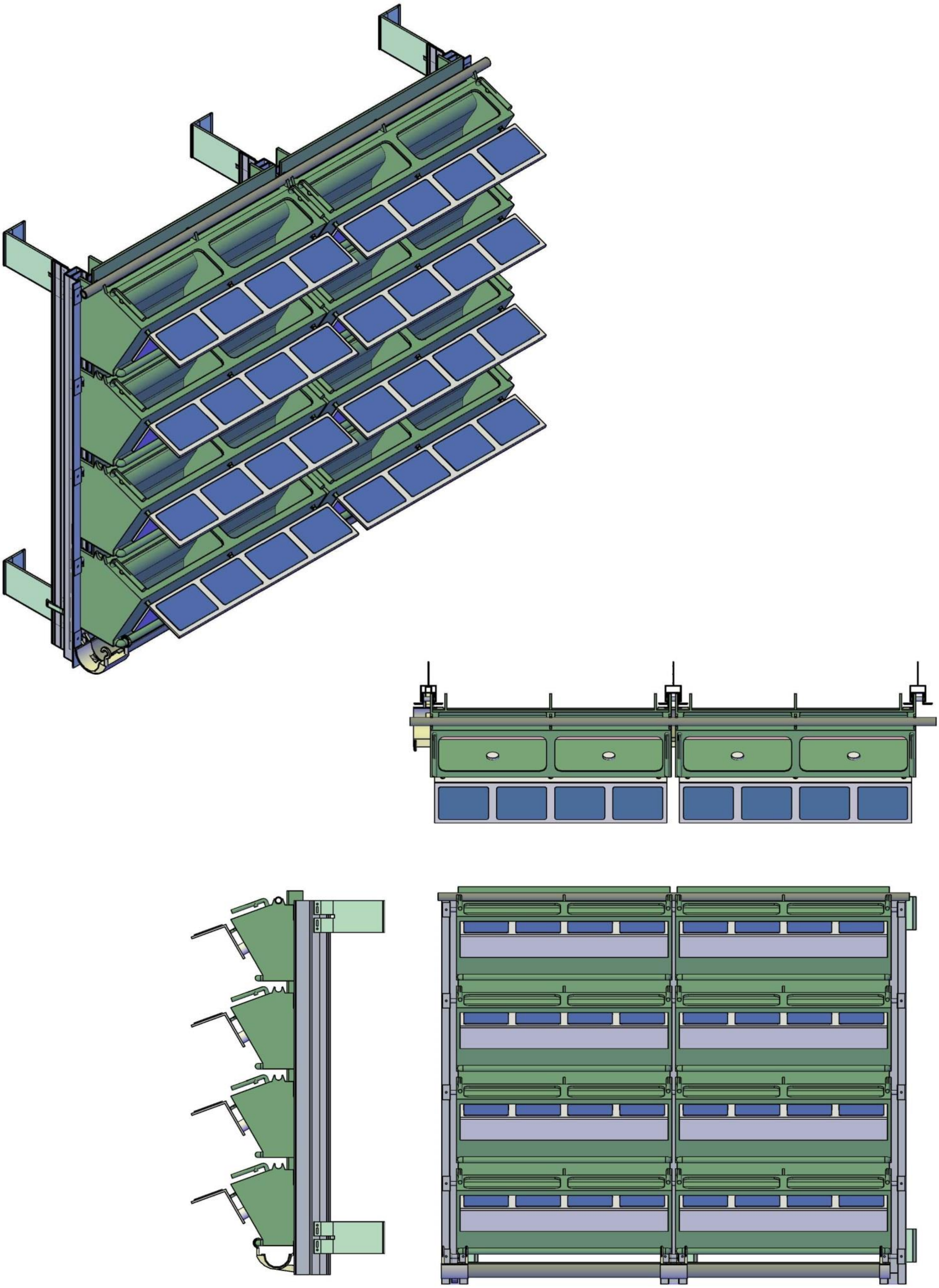


Figure 111: Plug 'n Plant system with energy collecting add-on, isometric view, top view, front view and side view

7.4 Details

This paragraph will show the details of the Plug 'n Plant system as it would be placed on the façade of the Marconi towers. It is important to notice that two different scenarios have been created for portraying these details. In one scenario, The Marconi towers have not undergone any redesign regarding the façade apart from the façade cover, meaning the marble plates have been replaced with the Plug 'n Plant living wall system. In the second scenario, however, additional changes have been implemented to bring the façade of the Marconi towers up to date with today's standards. This means the second scenario has improved insulation and less unwanted air infiltration.

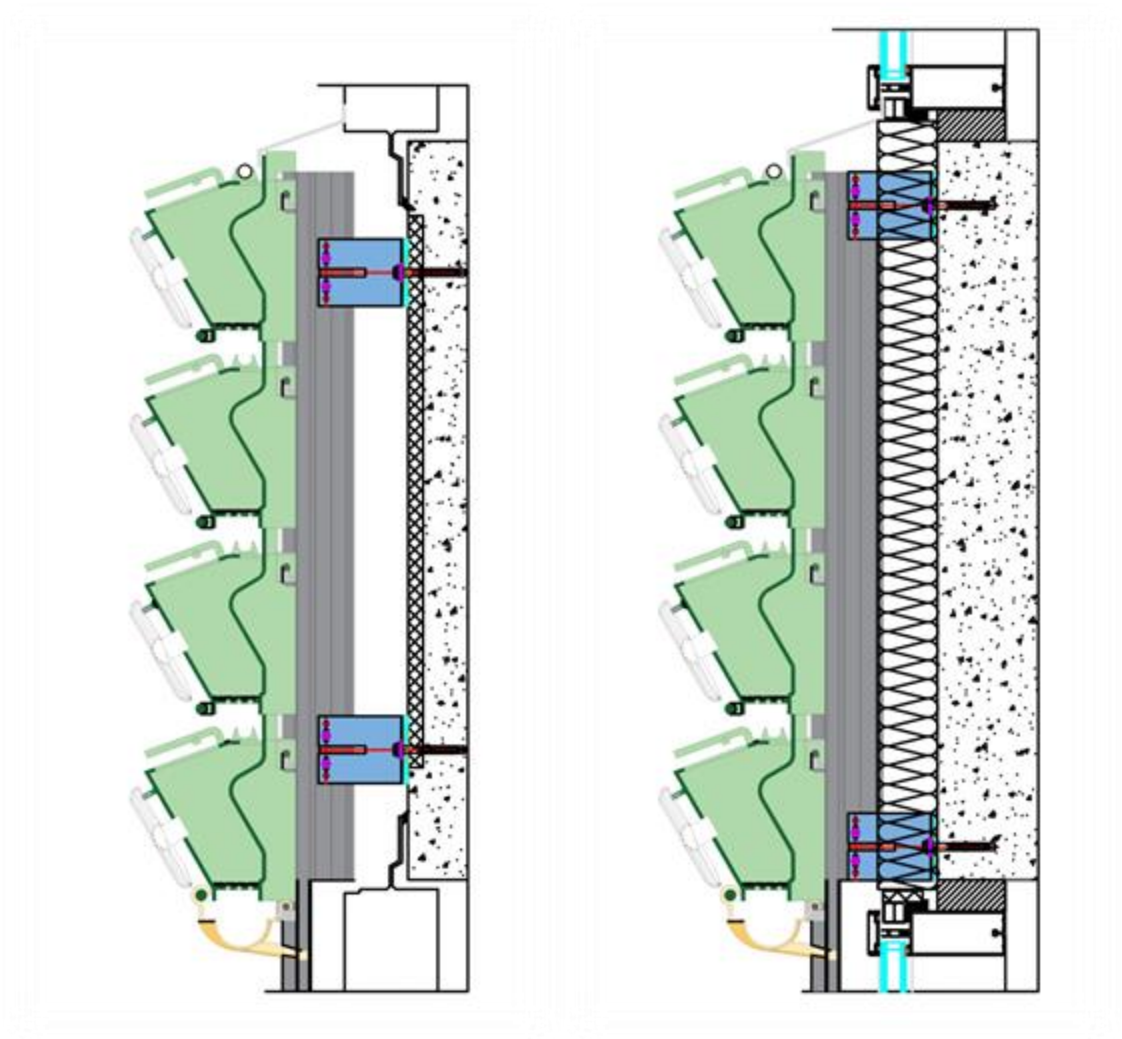


Figure 112 (left): Detail section Plug 'n Plant system on Marconi Towers without redesign façade 1:10

Figure 113 (right): Detail section Plug 'n Plant system on Marconi Towers with redesign façade 1:10

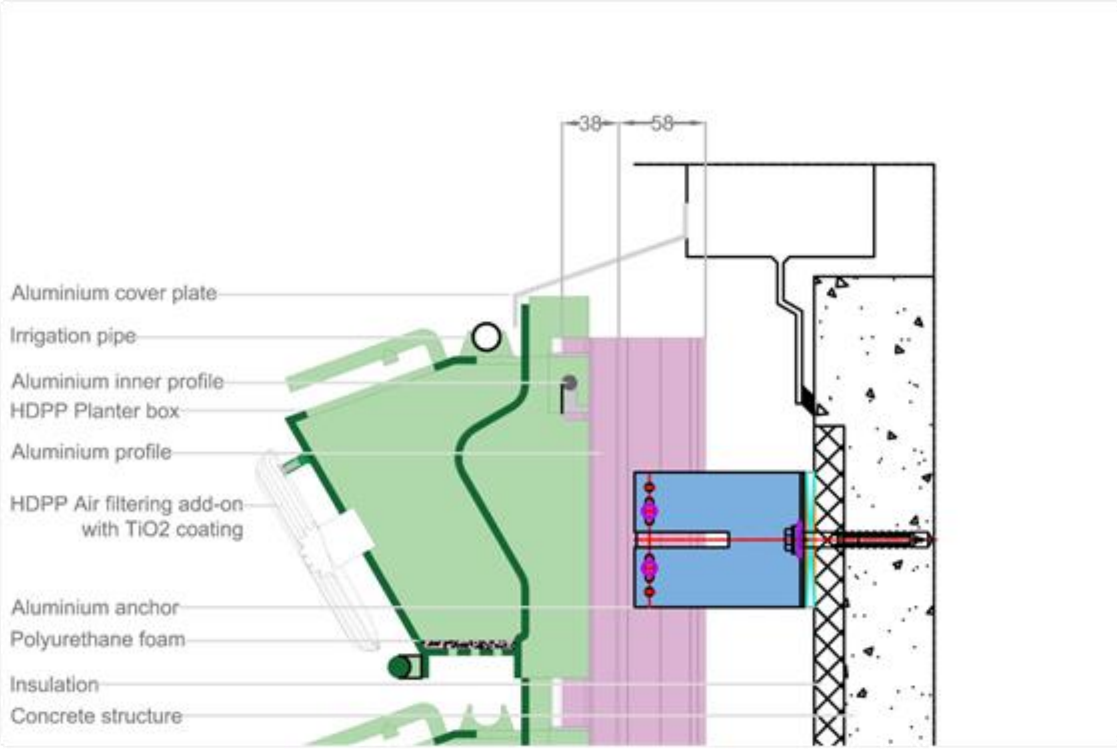


Figure 114: Detail section Plug 'n Plant system on Marconi Towers without redesign façade 1:5

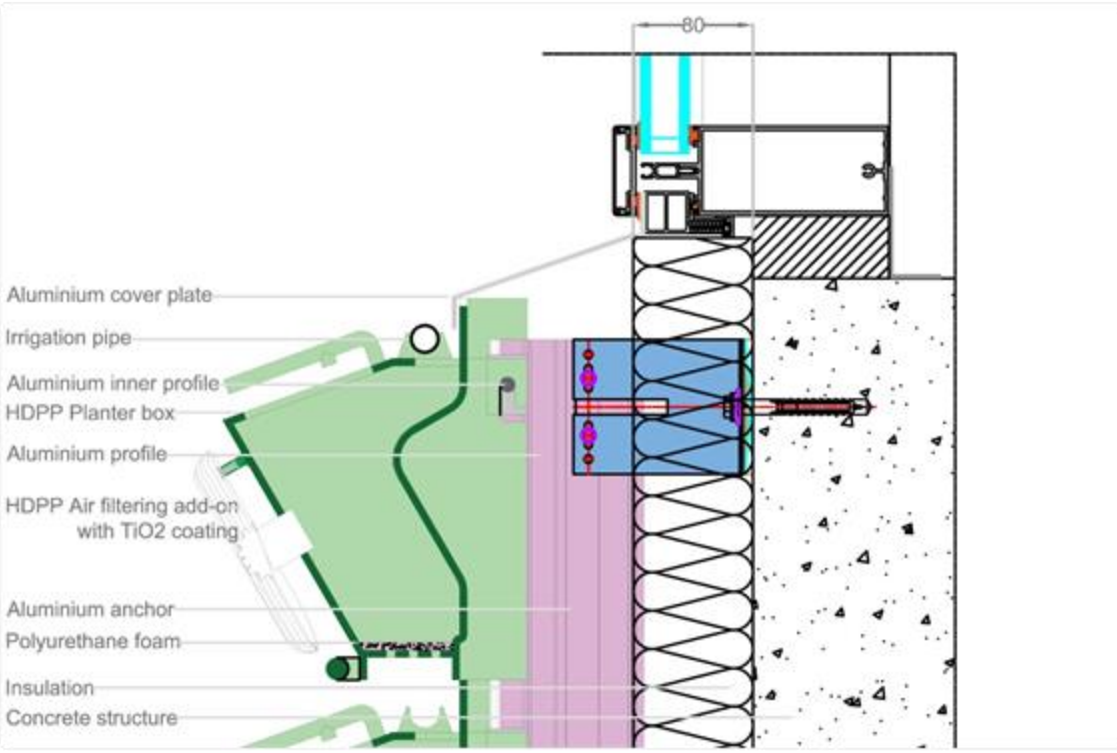


Figure 115: Detail section Plug 'n Plant system on Marconi Towers without redesign façade 1:5

7.5 Model

A model of the Plug 'n Plant system was built to see if a single planter box could be easily placed and retrieved from the structure and to measure the weight of a dry and saturated element. The model contains three planter boxed made from wood instead of polypropylene, which have been decorated with two plants; the Nephrolepis and Princettia.

Figure 116: Picture of the planter box model

3

Figure 117: Picture of the decorated planter box model

Figure 118: Picture of the entire decorated model

7.6 Checking the requirements and boundaries

Now the design is complete, it is important to check if all the design requirements have been fulfilled. Therefore, this paragraph will do a final check of the requirements regarding the dimensions and the weight of the system.

7.6.1 Dimensions check

Requirement: The LWS is able to be transported by truck, which means a single element needs to fit within a container of 2,55 m x 4, 00 m x 12,00 m.

The dimensions of the planter box are 0,2 m x 0,25 m x 0,6 m, which is far less than the maximum allowed dimensions of 2,55 m x 4, 00 m x 12,00 m. This means the requirement has been fulfilled.

7.6.2 Planter box weight check

Requirement: The LWS can be installed and removed easily and quickly by no more than two people, which means as single element cannot weigh more than 20 kg when dry.

Thanks to the 3D computer model, the exact volume of a planter box could be determined.

Volume planter box: 0,0022975 m^3
Density HD polypropylene: 900 kg/m^3
Weight planter box: 0,0022975 * 900 = 2,07 kg

Volume potting soil: 0,0078148
Density potting soil: 300 kg/m^3
Weight potting soil: 0,0078148 * 300 = 2,34 kg

Total covered area: 0,6 m x 0,25 m= 0,15 m^2
Weight plants per area: 5 kg/m^2
Weight plants : 0,15 x 5 = 0,75 kg

Total weight filled planter box: 2,07 + 2,34 + 0,75 = 5,16 kg

A model of the planter box has been made to compare its weight to the calculations. The model had a weight of 4,8 kg. The largest number will be used for further calculations, which means the weight of the planter box will be assumed as 5,16 kg.

A filled planter box has a total weight of 5,16 kg, which is less than the maximum allowed weight of 10 kg. This means the requirement has been fulfilled.

7.6.3 Element weight check

Requirement: The LWS needs to be supported by the structure of the building, which means it cannot be heavier than the total maximum weight of 108 kg/m^2.

Weight filled planter box when dry: 5,16 kg

A model has been made of the planter box, which was then fully saturated. It increased the weight of the planter box with 1,1 kg. For safety reasons a margin has been added, which assumes the increase in weight as 1,5 kg.

5,16 + 1,5 = 6,66 kg
Number of planter boxes per element: 4
Weight dry planter boxes: 4 x 5,16 = 20,64 kg
Weight saturated planter boxes: 4 x 6,66 = 26,64 kg

Number of aluminum profiles: 2
Volume aluminum profile: 0,0005526
Number of aluminum anchors: 4
Volume aluminium anchor: 0,0000837
Density aluminum: 271 kg/m^3
Weight aluminum: (2 x 0,0005526 + 4 x 0,0000837) * 271 = 0,39 kg

Volume PVC gutter: 0,00041961
Density PVC: 1350 kg/m^3
Weight PVC gutter: 0,00041961 * 1350 = 0,57 kg

Total weight single dry element: 20,64 + 0,39 + 0,57 = 21,60
Total weight single dry element: 26,64 + 0,39 + 0,57 = 27,60
Cover area single element: 1 m x0,6 m = 0,6 m^2
Dry weight per m^2: 21,60 / 0,6 = 36 kg/m^2
Saturated weight per m^2: 27,60 / 0,6 = 46 kg/m^2

The total weight of a fully saturated element per m^2 is 46 kg/m^2, which is less than the maximum allowed weight of 108 kg/m^2. This means the requirement has been fulfilled.

The weight can now be compared to the weight of the other systems.

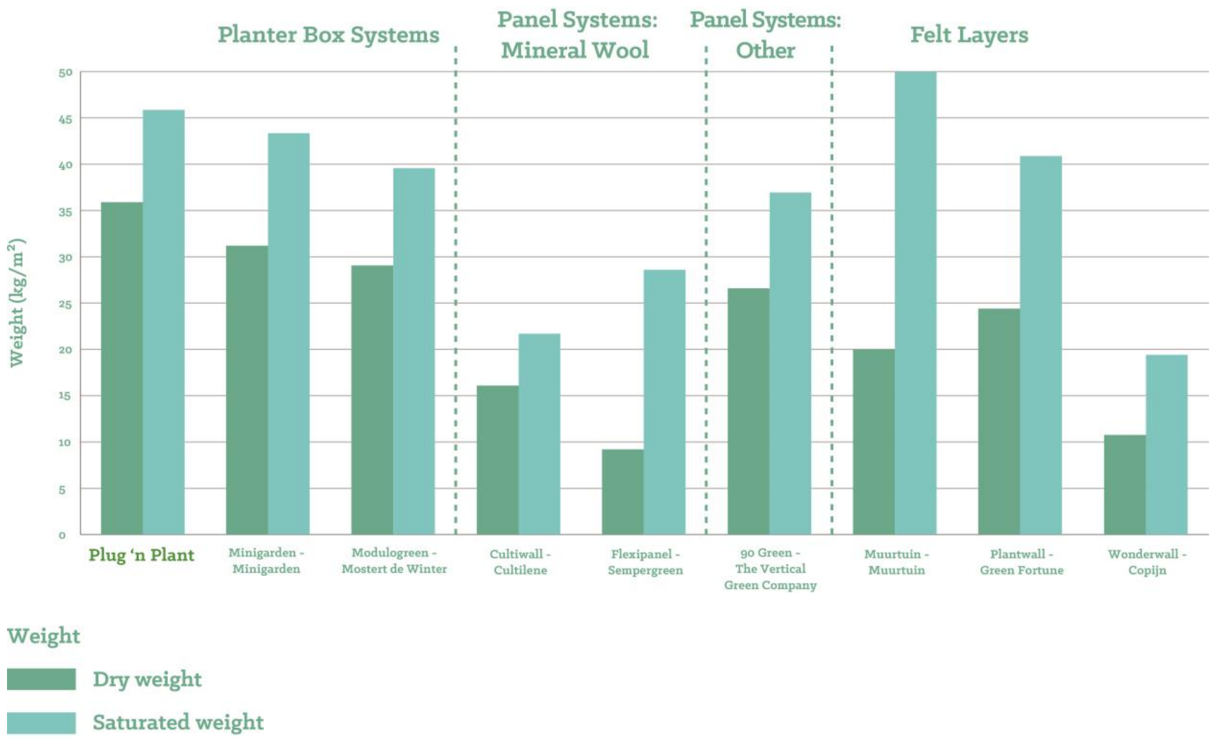


Table 11: Comparison on weight

In this graph we can see that the Plug 'n Play is slightly heavier than the already existing planter box systems. However, these existing systems need to be installed on top of the outer skin of the building, which isn't included in the weight here, so when the full building skin would be taken into account, the Plug 'n Plant system would be the planter box system with the lowest weight. It is possible to even lower the weight of the Plug 'n Plant system by using different substrates or different substrate compositions.

7.6.4 System comparison

This final table has been made to show the differences between the functionalities of the Plug 'n Plant system and the other systems on the current Dutch market.

Comparison systems	Plug 'n Plant system	Other systems	Benefits
Elements can be used as single planter box	✓	–	Increases applicability
Fully made out of circulair materials	✓	–	Decreases costs and environmentally friendly
Fully made out of seperable components	✓	–	Decreases costs and environmentally friendly
Improvements to decrease water consumption	✓	–	Decreases costs and environmentally friendly
Available in various colours and sizes	✓	–	Increases applicability
Provides additional components that improve air quality	✓	✗	Increases applicability and environmentally friendly
Provides additional components that increase biodiversity	✓	✗	Increases applicability and environmentally friendly
Provides additional components that collect energy	✓	✗	Increases applicability and environmentally friendly
Can replace the outer layer of a building	✓	✗	Decreases costs
Can be transported by drones	✓	✗	Decreases maintenance

Legend	
✓	Available for these systems
–	Possibly available for these systems
✗	Not available for these systems

Table 12: Comparison systems on functionality

7.7 Visualizations

Figure 119: Europoint-complex without full redesign of the façade

Figure 120: Europoint-complex with full redesign of the façade

Figure 121: Close-up of Europoint-complex without full redesign of the façade

8. CONCLUSION

8.1 Introduction

This chapter of the Thesis will present all the conclusions and recommendations about vertical green, modularity and the research and design process mentioned in this Thesis. The next paragraph will focus on reviewing the conclusions of this Thesis, while the last paragraph mentions a set of recommendations for future research. These recommendations can lead to even more improvement of vertical green or modular designs within the building industry.

8.2 Conclusion

The main problem statement of this Thesis was formulated as follows:

Living wall systems aren't implemented on a big scale, even though they offer multiple benefits to both the user as the environment, and can't be easily used on the existing utility sector, due to the lack of a fully modular living wall system façade element.

The main goal of this Thesis was to design this fully modular living wall system element, but before doing so, it was important to understand aspects of both modularity and living wall systems. The first part of this Thesis focused on researching the principles of modularity and disassembly:

1. Design with repeating components
2. Design for prefabrication
3. Design for disassembly
4. Design for a catalogue

The principles have a clear order of importance. Designing with repeating components is the core principle of modularity. Designing these repeating modules for prefabrication reveals all the benefits of modularity, since the element becomes cheaper and the quality goes up. By designing for assembly the installation and maintenance becomes easier, since modules can be easily replaced and reused. This requires the need for direct connections using form and shape or indirect connections using objects. No material connections should be used. Finally, by designing for a catalogue, one element can be improved for certain users by providing additional elements for the module.

The next step would be to research vertical green and living wall systems. Vertical green can be divided into three categories: wall vegetation, green façades, and living wall systems. Living wall systems have the most effective benefits, but also require more maintenance. Living wall systems appear in four types: based on planter boxes, based on panels without mineral wool, based on panels with mineral wool, and based on felt layers.

Green façades have a set of disadvantages, such as high cost, high maintenance and increase of insects. However they also have a lot of benefits, such as these four benefits regarding the acclimatization of temperature:

1. Reduce the urban heat island effect
2. External shading
3. Create a microclimate
4. Improve insulation properties

And they have a few benefits regarding other effects:

1. Improving air quality
2. Provide sound insulation
3. Increase biodiversity
4. Aesthetical effects
5. Social and psychological benefits

Various benefits could be optimized in a modular design by improving it with additional components. These benefits are creating external shading, improving insulation properties, improving air quality, providing sound insulation and increasing the biodiversity. The other benefits cannot be optimized by modular design components.

By researching these living wall systems it became clear that the main reason to buy a living wall system is aesthetics. To achieve these aesthetics, living wall systems need proper plant selection and maintenance. The prices of a living wall system range between €400,- per m^2 and €1000,- per m^2. A system based on planter boxes has low water consumption, a high lifespan and many of the components are deemed reusable. Systems based on panels with mineral wool are the lightest, score better on the use of circular materials and have, along with systems based on felt layers, more separable components.

With this information it was possible to design a new living wall system with a focus on modularity for the Marconi Towers in Rotterdam. Planter boxes have been chosen as design basis, since the large area that needs to be covered asks for a low water consumption. Extra attention was given to the separability and the use of circular materials. The design uses planter boxes that are hung onto aluminum profiles. These planter boxes function as the outer layer of the building and can be placed directly over the insulation. They can be easily replaced when needed and the entire system is made out of circular materials. The living wall system also offers various additional components to improve certain benefits. One add-on improves the air quality, a second increases the biodiversity and a third collects energy.

8.3 Recommendations

This paragraph provides a number of recommendations for future research, which could improve modular design and/or applications of vertical green. The following design and research topics are commended:

- Research towards more in-depth design guidelines for designing with modularity.
- Research towards ways to make living wall systems cheaper.
- Research towards ways to decrease the maintenance of living wall systems.
- Research towards living wall systems which have no waste water.
- A design for a complete modular living wall system with an integrated structural wall.
- A design for a modular version of a living wall system based on panels.
- A design for a modular version of a living wall system based on felt layers.
- A design for a modular living wall system that can be placed within a curtain wall.
- Additions to living wall systems that improve the benefit of reducing sound.

10.REFLECTION

It is important to reflect on this Thesis so the strong points and the weak points become clear. This will add to the learning process. Secondly, a weak point of this study could be researched in more detail as a subject for a future study. To reflect this Thesis, it is not only important to look at the results and their accuracy or the effect of the design, but also the relationship of the research and design, the relationship between the research and the chosen subject and the relationship between the design and the social context.

There is a direct connection between the research and the design present. The research contains understanding living wall systems (LWS) that are currently on the market, which is the basis for designing a new living wall system. Not only does this offer a set of ideas and the needed specifications for a LWS, such as weight and water consumption, to enter the market, but it also provides the numbers to compare the various systems in their specifications, which can be used in the design phase for optimization. The research also provides a set materials and connections that can be used in the design process.

The chosen method for this research might not be optimal, but can still be considered effective. While a common design project would indeed start with a literature study, contextual study and a research of a certain aspect leading to a design, this has not been the case with the current LWS on the market. Most of the LWS start from an innovation, which is turned into an economical design that can be used almost everywhere. This approach, however, would not utilize the research part. Taking this different approach leads to different solutions and innovations.

The personal experience of this literature research was rather solid. The information available on vertical green and especially living wall systems was easy to find and concentrated within a few books and reports. This is probably due to the fact that vertical living wall systems are a fairly young concept. Information on modularity was rather broad with many sources leading to different interpretations of modularity. Eventually these interpretations could be collected and were merged into the four main principles for designing with modularity.

The analysis of the living wall systems currently on the market was a big job, which is why this had to be done along with my colleague Maaike Kok. The communication with the companies providing living wall systems was a large part of this analysis and led to a variety of problems. Some of the companies either didn't want to share information about their product. Other companies showed their willingness to help with this analysis, but eventually kept sending us from one contact to another. This was shown to be a tedious process, but eventually it was possible to compare eight LWS, while the actual goal was to compare a minimum of five systems.

Although the method of literature research and analysis of systems on the current market is fairly good towards the design phase in terms of general properties of systems, it could be stronger in determining the circularity of the researched systems. Perhaps an existing method, such as a cradle-to-cradle scoring or a NIBE scoring would be more interesting for companies, since these methods could lead to a certificate.

The design process had a quick start due to the fact that a lot of work had been prepared, like understanding of the context and the requirement. Eventually there were many moments where the design was reviewed to ensure it was still on the right track to becoming a successful LWS. Many steps backwards had to be made to improve the design. There were many requirements and the idea was to integrate all of them in a smooth and simple way. The drainage within the aluminum profiles is a great example of a successful integration. As the design process continued, some element just seemed to be simply attached to the planter box. This led to many elements affecting the aesthetical value. Decreasing this impact was a big problem within the design process.

Another element that deemed problematic in the design process was the gutter. For modular design one always strives for rectangular elements in a horizontal or vertical direction. The gutter, however, needs to be provided with a slope, so water can easily find its way out of the system, which means the gutter needs to be placed at different heights all over the façade. This problem was eventually solved by connecting the gutter to the inner aluminum profiles which can be adjusted on their height when installing the system.

The final big problem in the design process was the maintenance of the system. Although a single planter box could be easily retrieved from the structure, it was important to look at the maintenance on a larger scale and think of the building maintenance units that are used to retrieve this planter box. Considering the Europoint-complex was already provided with a façade elevator, the most effective building maintenance unit, thinking out of the box and with an eye for the future was critical here. Eventually, making the LWS futureproof by designing with drones in mind, the maintenance of the LWS was taken one step further.

As for the final design itself, the focus on modularity has led to a probably cheaper and easier design then what's currently on the market. In the wider social context this could improve and enlarge the application of living wall systems. The user has more options by choosing what benefits of the living wall system he wants to amplify. The design is not perfect, however, and could be improved by redesigning it at a smaller scale with industrial engineering values and economical values. It would be recommended to do this before making this product available for the public market.

In conclusion, an understanding of what's currently on the market leads to great insights that could help industry as a whole. By collecting the problems and solutions of every company and combining them with the principles of modularity and other innovations that could tackle these problems or increase the benefits of the systems, it was possible to create a better product. The living wall system is now ready for large scale implementation.

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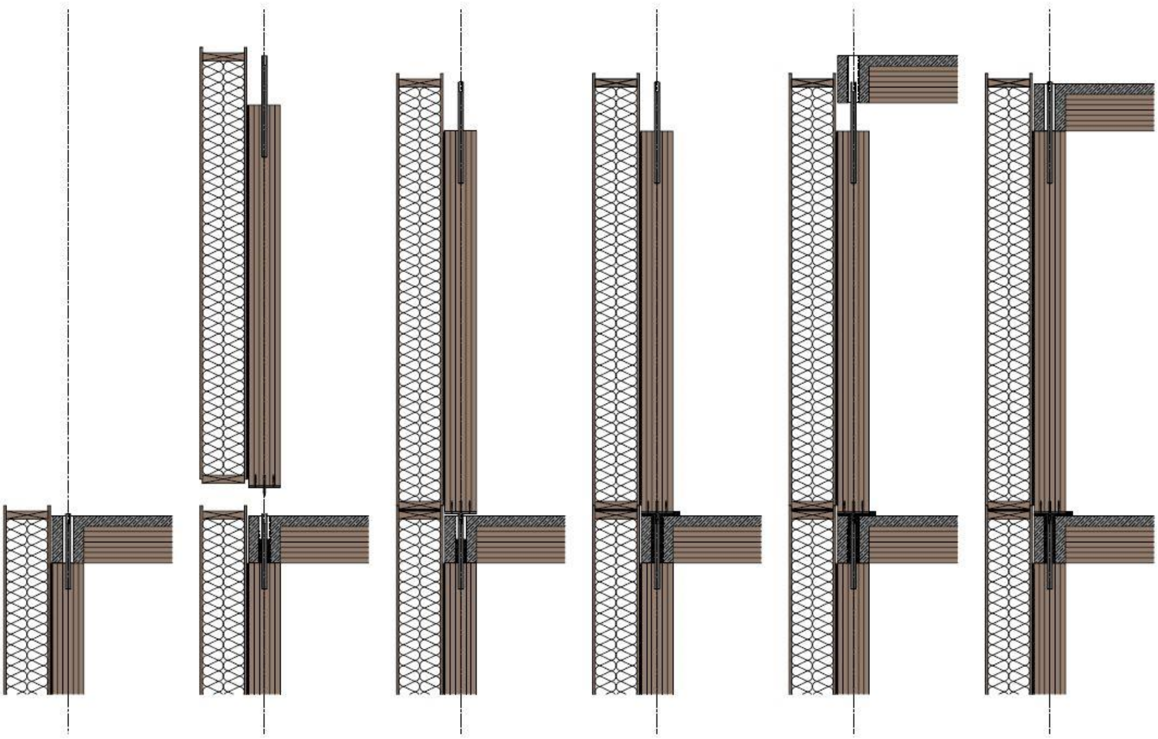
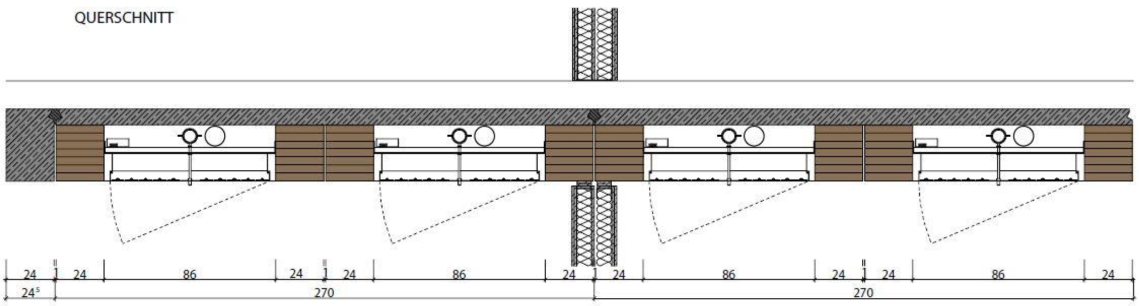
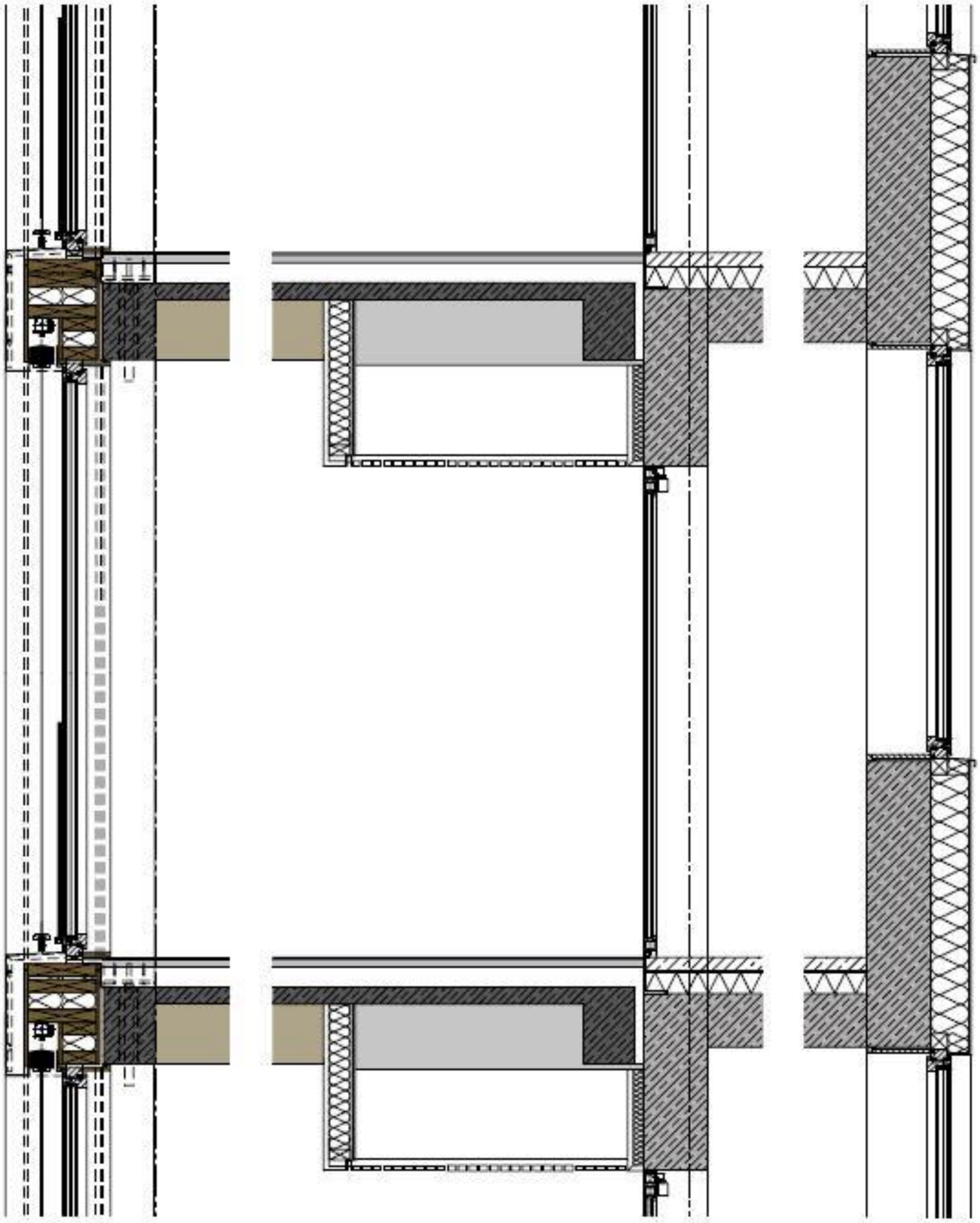
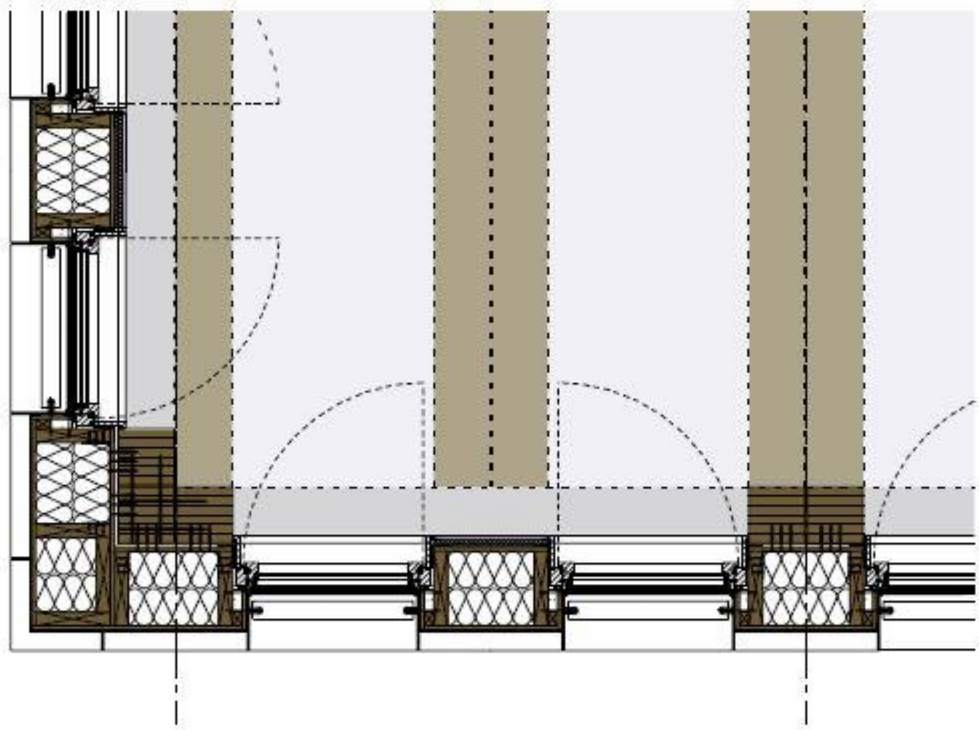
APPENDIX A: LIFECYCLE TOWER DETAILS









APPENDIX B: OVERVIEW AVAILABLE LWS

Planter boxes

Bin Fen Green Wall

Name:	*Modular system*	
System type:	Planter boxes	
Maintenance:	Unknown	
Materials & Layers:	Plant pots & Frame made out of PP (Recycled). The substrate is compost.	
Functionalities:	Facility to integrate automatic irrigation system	
Plant species:	Divers	
Weight:	Frame (1 pcs.):	0,58 kg
	Plant Pot (1 pcs.):	0,12 kg
	Frame incl. 5 pots):	1 kg (without substrate and water)
	Bracket:	Unknown
	Compost:	0,00055 m3 (weight depends on compost used)
	Water:	50 ml = 49,8 kg
System height:	Unknown	
Dimensions:	Frame: 790 mm x 195 mm x 20 mm (height x width x thickness) Plant pots: 130 mm x 110 mm x 120 mm (length x width x height) Brackets: 170 mm x 40 mm x 40 mm (length x width x height) 8 frames = 1 m²	
Modular:	Yes	
Other:	Compost and water are separated by a water absorbent membrane. Needs to be mounted on supporting structure (brackets). Plants can easily be changed. No waterproof membrane is required. Frame (order per 20 pcs.) Plant pots (order per 100 pcs.) Brackets (order per 1 pcs.)	

Name:	*Bespoke system*	
System type:	Planter boxes	
Maintenance:	Unknown	
Materials & Layers:	Weldmesh (Concrete mesh), Plant pots made out of PP (Recycled). The substrate is compost.	
Functionalities:	Faciliting the integration of an automatic irrigation system	
Plant species:	Divers	
Weight:	Weldmesh:	Unknown
	Plant Pot (1 pcs.):	0,12 kg
	Bracket:	Unknown
	Compost:	0,00055 m3 (weight depends on compost used)
	Water:	50 ml = 49,8 kg
Dimensions:	Weldmesh: 50 mm x 50 mm x 3 mm (rastersize x thickness). Plant pots: 130 mm x 110 mm x 120 mm (length x width x height) Brackets: 170 mm x 40 mm x 40 mm (length x width x height)	
Modular:	No	
Other:	Compost and water are separated by a water absorbent membrane Needs to be mounted on supporting structure (brackets), pots are hanging	

onto the weldmesh.
Plants can easily be changed.
No waterproof membrane is required.
Weldmesh (order per m²)
Plant pots (order per 100 pcs.)
Brackets (order per 1 pcs.)

Green Fortune

Name:	Tubegarden
System type:	Planter boxes
Maintenance:	Low, due to hydroponics systems
Materials & Layers:	A set of four connected white tubes serve as planter boxes. A hydroponics system is integrated within the tubes, connected to a pump. The tubes are attached to wall, using a steel frame. The four tubes can be organized in any wall, from a wall system to a garden table.
Functionalities:	Hydroponics system and LED lights.
Plant species:	Low variety of plants.
Weight:	Unknown
Dimension:	1000 mm x 1000 mm x 1600 mm (length x width x height)
Modularity:	Yes
Other:	The current system can't be used outside, so it would have to be adapted to withstand the outdoor environment.

Greenwave

Name:	Greenwave 4.0
System type:	Planter boxes
Maintenance:	Low, wall is mostly self-sustaining
Materials & Layers:	Steel profiles are fixed onto the wall with mounting brackets. Planter boxes, made from recyclable fiber-reinforced HDPP plastic are attached to the steel profiles. These planter boxes hold the substrate and the plants. The substrate is compost.
Functionalities:	It has an irrigation system, but is designed to work without pumps and for a selection of plants.
Plant species:	Medium variety of plants
Weight:	Unknown
Dimension:	600 mm x 510 mm (height x width)
Modularity:	Yes
Other:	-

Koberg

Name:	ANS Living Wall System
System type:	Planter boxes
Maintenance:	Low, wall is mostly self-sustaining
Materials & Layers:	Modular planter box elements with irrigation pipe and capillary matting is placed upon a horizontal fixing rail and attached with a 60mm stainless steel screw. The horizontal fixing rails is attached to vertical PFC rails with a damp proof membrane in between them. The substrate is compost.
Functionalities:	Automatic irrigation system
Plant species:	Large variety of plants
Weight:	Unknown
Dimension:	500 mm x 200 mm x 100 mm (estimated height x width x depth)
Modularity:	Yes
Other:	Fully recyclable model available 10 year guarantee

Minigarden

Name:	Minigarden	
System type:	Planter boxes	
Costs:	Irrigation kit:	€ 25,95 (Suitable for 27 plants, 9 vertical modules)
	Minigarden Vertical Module:	€ 16,50 (incl. 1 x minigarden vertical module, 1 x top cover, 4 mounting clips).
	Set of 3 modules:	€ 53,95 (incl. 3 x minigarden vertical module, 3 x top cover with drainage function, 1 x baseplate, 18 mounting clips & irrigation system).
	Set of 8 modules:	€ 164,50 (incl. 8 x minigarden vertical module, 8 x top cover with drainage function, 1 x baseplate, 18 mounting clips).
	Baseplate:	€ 5,50
	Wall bracket:	€ 7,50 (Incl. 1 x Minigarden Wall Support Brackets, 2 x Stainless steel screws, 2 x wall plugs, 4 x special connection pieces for stability).
	Minigarden Fixers:	€ 7,50 (Incl. 4 x Minigarden Fixers, 16 x Nails). For standing and hanging systems).
	Corner 3 modules:	€ 24,95
Maintenance:	Unknown	
Materials & Layers:	Polypropylene Moplen with UV protection. Consist of four elements: stackable vertical module/plant container, drainage layer, baseplate & mounting clips.	
Functionalities:	Unknown	
Plant species:	Alternanthera (min. 6 hours of sunlight, avoid -4 C) Lantana montevidensis (min. 6 hours of sunlight, avoid -4 C) Lavandula angustifolia (min. 6 hours of sunlight, avoid -4 C) Lavandula Stoecha (min. 6 hours of sunlight, avoid -4 C) Ophiopogon planiscapus nigrescens (min. 6 hours of sunlight, avoid -4 C)	

Peperomia Red Shumi (min. 6 hours of sunlight, avoid -4 C)
Other plants, above are most selected plants.

Weight: Set of 1 module: 0,72 + 0,34kg = 1,06 kg (Minigarden Vertical Module + Baseplate)
Set of 3 modules: 3,34kg
Set of 8 modules: 9,9 kg

System height: Unknown

Dimensions: Set of 1 module: 200 mm x 646 mm x 190 mm (height x width x depth)
Set of 3 modules: 570 mm x 646 mm x 190 mm (height x width x depth)
Set of 8 modules: 1470 mm x 646 mm x 190 mm (height x width x depth

Modular: Yes

Other: 3 year guarantee
Free standing or wall mountable.
Great variety in design possibilities
Irrigation kit can be bought separately.
100 % recyclable

Mostert de Winter

Modulogreen

System type: Planter boxes

Maintenance: Unknown

Materials & Layers: Aluminium or wooden supporting structure. Panels are made out of shockproof glass fiber-reinforced PP. Mineral substrate made out of Lava, pumice (bims), clay, tree bark. Thermally insulated wall brackets, self-drilling screws. Frame cover. Drip irrigation system and control unit. The substrate is compost.

Functionalities: Optional feature to monitor the system at distance and thermal insulation of the facade.

Plant species: Large variety of plants.

Weight: Unknown

System height: Unknown

Dimensions: Two dimensions known, unclear which is correct:
From picture and text
237 mm, 427 mm or 807 mm height, 300 mm, 600 mm or 900 mm width, 178 mm depth

Modular: Yes

Other: Can replace outer leaf/skin.
No damage from intense cold.
Not much water needed.
Water tight (by overlapping connection) and thermal skin building envelop.
Soundproofing qualities.
10 year guarantee.

Foam

The Vertical Green Company

Name: Fytowall
System type: Foam
Maintenance: Unknown
Materials & Layers: Aminoplast resin foam is used as a growing medium of plants. This foam is fixed onto a wall.
Functionalities: Unknown
Plant species: Medium variety of plants.
Weight: 88 kg/m² without plants, 100 kg/m² with plants
Dimension: 1000 mm x 490 mm x 140 mm (height x width x depth)
Modularity: Yes
Other: -

Mineral wool

Wallflore Systems N.V.

Name: Wallflore EFIX-e
System type: Mineral wool
Maintenance: Low, wall is mostly self-sustaining
Materials & Layers: A steel coop with Rockwool is fixed on the wall using U-profiles.
Functionalities: Automatic irrigation system
Plant species: Large variety of plants
Weight: 35 kg/m²
Dimension: 600 mm x 1000 mm / 600 mm x 750 mm / 600 mm x 500 mm / 600 mm x 250 mm / 450 mm x 1000 mm / 450 mm x 750 mm / 450 mm x 500 mm / 450 mm x 250 mm / 300 mm x 1000 mm / 300 mm x 750 mm / 300 mm x 500 mm / 300 mm x 250 mm (height x width). Depth is 135 mm without cavity.
Modularity: Yes
Other:

Sempergreen

Name: Flexipanel
System type: Mineral wool
Maintenance: Panels are checked every month by Sempergreen.
Materials & Layers: Panel consists of, from innermost to outermost layer, a TPO membrane, a specially designed pressed substrate matt and a capillary UV-resistant membrane.
Functionalities: -
Plant species: Shrubs, perennials and ferns.
Weight: 20-25 kg/m² dry and 40-45 kg/² saturated
Dimension: 620 x 520 x 100
Modularity: Yes
Other: A web based irrigation system with a maintenance contract guarantees an evergreen facade.

Name:	Framepanel
System type:	Mineral wool
Maintenance:	Panels are checked every month by Sempergreen.
Materials & Layers:	A steel coop holds a specially designed pressed substrate matt, along with pumice and a capillary layer.
Functionalities:	-
Plant species:	Shrubs, perennials and ferns.
Weight:	30-40 kg/m² dry and 50-60 kg/² saturated
Dimension:	2000 x 600 x 130
Modularity:	Yes
Other:	A web based irrigation system with a maintenance contract guarantees an evergreen facade. ‘

Felt

Copijn

Name:	Wonderwall Modular
System type:	Felt
Maintenance:	Unknown
Materials & Layers:	A structure made of nature based composites, flax and hennep, hold plants in their place. The substrate is placed behind the structure, although it is unclear what the substrate is made of.
Functionalities:	-
Plant species:	Unknown
Weight:	Unknown
Dimension:	600 x 600
Modularity:	Yes
Other:	-

Dutch Impressive Green

Name:	Dutch Impressive Green Wall
System type:	Felt
Maintenance:	Presented as low, although it is not clear why
Materials & Layers:	Felt layer with pockets hold plants. A stainless steel gutter is placed at the bottom of the wall.
Functionalities:	Irrigation system.
Plant species:	Medium variety of plants
Weight:	Unknown
Dimension:	2000 x 1200
Modularity:	Unknown
Other:	-

Green Fortune

Name:	Plantwall
System type:	Felt
Maintenance:	Unknown

Materials & Layers: Four layers of textile contain felt pockets to hold the plants. Within this textile, horizontal strips have been made that hold drip lines for irrigation. The textile layers are placed upon a layer of plastic that is connected with vertical rails to the wall. Beneath each wall, a stainless steel gutter is placed.
Functionalities: Irrigation and lightning.
Plant species: Medium variety of plants
Weight: 25 kg/m²
Dimension: 1000 x 1000 x 300
The height and width are the minimum size and can be as large as the client wants.
Modularity: No
Other: -

Mobilane

Name: Livepanel
System type: Felt
Maintenance: Low, due to it being designed for a small selection of plants.
Materials & Layers: Recyclable cassettes with cups made of PA6 plastic hold the plants. Every row has an aluminium profile that works as gutter and water buffer.
Functionalities: Irrigation system not needed, but few plants available.
Plant species: 17 plants are chosen for this system
Weight: 40 kg/m²
Dimension: 484 mm x 400 mm x 565 mm (height x width x depth)
400 mm is the minimum width and can be stretched to 5200 mm.
Modularity: Yes

Moooz B.V.

Name: *Moooz Outdoor Green Wall*
System type: Felt system
Maintenance: Low, wall is completely self-sustaining
Materials & Layers: Plant bags of UV-resistant polypropylene fleece cloth mounted on bioplastic rear plate of PLA (polylactic acid). The PLA plate is made from sugar cane with sackcloth (Jute). If flexibility is important bags can be mounted on rear plate by means of Velcro. The Velcro is sewed on the plant bags and is attached to the rear plate by means of ultrasonic welding. According to Moooz this technique makes it possible to remove the Velcro from the rear plate after use. Moooz systems are made out of materials that do not emit VOC's. All materials are recyclable or upcyclable
→ *It is uncertain if these materials apply to the indoor or outdoor system.*
Functionalities: Irrigation system with frost protection (Can be extended with sensors and watercomputer)
Plant species: Mosses (mats) & variety of plants or a combination of both
Weight: Unknown
Dimensions: Slim construction of a few centimeters. Plant bags can be made in every size
Modular: Unknown
Other: System parts can be replaced easily without influencing the rest of the system. System designed with the method of design for disassembly in mind.
Location: Sun & Shadow

Name:	*Moooz Flex Wall*
System type:	Felt system
Maintenance:	Unknown
Materials & Layers:	Plant bags of UV-resistant polypropylene fleece cloth mounted on bioplastic rear plate of PLA (polylactic acid). The PLA plate is made from sugar cane with sackcloth (Jute). If flexibility is important bags can be mounted on rear plate by means of Velcro (klittenband). The Velcro is sewed on the plant bags and is attached to the rear plate by means of ultrasonic welding. According to Moooz this technique makes it possible to remove the Velcro from the rear plate. Moooz systems are made out of materials that do not emit VOC's. All materials are recyclable or upcyclable → *It is uncertain if these materials apply to the Flex system as well.*
Functionalities:	Plugged in water tank
Plant species:	In consultation, other systems include mosses (mats) & variety of plants or a combination of both
Weight:	Unknown
Dimensions:	Unknown
Modular:	Yes
Other:	System parts can be replaced easily without influencing the rest of the system. System designed with the method of design for disassembly in mind.

APPENDIX C: CALCULATIONS MINIGARDEN

Specifications

	1 Minigarden vertical module
Length (L) [m]	0.646
Depth (D) [m]	0.190
Height (H) [m]	0.200
Horizontal space between two modules (assumed)	0.000
Vertical space between two modules (assumed)	0.000
Volume per module [m^3]	0.01
Weight per module [kg]	1.01

	Modules per m^2 [n]
Value	7.74
Formula	(1/(L+horizontal interspace))*(1/(H+vertical interspace))
Calculation	(1/(0.646+0.000))*(1/(0.200+0.000))

Density polypropylene [kg/m^3]	900.0

	Substrate (100% Potting soil)
Dry density [kg/m^3]	300
Assumed saturation [%]	50
Saturated density [kg/m^3]	450

Calculations dry weight

	Dry weight Minigarden vertical module [kg/m²]	Dry weight potting soil [kg/m²]	Total dry weight [kg/m²]
Value	**7.82**	**23.22**	**31.04**
Formula	Modules per m2 * Weight per module	Modules per m2 * Volume per module * Dry density potting soil	Dry weight Minigarden vertical module + Dry weight potting soil
Calculation	7.74*1.01	7.74*0.01*300	7.82+23.22

Calculations saturated weight

	Saturated weight potting soil [kg/m²]	Total saturated weight [kg/m²]
Value	**34.83**	**42.65**
Formula	Modules per m2 * Volume per module * Saturated density potting soil	Dry weight Minigarden vertical module + Saturated weight potting soil
Calculation	7.74*0.01*450	7.74+34.83

Calculations material weight

	Weight polypropylene [kg/m²]	Weight potting soil [kg/m²]
Value	**7.82**	**23.22**
Formula	Modules per m2 * Weight per module	Modules per m2 * Volume per module * Dry density potting soil
Calculation	7.74*1.01	7.74*0.01*300

Calculations material volume

	Volume polypropylene [m³/m²]	Volume potting soil [m³/m²]
Value	**8.69E-03**	**7.74E-02**
Formula	Weight polypropylene [kg/m²]/Density polypropylene [kg/m³]	Modules per m2 * Volume per module
Calculation	7.82/900	7.74*0.01

APPENDIX D: CALCULATIONS MODULOGREEN

Specifications

	1 Modulogreen module
Length (L) [m]	0.900
Depth (D) [m]	0.178
Height (H) [m]	0.807
Horizontal space between two modules (assumed)	0.000
Vertical space between two moldules (assumed)	0.000
Dry weight [kg/m^2]	9.76

	Modules per m^2 [n]
Value	1.38
Formula	(1/(L+horizontal interspace))*(1/(H+vertical interspace))
Calculation	(1/(0.900+0.000))*(1/(0.807+0.000))

Density EPDM	865.0
Density geotextile	90.0
Density polypropylene (glass fibre reinforced)	1140.0
Density coarse peat [kg/m^3]	400.0
Density lignocell coco chip [kg/m^3]	157.0
Density perlite [kg/m^3]	92.5
Density pumice [kg/m^3]	641.0
Density red scoria [kg/m^3]	1200.0
Density sunterra reg. peat [kg/m^3]	400.0

	Substrate
	(5% coarse peat, 5% lignocell coco chip, 5% perlite, 20% pumice, 50% red scoria and 15% sunterra reg. peat,)
Dry weight [kg/m²]	19.53
Max saturation [%]	-
Saturated weight [kg/m²]	29.29
Waterabsorption [kg/m²]	-

	Dimensions EPDM (estimated) **[m]**	**Dimensions geotextile (estimated)** **[m]**
Length (L) [m]	0.980	0.134
Depth (D) [m]	0.010	0.002
Height (H) [m]	0.005	0.800
Amount per module	2	1

	Weight polypropylene [kg/m²]	**Weight potting soil [kg/m²]**
Value	**7.82**	**23.22**
Formula	Modules per m2 * Weight per module	Modules per m2 * Volume per module * Dry density potting soil
Calculation	7.74*1.01	7.74*0.01*300

Calculations dry weight

	Total dry weight [kg/m²]
Value	**29.29**
Formula	Dry weight Modulogreen module + Dry weight substrate
Calculation	9.76+19.53

Calculations saturated weight

	Total saturated weight [kg/m²]
Value	**39.05**
Formula	Dry weight Modulogreen module + Saturated weight substrate
Calculation	9.76+29.29

Calculations material weight

	Dry density substrate [kg/m²]
Value	**820.68**
Formula	(5% coarse peat * Density coarse peat) + (5% lignocell coco chip * Density lignocell coco chip) + (5% perlite * Density perlite) + (20% pumice * Density pumice) + (50% red scoria * Density red scoria) + (15% sunterra reg. peat * Density sunterra reg. peat)
Calculation	(0.05*400)+(0.05*157)+(0.05*93)+(0.20*641)+(0.50*1200)+(0.15*400)

	Total substrate volume [m³/m²]
Value	**0.02**
Formula	Dry weight substrate / Dry density substrate
Calculation	19.53/820.70

	Weight EPDM [kg/m²]	Weight geotextile [kg/m²]	Weight polypropylene [kg/m²]
Value	**0.12**	**0.03**	**9.62**
Formula	Volume EPDM * Density EPDM	Volume geotextile * Density geotextile	Dry weight per module - Weight EPDM - Weight geotextile
Calculation	1.35E-04*865	2.94E-04*90	9.76-0.12-0.03

	Weight coarse peat [kg/m²]	Weight lignocell coco chip [kg/m²]	Weight perlite [kg/m²]
Value	**0.48**	**0.19**	**0.11**
Formula	Density coarse peat * Volume coarse peat	Density lignocell coco chip * Volume lignocell coco chip	Density perlite * Volume perlite
Calculation	400*1.19E-03	157*1.19E-03	93*1.19E-03

	Weight pumice [kg/m²]	Weight red scoria [kg/m²]	Weight sunterra reg. peat [kg/m²]
Value	**3.05**	**14.28**	**1.43**
Formula	Density pumice * Volume pumice	Density red scoria * Volume red scoria	Density sunterra reg. peat * Volume sunterra reg. peat
Calculation	641*4.76E-03	1200*1.19E-02	400*3.57E-03

Calculations material volume

	Volume EPDM [m³/m²]	Volume geotextile [m³/m²]	Volume polypropylene [m³/m²]
Value	**1.35E-04**	**2.94E-04**	**8.44E-03**
Formula	Modules per m2 * Length EPDM * Depth EPDM * Height EPDM * Amount of EPDM per module	Modules per m2 * Length geotextile * Depth geotextile * Height geotextile * Amount of geotextile per module	Weight polypropylene / Density polyproylene
Calculation	1.38 * ((0.980 * 0.010 * 0.005) * 2)	1.38 * ((0.134 * 0.002 * 0.800) * 1)	9.62/1140

	Volume coarse peat [m³/m²]	Volume lignocell coco chip [m³/m²]	Volume perlite [m³/m²]
Value	**1.19E-03**	**1.19E-03**	**1.19E-03**
Formula	5% coarse peat * Total substrate volume	5% lignocell coco chip * Total substrate volume	5% perlite * Total substrate volume
Calculation	0.05*0.02	0.05*0.02	0.05*0.02

	Volume pumice [m³/m²]	Volume red scoria [m³/m²]	Volume sunterra reg. peat [m³/m²]
Value	**4.76E-03**	**1.19E-02**	**3.57E-03**
Formula	20% pumice * Total substrate volume	50% red scoria * Total substrate volume	15% sunterra reg. peat * Total substrate volume
Calculation	0.20*0.02	0.50*0.02	0.15*0.02

APPENDIX E: CALCULATIONS CULTIWALL

Specifications

	1 CultiWall module
Length (L) [m]	0.600
Depth (D) [m]	0.070
Height (H) [m]	1.000
Horizontal space between two modules (assumed)	0.020
Vertical space between two modules (assumed)	0.020
Weight per module [kg]	10.20

	Modules per m² [n]
Value	1.58
Formula	(1/(L+horizontal interspace))*(1/(H+vertical interspace))
Calculation	(1/(0.600+0.020))*(1/(1.000+0.020))

Density powder coated steel [kg/m³]	7875.0
Density geotextile [kg/m³]	90.0
Density recycled foam [kg/m³]	27.0
Density stonewool [kg/m³]	40.0

	Substrate (Stonewool+recycled foam)
Waterabsorption [kg/m²]	6.20

	Dimensions geotextile (estimated) [m]	Dimensions recycled foam (estimated) [m]	Dimensions stonewool (estimated) [m]	Dimensions stainless steel (estimated) [m]
Length (L) [m]	0.600	0.600	0.600	0.02
Depth (D) [m]	0.002	0.070	0.070	-
Height (H) [m]	1.000	0.010	0.116	-
Diameter [m]	-	-	-	0.004
Amount per module	2	7	8	

Calculations dry weight

	Dry weight CultiWall module [kg/m²]	Total dry weight [kg/m²]
Value	**16.13**	**16.13**
Formula	Modules per m2 * Weight per module	Dry weight CultiWall module
Calculation	1.58*10.20	16.13

Calculations saturated weight

	Total saturated weight [kg/m²]
Value	**22.33**
Formula	Dry weight CultiWall module + Waterabsorption substrate
Calculation	16.13+6.20

Calculations material weight

	Weight powder coated steel [kg/m²]	Weight stainless steel [kg/m²]	Weight geotextile [kg/m²]
Value	**13.17**	**2.51E-02**	**0.34**
Formula	Dry weight CultiWall module - Weight geotextile - Weight recycled foam - Weight stonewool – Weight stainless steel	Volume stainless steel *Density	Volume geotextile * Density geotextile
Calculation	16.13-0.34-0.13-2.47-0.03	3.18E-06*7910	3.80E-03*90

	Weight recycled foam [kg/m²]	Weight stonewool [kg/m²]
Value	**0.13**	**2.47**
Formula	Volume recycled foam * Density recycled foam	Volume stonewool * Density stonewool
Calculation	4.65E-03*27	6.18E-02*40

Calculations material volume

	Volume powder coated steel [m³/m²]	Volume stainless steel [m³/m²]	Volume geotextile [m³/m²]
Value	1.67E-03	3.18E-06	3.80E-03
Formula	Weight powder coated steel / Density powder coated steel	Length stainless steel * π * (radius stainless steel)² *Amount of stainless steel per module *modules per m²	Modules per m2 * Length geotextile * Depth geotextile * Height geotextile * Amount of geotextile per module
Calculation	13.17/7875	0.02 * π * ((0.004/2)^2)*8*1.58	1.58*((0.600*0.002*1.000) *2)

	Volume recycled foam [m³/m²]	Volume stonewool [m³/m²]
Value	4.65E-03	6.18E-02
Formula	Modules per m2 * Length geotextile * Depth geotextile * Height geotextile * Amount of geotextile per module	Modules per m2 * Length geotextile * Depth geotextile * Height geotextile * Amount of geotextile per module
Calculation	1.58*((0.600*0.070*0.010) *7)	1.58*((0.600*0.070*0.116) *8)

APPENDIX F: CALCULATIONS FLEXIPANEL

Specifications

	1 Flexipanel
Length (L) [m]	0.600
Depth (D) [m]	0.060
Height (H) [m]	0.500
Horizontal space between two modules (assumed)	0.020
Vertical space between two modules (assumed)	0.020
Weight per module [kg]	2.800

	Modules per m^2 [n]
Value	3.10
Formula	(1/(L+horizontal interspace))*(1/(H+vertical interspace))
Calculation	(1/(0.600+0.020))*(1/(0.500*0.020))

Density TPO [kg/m³]	936.5
Density polyamide [kg/m³]	1130.0
Density polypropylene [kg/m³]	900.0
Density recycled cloth [kg/m³]	65.8
Density stonewool [kg/m³]	40.0

	Substrate (Stonewool)
Waterabsorption [kg/m²]	19.23

	Dimensions TPO (estimated) [m]	Dimensions polyamide (estimated) [m]	Dimensions recycled cloth (estimated) [m]	Dimensions stonewool (estimated) [m]
Length (L) [m]	0.720	7.001	0.600	0.600
Depth (D) [m]	0.002	0.001	0.008	0.060
Height (H) [m]	0.620	0.001	0.560	0.500
Amount per module	1	1	1	1

Calculations dry weight

	Dry weight Flexipanel [kg/m²]	Total dry weight [kg/m²]
Value	**8.68**	**8.68**
Formula	Modules per m2 * Weight per module	Dry weight Flexipanel module
Calculation	3.10*10.20	8.68

Calculations saturated weight

	Total saturated weight [kg/m²]
Value	**27.92**
Formula	Dry weight Flexipanel + Waterabsorption substrate
Calculation	8.68+19.23

Calculations material weight

	Weight TPO [kg/m²]	Weight polyamide [kg/m²]	Weight polypropylene [kg/m²]
Value	**2.59**	**0.02**	**3.29**
Formula	Volume TPO * Density TPO	Volume polyamide * Density polyamide	Dry weight Flexipanel - Weight TPO - Weight polyamide - Weight recycled cloth - Weight stonewool
Calculation	2.77E-03*936.5	2.17E-05*1130	8.68-2.59-0.02-0.55-2.23

	Weight recycled cloth [kg/m²]	Weight stonewool [kg/m²]
Value	**0.55**	**2.23**
Formula	Volume recycled cloth * Density recycled cloth	Volume stonewool * Density stonewool
Calculation	8.34E-03*65.8	5.58E-02*40

Calculations material volume

	Volume TPO [m³/m²]	Volume polyamide [m³/m²]	Volume polypropylene [m³/m²]
Value	2.77E-03	2.17E-05	3.65E-03
Formula	Modules per m2 * Length TPO * Depth TPO * Height TPO * Amount of TPO per module	Modules per m2 * Length polyamide * Depth polyamide * Height polyamide * Amount of polyamide per module	Weight polypropylene / Density polypropylene
Calculation	3.10*((0.720*0.002*0.620)*1)	3.10*((7.001*0.001*0.001)*1)	3.29/900

	Volume recycled cloth [m³/m²]	Volume stonewool [m³/m²]
Value	8.34E-03	5.58E-02
Formula	Modules per m2 * Length recycled cloth * Depth recycled cloth * Height recycled cloth * Amount of recycled cloth per module	Modules per m2 * Length stonewool * Depth stonewool * Height stonewool * Amount of stonewool per module
Calculation	3.10*((0.600*0.008*0.560)*1)	3.10*((0.600*0.060*0.500)*1)

APPENDIX G: CALCULATIONS 90GREEN

Specifications

	1 90Green module
Length (L) [m]	0.500
Depth (D) [m]	0.150
Height (H) [m]	0.430
Horizontal space between two modules (assumed)	0.020
Vertical space between two modules (assumed)	0.090

	Modules per m2 [n]
Value	3.70
Formula	(1/(L+horizontal interspace))*(1/(H+vertical interspace))
Calculation	(1/(0.500+0.020))*(1/(0.430*0.090))

Density stainless steel [kg/m³]	7910.0
Density polyester [kg/m³]	1220.0
Density polyethylene [kg/m³]	949.5
Density potting soil [kg/m³]	300.0
Density urea-formaldehyde polymer [kg/m³]	20.0

	Substrate (Potting soil)	**Substrate (Urea-formaldehyde polymer)**
Dry density [kg/m³]	300	20
Assumed saturation [%]	50	-
Max saturation	-	75
Saturated density [kg/m³]	450	35

	Dimensions stainless steel (estimated) [m]	Dimensions polyester (estimated) [m]	Dimensions polyethylene (estimated) [m]	Dimensions substrate (estimated) [m]
Length (L) [m]	13.920	2.660	-	0.490
Depth (D) [m]	-	-	0.001	0.140
Height (H) [m]	-	-	-	0.420
Surface area [m²]	-	-	0.599	-
Wire diameter [m]	0.003	0.001	-	-
Amount per module	1	1	1	1

Calculations dry weight

	Total dry weight [kg/m²]
Value	**4.99**
Formula	Weight stainless steel + Weight polyester + Weight polyethylene + Weight urea-formaldehyde polymer + Weight potting soil
Calculation	2.88+2.10+0.01+0.75+20.78

Calculations saturated weight

	Saturated weight urea-formaldehyde polymer [kg/m²]	Saturated weight potting soil [kg/m²]	Total saturated weight [kg/m²]
Value	**1.31**	**31.17**	**37.46**
Formula	Modules per m2 * Volume urea-formaldehyde polymer * Saturated density urea-formaldehyde polymer	Modules per m2 * Volume potting soil * Saturated density potting soil	Weight stainless steel + Weight polyester + Weight polyethylene + Saturated weight urea-formaldehyde polymer + Saturated weight potting soil
Calculation	3.73E-02*35	6.93E-02*450	1.31+31.17

Calculations material weight

	Weight stainless steel [kg/m²]	Weight polyester [kg/m²]	Weight polyethylene [kg/m²]
Value	**2.88**	**0.01**	**2.10**
Formula	Volume stainless steel * Density stainless steel	Volume polyester * Density polyester	Volume polyethylene * Density polyethylene
Calculation	3.64E-04*7910	7.73E-06*1220	2.22E-03*949.5

	Weight potting soil [kg/m²]	Weight urea-formaldehyde polymer [kg/m²]
Value	**20.78**	**0.75**
Formula	Volume potting soil * Density potting soil	Volume urea-formaldehyde polymer * Density urea-formaldehyde polymer
Calculation	6.93E-02*300	3.73E-02*20

Calculations material volume

	Volume stainless steel [m³/m²]	Volume polyester [m³/m²]	Volume polyethylene [m³/m²]
Value	3.64E-04	7.73E-06	2.22E-03
Formula	Modules per m2 * Length stainless steel * π*r² * Amount of stainless steel per module	Modules per m2 * Length polyester * π*r² * Amount of polyester per module	Modules per m2 * Depth polyethylene * Surface area polyethylene * Amount of polyethylene per module
Calculation	3.70*(13.920*(PI()*((0.5*0.003)^2))*1)	3.70*(2.660*(PI()*((0.5*0.001)^2))*1)	3.70*(0.001*0.599)*1

	Volume potting soil [m³/m²]	Volume urea-formaldehyde polymer [m³/m²]
Value	6.93E-02	3.73E-02
Formula	Modules per m2 * Length substrate * Depth substrate * Height substrate * 65% potting soil * Amount of substrate per module	Modules per m2 * Length substrate * Depth substrate * Height substrate * 35% urea-formaldehyde polymer * Amount of substrate per module
Calculation	3.70*((0.490*0.140*0.420)*0.65)*1	3.70*((0.490*0.140*0.420)*0.35)*1

APPENDIX H: CALCULATIONS MUURTUIN

Specifications

	1 90Green module
Length (L) [m]	0.600
Depth (D) [m]	0.015
Height (H) [m]	0.600
Horizontal space between two modules (assumed)	0.000
Vertical space between two modules (assumed)	0.000

	Modules per m² [n]
Value	2.78
Formula	(1/(L+horizontal interspace))*(1/(H+vertical interspace))
Calculation	(1/(0.600+0.000))*(1/(0.600*0.000))

Density iron [kg/m³]	7700.0
Density geotextile [kg/m³]	90.0
Density stonewool [kg/m³]	40.0
Density humus [kg/m³]	563.0
Density volcanic rocks [kg/m³]	1200.0

	Substrate (humus)	**Substrate (volcanic rocks)**	**Substrate (stonewool)**
Dry density [kg/m³]	563	1200	40
Assumed saturation [%]	50	70	-
Saturated density [kg/m³]	844.5	2040	-
Waterabsorption [kg/m²]	-	-	22.00

	Dimensions iron (estimated) [m]	Dimensions geotextile (estimated) [m]	Dimensions stonewool (estimated) [m]	Dimensions substrate (estimated) [m]
Length (L) [m]	4.800	0.600	0.600	0.180
Depth (D) [m]	-	0.003	0.005	0.070
Height (H) [m]	-	0.600	0.600	0.180
Surface area [m²]	-	-	-	-
Wire diameter [m]	0.006	-	-	-
Amount per module	2	2	1	9

Calculations dry weight

	Total dry weight [kg/m²]
Value	**6.46**
Formula	Weight iron + Weight geotextile + Weight stonewool + Weight humus + Weight volcanic rock
Calculation	5.81+0.45+0.20+4.18+8.91

Calculations saturated weight

	Saturated weight humus [kg/m²]	Saturated weight volcanic rocks [kg/m²]	Total saturated weight [kg/m²]
Value	**6.27**	**15.14**	**49.86**
Formula	Volume humus * Saturated density humus	Volume volcanic rocks * Saturated density volcanic rocks	Weight iron + Weight geotextile + Weight stonewool + Saturated weight humus + Saturated weight volcanic rocks + Waterabsorption stonewool
Calculation	7.42E-03*844.5	7.42E-03*2040	5.81+0.45+0.20+6.27+15.14 +22

Calculations material weight

	Weight iron	Weight geotextile	Weight stonewool

	[kg/m²]	[kg/m²]	[kg/m²]
Value	**5.81**	**0.45**	**0.20**
Formula	Volume iron * Density iron	Volume geotextile * Density geotextile	Volume stonewool * Density stonewool
Calculation	7.54E-04*7700	9.00E-03*90	8.00E-03*40

	Weight humus [kg/m²]	**Weight volcanic rocks [kg/m²]**
Value	**4.18**	**8.91**
Formula	Volume humus * Density humus	Volume volcanic rocks * Density volcanic rocks
Calculation	7.42E-03*563	7.42E-03*1200

Calculations material volume

	Volume iron [m³/m²]	**Volume geotextile [m³/m²]**	**Volume stonewool [m³/m²]**
Value	7.54E-04	5.00E-03	5.00E-03
Formula	Modules per m2 * Length iron * π*r² * Amount of iron per module	Modules per m2 * Length geotextile * Depth geotextile * Height geotextile * Amount of geotextile per module	Modules per m2 * Length stonewool * Depth stonewool * Height stonewool * Amount of stonewool per module
Calculation	2.78*(4.800*(PI()*((0.5*0.006)^2))*2)	2.78*(0.600*0.005*0.600)*2	2.78*(0.600*0.008*0.600)*1

	Volume humus [m³/m²]	**Volume volcanic rocks [m³/m²]**
Value	7.42E-03	7.42E-03
Formula	Modules per m2 * (((1/6)*π*L*H*D)/2) * 50% humus * Amount of substrate per module	Modules per m2 * (((1/6)*π*L*H*D)/2) * 50% volcanic rocks * Amount of substrate per module
Calculation	2.78*(((1/6)*PI()*0.180*0.070*0.180)/2)*0.5*9	2.78*(((1/6)*PI()*0.180*0.070*0.180)/2)*0.5*9

APPENDIX I: CALCULATIONS PLANTWALL

Specifications

	1 m² Plantwall

Length (L) [m]	1.000
Depth (D) [m]	0.044
Height (H) [m]	1.000
Horizontal space between two modules (assumed)	0.000
Vertical space between two modules (assumed)	0.000

	Modules per m² [n]
Value	1.00
Formula	(1/(L+horizontal interspace))*(1/(H+vertical interspace))
Calculation	(1/(1.000+0.000))*(1/(1.000*0.000))

Density aluminium [kg/m³]	2710.0
Density polyethylene [kg/m³]	949.5
Density polyester [kg/m³]	1220.0
Density recycled cloth [kg/m³]	65.8
Density potting soil [kg/m³]	300.0

	Substrate (potting soil)	**Substrate (recycled cloth)**
Dry density [kg/m³]	300	65.8
Assumed saturation [%]	50	-
Saturated density [kg/m³]	450	-
Waterabsorption [kg/m²]	-	15.56

	Dimensions aluminium (estimated) [m]	**Dimensions polyethylene (estimated) [m]**	**Dimensions polyester cloth (estimated) [m]**	**Dimensions polyethylene yarn (estimated)**	**Dimensions recycled cloth (estimated) [m]**	**Dimensions substrate (estimated) [m]**

Length (L) [m]	1.000	1.000	1.000	8.000	1.000	0.180
Depth (D) [m]	0.001	0.003	0.010	-	0.010	0.070
Height (H) [m]	1.000	1.000	1.000	-	1.000	0.160
Surface area [m²]	-	-	-	-	-	-
Wire diameter [m]	-	-	-	0.001	-	-
Amount per module	2	1	1	1	3	28

Calculations dry weight

	Total dry weight [kg/m²]
Value	**17.28**
Formula	Weight aluminium + Weight polyethylene + Weight polyester (cloth) + Weight polyester (yarn) + Weight recycled cloth + Weight potting soil
Calculation	2.71+2.37+12.20+0.01+0.26+4.40

Calculations saturated weight

	Saturated weight potting soil [kg/m²]	Total saturated weight [kg/m²]
Value	**6.60**	**39.70**
Formula	Volume potting soil * Saturated density potting soil	Weight aluminium + Weight polyethylene + Weight polyester (cloth) + Weight polyester (yarn) + Weight recycled cloth + Saturated weight potting soil + Waterabsorption recycled cloth
Calculation	1.47E-02*450	2.71+2.37+12.20+0.01+0.26+6.60+15.56

Calculations material weight

	Weight aluminium [kg/m²]	Weight polyethylene [kg/m²]	Weight polyester (cloth) [kg/m²]
Value	**2.71**	**2.37**	**12.20**
Formula	Volume aluminium * Density aluminium	Volume polyethylene * Density polyethylene	Volume polyester * Density polyester

Calculation	1.00E-03*2710	2.50E-03*949.5	1.00E-02*1220

	Weight polyester (yarn) [kg/m²]	Weight recycled cloth [kg/m²]	Weight potting soil [kg/m²]
Value	**0.01**	**0.26**	**4.40**
Formula	Volume polyester * Density polyester	Volume recycled cloth * Density recycled cloth	Volume potting soil * Density potting soil
Calculation	6.28E-06*1220	3.33E-03*65.8	7.42E-03*300

Calculations material volume

	Volume aluminium [m³/m²]	Volume polyethylene [m³/m²]	Volume polyester (Cloth) [m³/m²]
Value	1.00E-03	2.50E-03	1.00E-02
Formula	Modules per m2 * Length aluminium * Depth aluminium * Height aluminium * Amount of aluminium per module	Modules per m2 * Length polyethylene * Depth polyethylene * Height polyethylene * Amount of polyethylene per module	Modules per m2 * Length polyester * Depth polyester * Height polyester * Amount of polyester per module
Calculation	1*(1.000*0.001*1.000)*2	1*(1.000*0.003*1.000)*1	1*(1.000*0.010*1.000)*1

	Volume polyester (yarn) [m³/m²]	Volume recycled cloth [m³/m²]	Volume potting soil [m³/m²]
Value	6.28E-06	3.93E-03	1.47E-02
Formula	Modules per m2 * Length polyester * π*r² * Amount of polyester per module	Modules per m2 * Length recycled cloth * Depth recycled cloth * Height recycled cloth * Amount of recycled cloth per module	Modules per m2 * (((1/6)*π*L*H*D)/2) * Amount of substrate per module
Calculation	1*(8.000*(PI()*((0.5*0.001)^2))*1)	1*(1.000*0.010*1.000)*3	1*(((1/6)*PI()*0.180*0.070*0.160)/2)*28

APPENDIX J: CALCULATIONS WONDERWALL

Specifications

	1 m² Wonderwall

Length (L) [m]	1.000
Depth (D) [m]	0.024
Height (H) [m]	1.000
Horizontal space between two modules (assumed)	0.000
Vertical space between two modules (assumed)	0.000

	Modules per m² [n]
Value	1.00
Formula	(1/(L+horizontal interspace))*(1/(H+vertical interspace))
Calculation	(1/(1.000+0.000))*(1/(1.000*0.000))

Density PVC foam [kg/m³]	400.0
Density polypropylene [kg/m³]	900.0
Density recycled cloth [kg/m³]	65.8
Density potting soil [kg/m³]	300.0
Stainless steel	7910

	Substrate (potting soil)	Substrate (recycled cloth)
Dry density [kg/m³]	300	65.8
Assumed saturation [%]	50	-
Saturated density [kg/m³]	450	-
Waterabsorption [kg/m²]	-	6.22

	Dimensions PVC foam (estimated) [m]	Dimensions polypropylene (estimated) [m]	Dimensions recycled cloth (estimated) [m]	Dimensions substrate (estimated) [m]	Dimensions stainless steel [m]
Length (L) [m]	1.000	1.000	1.000	0.180	0.028
Depth (D) [m]	0.010	0.002	0.006	0.070	0.0001
Height (H) [m]	1.000	1.000	1.000	0.160	0.0002
Surface area [m²]	-	-	-	-	-
Wire diameter [m]	-	-	-	-	-
Amount per module	1	1	2	28	112

Calculations dry weight

	Total dry weight [kg/m²]
Value	**6.14**
Formula	Weight PVC foam + Weight polypropylene + Weight recycled cloth + Weight stainless steel + Weight potting soil
Calculation	4.00+1.35+0.79+4.96E-04+4.40

Calculations saturated weight

	Saturated weight potting soil [kg/m²]	Total saturated weight [kg/m²]
Value	**6.60**	**18.96**
Formula	Volume potting soil * Saturated density potting soil	Weight PVC foam + Weight polypropylene + Weight recycled cloth + Weight stainless steel + Saturated weight potting soil + Waterabsorption recycled cloth
Calculation	1.47E-02*450	4.00+1.35+0.79+4.96E-04+6.60+6.22

Calculations material weight

	Weight PVC foam [kg/m²]	Weight polypropylene [kg/m²]	Weight recycled cloth [kg/m²]
Value	**4.00**	**1.35**	**0.79**
Formula	Volume PVC foam * Density PVC foam	Volume polypropylene * Density polypropylene	Volume recycled cloth * Density recycled cloth
Calculation	1.00E-02*400	1.50E-03*900	1.20E-02*65.8

	Weight stainless steel [kg/m²]	Weight potting soil [kg/m²]
Value	**4.96E-04**	**4.40**
Formula	Volume stainless steel * Density stainless steel	Volume potting soil * Density potting soil
Calculation	6.27E-08*7910	7.42E-03*300

Calculations material volume

	Volume PVC foam [m³/m²]	Volume polypropylene [m³/m²]	Volume recycled cloth [m³/m²]
Value	1.00E-02	1.50E-03	1.20E-02
Formula	Modules per m2 * Length PVC foam * Depth PVC foam * Height PVC foam * Amount of PVC foam per module	Modules per m2 * Length polypropylene * Depth polypropylene * Height polypropylene * Amount of polypropylene per module	Modules per m2 * Length recycled cloth * Depth recycled cloth * Height recycled cloth * Amount of recycled cloth per module
Calculation	1*(1.000*0.010*1.000)*1	1*(1.000*0.002*1.000)*1	1*(1.000*0.006*1.000)*2

	Volume stainless steel [m³/m²]	Volume potting soil [m³/m²]
Value	6.27E-08	1.47E-02
Formula	Modules per m2 * Length stainless steel * Depth stainless steel * Height stainless steel * Amount of stainless steel per module	Modules per m2 * (((1/6)*π*L*H*D)/2) * Amount of substrate per module
Calculation	1*(0.028*0.0001*0.0002)*112	1*(((1/6)*PI()*0.180*0.070*0.160)/2)*28

APPENDIX K: MATERIAL LIST

Materials	Density	Price***	Healthy		Material flow		Lifespan	Remarks msds
	[kg/m³]	[EURO/kg]	Environment	People	Biodegradable	Recyclable	[years]	
Metals								
Aluminum	2710.0	€1.58	Y/N	Y	N	Y	30	Toxic to aquatic organisms
Aluminum (coated)	-	€1.86	Y/N	Y	N	Y	40	Toxic to aquatic organisms
Copper	8935.0	€5.56	Y/N	Y	N	Y	100	Could be harmful to aquatic environment on the long term
Iron	7700.0	€0.36	Y	Y	N	Y	50	
Steel (Galvanized)	7850.0	€0.48	Y	Y	N	Y	30	
Steel (powder coated)	7875.0	€0.96	Y	Y	N	Y	30-60	
Steel (stainless)	7910.0	€2.49	Y	Y	N	Y	35	
Substrates								
Humus	563.0	€0,89	Y	Y	Y	N	?	
Lignocell coco chip	157.0	€0.17	Y	Y	Y	N	?	
Peat	400.0	€0,09	Y	Y	Y	N	?	
Perlite (expanded)	92.5	€0,29	Y	N	N	Y	?	Long term exposure could cause troubles with breathing and diseases. Might irritate skin.
Potting soil	300.0	€0,17	Y	Y	Y	N	?	
Pumice	641.0	€0,02	Y	Y	N	N	?	
Red scoria (volcanic)	1200.0	€0,14	Y	Y	N	N	?	
Stonewool	40.0	€4.29	Y	Y	N	Y	75*	
Urea - formaldehyde polymer (Fytocell)	20.0	€17.80	Y	N	Y	N	?	
Textiles								
Geotextile (PE, PET, PP or PA)	90.0	€1.84	Y	Y	N	N	20	Can harm aquatic life when disposed into the ocean, since they're not biodegradable.
Recycled cloth (painter fleece)**	65.8	€2,72	Y	Y	N	Y	75*	Can harm aquatic life when disposed into the ocean, since they're not biodegradable.
Plastics								
EPDM	865.0	€3,28	Y/N	Y	N	Y	50	Toxic to aquatic organisms
Polyamide (PA)	1130.0	€3,21	Y	Y	N	Y	10	Can harm aquatic life when disposed into the ocean, since they're not biodegradable.
Polybutylene (PB-1)	950.0	€1,67	Y	Y	N	Y	50	Can harm aquatic life when disposed into the ocean, since they're not biodegradable.
Polyester	1220.0	€3.05	Y	Y	N	N	25	Can harm aquatic life when disposed into the ocean, since they're not biodegradable.
Polyethylene (PE)	949.5	€1,63	Y	Y	N	Y	20	Can harm aquatic life when disposed into the ocean, since they're not biodegradable.
Polypropylene (PP)	900.0	€1,69	Y	Y	N	Y	20	Can harm aquatic life when disposed into the ocean, since they're not biodegradable.
Polypropylene (glass fibre reinforced)	1140.0	€2,98	Y	Y	N	Y	50	Can harm aquatic life when disposed into the ocean, since they're not biodegradable.
PVC Foam	400.0	€1,58	Y	Y	N	N	20	Can harm aquatic life when disposed into the ocean, since they're not biodegradable.
Recycled foam (polyurethane)	27.0	€1,60	Y	Y	N	Y	25	Can harm aquatic life when disposed into the ocean, since they're not biodegradable.
TPO	936.5	€0,43	Y	Y	N	Y	30	Can harm aquatic life when disposed into the ocean, since they're not biodegradable.

Bron prijs: CES EdupackBron lifespan: http://www.nibe.info/nl/members#product-4945-89-26 http://www.geosynthetic-institute.org/papers/paper6.pdf
Bron healthyness: MSDS data sheets, NIBE
Bron Biodegradabiliy / Recyclability: CES Edupack, NIBE

Healthyness, based on msds sheets. Can be no information available. Only during transport and use, production is excluded.
* Under wet circumstances probably a lot lower. Around 10 years is estimated.
** Could contain antislip foil made from PE. This data could not be verified, as the types of plastics in the cotton are unknown. But probably contains more plastics than identified during this study. Results are based on data on PE, PP, PVC and organic cotton.

*** Estimates of average

APPENDIX L: EUROPOINT-COMPLEX FAÇADE DETAILS

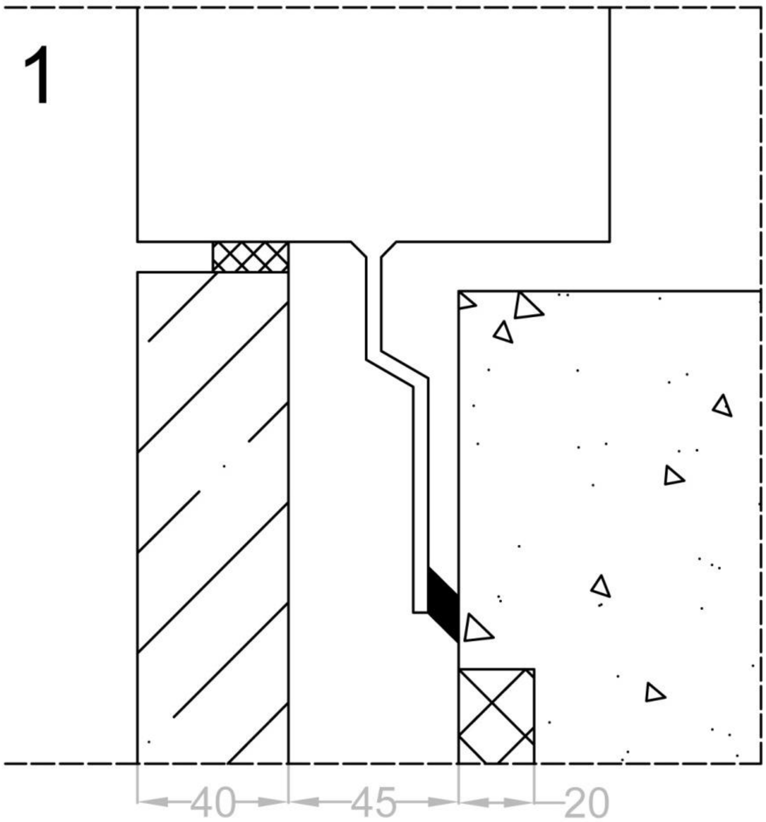


Figure 122: Detail 1; 1:2

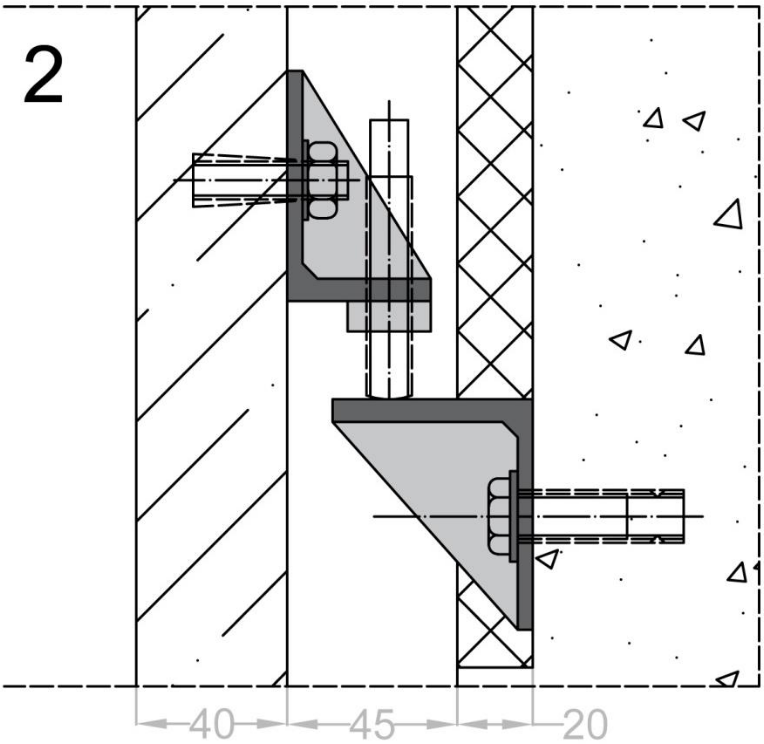


Figure 123: Detail 2; 1:2

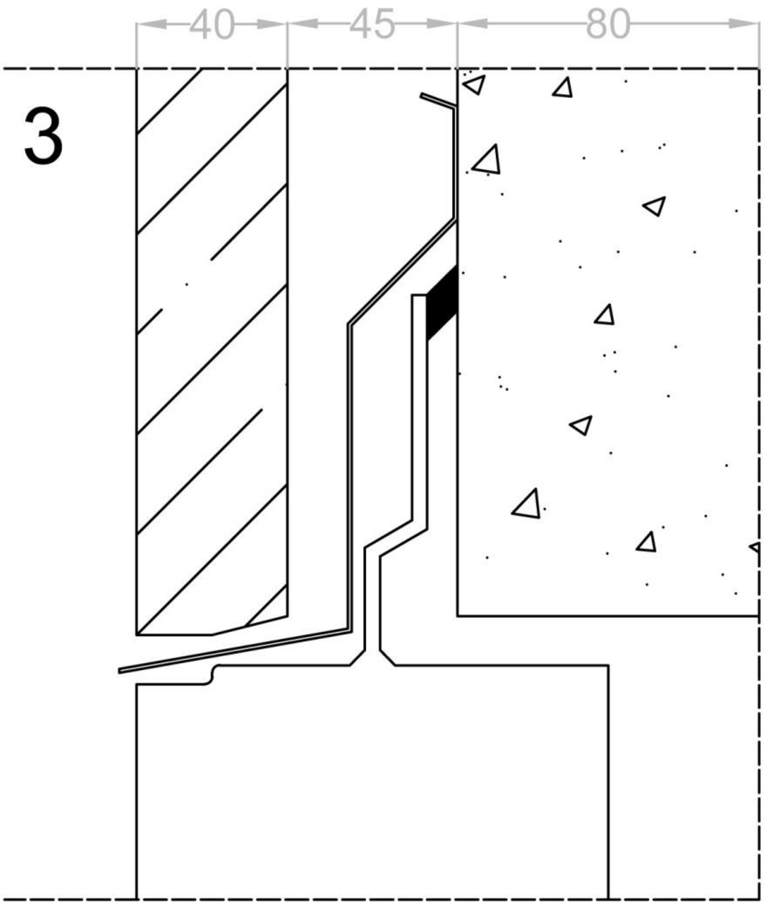


Figure 124: Detail 3; 1:2

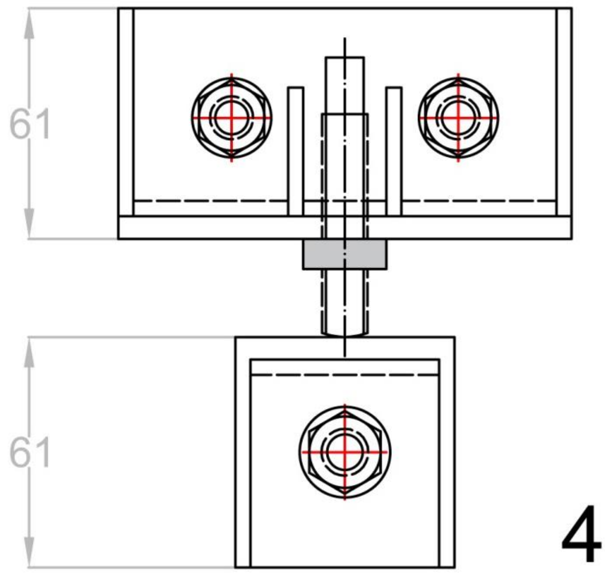


Figure 125: Detail 4; 1:2

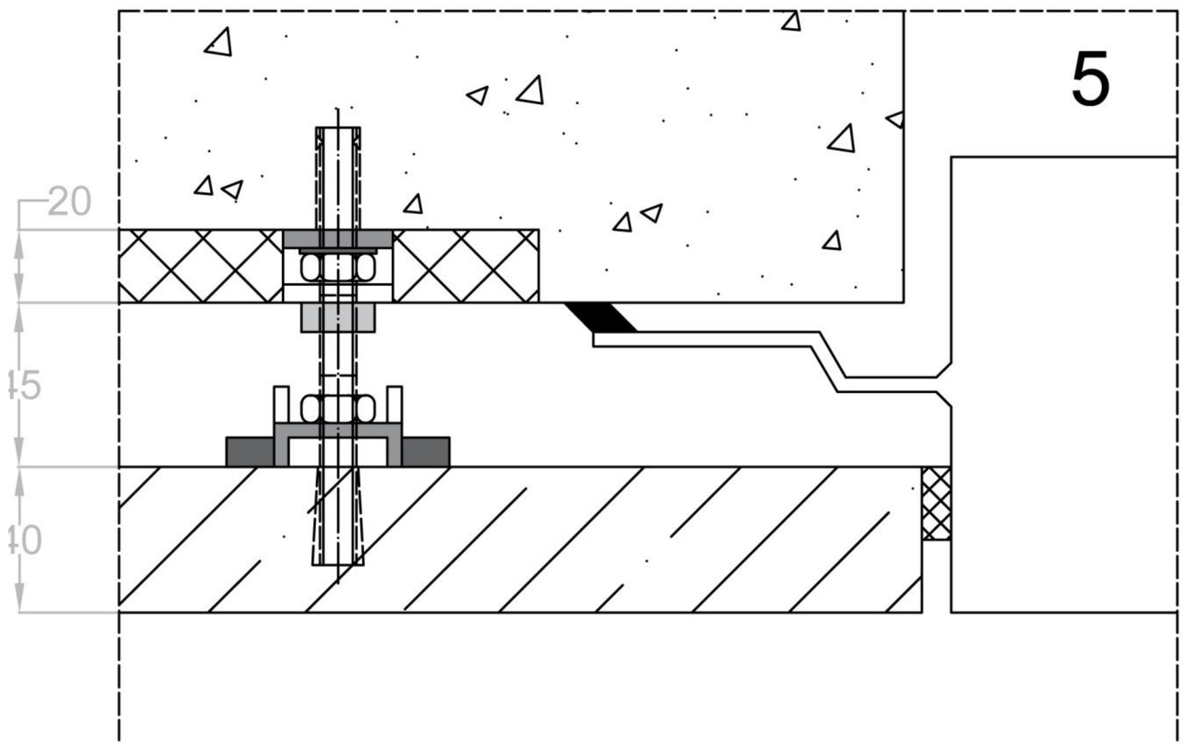


Figure 126: Detail 5; 1:2

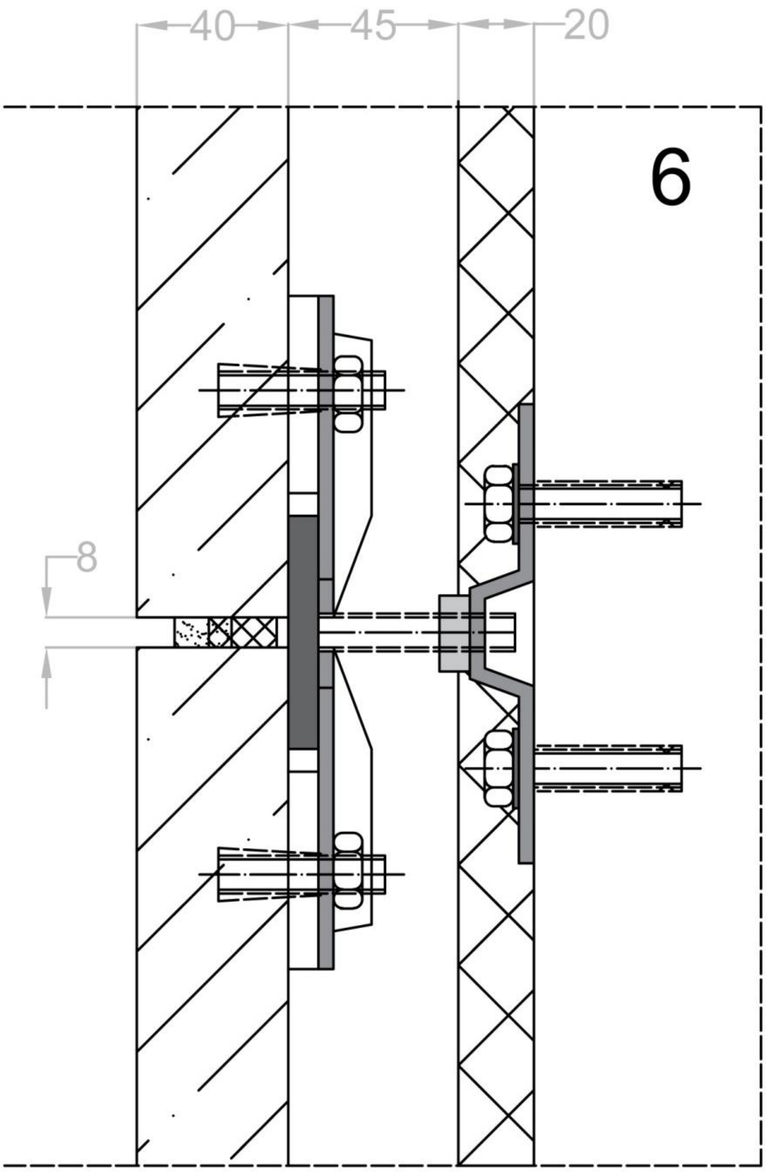


Figure 127: Detail 6; 1:2

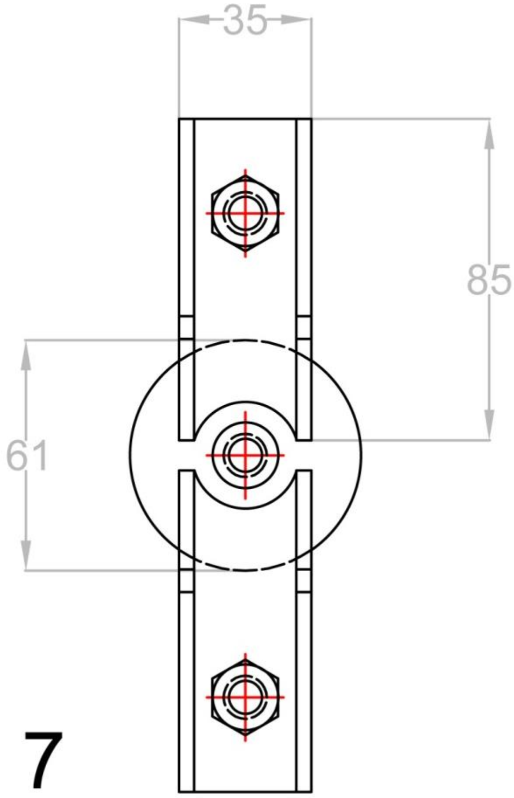


Figure 128: Detail 7; 1:2