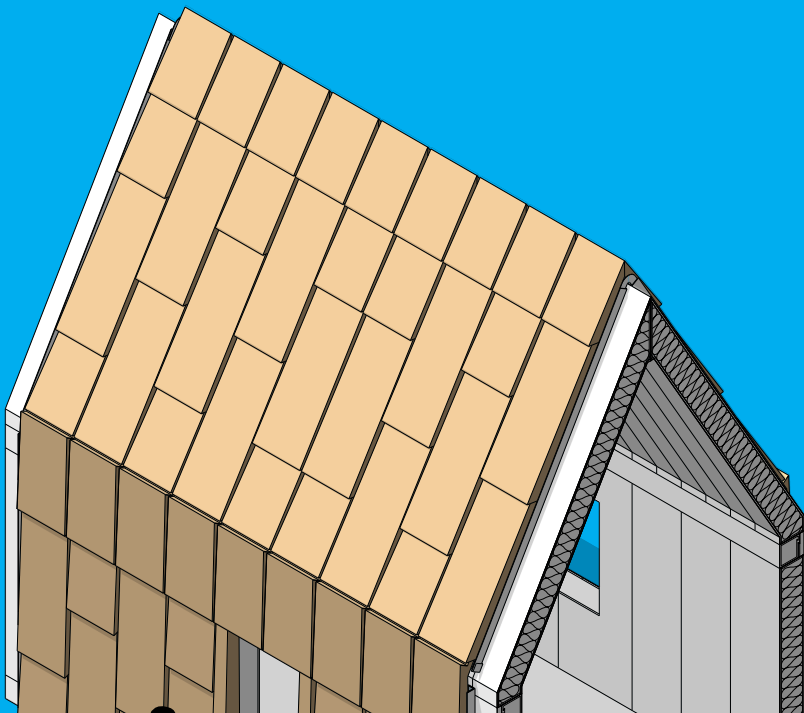


**PD LAB**

# THE DEVELOPMENT OF A BIOBASED CLADDING SYSTEM

Master thesis by Mitchell Mac-Lean



**Master thesis**

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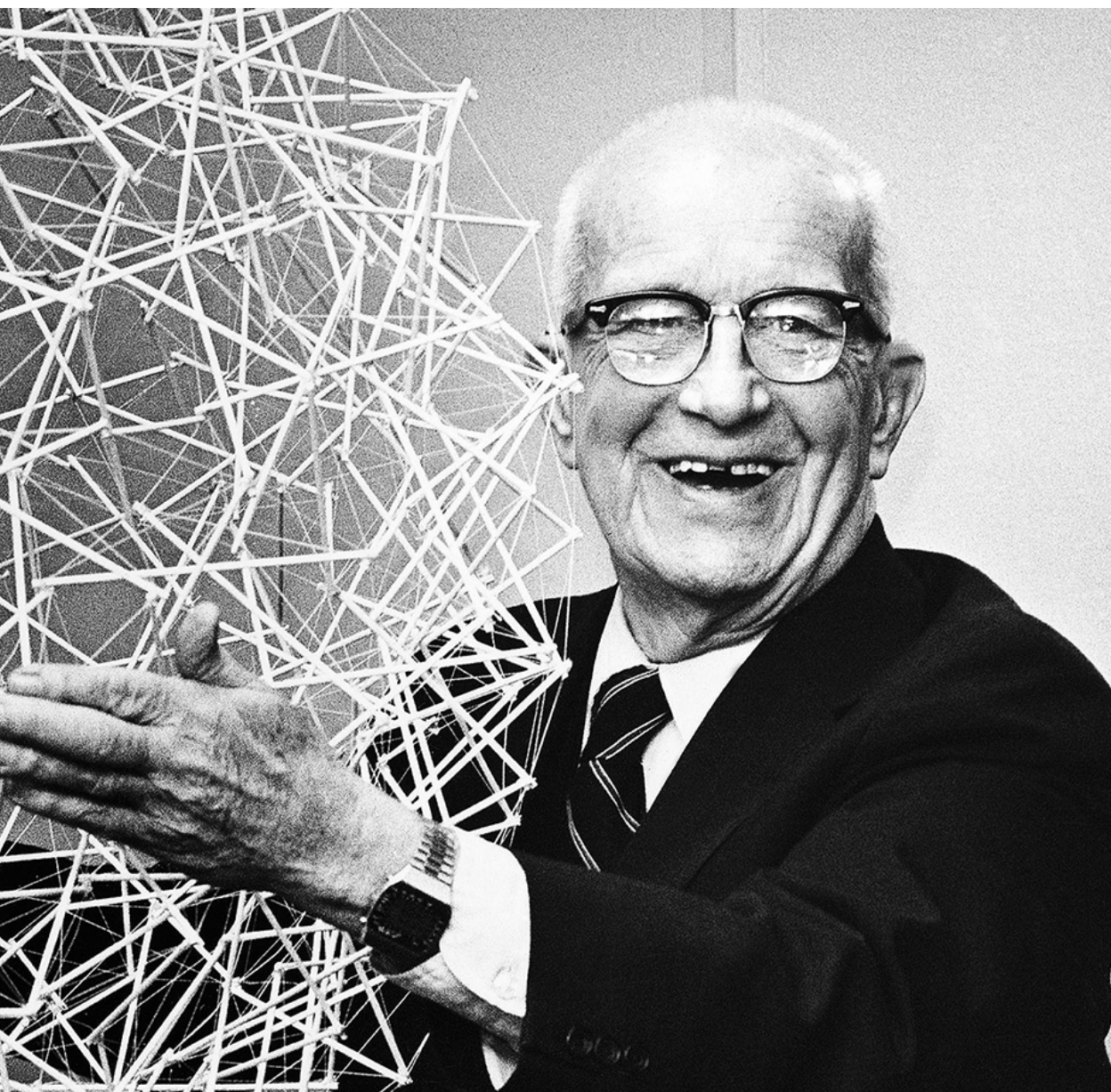
THE DEVELOPMENT  
OF A BIOBASED  
CLADDING SYSTEM

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**Mistakes are great,  
the more I make  
the smarter I get.**





**Richard Buckminster Fuller**  
Designer, author, inventor



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This master thesis is the final result of an interesting and challenging graduation period at the Faculty of Architecture and the Built Environment of the TU Delft. During the past months, I was not only able to learn more about my research topic, but also about myself as a person. The moments that were intense shaped me and made me realise once again of what great value the people around me are.

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With this master thesis, an end has come to seven years of studying at the TU Delft. It has been a great time, in which I was able to make friends for life and learn valuable lessons. These lessons would not have been possible without having the opportunity to make mistakes. Hopefully, many more of these learning moments will follow. To speak with the words of Richard Buckminster Fuller: Mistakes are great!

Mitchell Mac-Lean  
Delft, June 2018

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# 1. INTRODUCTION

The final design consists of all the parts that together cover a principle section of the PD lab. Besides a description of the assembly, detailing and parts of the principle section, this chapter also shows some suggestions for cladding solutions at parts of the building that are more complex and demand further development, such as the end of the roof top and roof edges.

### Energy, material and waste

Nowadays, the building industry has to deal with all sorts of environmental and economic problems. The first factor that plays a large role in these problems is energy. The building industry mainly uses fossil fuels, which not only contribute to climate change, they are also getting scarcer and therefore more expensive. If nothing changes, fossil fuels will either deplete or get too expensive to use (Grant, 2005). The second factor of influence is material. Minerals such as metal are slowly depleting due to an increasing demand and the irreversible mixing of materials which makes complete recycling too expensive or simply impossible. Thirdly, waste generation is a problem. Waste on land, in the water and in the air has a negative impact on the environment (Ashby, 2015).

The building industry is a large consumer of energy: it accounts for 40% of the worldwide energy consumption with a continued growth expected (International Energy Agency, 2008; Ürge-Vorsatz, Danny Harvey, Mirasgedis & Levine, 2007). At the same time, the building industry is also one of the most promising sectors in terms of potentials to help reduce the energy problem (Ürge-Vorsatz & Metz, 2009). Besides a high energy consumption, the building industry is a large user of materials: it accounts for 40% of the worldwide material use (Pulselli, Simoncini, Pulselli & Bastianoni, 2007). In terms of waste, the building industry is responsible for 50% of the worldwide CO<sub>2</sub> emission (Joseph & Tretsiakova-McNally, 2010) and for 35% of industrial waste generated in the world (Hendriks & Pietersen, 2000).

Although the current building industry is aware of the necessity of reducing its large energy consumption, material use and waste generation, the focus mainly lies on making products more energy efficient, which only applies to its use phase. However, to achieve a world that develops in a sustainable way<sup>1</sup>, material use, energy consumption and waste generation through the complete life cycle of products should be taken into account.



Energy



Material



Waste

<sup>1</sup> Brundtland (1987) defines sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”

### Towards a circular economy

Our current economy has a linear character in which materials are taken, products are made and disposed after use (Ellen MacArthur, 2013). The problem of this one way perspective approach is that products are not designed to have multiple use phases. This means that, if a product is at the end of the use phase, it is broken down to its smallest particles, losing quality, energy, labour, money and materials that were invested during the design, engineering and realization phase.

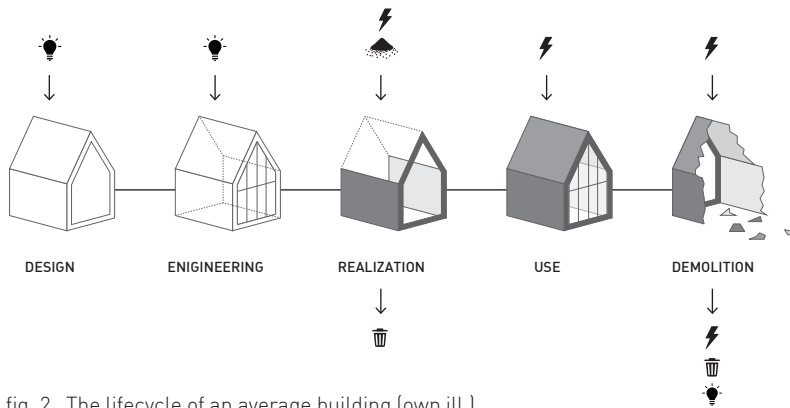


fig. 2. The lifecycle of an average building (own ill.)

One of the possible solutions to this problem is a transition to a circular economy. Instead of a 'take, make, dispose' approach, products are used in cycles to ensure their quality as long as possible and minimize the material loss, energy use and waste generation.

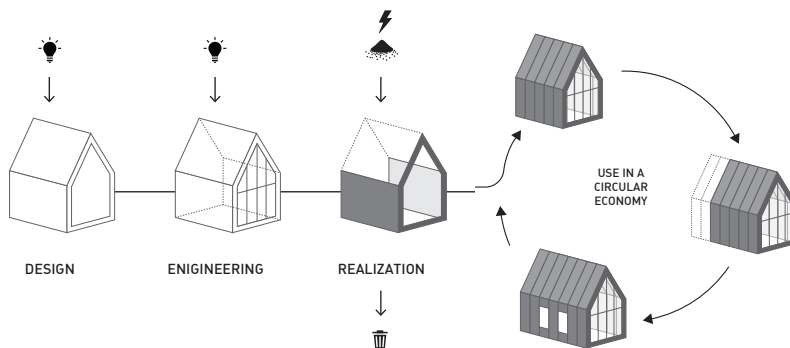


fig. 3. The lifecycle of a building in the circular economy (own ill.)

### The Product Development lab

To find out how the building industry can adapt to a circular economy, various research projects are being conducted. One of them is the Product Development (PD) lab, an experimental platform that researches the potentials of industrial production techniques and modular, demountable building components in order to decrease the energy consumption, material use, waste generation, construction time and costs in the building industry.

In the spring of 2017, a physical PD lab was built next to the Faculty of Architecture at the Delft University of Technology (see fig. 4). This PD test lab helps researchers and students to further develop the PD lab platform. By installing prototypes of newly designed components, they are enabled to test and evaluate the behaviour of the products they are developing in practice.



fig. 4. Construction of the PD test lab (Bilow, 2017)

The PD test lab is made of a CNC-milled structure and cladding system. The structure was developed by Nick van der Knaap (2016) and is made of Ecoboard panels, a biobased material made of wood fibres. The cladding system, which is the outer leaf of the facade that protect the building against external forces such as rain, wind and sunlight, was designed by Jeroen van Veen (2016) and is made of Reynobond panels.

Reynobond is a sandwich material, which consists of two layers of aluminium glued on a core of polyethylene (PE). Although the material itself is very suitable as a cladding material and is applied in a modular and demountable system, the ingredients are mixed, which makes it hard to separate them and recycle them into products of similar quality. Combined with the fact that aluminium and polyethylene come from non-renewable sources, Reynobond is not the most optimal choice in terms of circularity. The question rises if, instead of Reynobond, a renewable material can be used to develop a cladding system that fits in a circular economy even better.

**Biobased materials**

Biobased materials are organic, renewable materials, of which some are also biodegradable. The use of biobased materials on itself is not something new. For ages, renewable agricultural and forestry resources have been the main resource for various materials and products. Only since the beginning of the 20th century, when most industries started to switch towards fossil fuel based products, biological resources have become a secondary resource for energy, materials and chemicals. Around 1970, about 95% of the markets that used to be based on biological resources were now based on petroleum resources. However, nowadays the world has to deal with the depletion of fossil fuels and therefore has a large material and energy problem. Due to these problems, a renewed interest in biobased materials has arisen over the last few decades (National Research Council, 2000).

**Problem statement**

By going from a linear economy towards a circular economy, the material use, energy consumption and waste generation in the building industry could be reduced. This means that a building product's complete life cycle should be taken into account, instead of only focussing on the energy consumption during its use phase. In this perspective, both design and materials will become increasingly important.

At the moment, the cladding system of the PD lab is made of aluminium sandwich panels. Although the design already anticipates on application in a circular economy, the material doesn't since the ingredients are non-renewable and hard to separate and thus recycle. Therefore, the problem statement is as follows:

The current cladding system of the PD lab is made of non-renewable materials that are difficult to separate, which makes them hard to recycle into products of similar quality.



### Research goal and research questions

Ashby and Johnson (2013) state that design is all about making things out of materials. Following from their inseparability, this research will both focus on material and design. The ultimate goal is to develop a biobased cladding system that is modular and demountable. The PD lab will function as the case for which the cladding system will be developed. The main research question that will be used is:

How can biobased materials be applied to develop a modular and demountable cladding system for the PD lab?

In order to find an answer to this question, the following sub-research questions will be used:

- What are biobased materials, how can they be categorized and which biobased materials are available as market (cladding) products?
- How can suitable biobased materials be selected for further development in a cladding system for the PD lab?
- Which concepts for the cladding system of the PD lab can be developed with the selected materials?
- How can suitable concepts be selected for further design development?

### Methodology

In order to find answers to the research questions, the following methodology will be used (see fig. 5):

### Design problems

Ashby and Johnson (2013) write that a design is always made to fulfil a certain need. The PD lab will be used as the case for which the cladding system will be developed. In order to find the need that has to be fulfilled, the PD lab and its existing cladding system will be examined first. The design problems that are found will be used to formulate boundary conditions and criteria that will be used during the material selection and concept and design development.

### Material selection

In this research, the material will get a leading role over the design. Form follows material. By looking at the properties of materials and the way of application in which they excel, a better product design is pursued. Since biobased materials have a central role in this research, this step will orientate on what they are exactly, how they can be categorized and which materials are available on the market. However, this research is not focussed on the development of new materials. In order to keep the material selection compact, a category will be chosen prior to the selection of a material. Moreover, only materials that are already further developed and available as market products will be included in the material comparison and assessment. To conclude this step, one material will be selected.

### Concept development

The chosen material from the previous step will be used as a starting point for the concept development. By looking at the properties of the material, the design problems and the criteria, this step examines all kinds of concepts. This will be done by looking at different aspects of a cladding system and generating concepts for all of them. The aspects are: assembly, connection, horizontal joints, vertical joints, sub-construction, panel stiffness and processing techniques. The resulting aspect concepts will then be assessed and combined into several total concepts. With the help of another assessment, one of these total concepts will be chosen for further design development.

### Design development

The goal of this step is to make the selected total concept into a design that can be produced. The ultimate goal of this research is to develop the part of a cladding system that covers the sectional profile of the PD lab. Therefore, the design will be elaborated into principle cladding parts.

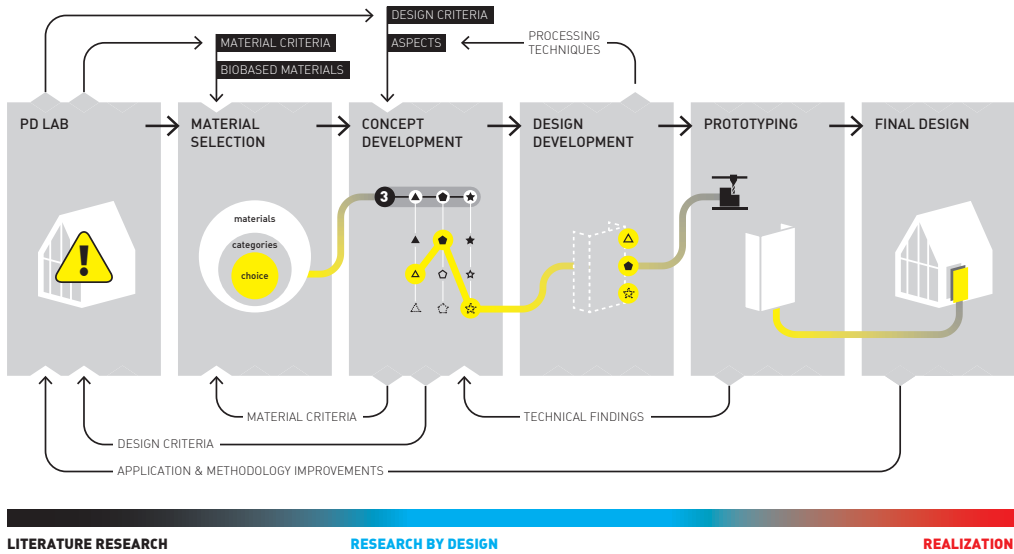


fig. 5. Research methodology

### Prototyping

Prototyping allows to test theoretical ideas in practice and learn lessons from it. The same goes for the design in this research. The prototyping can take place throughout the process, both on a small scale or 1:1 scale. If it turns out that the material or design does not function as expected, the process can return to an earlier step in the methodology.

### Final design

This is the resulting design, showing the parts and details of the cladding system and explaining the way it is assembled.

## 2. PRODUCT DEVELOPMENT LAB

A design is always made to fulfil a certain need (Ashby & Johnson, 2013). In order to find out how to fulfil this need, it is important to look at the current situation and the occurring problems. By making the design problem clear, a more optimal solution can be found.

Since the PD lab functions as the case for which a new cladding system will be developed, this chapter will zoom in further on the theory behind it. Also, the PD test lab with its Reynobond cladding system will be discussed, in order to find the design problems that have to be solved.

## 2.1 The theory behind the PD lab

### 2.1.1 The separation of design, engineering and realization

The role of the architect nowadays is completely different from the role of the historical master builder. Centuries ago, architects were both experts in designing, engineering and realization (see fig. 8) (Kolarevic, 2003). The master builders were the embodiment of architecture, since they were both architect, building engineer and material scientist (Kieran & Timberlake, 2004). With the increasing complexity of buildings, the number of layers between the architect and the construction site increased, together with the number of errors and inefficiency as a result of miscommunication. The architect's knowledge of construction decreased and the gap between the architect (design) and the construction site (realization) grew (Kolarevic, 2003). Nowadays, an architect works together with structural engineers, climate consultants, façade designers, a general contractor, sub-contractors, project managers and investors in order to realise a building. The question rises if it is possible to integrate these disciplines again in order to decrease the errors and inefficiency in the building industry.

#### 2.1.2 Sharing building information

In an average building process, there are all kinds of involved parties with their own specialism and contribution to the project. In order to prevent errors and inefficiency during the design or build phase, it is essential that all involved parties have the same, up-to-date information. Until a few decades ago, when the internet wasn't as common as it is today, all building information had to be shared via physical media such as drawings on paper (see fig. 6). This meant that building information was not only updated less often, it was also less accurate compared to digital drawings, resulting in miscommunication, inefficiency and building errors. With the rise of the internet and digital software, such as CAD and CAM software, the sharing of digital information became much easier and made it possible to update the information for all parties with the touch of a button. Besides the speed and ease of updating of information, the accuracy of drawings improved, resulting in a more efficiency and less building errors.



Because of the increasing complexity of buildings and the building process, BIM is the way to go nowadays. BIM, which stands for 'Building Information Modelling' is a central shared source of information regarding the physical and functional properties of a building. Instead of having various documentations of a specific part of the building, BIM collects all the information in one digital file (see fig. 7). Although BIM integrates design and engineering, it lacks information regarding the actual manufacturing of the building components. However, just as the digital revolution brought the design and engineering aspects closer together, it might bring us another step further: integration of design, engineering and realization.

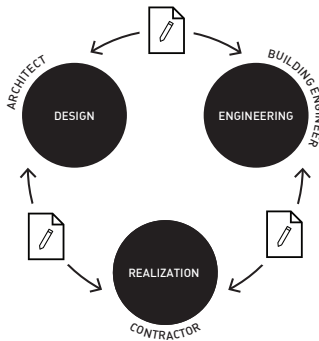


fig. 6. Sharing building information by physical documents (own ill.)

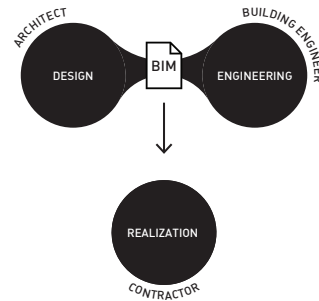


fig. 7. Sharing building information by digital documents (own ill.)

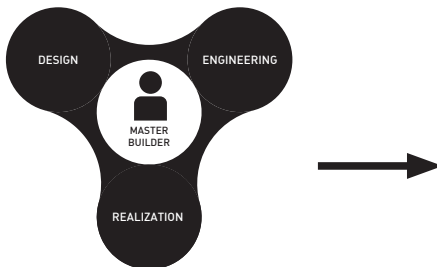


fig. 8. The master builder as the centre of the building process (own ill.)

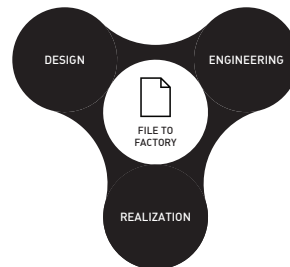


fig. 9. Integration of design, engineering and realization by using a file-to-factory approach (own ill.)

### 2.1.3 File-to-factory approach

To integrate design, engineering and realization, the PD lab uses a 'file-to-factory' approach. The idea is that one digital file is used in which all information regarding design, engineering and realization is used, from the start to the end of the building process (see fig. 9). By integrating digital models and digital manufacturing techniques such as CNC-milling, the step from design towards realization becomes much more fluent in comparison to conventional building processes. By using a digital file that already contains all the information that the digital machinery needs, building components can be produced right away. The added values of this approach are the speed, accuracy and efficiency. This will be further discussed in section 2.1.4.

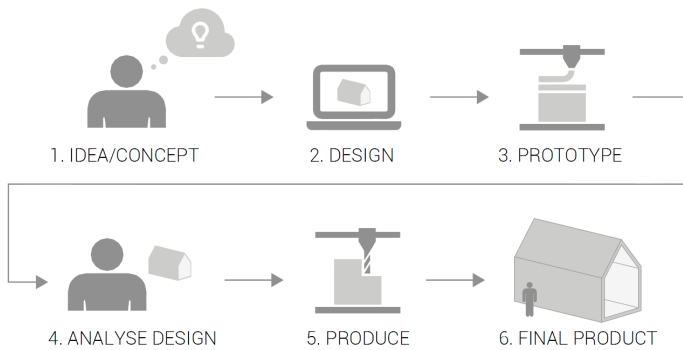


fig. 10. The file-to-factory approach (Van der Knaap, 2016)

Besides a higher speed, accuracy and efficiency in production, the file-to-factory also makes it easier to make prototypes. Prototyping enables the designer to see if the theoretical design functions in practice like desired. Since the file-to-factory approach takes the information for production into account from the start of the design process, prototyping can take place from an early stage of the design process. This enables for early prototyping, analysis and feedback to the design (see fig. 10).

### 2.1.4 PD lab: IFD-building

The PD lab is an 'IFD-building': industrial, flexible and demountable.

**Industrial production** - As discussed before, the PD lab uses a 'file-to-factory' approach, in which one digital file is used from design to industrial production. By using a file-to-factory approach, there is a much lower chance of wrong interpretation between the design, engineering and realization phases. Industrial production techniques like CNC-milling enable prefabrication under controlled conditions, a very high level of accuracy and efficient material usage (Stoutjesdijk, 2013). This way, errors are prevented and thus unnecessary material use and waste generation prevented.

**Flexible** - Flexibility is present in the PD lab in both the process and the product. The CNC-milling technique makes mass customization possible, which means it doesn't make a difference if many uniform or non-uniform parts have to be produced. In terms of product, the modular building components enable the system to make various configurations and change the configuration during the use phase, resulting in a better adaption to the users demands and an extended functional lifespan (see fig. 3 and fig. 11).

**Demountable (and remountable)** - A product or building that can be disassembled has an increased chance to be repaired, reused or remanufactured before being recycled or considered as waste. This also applies to the PD lab. By applying dry connections, the modular building components can easily be maintained, updated or reused. This way, the building can extend its economical, and technical lifespans.

To conclude: By being an experimental IFD-building, the PD lab aims to develop a building system that 1) reduces the material and energy consumption during production, 2) improves the way the building adapts to the demands of the user and 3) makes it possible to use building components multiple times, which reduces material use, energy consumption and waste generation.



fig. 11. Lego: one of the best known examples of a modular, demountable and remountable building system (source: Lego.com)

## 2.2 The PD test lab in practice

The PD test lab was constructed in the spring of 2017, next to the faculty of Architecture and the Built Environment of the TU Delft. With the PD test lab, the structure developed by Van der Knaap (2016) and cladding system developed by Van Veen (2016) could be analysed in practice on a full scale for the first time. The findings that were made will be discussed in this section, as they will be used as feedback and input for the new cladding system design.



fig. 12. The Product Development Test Lab (Bilow, 2017)

### 2.2.1 Reynobond

The current cladding system of the PD test lab was developed by Van Veen (2016). It is made of Reynobond, which is an aluminium composite material. It consists of two layers of 0.5 mm aluminium with a layer of 3mm PE (polyethylene) laminated in between (see fig. 13). The material is processed by a CNC-milling machine, which makes cutting and bending lines that allow it to be bent into various shapes of cladding panels (see fig. 14).

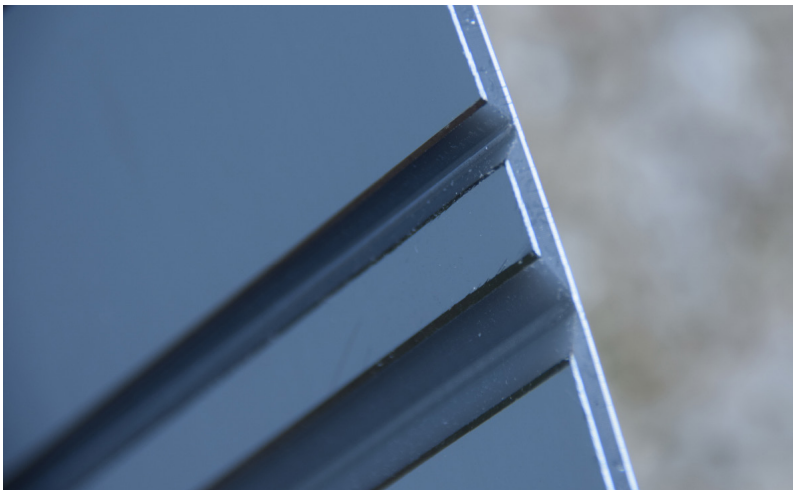


fig. 13. Reynobond panel including milled bending lines (Van Veen, 2016)



fig. 14. A bent Reynobond panel (Van Veen, 2016)



### 2.2.2 Concept development

The design of the current cladding system started by generating various concepts per aspect, which are: assembly, connection, horizontal joints, vertical joints and sub-construction. Subsequently, these aspect concepts were combined into one cladding concept. This method enables the designer to quickly come up with many different concepts and make various combinations with them. The characteristic property of Reynobond that enables it to be milled and bent was taken into account during the generation of aspect concepts. The concepts per aspect, including the ones that were combined are shown in fig. 15.

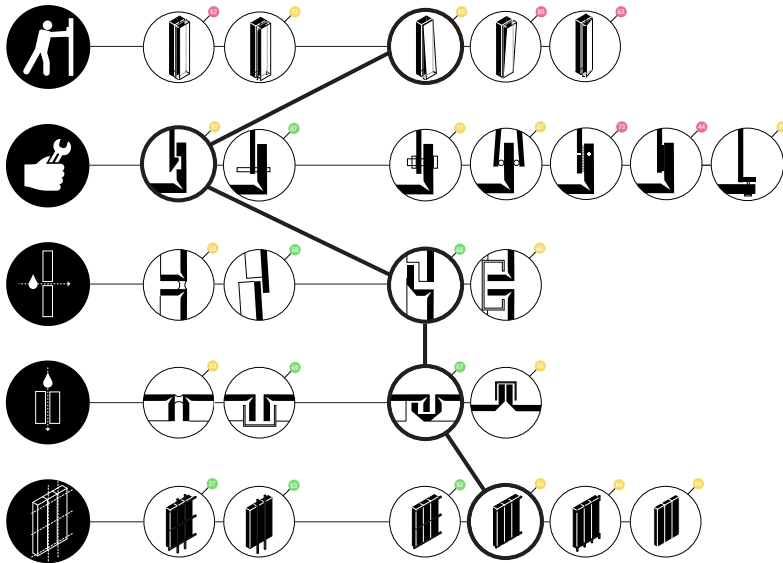


fig. 15. Aspect concepts, including the flow line that shows which aspect concepts were combined (Van Veen, 2016)

### 2.2.3 Final design

The concept that followed from the aspect concept combination eventually led to the final design shown in fig. 16. The system consists of male and female parts, enabling an overlap at the vertical joints and the integration of vertical drainage gutters. The panels are fixed at the top and the bottom by brackets, which are made of Reynobond as well. Horizontal gutters are integrated in the cladding at the roof edge.

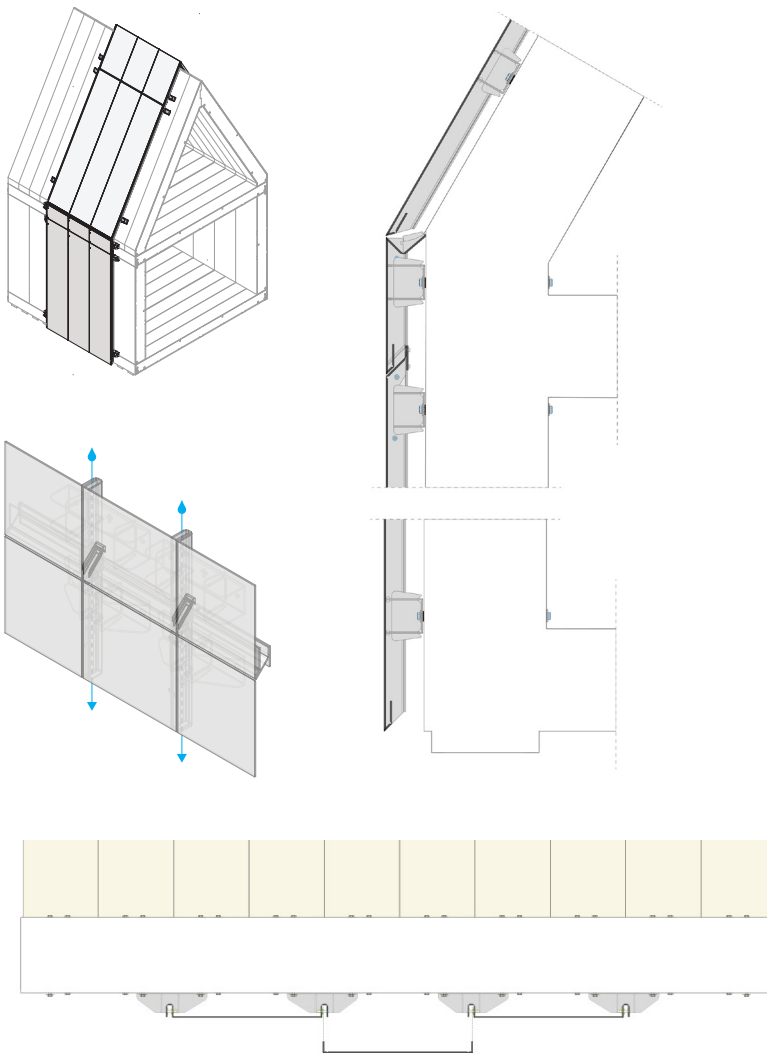


fig. 16. Detail drawings of the Reynobond cladding system (Van Veen, 2016)

### 2.2.4 Assembly

The cladding panels have a hinged connection at the top and a clicked connection at the bottom, which enable it to be assembled easily and fast, without needing any tools. In fig. 17, the assembly of the male and female panels to the structure is shown.

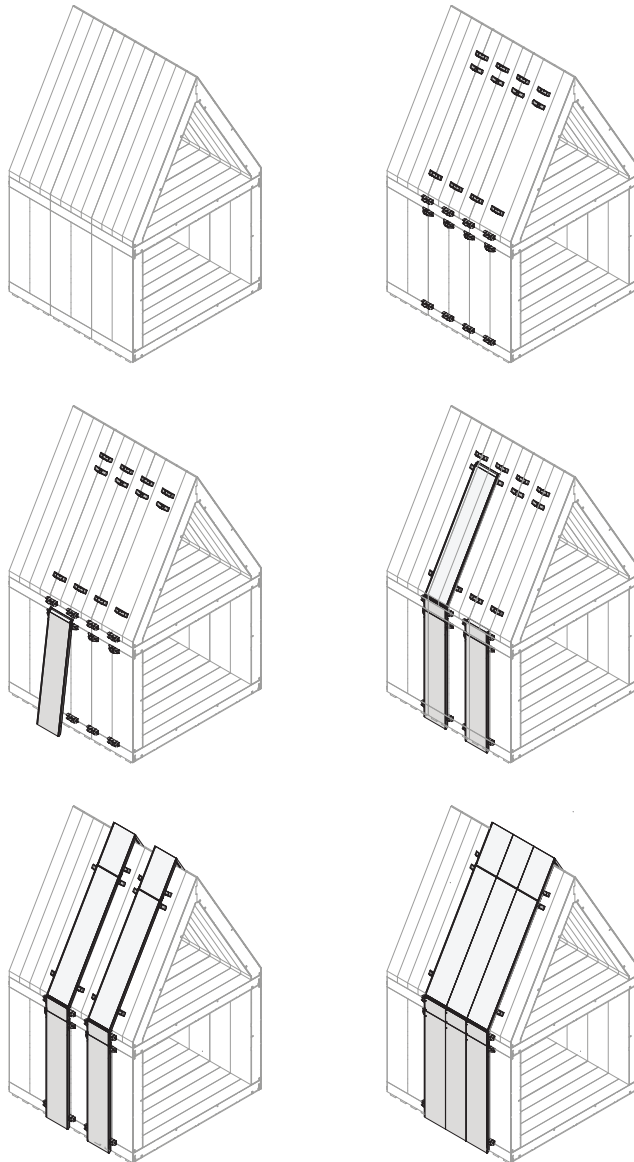


fig. 17. Assembly order of the cladding system on the structure of the PD lab (Van Veen, 2016)

### 2.2.5 Application in the PD test lab

The PD test lab, that was constructed in the spring of 2017, made it possible to test the full Reynobond cladding system for the first time. Besides the sectional profile cladding system that was developed by Van Veen (2016), extra developed parts were applied that cover the critical parts at the front and back edges of the PD test lab.

#### **Encountered design problems**

During the construction of the PD test lab, several problems were encountered. First of all, the cladding system lacked space for adjustment to solve dimensional deviations that were caused by production or assembly inaccuracies or (thermal) expansion of the material (see fig. 18). Also, critical points such as the overlap between the vertical gutters of separate panels and between the vertical gutter and horizontal gutter did not always fit together properly (see fig. 19). As a result of the minimal overlap, combined with the lack of space for adjustment, the water tightness at these points is vulnerable. Finally, it appeared to be difficult to hinge the cladding panels into place at some points, since the scaffolding did not always allow enough space.

#### **Design features to preserve**

Besides the design problems that were encountered during the construction of the PD test lab, there are also multiple design features in the current cladding system that are wished to be preserved in the new cladding system. The first one is the functionality of a rainscreen cladding. This means that the cladding system has to prevent any rainwater from reaching the layer underneath. To enable the rainwater to flow to a drain point, some sort of drainage system is necessary. To minimize the number of parts and that way assembly time, it would be favourable to integrate this drainage system in the cladding panels. Taking the IFD-building approach of the PD lab into account, the material that will be selected should allow for industrial production, while the design should allow for easy, fast and flexible assembly and disassembly.



fig. 18. A lack of space for adjustment, causing unequal seams between cladding panels at the roof top (Bilow, 2017)



fig. 19. Gaps between the panel joints and surfaces (Bilow, 2017)

## 2.3 Conclusion

### **The theory behind the PD lab**

Architects used to be master builders, who were both experts in designing, engineering and realization. Due to the increasing complexity of buildings and the building process, an architect nowadays works together with many other actors in the building process. As a result, the gap between the architect (design) and the construction site (realization) grew. With the separation of design, engineering and realization, the number of errors and inefficiency in the building process increased.

With the increased number of involved actors, proper sharing of building information became more important than ever in order to prevent errors and inefficiency during the design, engineering or realization phase. Until a few decades ago, building information was shared via drawings on paper. With the rise of the internet and digital software, such as CAD and CAM software, drawings could be shared quicker, more often and more accurately. Nowadays, building information is shared via BIM, which is a central source of building information in which all involved actors can work together. Although BIM integrates design and engineering, it still lacks information regarding the actual realization of the building components.

To integrate design, engineering and production, the PD lab uses a 'file-to-factory' approach. The idea is that one digital file is used in which all information regarding design, engineering and realization is used, from the start to the end of the building process. The added values of this approach are the speed, accuracy and efficiency of production and the possibility to start prototyping from a very early stage of the design process. This enables for early analysis of and feedback to the design.

The PD lab is an 'IFD-building', which is an abbreviation for Industrial, Flexible and Demountable. This way the PD lab aims to develop a building system that 1) reduces the material and energy consumption during production, 2) improves the way the building adapts to the demands of the user and 3) makes it possible to use building components multiple times, which reduces material use, energy consumption and waste generation.

**The theory behind the PD lab**

The PD test lab made it possible to test the structure developed by Van der Knaap (2016) and cladding system developed by Van Veen (2016) on a full scale for the first time. During the construction of the cladding system, several design problems were found:

The cladding design lacks a possibility to adjust parts to solve dimensional deviations as a result of production inaccuracies, assembly errors or thermal expansion  
Critical points in the vertical and horizontal gutters make the system vulnerable in terms of water tightness  
Hinging the cladding panels into place seemed to be difficult, since the scaffolding did not always allow enough space

Besides the design problems that are aimed to be solved in the new cladding system, the following design features are aimed to preserve:

Rainscreen cladding function  
Integrated drainage  
Industrial production  
Easy, fast and flexible assembly and disassembly

### 3. BIOBASED MATERIALS

The goal of this chapter is to get a better understanding of biobased materials and in the end select a suitable material for the cladding system. The following sub-research questions will be used:

- What are biobased materials, which biobased materials are available as market (cladding) product, and how can they be categorized?
- How can suitable biobased materials be selected for further development in a cladding system for the PD lab?

Eventually, this chapter has to result in a material choice. However, with thousands of materials available on the market, let alone in the world, the material selection can quickly become very extensive. In order to keep it compact, a category will be chosen prior to the actual material selection. From this category, several materials that are available on the market will be assessed, which will eventually lead to a material choice that will be used in the further concept development (see fig. 20).

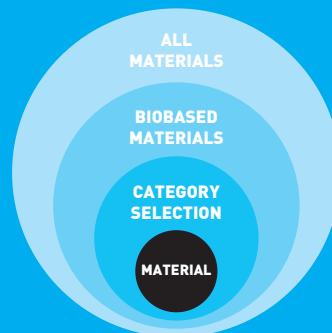


fig. 20. Material selection approach  
(own ill.)



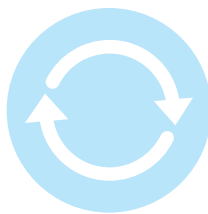
### 3.1 Definition

In the literature, multiple definitions of 'biobased' can be found. The Netherlands Standardization Institute (NEN), for example, defines biobased as "derived from biomass, can have undergone physical, chemical or biological treatment(s)". Biomass, in turn, is defined here as "material of biological origin excluding material embedded in geological formations and/or fossilized" (NEN, 2014). The USDA (2002) prefers to speak of 'biobased products' which are defined as "commercial or industrial products that are composed in whole, or in significant part, of biological products or renewable domestic agricultural materials or forestry materials". Jones (2017) uses the word 'biobased' explicitly in combination with building materials: "plant-, tree- and animal-derived materials, either in their sourced format or resulting from modification or treatment or from incorporation into other materials".

The definition used by Jones (2017) fits the context of this research already quite good, but lacks precision and boundaries to be of good use for this research. Therefore, it will be complemented with elements from the other definitions: "Biobased materials are materials that consists completely or for a significant part out of renewable<sup>2</sup> organic substances, either in their sourced format or resulting from modification or treatment." It should be mentioned that, contrary to what is easily assumed, biobased materials are not necessarily biodegradable. Both biodegradable and non-biodegradable biobased materials exist.



**Organic**



**Renewable**



**Can be biodegradable**

<sup>2</sup> In this context, 'renewable' refers to the criteria "that a resource recovers faster than it is drained" (Jones & Brischke, 2017).

### 3.2 Categorization of biobased materials

A categorization of the most common materials is shown in fig. 21 (Kula, Ternaux, Hirsinger, de Boer-Schultz & van Leeuwen, 2013). As can be seen, some of these material categories are not renewable and not biobased by definition. Metals, glass/ceramics, stone and concrete will therefore not be further examined.

The other six categories, however, are renewable or available as such. From these six categories, three categories are not suitable for application in a cladding system in their basic form. The first one, paper/cardboard, is a lightweight material, but has a weak performance in wet conditions. The second one, leather/hide, could be suitable as cladding material, but is maintenance-intensive and may be unethical to use, especially on the scale of buildings. The third category, textiles, is flexible and lightweight, which is advantageous for the freedom of design. However, the biobased textiles that are currently on the market have a weak performance in wet conditions. Therefore, only the following three categories will be researched further:

- Wood
- Bio-plastics
- Bio-composites

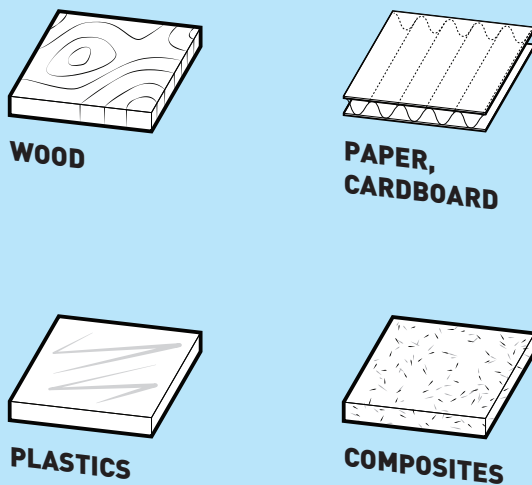
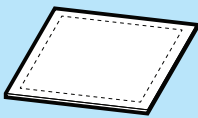
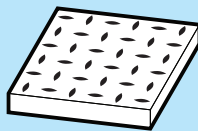


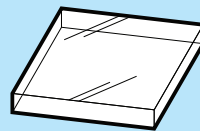
fig. 21. Categorization of the most common materials (Kula et al., 2013)



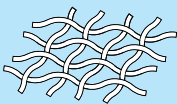
**LEATHER,  
HIDE**



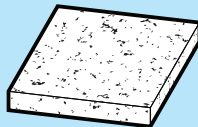
**METAL**



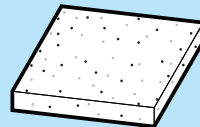
**GLASS,  
CERAMICS**



**TEXTILES**



**STONE**



**CONCRETE**

### 3.2.1 Wood

Wood is one of the most traditional building materials. Its high availability, the comfortable look and feel and the relatively easy and far developed processing techniques make it a popular choice as building material.

#### **Categorization**

Wood can roughly be divided into softwoods and hardwoods. Although the names may indicate the hardness of the wood, this is not always the case. Instead, these names refer to the specie of the tree of which the wood originated from. In general, hardwood comes from deciduous trees, which have broad leaves, enclosed seeds and a porous structure with vessel elements. Softwood however comes from coniferous trees, which have needle- or scale-like leaves, exposed seeds and a non-porous structure (Ross, 2010).

Hardwood and softwood appear in various forms. The first, most obvious are solid wood products such as panels or beams. The other ones are wood-based products such as: layered panels, particleboards and fibreboards. Wood-based products are often made of smaller pieces of residual wood. By binding them together with some sort of binder, new panels can be made.

#### **Application**

Wooden claddings often are applied as shingles or boards. Shingles are square, flat pieces of timber that can be placed in an overlapping configuration. Boards are long pieces of timber that often have a specific profile, such as tongue-groove, that allows for overlapping between the separate parts. As said, wood is a popular building material. However, wood also demands some maintenance, especially when applied as an exterior cladding material. This makes the material less favourable for application on a large scale. Also, the variability in the properties of wood as a result of difference in temperature, humidity or origin (specie, tree or part of a tree) is seen as one of its main deficiencies, especially in the perspective of industrial application (Kitek Kuzman & Kutnar, 2014).

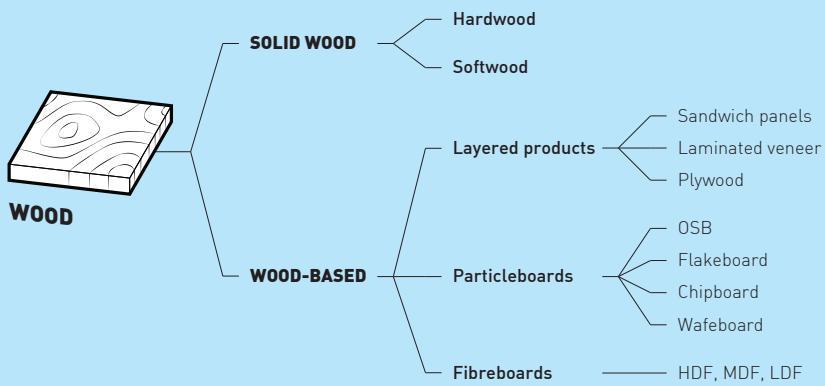


fig. 22. Wood categorization (own ill.)

### 3.2.2 Plastics

The word plastic comes from the Latin word 'plasticus' and the Greek word 'plastikos', which both mean 'able to be moulded, pertaining to moulding' (Liddell & Scott, 1940). Due to its low cost, ease of processing, water tightness, and versatility, plastic is a popular choice by product designers. The plasticity of the material makes it possible to be processed into various shapes.

#### **Categorization**

Plastics consist of polymers, which are very long shaped molecules. Based on the type of connection between these polymers, plastics can be divided into thermoplastics and thermosets. Thermoplastics are able to soften again when heated, due to the loose connection between the polymers. This allows for recycling of the material by melting it and using it in new products. Thermosets, however, only become harder when heated due the strong connection between the polymers. This means that thermosets are not able to be recycled directly (Kula et al., 2013).

Bioplastics are plastics that are (partially) made of renewable sources and/or are biodegradable (Oskam, de Jong, Lepelaar & ten Kate, 2015). This means there are three categories of bioplastics:

- Biobased, biodegradable plastics
- Biobased, non-biodegradable plastics
- Non-biobased, biodegradable plastics

#### **Application**

Bioplastics are already used in packaging material, catering products, consumer electronics, automotive products and toys. Due to the many applications, (bio) plastics are mixed with additives to achieve specific material properties, such as processability and colour. Most of the additives being used at the moment are not biobased yet and the biobased alternatives that do exist are still in their infancy. However, in terms of material properties such as strength and stiffness, natural fibres can be used. This way, composites are made (Oskam et al., 2015). See section 3.2.3 for more information.

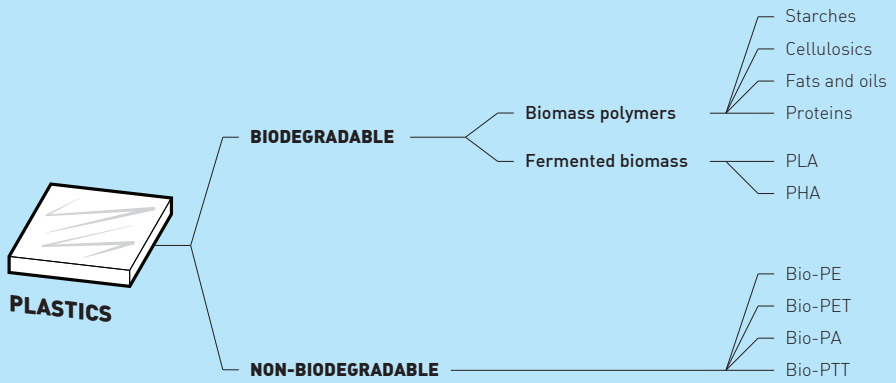


fig. 23. Plastic categorization (own ill.)

### 3.2.3 Composites

Composites are made by combining two or more materials with different material properties. By doing so, material properties can be achieved that are superior over those of the separate materials (Kalpakjian & Schmid, 2014). Composites consist of a matrix and reinforcement material. The matrix is the part that keeps everything together, while the reinforcement increases the mechanical properties of the matrix material (Chawla, 2012).

Composites are not new, since the oldest known example of a composite, a brick made of clay and straw, dates back already to 4000 B.C. (Kalpakjian & Schmid, 2014). However, composites are applied in aircraft and aerospace only since a few decades ago (Niu, 1992).

#### Categorization

Based on the type of reinforcement, there are three categories of composites: fibre reinforced composites, particle reinforced composites and laminated composites (Callister, 1997; Smitthipong, Chollakup & Nardin, 2014). In bio-composites, natural fibres are most often used as reinforcement because of their abundance, low cost, advantageous weight to strength ratio and ability to achieve interesting properties in terms of thermal and acoustic insulation (Joshi, Drzal, Mohanty & Arora, 2004; La Mantia & Morreale, 2011).

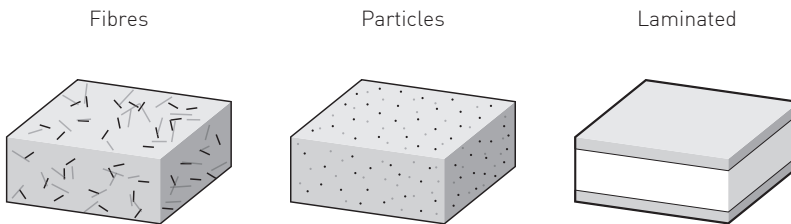


fig. 24. The three most common types of composite reinforcement (own ill.)

#### Application

Gradually, (bio-)composites are also introduced in the building industry. They are characterized by their design flexibility, high strength to weight ratio, impact strength, corrosion resistance, fatigue resistance and little thermal expansion (Thakur, 2013) which are quite interesting in the perspective of a cladding material.



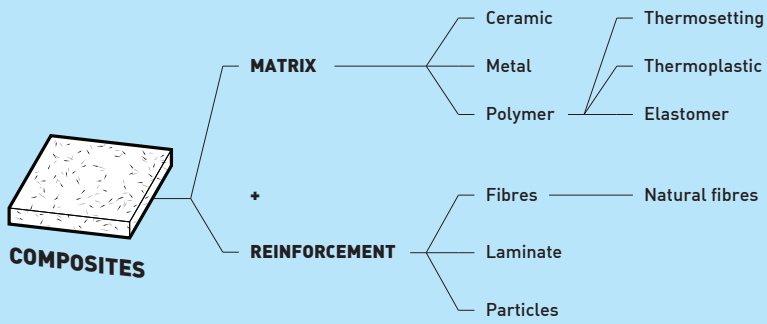


fig. 25. Composite categorization (own ill.)

### 3.2.4 Category selection

After having discussed the categories wood, plastics and composites, the following conclusions can be drawn:

Wood is the more traditional choice, with processing techniques that are far developed and readily easy to apply.

Biobased plastics and composites have some overlap in the sense that most bio-composites are (bio-)plastics that are strengthened by adding natural fibres.

Composites are characterized by their design flexibility, high strength to weight ratio, corrosion resistance, fatigue resistance and little thermal expansion, which are all interesting material properties in the perspective of a cladding material.

Because of its suitability as cladding material and the interesting opportunities that come with possible future innovations, a material from the category of bio-composites will be chosen.

## 3.3 Material selection

From the bio-composites category that was selected in section 3.2.4, several market products will now be discussed and assessed. The criteria that are used for this assessment can be found in appendix A. Since the PD lab is an IFD-building, industrial production and suitable processing techniques of the market products will get special attention. Further information regarding processing techniques can be found in section 4.3.7. Eventually, this assessment will result in a material choice that will be used for the concept development in chapter 4.

### 3.3.1 Market products



Trespa is a common cladding material in the Netherlands. It can be applied both vertically, on facades and balconies, and horizontally, to cover exterior ceilings. Trespa panels are high-pressure laminates that consist for approximately 70% of residual wood fibres and for 30% of a thermosetting resin (phenol formaldehyde) that serves as a composite matrix. Suitable processing techniques are: cutting and machining (Institut Bauen und Umwelt, 2012).

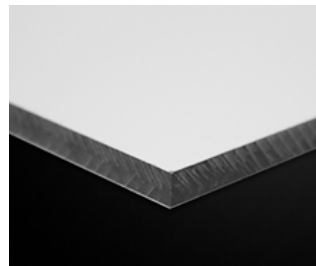
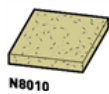


fig. 26. Trespa (tespa.nl)



N8010 is a fairly new bio-composite produced by NPSP which has various applications such as furniture, traffic signs and the automotive industry. It is based on natural fibres (such as flax and reed), chalk and a thermosetting bio-resin. In terms of recycling, N8010 can be used as a filler for new products in a ratio of 2/3 virgin and 1/3 used material. Suitable processing techniques are: cutting, machining and moulding [Böttger, 2018].



fig. 27. N8010 (own ill.)



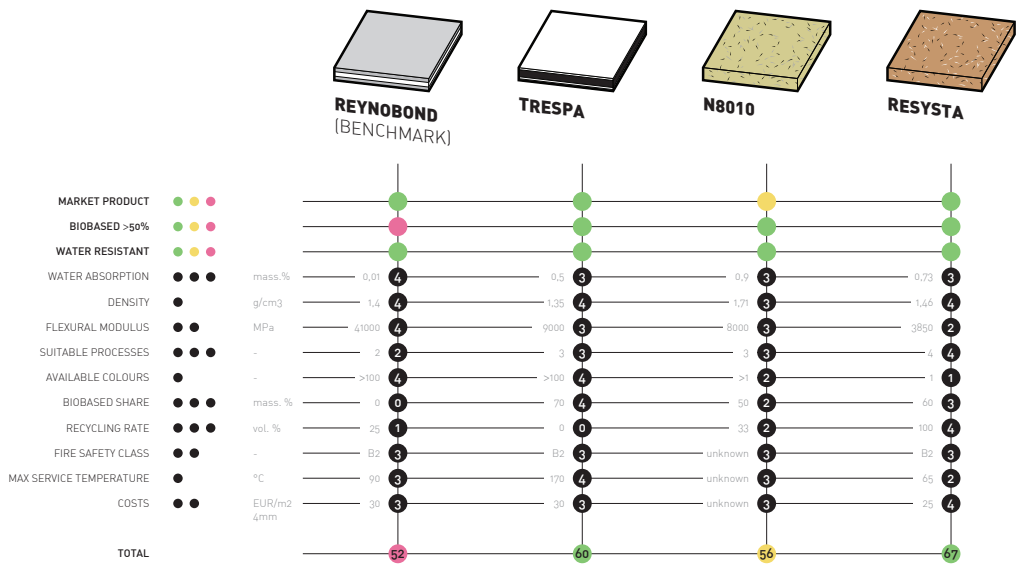
Resysta is a bio-composite that is mainly applied in extruded profiles for decking, fences and facades. It consist for approximately 60% of residual rice husks, 22% of salt and 18% of oil. This last ingredient is used to make the polyvinylchloride matrix which sticks together the rice husks. Although polyvinylchloride is a far from biobased material, it is a thermoplastic and enables Resysta to be processed by cutting, deforming, machining and moulding [BRE Global, 2017].



fig. 28. Resysta (resysta.com)

3.3.2 Market products

The market products that were discussed earlier will now be assessed. An explanation of the criteria that are used can be found in appendix A.



## 3.4 Conclusion

### **Biobased materials**

Biobased materials are organic, renewable materials of which some are also biodegradable. They can be divided into six categories: Wood, paper/cardboard, leather/hide, plastics, composites and textiles (see fig. 29). In order to keep the material selection compact, one of these categories is chosen prior to the assessment of materials. Since this research is not focussed on the development of a new material, the assessment only includes materials that are already further developed and available as market products.

### **Category selection**

From the six biobased material categories, three are not suitable as cladding material in their basic form: paper/cardboard, textiles and leather/hide. Therefore, only the categories wood, plastics and composites are further discussed.

From these three categories, wood is the more traditional choice and already far developed as a building material. Plastics and composites are relatively new as building materials in comparison to wood, and further development is still possible for these two categories. Plastics and composites show some overlap, in the sense that most biobased composites are (bio-) plastics that are strengthened by adding natural fibres. The category of composites is chosen due to its design flexibility, high strength to weight ratio, corrosion resistance, fatigue resistance and little thermal expansion.

### **Material selection**

In the category of biobased composites, three market products are discussed: Trespa, N8010 and Resysta. Following from the assessment of these three materials, Resysta is chosen as the material to apply in the new cladding system. The thermoplastic behaviour of Resysta enables for many processing technique opportunities.

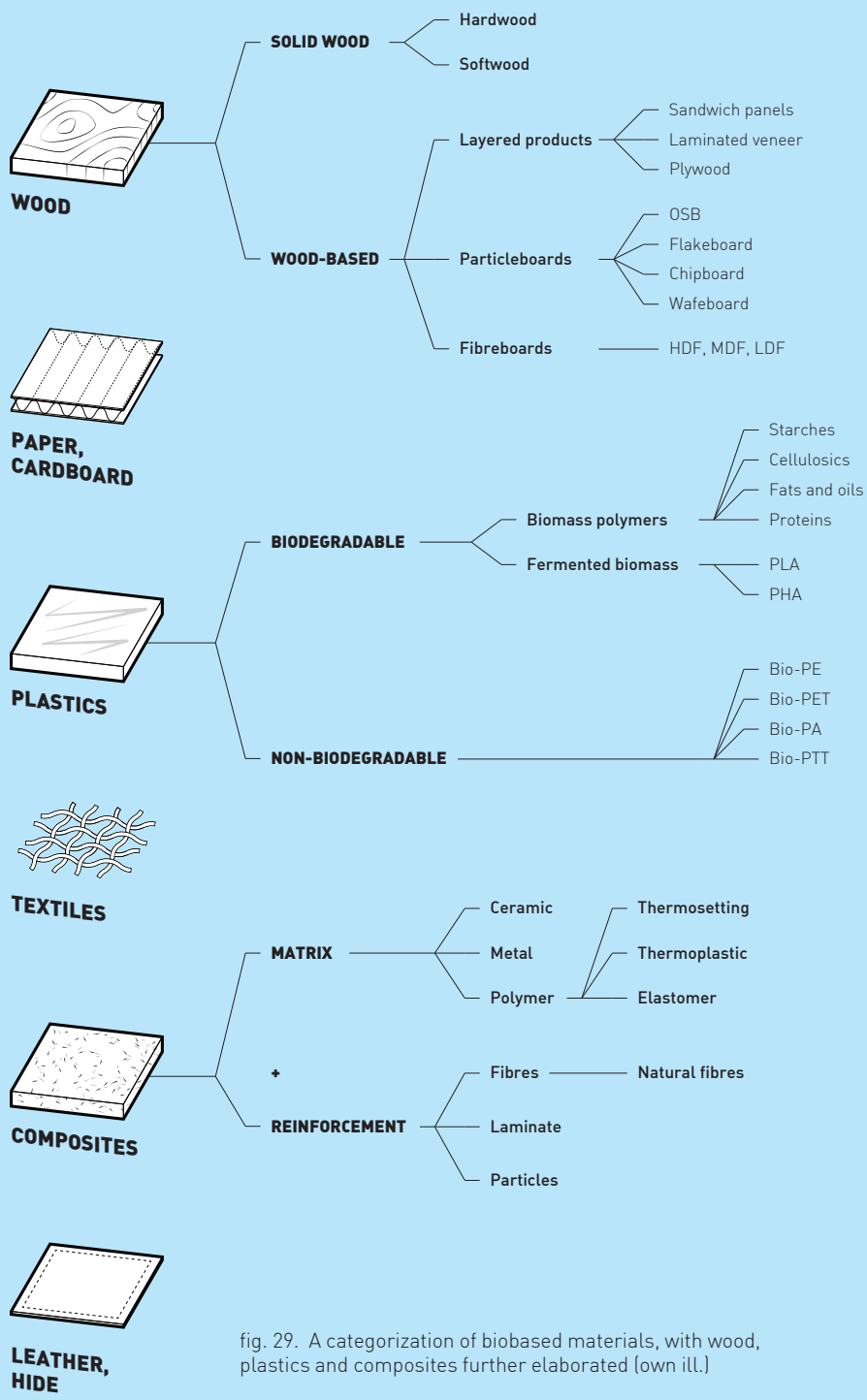


fig. 29. A categorization of biobased materials, with wood, plastics and composites further elaborated (own ill.)

## 4. CONCEPT DEVELOPMENT

This chapter focusses on developing concepts for the cladding system. To do so, an answer to the following two sub-research questions will be searched for:

- Which concepts for the cladding system of the PD lab can be developed with the selected material?
- How can suitable concepts be selected for further concept elaboration?

## 4.1 Design methodology

A design process has an iterative character and can be chaotic at times. There is a constant moving back and forth between the possible alternatives which are virtually countless. To bring some structure in the process, a design methodology will be used within the main methodology of this research. The essence of the design methodology that will be used is splitting the problem into sub-problems, coming up with sub-solutions and eventually combining them into one solution (see fig. 30).

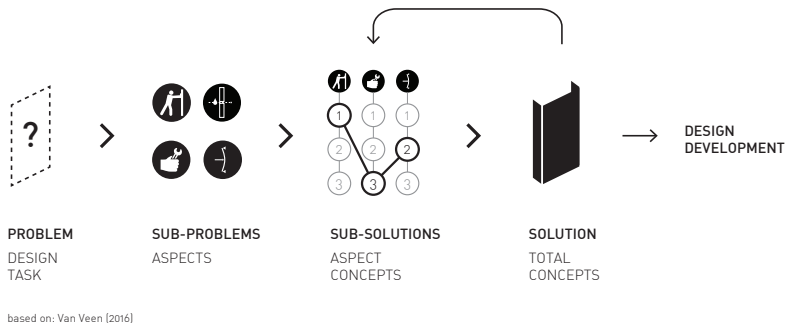


fig. 30. Design methodology

The sub-problems are represented by the aspects that define the physical and functional properties of a cladding system, such as the assembly, connections and joints. By coming up with concepts for every aspect, sub-solutions are found. Based on the assessment of these aspect concepts, various total concepts can be formed (see fig. 30). However, it should be stressed that this design methodology is an aid in the complete design process. Since a design is more than the sum of its parts, a constant interaction between aspect concepts and total concepts is necessary, in order to be able to take both the detail and the whole into account. This means that, if a total concept does not meet the requirements, a step back has to be taken and alternative aspect concept combinations have to be searched for. If the desired total concept is found, it will be elaborated in the next chapter.

## 4.2 Design direction

Design and material are inseparable and constantly influencing each other (Ashby & Johnson, 2013). Since concept development starts with a material already selected, the opportunity arises to start designing from its specific characteristics. By thinking from the material and asking 'what does the material want?', optimal use of its characteristics can be made.

Resysta, the material that was selected in chapter 3, is a bio-composite that is characterized by its ability to be processed both as a wood and a thermoplastic. Especially the thermoplastic behaviour of Resysta is an interesting property, since it enables extra suitable processing techniques and possible shapes.

## 4.3 Aspects and criteria

As explained in the introduction to the design methodology, the aspect concepts can be seen as sub-solutions. Although the new biobased cladding system has a different focus in terms of materials compared to the current cladding system of the PD lab, the main function is the same. Therefore, most of the aspects in the design methodology used by Van Veen (2016) will be taken into account in this design methodology as well, with some additions. The following aspects will be used to generate aspect concepts:

- Assembly
- Connection
- Horizontal joints
- Vertical joints
- Sub-construction
- Panel stiffness
- Processing technique

The design criteria shown in fig. 31 are used to assess the aspect concepts. These design criteria are further explained in appendix B.



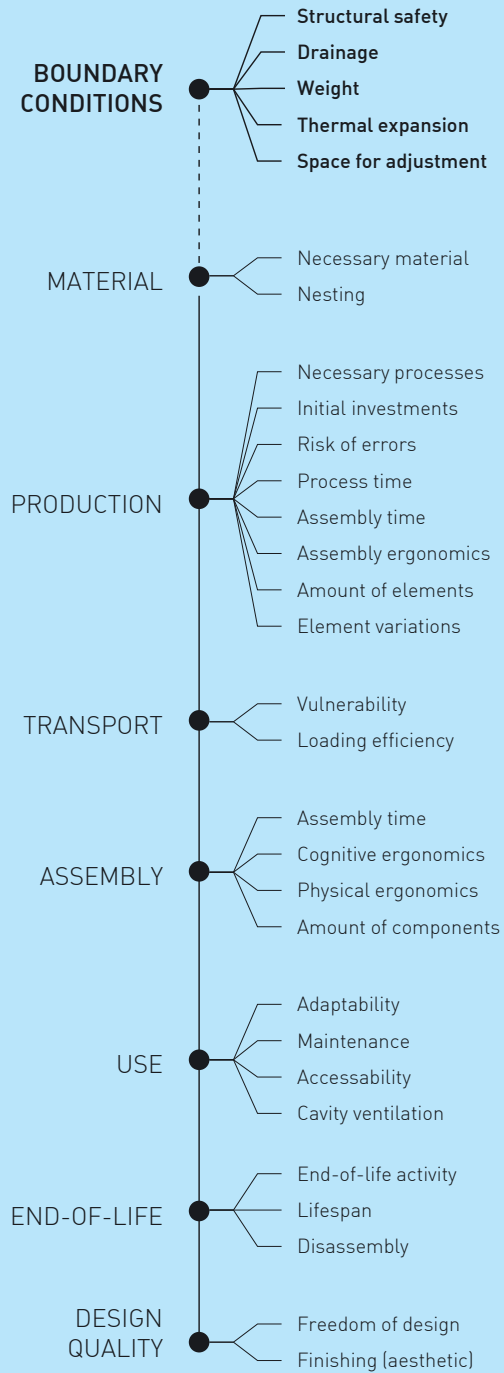
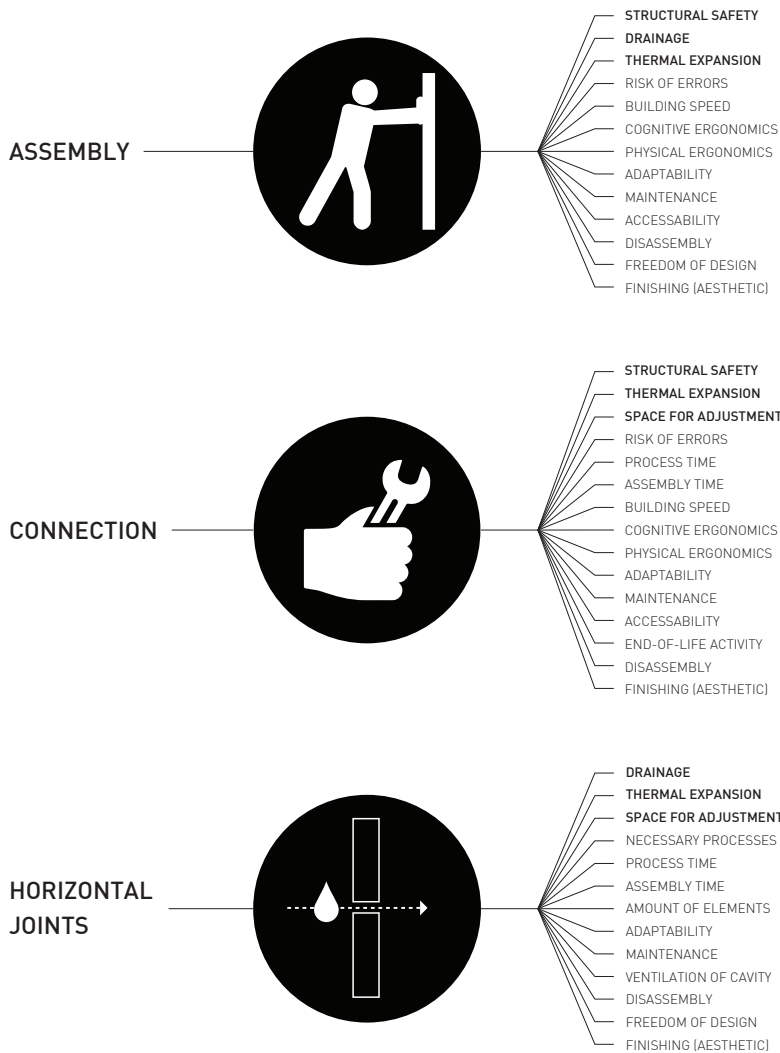
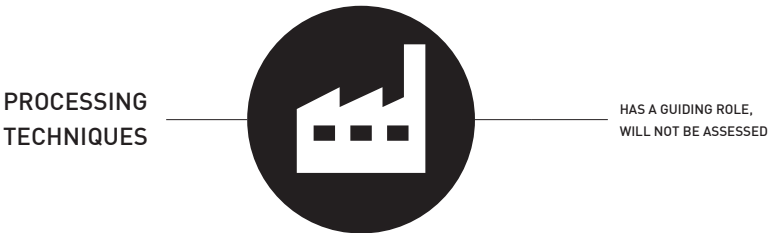
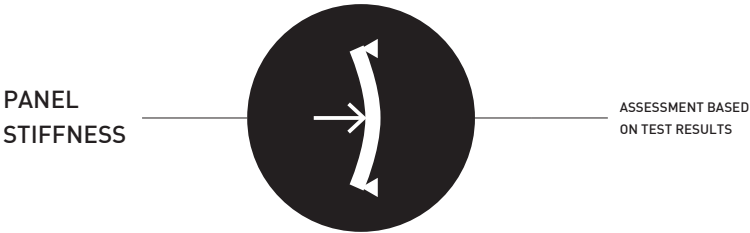
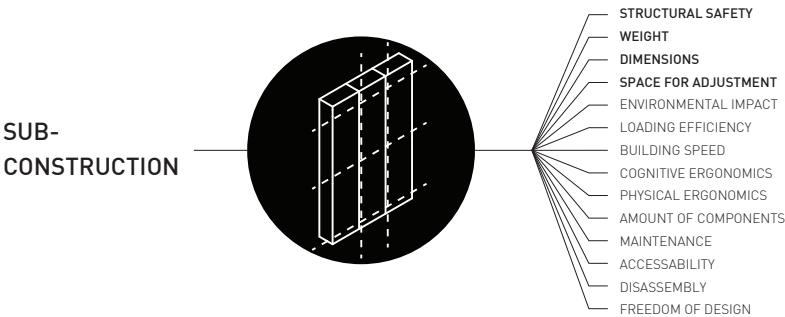
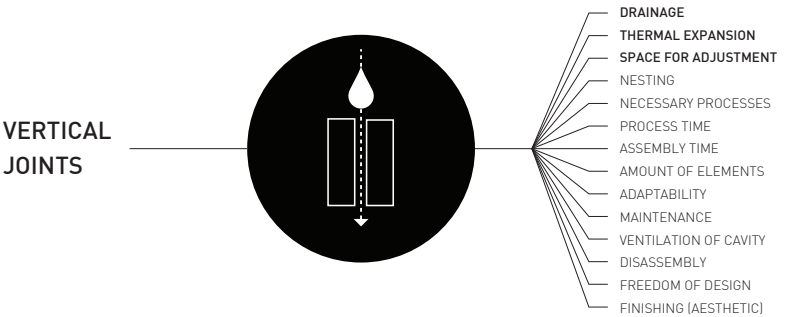
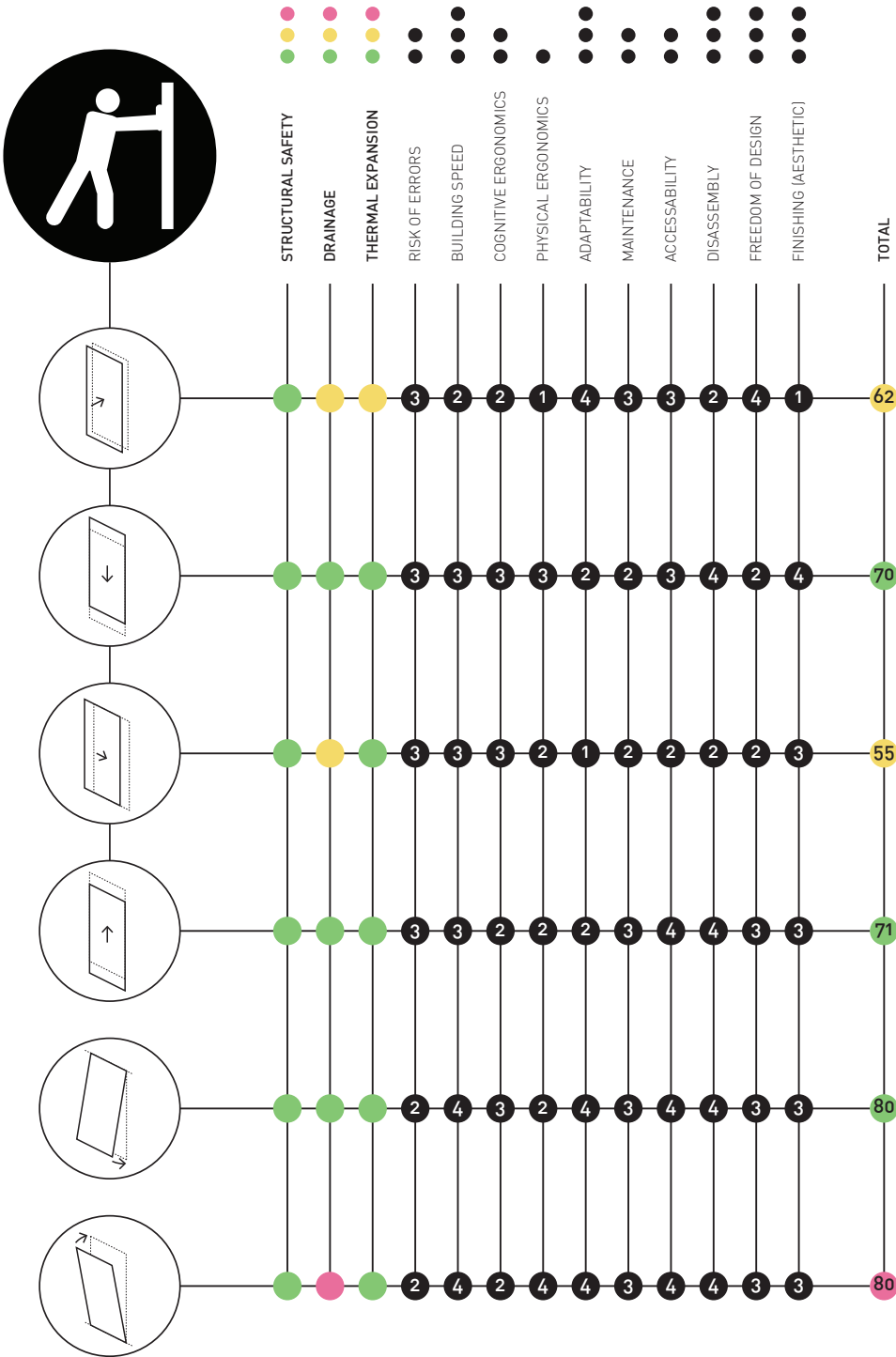


fig. 31. Design criteria (based on Van Veen, 2016)

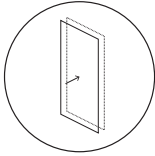
For all seven aspects, several criteria are used to assess the aspect concepts that will be generated. Exceptions to this are the aspect of panel stiffness, which will be assessed based on test results, and the processing technique aspect, which will not be assessed but will have a guiding role instead.





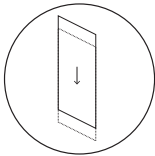


### 4.3.1 Assembly



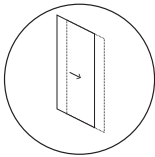
#### Front

- + Easy to (dis)assemble a single panel
- o Assembly by one person might be difficult
- Complex drainage in vertical direction



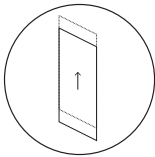
#### Top

- + Assembly by one person is possible
- + Easy drainage in vertical direction
- Hard to (dis)assemble single panel



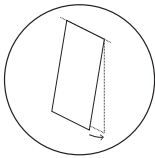
#### Side

- + Assembly by one person is possible
- + Easy drainage in horizontal direction
- Hard to (dis)assemble single panel



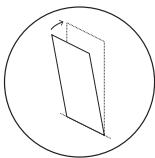
#### Bottom

- + Assembly by one person is possible
- + Easy drainage in vertical direction
- Hard to (dis)assemble single panel



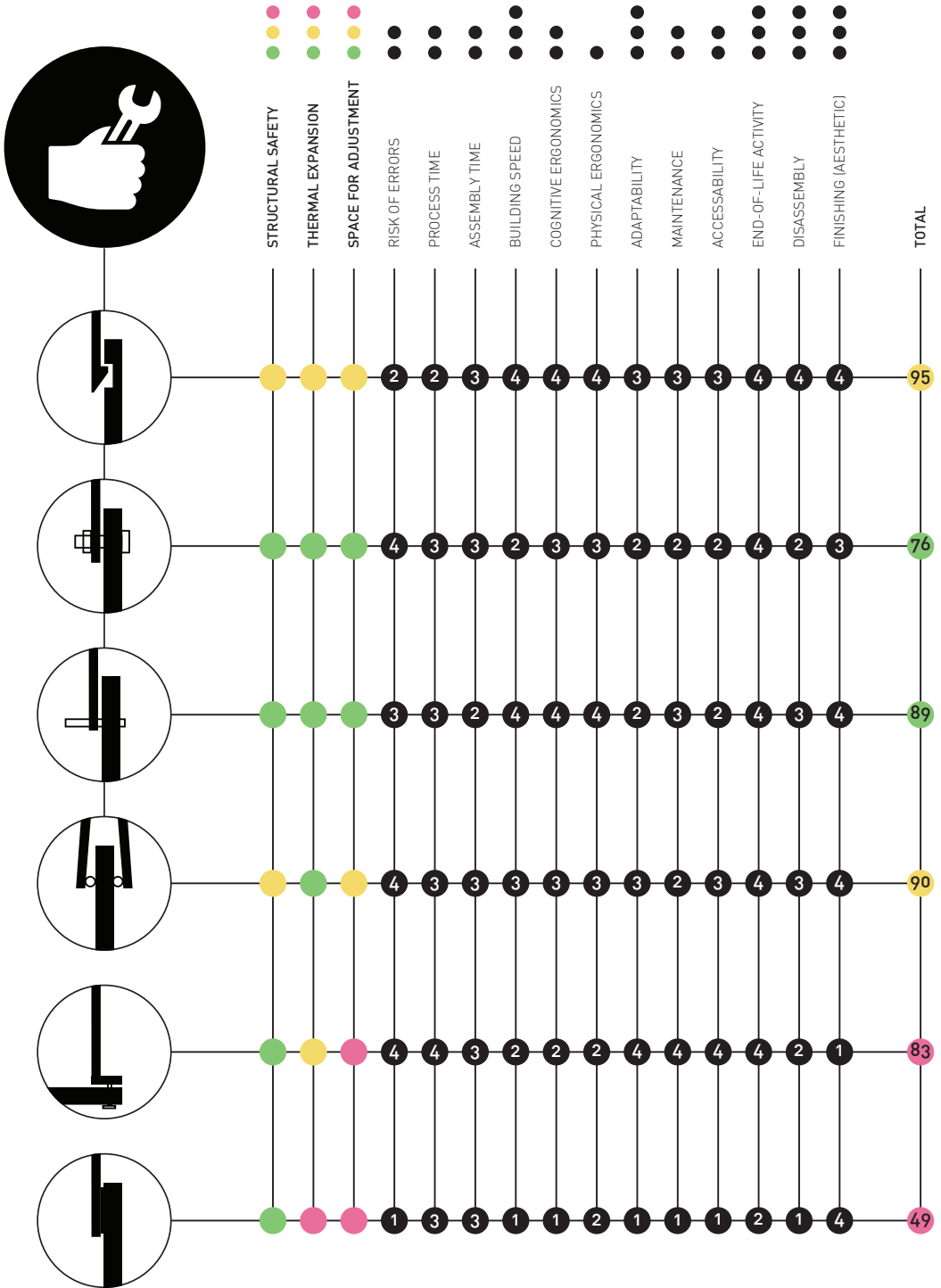
#### Top hinge

- + Simple drainage
- + Single panel (dis)assembly possible
- o Assembly by one person may be difficult

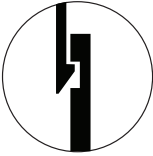


#### Bottom hinge

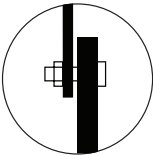
- + Single panel (dis)assembly possible
- + Assembly by one person possible
- Complex drainage in vertical direction



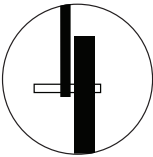
### 4.3.2 Connection

**Click**

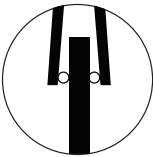
- + quick assembly and disassembly
- + no special tools needed
- might be difficult in disassembly

**Bolted**

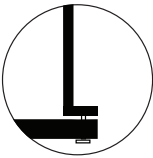
- + conventional solution
- + structurally safe
- many small parts

**Hung**

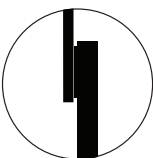
- + conventional solution
- + easy assembly
- single panel disassembly might be difficult

**Clamped**

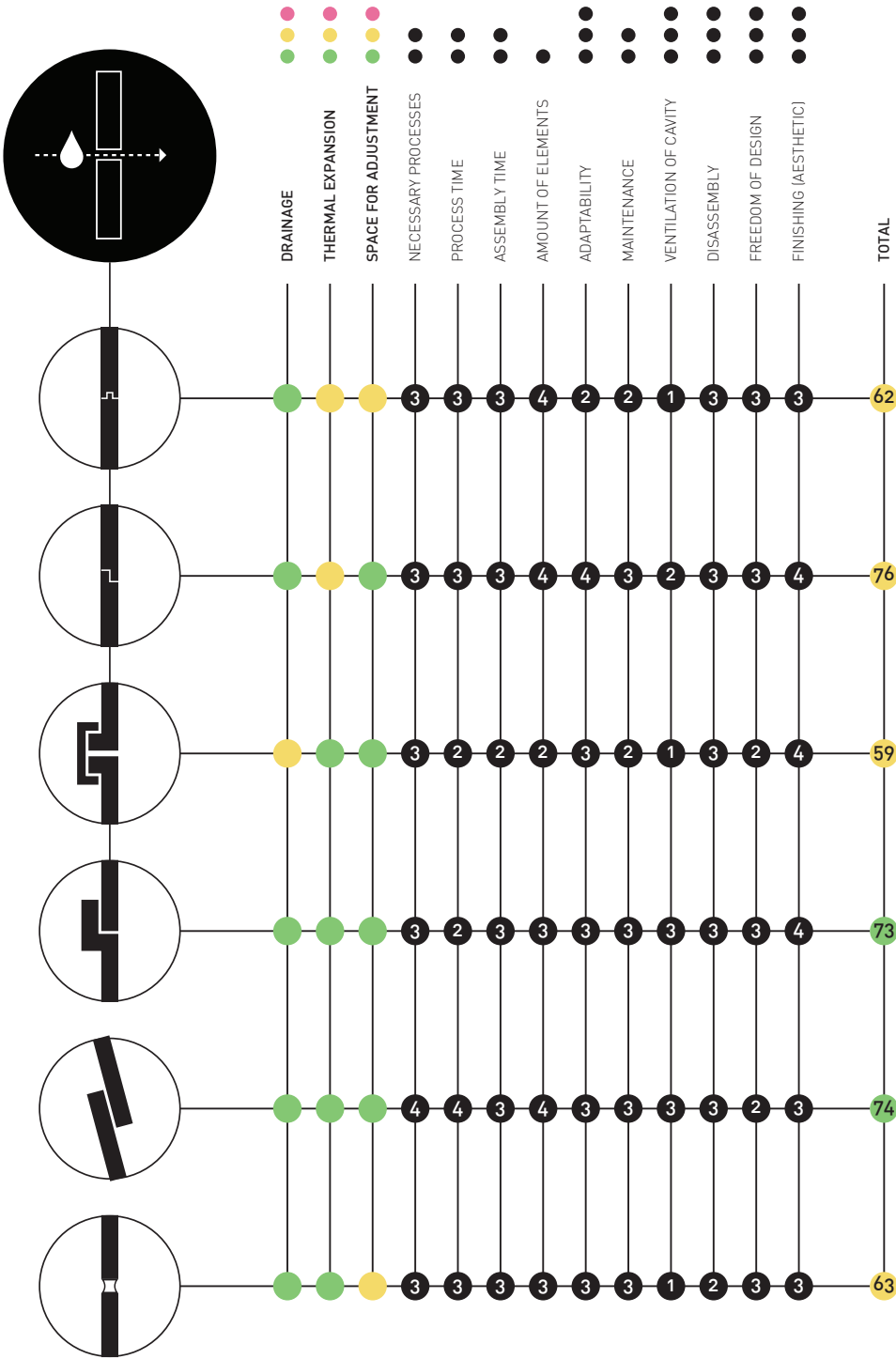
- + easy assembly and disassembly
- structural unsafety

**Screwed**

- + easy assembly
- difficult disassembly
- structural unsafety

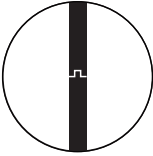
**Adhesive**

- + structural safety
- impossible disassembly
- no space for adjustment
- no space for thermal expansion



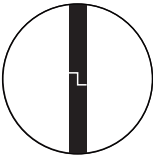


### 4.3.3 Horizontal joints



#### Tongue groove

- + Conventional proven method
- + Simple geometry and production
- Random (dis)assembly order impossible



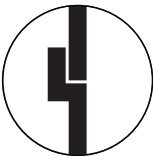
#### Labyrinth

- + Simple geometry and production
- + Aesthetics
- o Watertightness may not be guaranteed
- Random (dis)assembly order difficult



#### Gutter

- + Simple geometry and production
- + Aesthetics
- o Random (dis)assembly order possible
- Watertightness may not be guaranteed



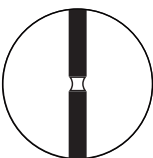
#### Overlap

- + Watertightness guaranteed
- + Aesthetics
- Random (dis)assembly order difficult



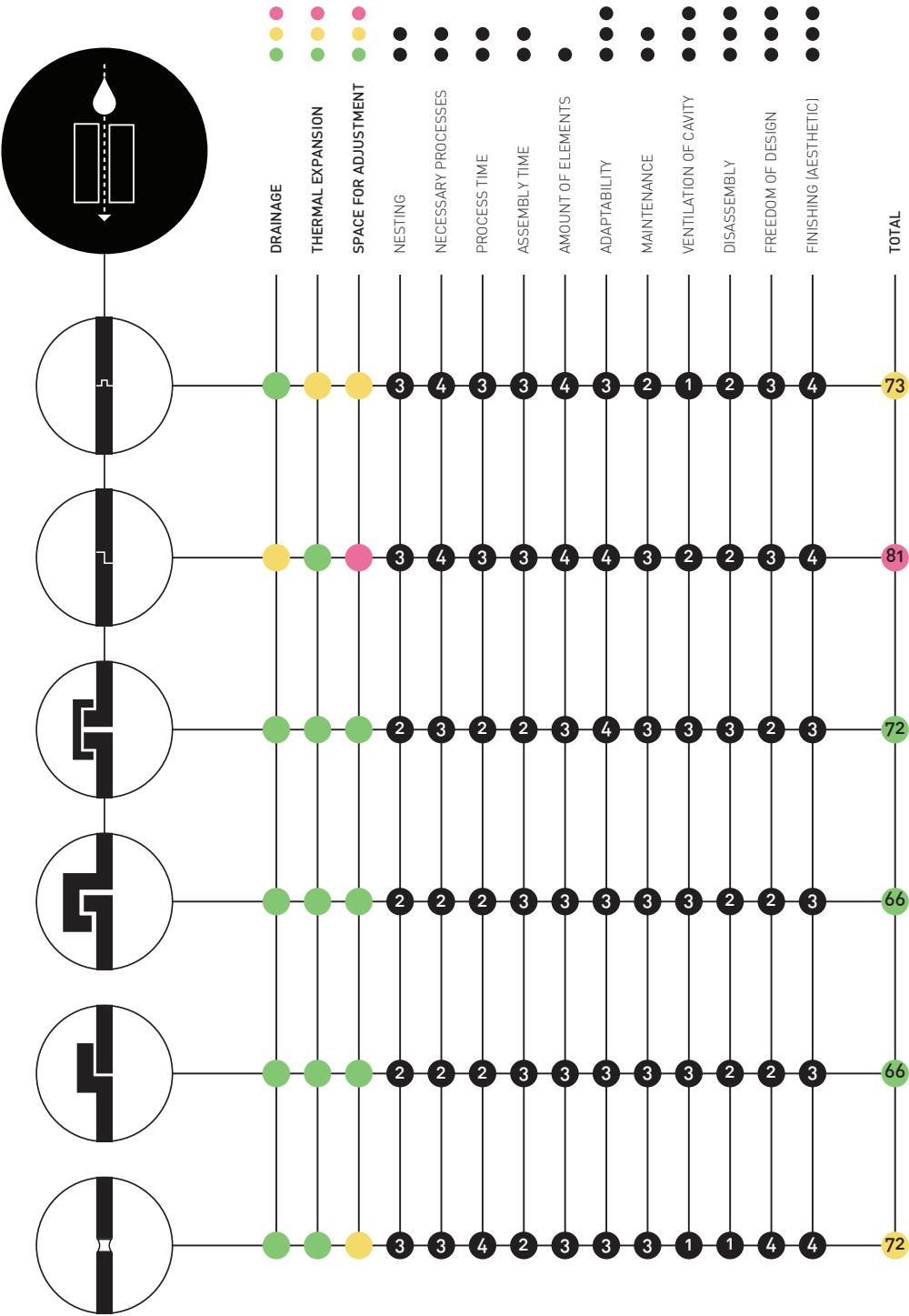
#### Weatherboard

- + Simple geometry and production
- + Adjustment and thermal expansion possible
- o Finish quality (aesthetics)
- Lower building speed

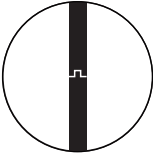


#### Wet sealing

- + Watertightness guaranteed
- + Aesthetics
- Wet connection

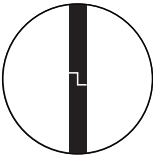


### 4.3.4 Vertical joints



#### Tongue groove

- + Conventional proven method
- + Simple geometry and production
- Random (dis)assembly order impossible



#### Labyrinth

- + Simple geometry and production
- + Aesthetics
- o Watertightness may not be guaranteed
- Random (dis)assembly order difficult



#### Gutter

- + Aesthetics
- + Drainage and sub-construction can be integrated



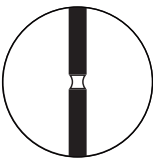
#### Overlap gutter

- + Less parts
- + Drainage and sub-construction can be integrated
- Complex geometry



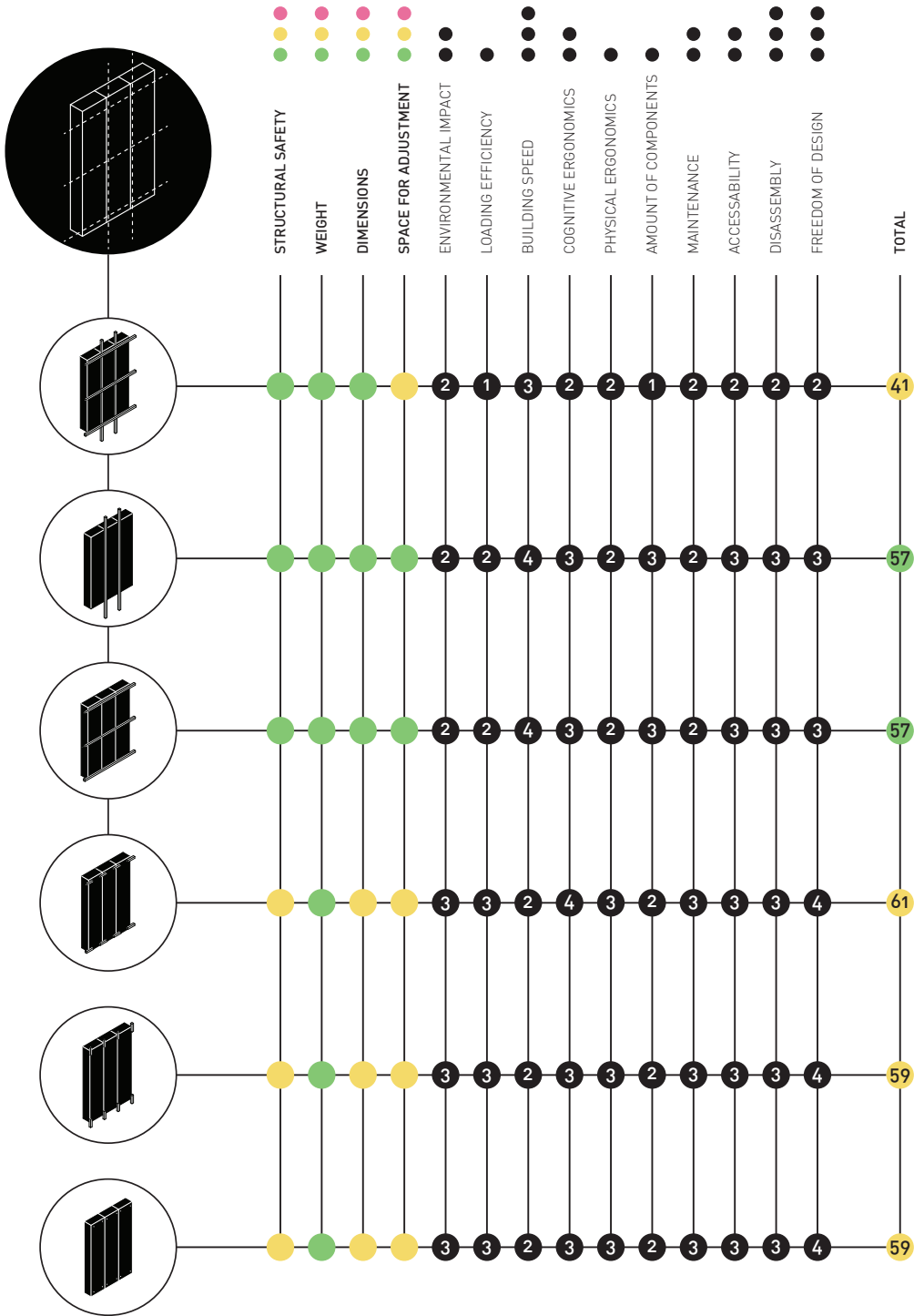
#### Overlap

- + Watertightness guaranteed
- + Aesthetics
- Random (dis)assembly order difficult

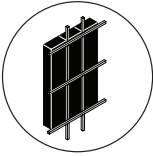


#### Wet sealing

- + Watertightness guaranteed
- + Aesthetics
- Wet connection

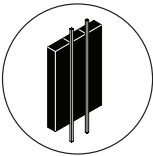


### 4.3.5 Sub-construction



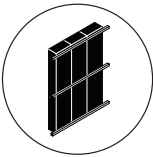
#### Horizontal + vertical

- + Design freedom
- + Possibility to integrate drainage gutter
- Many elements



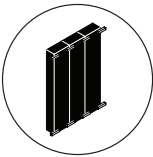
#### Vertical

- + Possibility to integrate drainage gutter
- + Space for adjustment of panels
- On site assembly time



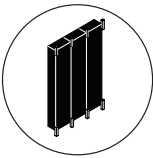
#### Horizontal

- + Space for adjustment of panels
- Obstructs cavity ventilation



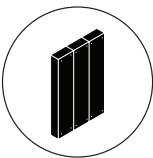
#### Local horizontal

- + Little material use
- Less support for panels
- Little space for adjustment of panels



#### Local vertical

- + Little material use
- Less support for panels
- Little space for adjustment of panels



#### Points

- + Little assembly time
- + (Dis)assembly per panel possible
- Little space for adjustment of panels

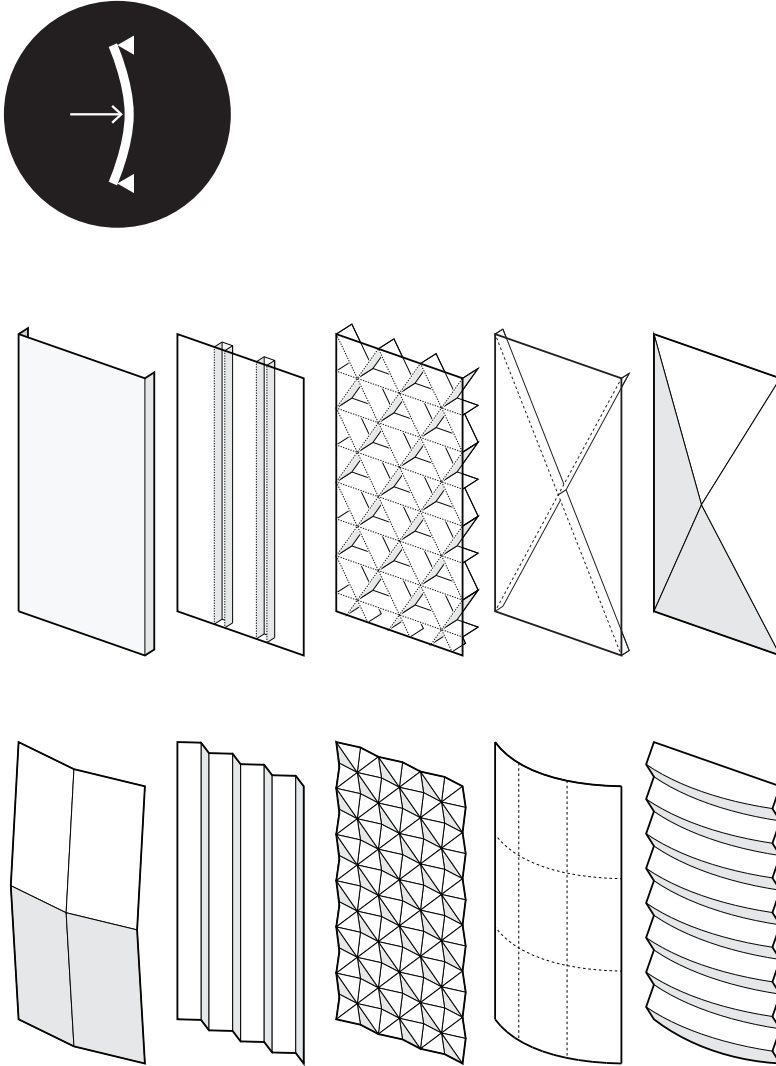


fig. 32. Panel stiffness aspect concepts

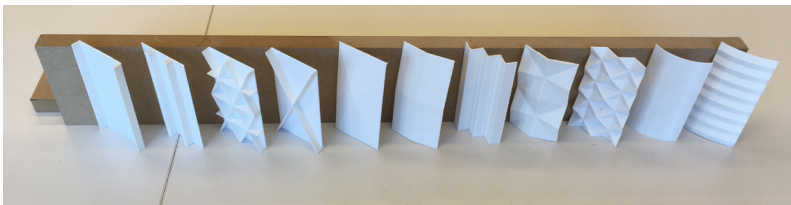


fig. 33. 3D-printed models of the panel stiffness aspect concepts

4.3.6 Panel stiffness

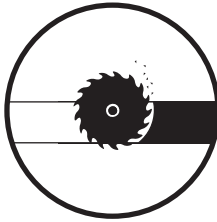
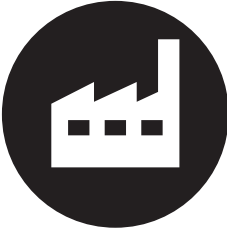
The goal of this aspect is to find the most optimal panel shape that has both stiffness and a low weight. To do so, the generated concepts (see fig. 32) were 3D-printed and compared in terms of deflection and volume (see fig. 33).

Table 1 shows the different panel stiffness shapes, with their deflection and volume. The last column shows the product of the deflection and volume. The shape with the lowest value, in this case the zigzag panel, can be seen as most optimal, since both the deflection and volume are desired to be as low as possible.

See appendix C for a more elaborate explanation on the calculation of these results.

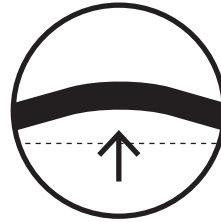
Panel shape		Deflection [mm]	Volume [mm3]	Deflection x volume (x 10 <sup>3</sup> )	Normalized scores
Folded	Zigzag	3,4	6516	22	4
Ribs	Edges	5,3	6144	33	4
Ribs	Triangular	3,7	9179	34	4
Folded	Diagonal	11,1	4764	53	3
Ribs	Hollow ribs	6,9	8448	58	3
Ribs	X-ribs	9,3	6325	59	3
Curved	Curved linear	14,6	4942	72	3
Folded	Crossed	36,8	4687	172	2
Folded	Pleated	39,7	4917	195	2
Curved	Curved zigzag	59,5	5121	305	0
Folded	Pleated 2	57,9	5747	333	0

table 1. Results of the comparison test of different panel shapes in terms of deflection and volume. The normalized data is calculated by giving the highest score to the lowest deflection x volume product and the lowest score to the highest deflection x volume product.



**CUTTING**

Sawing  
Cutting  
Punching



**DEFORMING**

Folding/bending  
Calendering  
Thermoforming  
3D printing

Based on: Kula et al., 2013

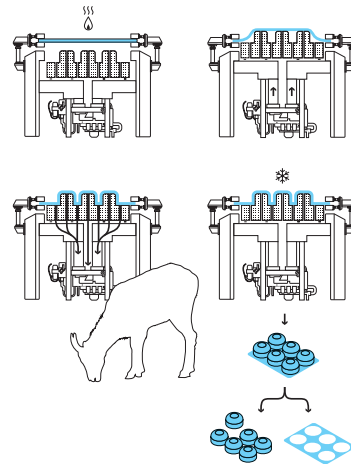
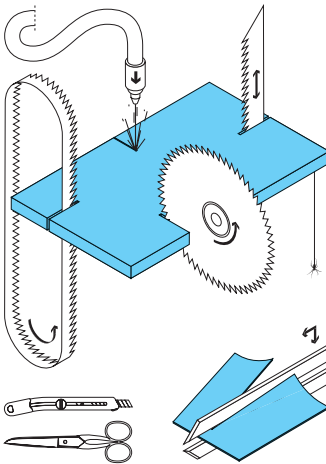
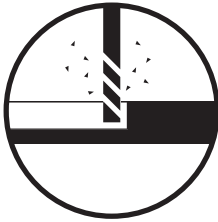


fig. 34. Processing techniques categories (based on Kula et al., 2013)



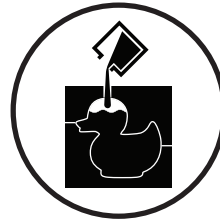
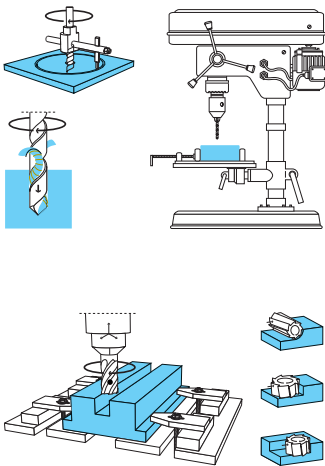
### 4.3.7 Processing techniques

Just like cutting or folding a piece of paper results in a different shape, so do processing techniques differ in operation, qualities, limitations and resulting shape. In fig. 34 an overview of common processing techniques is shown (Kula et al., 2013), divided into four categories: cutting, deforming, machining and moulding. Since all processing techniques have their own point on which they excel, they will not be assessed but rather have a guiding role in the concept development.



#### MACHINING

Drilling  
Milling  
Turning  
Routing



#### MOULDING

Founding  
Forging  
Sintering  
Cast moulding  
Resin moulding  
Injection  
Rotational moulding  
Extrusion

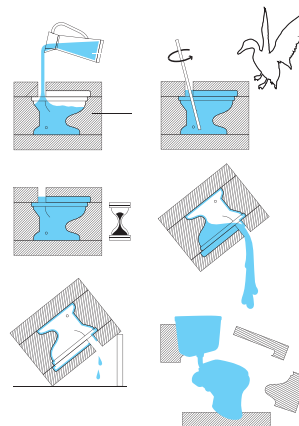
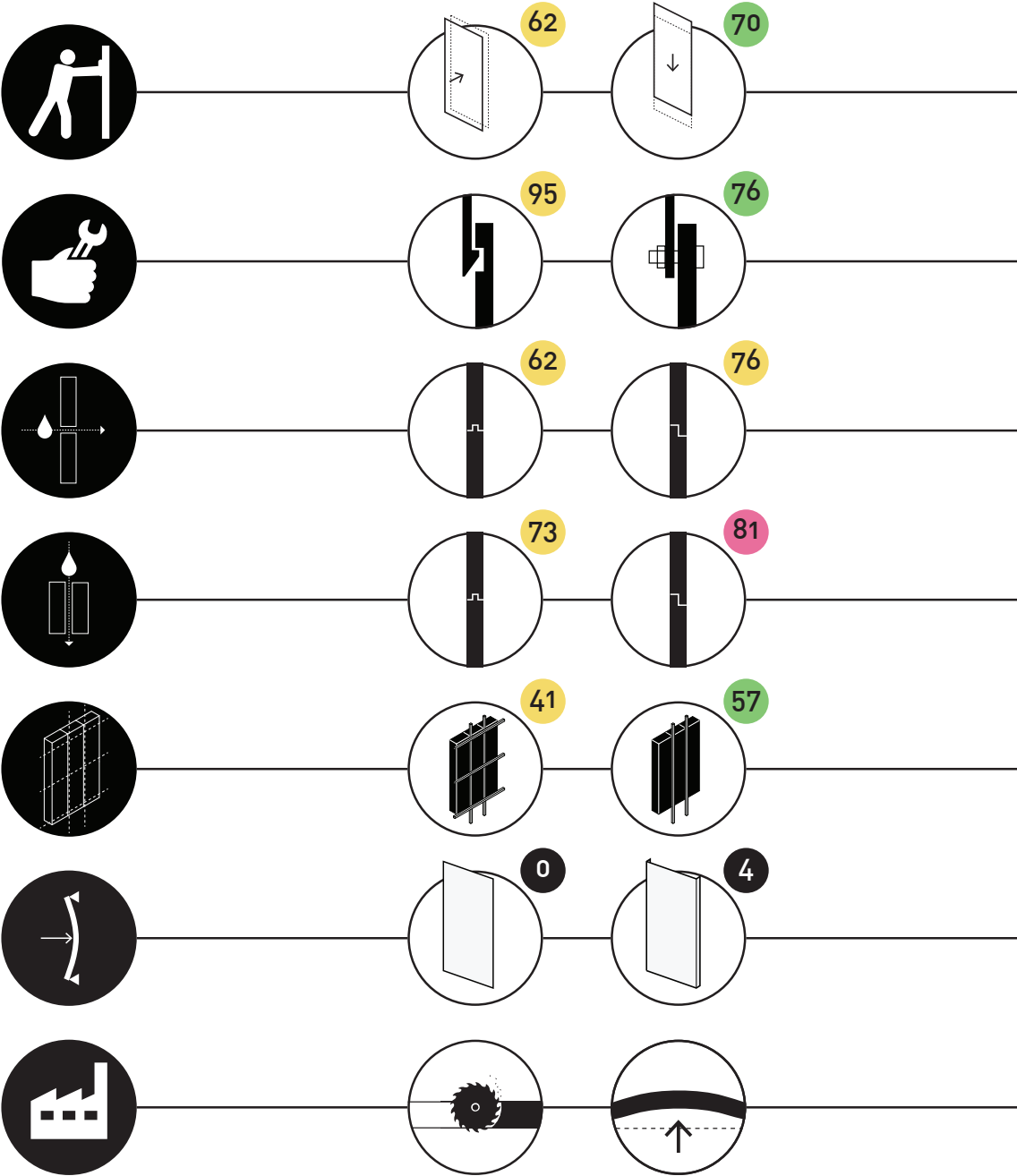
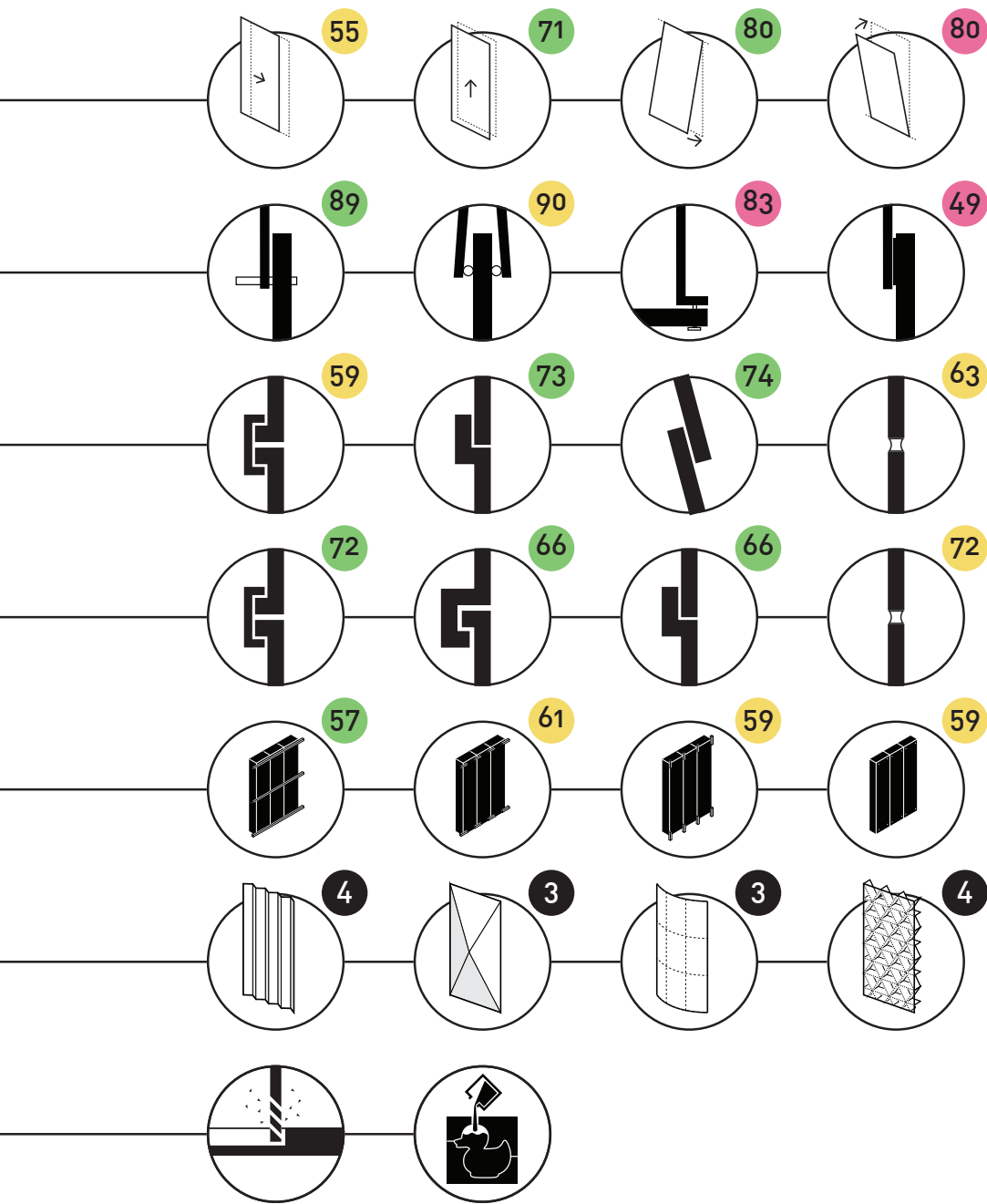


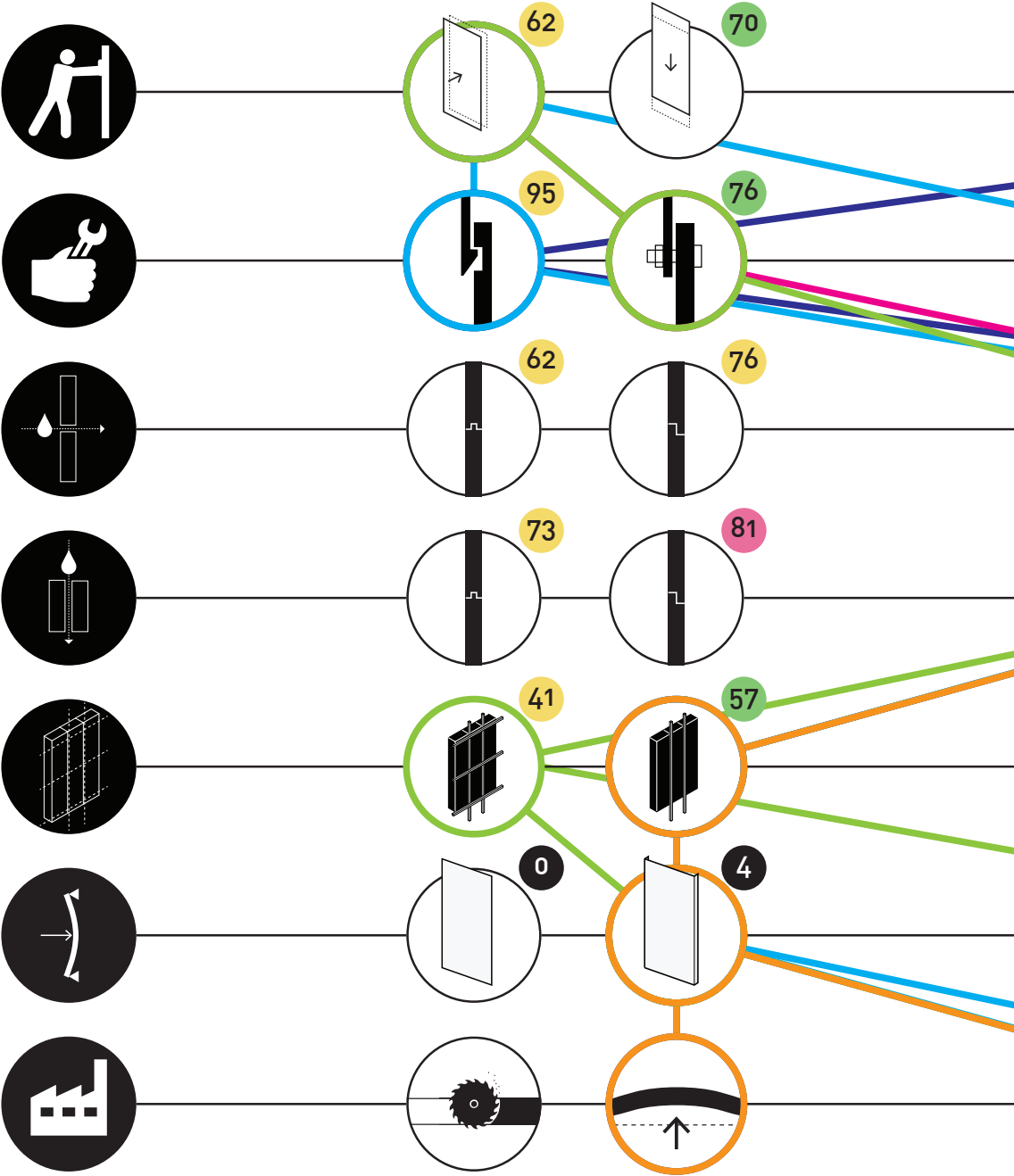
fig. 35. Aspect concepts, including their assessment score

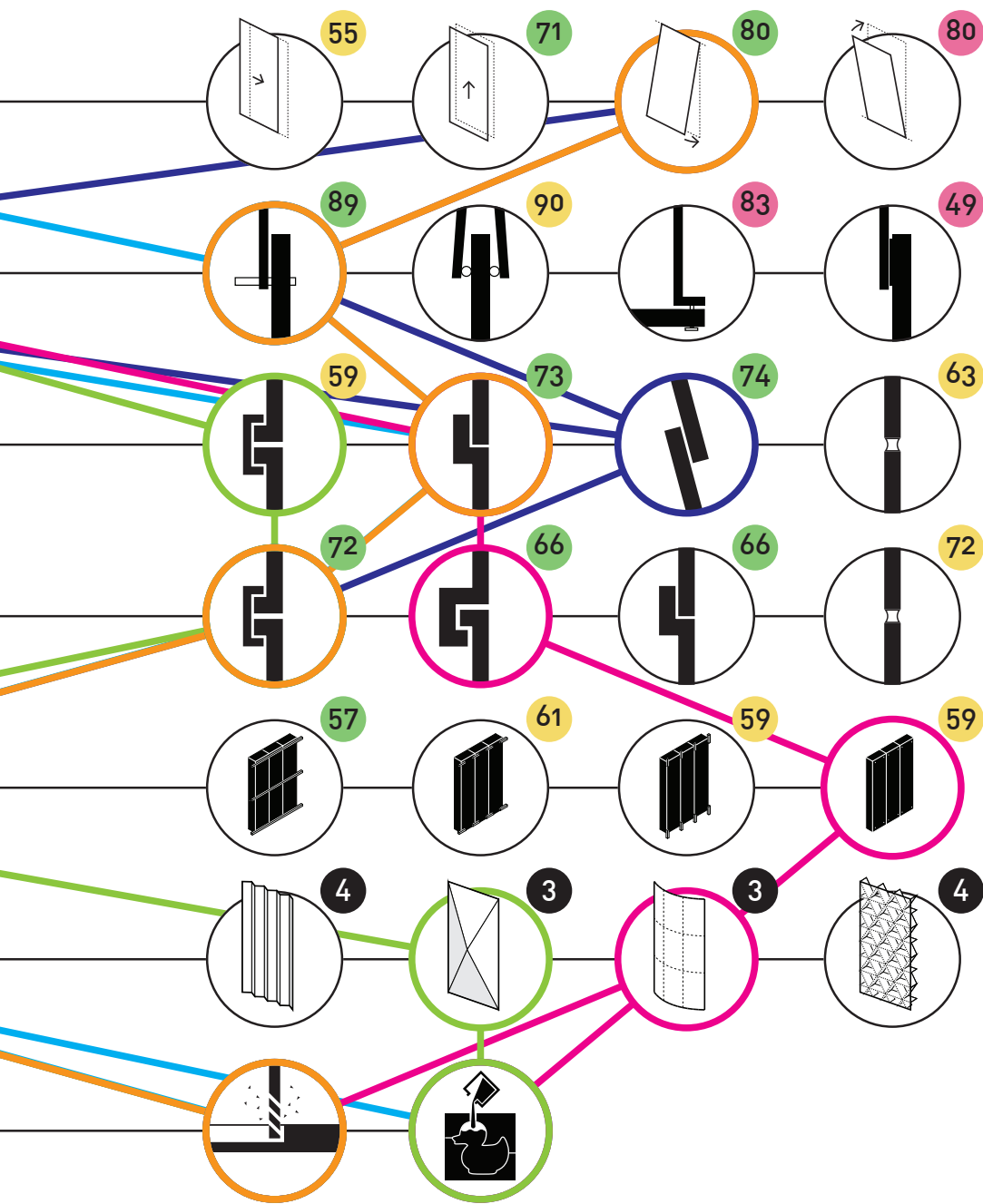




4.4 Total concepts

fig. 36. Aspect concept combinations that result in five total concepts (own. ill.)





#### 4.4.1 Rectangular panels

##### The idea

This total concept (see fig. 37) is based on the idea of hanging panels into vertical gutters, which function both as connection of the cladding system to the structure and drainage between the panels in horizontal direction. The ribs at the vertical edges of the panels allow for a good overlap into the gutters and improve the stiffness of the panels in vertical direction. The top of the panels are bent under the panels above to provide a good drainage in vertical direction.

Slots in the vertical ribs make it possible to hang the panels on the brackets that are integrated in the gutters. This makes the assembly of the cladding system easier and more ergonomic. The production of the panels consists of two stages: 1) CNC-milling of the contour shape and the slots in the ribs and 2) warm bending the double curved shape at the top.

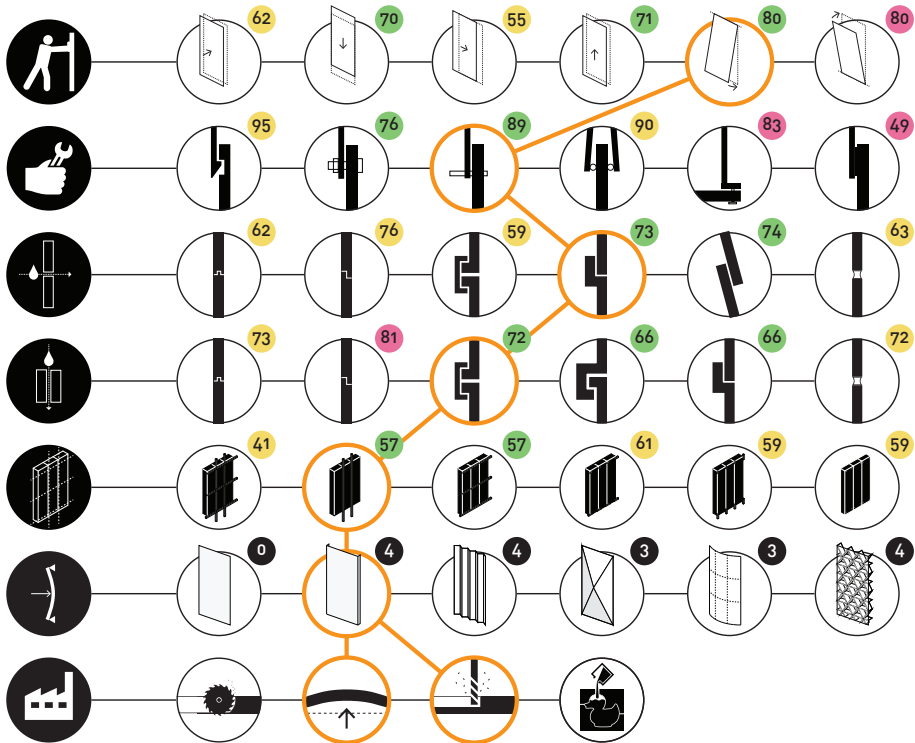


fig. 37. Aspect concepts combination into the rectangular panel total concept

### Pros and cons

- + easy assembly and disassembly
- + good drainage in vertical and horizontal direction
- + cavity ventilation
- + convenient main shape (rectangular)
- + physical and cognitive ergonomics
- number of necessary production processes
- finishing (aesthetics), wide seams due to gutter

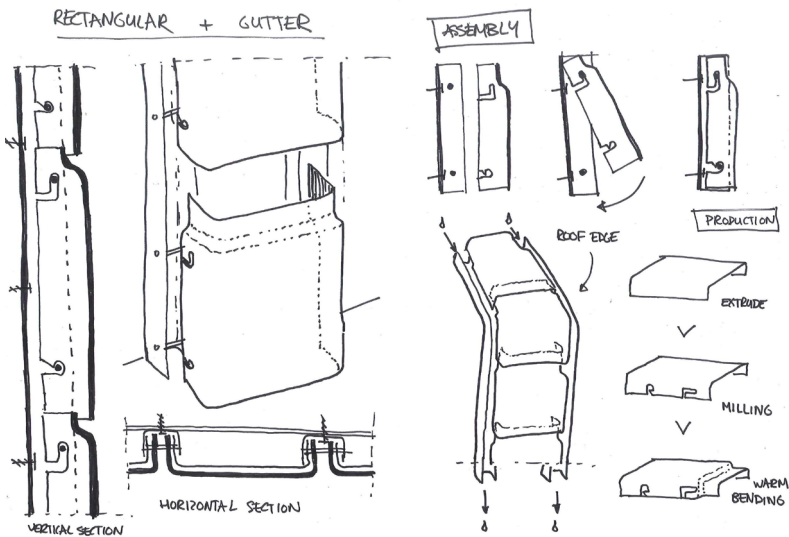


fig. 38. Drawings illustrating a first elaboration of the rectangular panel total concept

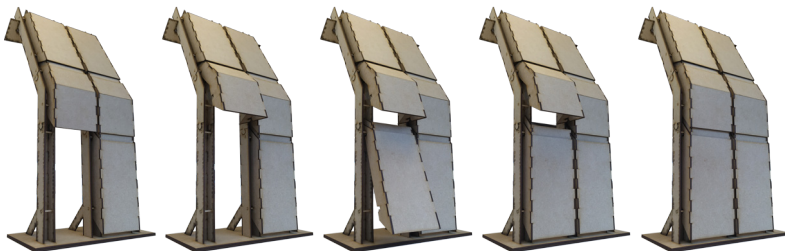


fig. 39. A prototype of the rectangular panel total concept showing the assembly

### 4.4.2 Diamond panels

#### The idea

A cladding system with a minimal number of panel types would be very advantageous for the modularity of the system. The surface division shown in fig. 40 shows diamond shaped panels with 30° and 150° angled corners. This shape is convenient in the sense that the panels also could be applied in difficult corners of the front and back facade.

However, when trying to take this concept from a surface division into a total cladding system concept, with all its boundary conditions and criteria, it appears that the concept gets complex very quickly (see fig. 41). Since the joints in the planar surface, at the roof edges and around the corners differ from each other, the modularity of the panels is one of the first features that is lost.

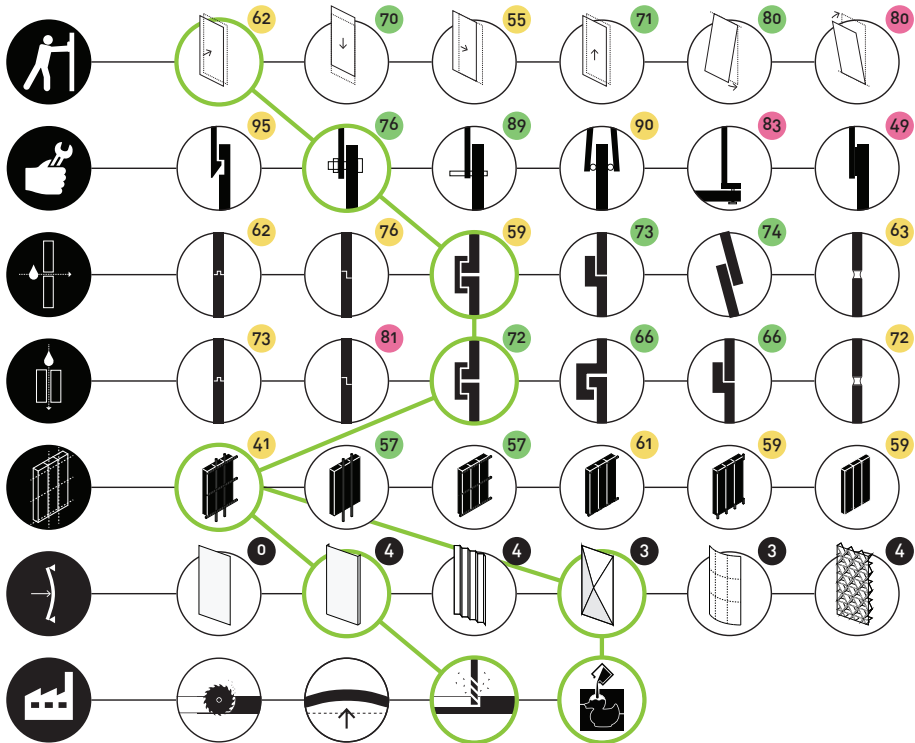


fig. 40. Aspect concepts combination into the diamond panel total concept (own ill.)



**Pros and cons**

- + interesting appearance
- + angled edges allow for interesting drainage opportunities
- inconvenient panel shape, many panel exceptions
- complex detailing
- complex production

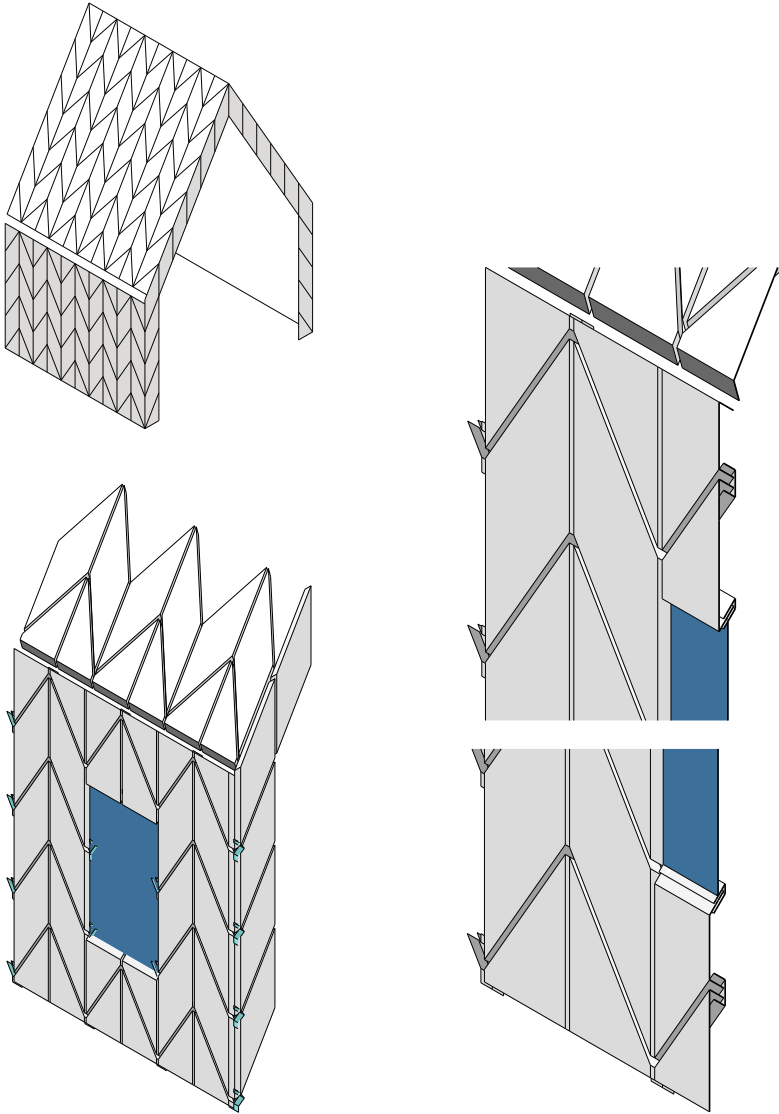


fig. 41. Drawings illustrating a first elaboration of the diamond panel total concept

### 4.4.3 Accolade panels

#### The idea

Compared to a flat panel, a double curved panel has the advantage of being much stiffer. Double curved panels with a constant radius have the extra advantage of being able to overlap and rotate into each other. This is an interesting feature when looked at the corner of the cladding system. Instead of needing an extra, differently shaped panel for the corner, it could be possible to use standard panels. Due to the curved border shape, the panels are placed in an alternating repeating pattern. Two types of overlap are used to achieve a good drainage in horizontal and vertical direction.

Due to the complex (double curved) shape of the panels, the connection, assembly and production get complex very quickly. The complexity increases even more when looked at the critical points in the cladding system, like the roof edges and corners, which is also the reason why this concept is less elaborated.

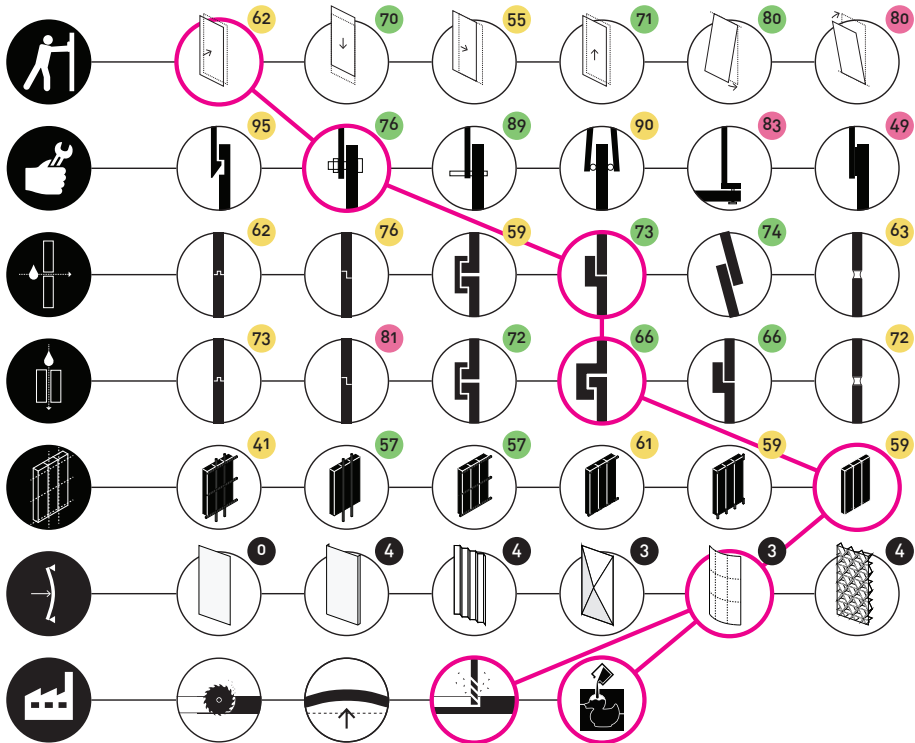


fig. 42. Aspect concepts combination into the diamond panel total concept (own ill.)

**Pros and cons**

- + interesting appearance
- + interesting opportunities to make panels rotatable into each other
- complex shape and production
- inconvenient panel shape, many panel exceptions
- complex joints and detailing

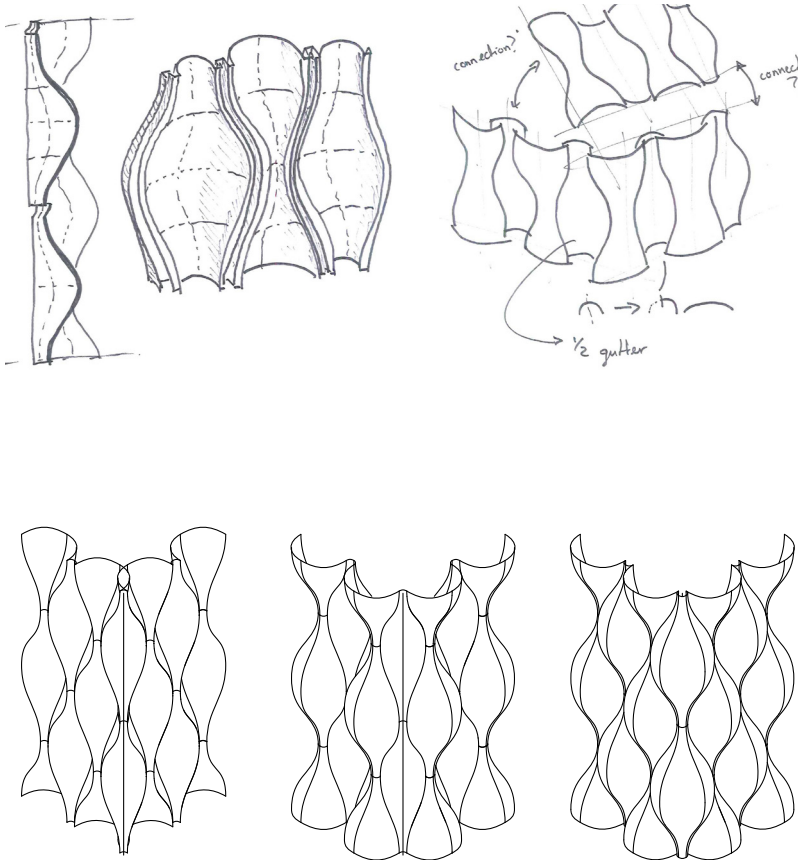


fig. 43. Drawings illustrating a first elaboration of the diamond panel total concept

#### 4.4.4 Extruded panels

##### The idea

Resysta is a thermoplastic material that is suitable for production by extrusion, which is a processing technique that is based on pushing material through a die. Extrusion allows for a great freedom of design in the cross-section. This way, functions such as the connection and drainage can be integrated. Besides, extrusion is continuous process, allowing for fast production.

In fig. 45, extruded panels that are overlapping in both horizontal and vertical direction are shown. The overlap in horizontal direction is achieved by using equal cladding panels in an upside down orientation. The characteristic fold in the panel, which enables an overlap in vertical direction, is achieved by milling away a part of the backside of the panel and warm bending the front side backwards.

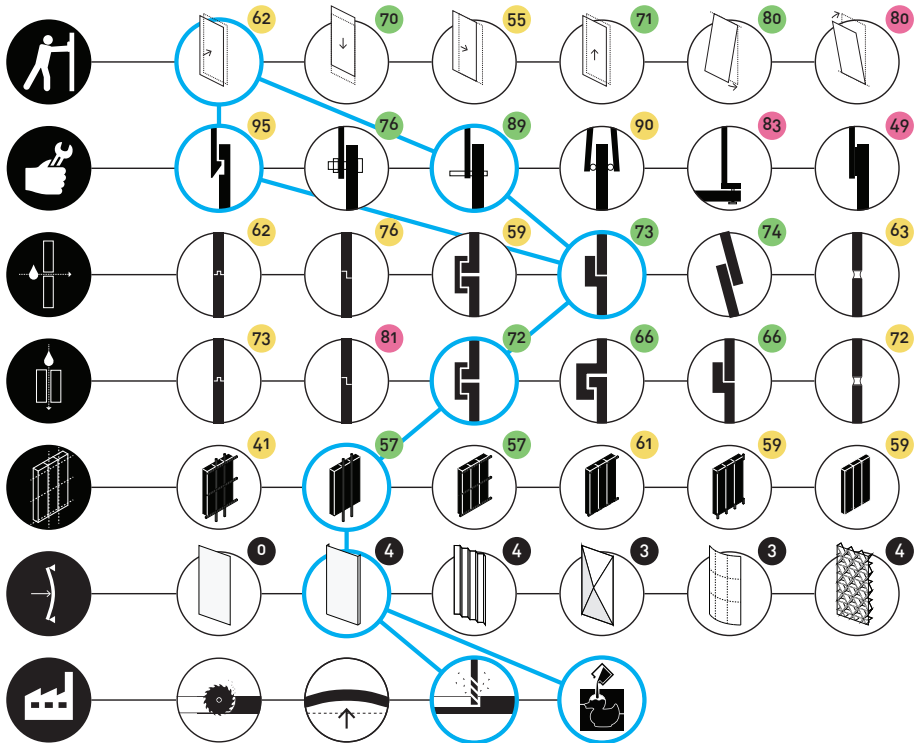


fig. 44. Aspect concepts combination into the extruded panel total concept (own ill.)

### Pros and cons

- + Extrusion allows for great freedom of design in the cross-section plane
- + Fast, continuous and accurate production
- Achieving overlap in the linear direction of panels might be hard without the use of additional parts or application of extra of production steps

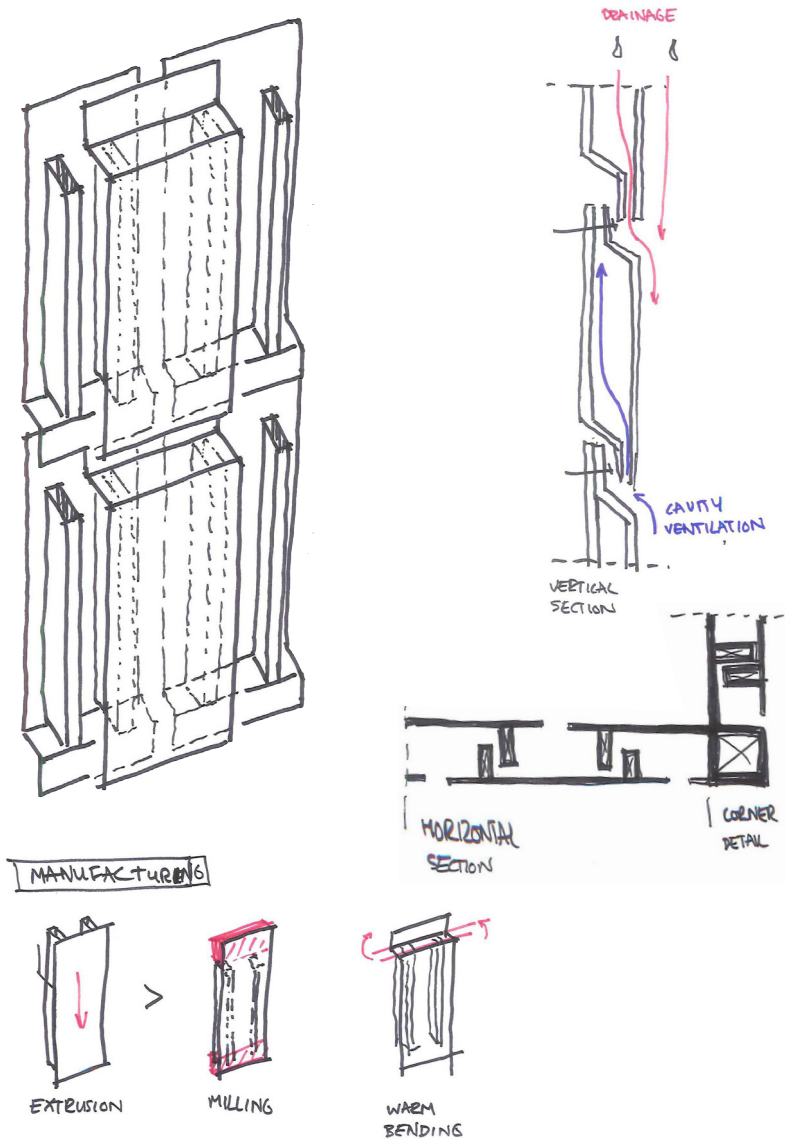


fig. 45. Drawings illustrating a first elaboration of the extruded panel total concept

### 4.4.5 Tapered panels

#### The idea

The tapered shape of the panels of this total concept allows overlapping horizontal joints. The vertical joints are established by panel edges that are placed into a vertical gutter profile. These gutter function both as a connection of the cladding panels and a vertical drainage. The assembly takes place by sliding the slots at the top of a panel over a set of pin connection from the bottom up. The panel is then fixed by sliding slots at the bottom of the panel over another set of pin connections (see fig. 49). The remarkable appearance of the tapered shaped panels is strengthened by alternating the panel sizes in vertical direction (see fig. 47).

The panels are made of flat sheets, which are processed by a CNC-milling machine first to cut the contour shape and slots, after which the panel is warm bent with the use of a bending press (see fig. 48).

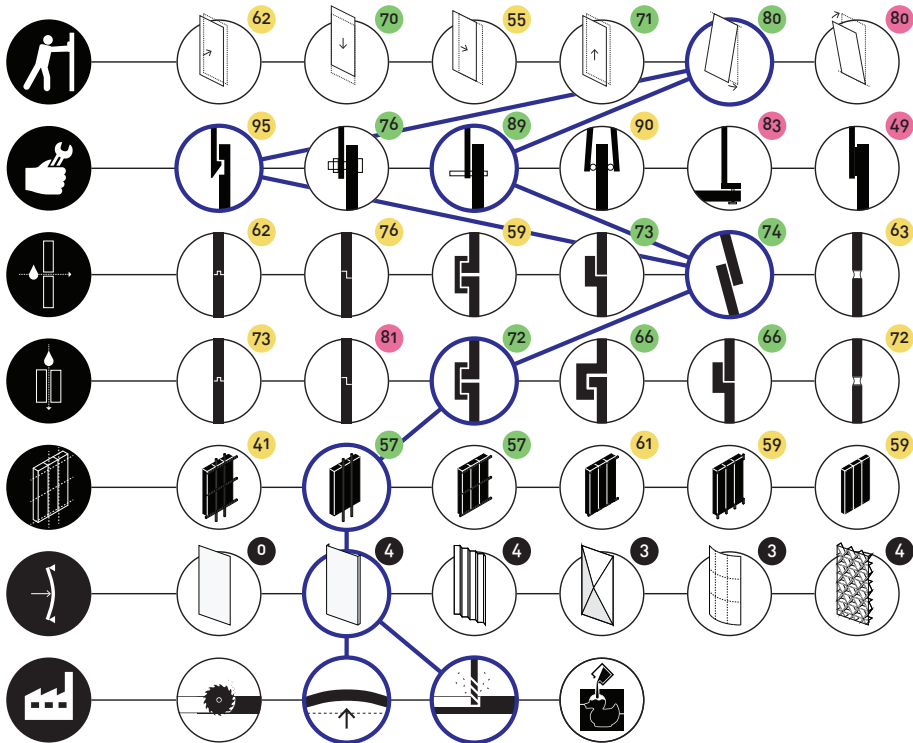


fig. 46. Aspect concepts combination into the tapered panel total concept (own ill.)

**Pros and cons**

- + Easy production
- + Design flexibility
- + Individual (dis)assembly possible
- Wide seams between panels

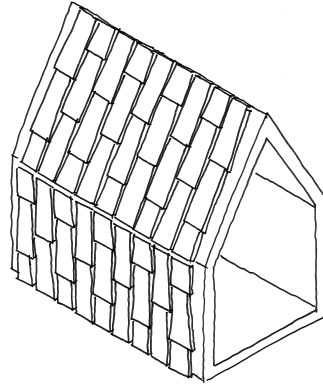


fig. 47. Alternating panels

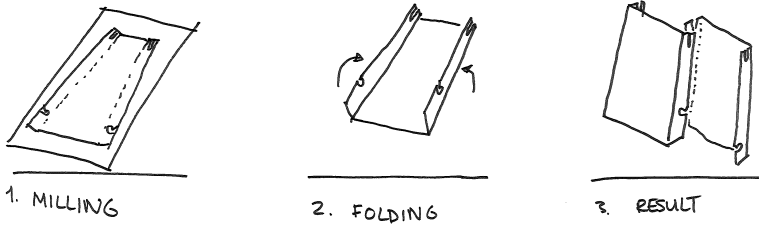


fig. 48. Drawings illustrating the production steps of the tapered panel total concept

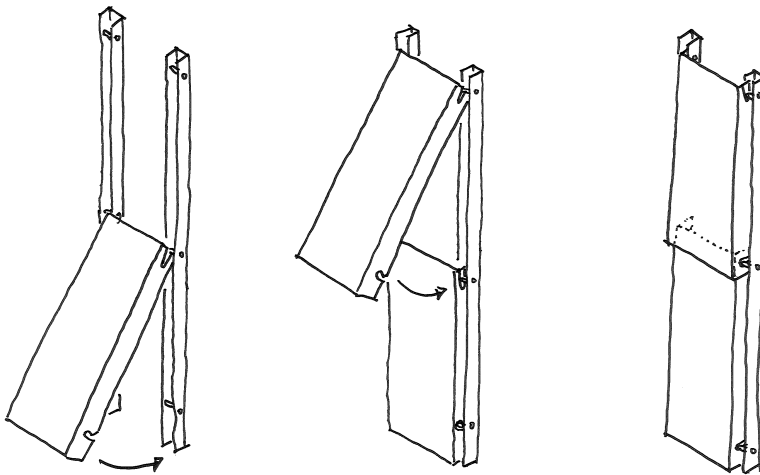


fig. 49. Drawings illustrating the assembly steps of the tapered panel total concept

4.4.6 Assessment + total concept choice

Assessment

In fig. 50 the a the assessment of the five total concepts that were generated is shown. As can be seen, the rectangular panel, extruded panel and tapered panel concepts clearly stand out in terms of total score. The rectangular panel and tapered panel total concepts mainly score on criteria regarding the assembly and use of the cladding system, while the extruded panel total concept mainly scores on the criteria regarding production. Besides CNC-milling, all three concepts require their own distinctive processing technique: the rectangular panel concept is based on thermoforming using custom moulds, the extruded panel concept is based on extrusion and the tapered panel concept is based on bending using a bending press.

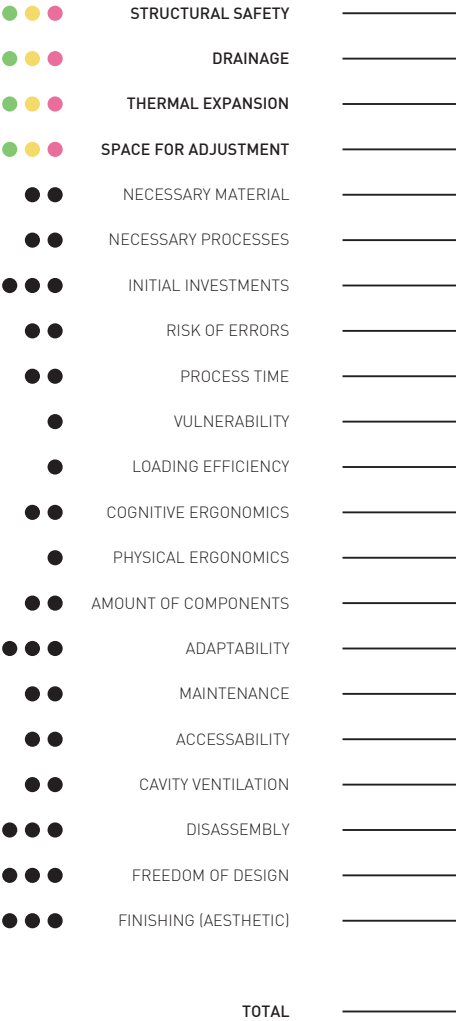
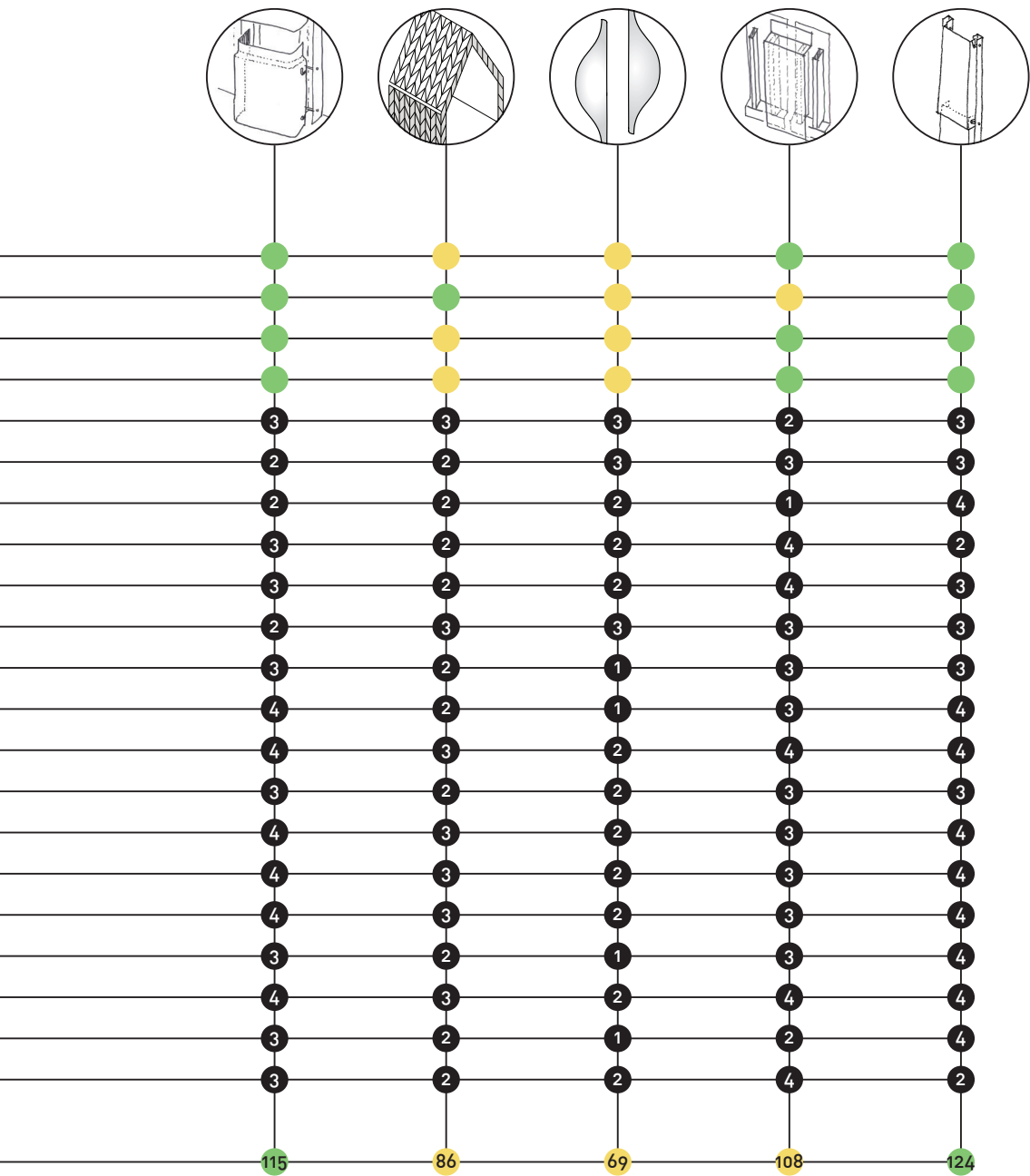


fig. 50. Assessment of the five total concepts





**Initial choice**

Initially, the extruded panel concept was chosen for further design development of which the elaboration towards a final design can be found in appendix D. The choice for this total concept was based on the fact that extrusion allows for great design freedom in the 2D cross-section plane, allowing for integration of functions, and the advantage of fast, continuous production over piece-by-piece production. However, later on in the design process, several limitations of this processing technique were found:

- Extrusions have a fixed cross-section by definition as a result of the way the processing technique works (see appendix D). This way it will always have open ends in the 3D shape, which makes the need for extra parts or processing steps almost inevitably.
- Extrusion is a processing technique which excels in mass production, which means the production of many, uniform products. For every type of product, a custom made extrusion die is needed. Not only does this make the initial investments relatively high, also the design freedom is reduced.
- At the moment, Resysta can be extruded to a maximum width of only 300mm.

Due to these limitations, the total concept choice was reconsidered.

**Final choice**

When looked at the rectangular and tapered panel total concepts in terms of initial investments and design freedom, the applied processing techniques make a clear difference again. The rectangular panel concept requires custom moulds and other equipment for thermoforming, while the tapered panel concept only requires a bending press. Not only does the latter one require lower initial investments, it also allows for greater design freedom, since the exact position of the bending line can be easily changed during production, while the moulds that are used for the rectangular panel concept are custom made for a specific shape. Therefore, also considering the fact that it has the highest total score in the assessment, the tapered panel total concepts will be further elaborated in the next chapters.

## 4.5 Conclusion

### Aspects

The design methodology that was used in this chapter focusses on the aspects (details) of a cladding system. The aspects that were used are: assembly, connection, horizontal joints, vertical joints, sub-construction, panel stiffness and processing technique. This way of working enables the designer to quickly generate a lot of concepts for that specific part of the cladding system, without being distracted by other aspects. On the basis of different criteria, these aspect concepts are finally assessed and combined into total concepts

### Aspect and total concepts

However, a design is more than the sum of its parts. This means that combining the aspects with the highest scores does not necessarily result in the best total concept. As this is an iterative step in the design methodology, the designer has to go through this cycle multiple times in order to generate multiple total concepts and compare them in a separate assessment.

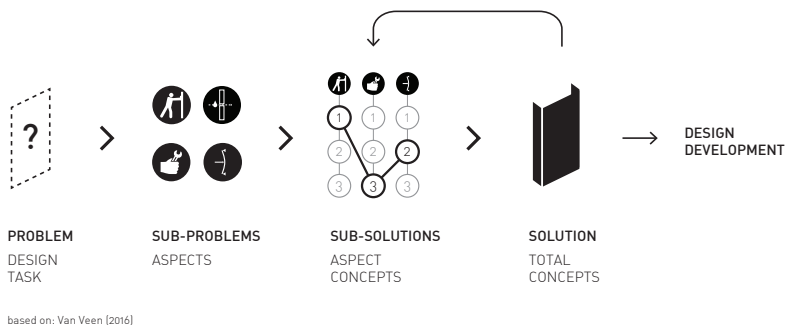


fig. 51. Design methodology (own ill.)

### Total concept choice

In this case, five total concepts were generated. When looked at the assessment, the rectangular panel, tapered panel and extruded panel concepts clearly stand out. Initially a choice was made for the extruded panel concept. However, due to critical limitations encountered later on in the design process, this choice was reconsidered. Due to the ease of production, design freedom and relatively low initial investments, the tapered panel total concept is chosen for further design development.

## 5. DESIGN DEVELOPMENT

The goal of this chapter is to elaborate the total concept found in the previous chapter into a cladding system design that can be manufactured. The cladding system eventually has to cover a sectional profile of the PD, which includes principle details such as the roof top, roof panels, roof edge, facade panels and panels around the window openings.

In order to get to a final design, this chapter will first of all search for solutions to achieve functions such as drainage, cavity ventilation, aesthetics, space for adjustments and thermal expansion. Finally, the production steps will be discussed.

## 5.1 Functions

### Drainage

Since water tightness is one of the most important functions of a rainscreen cladding system, it should have a proper drainage system. Following from the total concept found in the previous chapter, the drainage is integrated in the sub-construction. The vertical profiles will function as gutters through which the water will flow down. The overlapping horizontal joints ensure that water is not able to flow to the backside of the cladding panels.

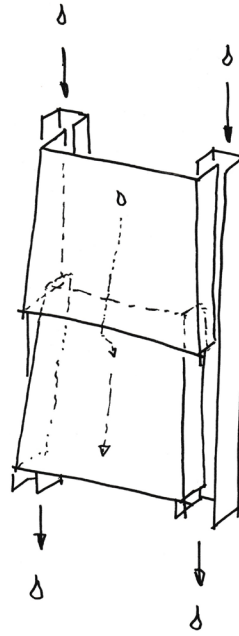


fig. 52. Drainage in vertical direction (own ill.)

### Cavity ventilation

Although the rainscreen cladding should prevent any rainwater from penetrating the cladding, there will always be some moisture in the cavity that either comes from inside the PD lab or outside, as a result of a rain shower. The characteristic tapered shape of the cladding panels not only provides an overlapping horizontal joint, it also has the flexibility to make wider open joints at the front of the panels to allow air to flow in and that way ventilate the cavity.

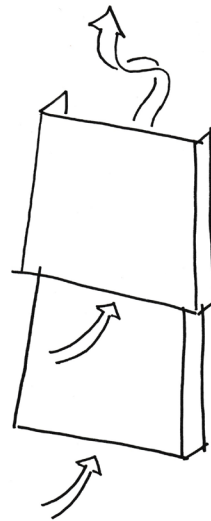


fig. 53. Cavity ventilation in vertical direction through the horizontal joints (own ill.)

### Aesthetics

The tapered shape of the cladding panels has quite an architectural impact on the PD lab, as it has a remarkable appearance. The dynamic, tilted vertical edges of the cladding panels might conflict with the static and clean horizontal lines that are present in the rest of the cladding system. To amplify the dynamic appearance of the cladding system, full-length and half-length panels will be applied that alternate each other in vertical direction.

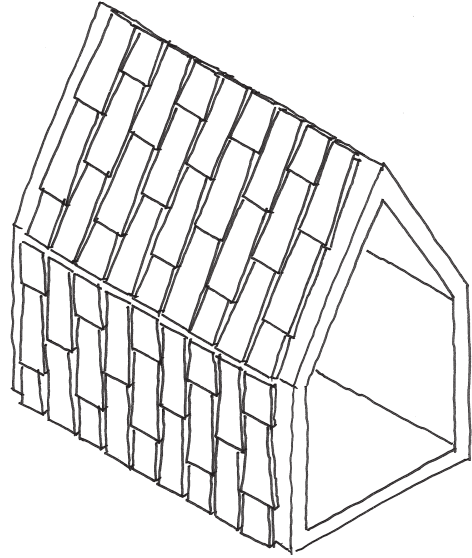


fig. 54. Aesthetics:  
alternating panels [own ill.]

### Assembly

Following from the design criteria, the assembly is one of the most important aspects of the cladding system. In this case, the assembly takes place by sliding vertical slots at the top of the panel upwards over two pin connections. Subsequently, by hinging the panel, slots at the bottom of the panel slide over two other pin connections. Finally, the panel is lowered to its final position. In order to prevent the panel from coming loose, the two top pin connections are adjusted downwards.

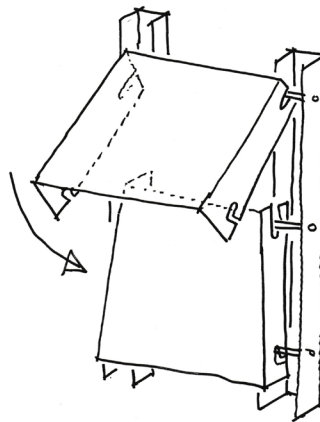


fig. 55. Assembly by hinged and  
hung connections [own ill.]

### Space for adjustment

During the construction of the PD test lab, it was found that the current cladding system lacks enough space for adjustment. Therefore, the new cladding system design needs space for adjustment in the brackets and at the pin connections. The brackets have slotted holes which enable it to be adjusted in three directions. The cladding panels are supported by the two bottom pin connections, while the two top pin connections can be adjusted. Moreover, the panels can slide in linear direction over all pin connections. Finally, the panel is fixed either at the two left or right pin connections.

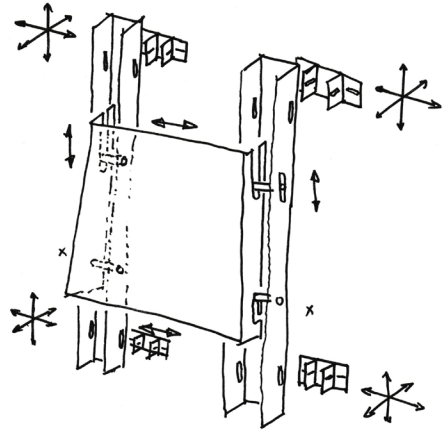


fig. 56. Space for adjustment in multiple directions (own ill.)

### Thermal expansion

Every material changes shape as its temperature changes. To allow for thermal expansion, the cladding panel should not be completely fixed at all connection points. In this case, the cladding panel will be supported by the two bottom pin connections, while the two pin connections on the left fix the panel in horizontal direction. This way, the panel is still able to thermally expand upwards and sideways.

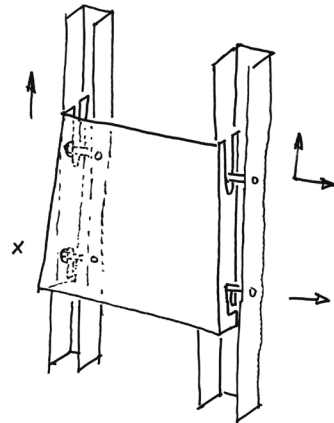
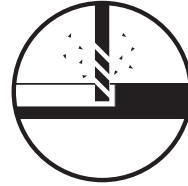


fig. 57. Space for thermal expansion in multiple directions (own ill.)

## 5.2 Production steps

### CNC-milling

CNC-milling is a digital manufacturing technique which allows for mass customization. This means that it does not matter if it has to produce many equal or different parts. Moreover, a CNC-milling machine is able to work very accurately and switch tools automatically.



Regarding the production of the cladding panels, the CNC-milling machine cuts out the contour shape of the cladding panels. Since the cladding system consists of multiple types of panels, the possibility of mass customization is of great value.

### Bending

Sheet bending usually takes place by cold bending with a bending press. However, since Resysta is a thermoplastic material, it will be warm bent. By pushing a V-shaped heating element into the sheet material, a bending line is created. As long as the material has the right temperature, it can be bent manually. Due to the V-shape, the bending radius can be minimized (see fig. 58).

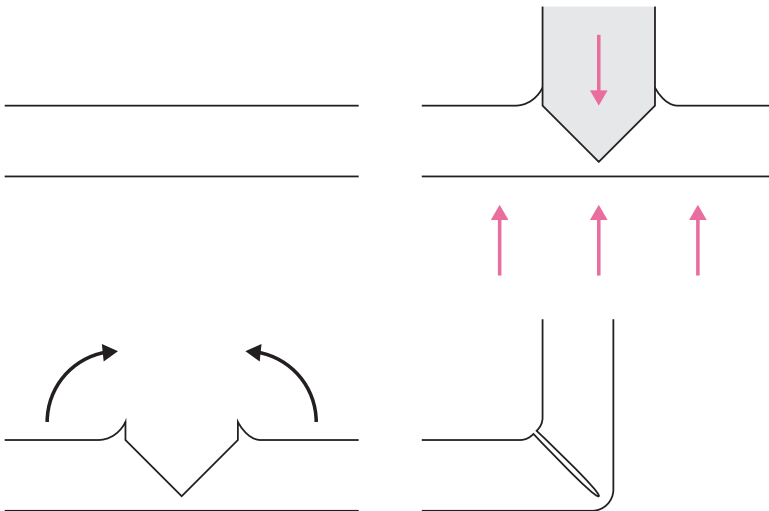
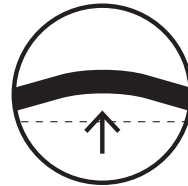


fig. 58. Schematic overview of the warm bending process. A V-shaped heated element is pushed into the thermoplastic material, after which the material can be bent manually (own ill.)



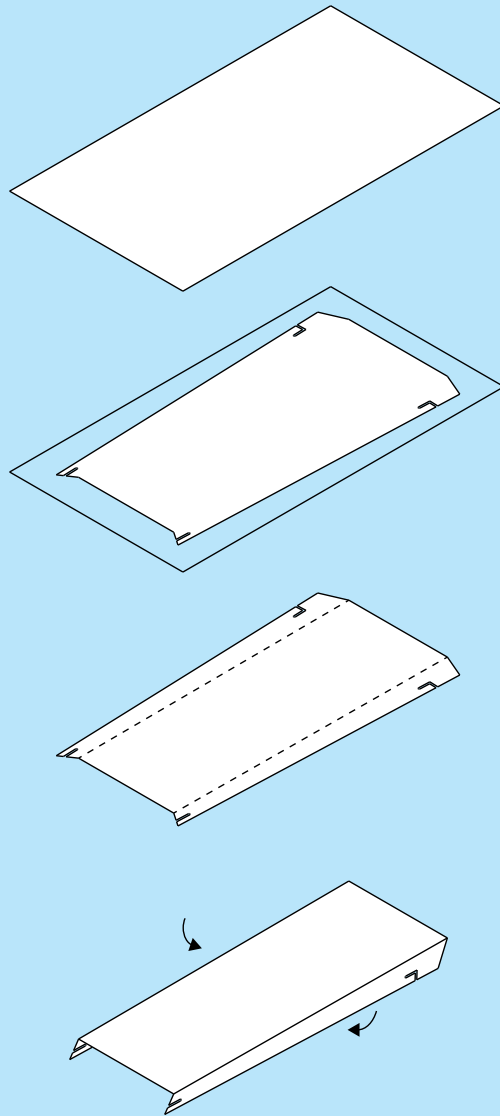


fig. 59. The production of a standard tapered cladding panel: 1. A sheet of Resysta is placed, 2. The contour shape is CNC-milled, 3. A V-shaped heating element pushes bending lines in the material, 4. The edges can be bent manually.

## 6. FINAL DESIGN

The final design consists of all the parts that together cover a sectional profile of the PD lab. This chapter will show the parts of which the cladding system consist, how they are assembled and the detailing of the complete system.

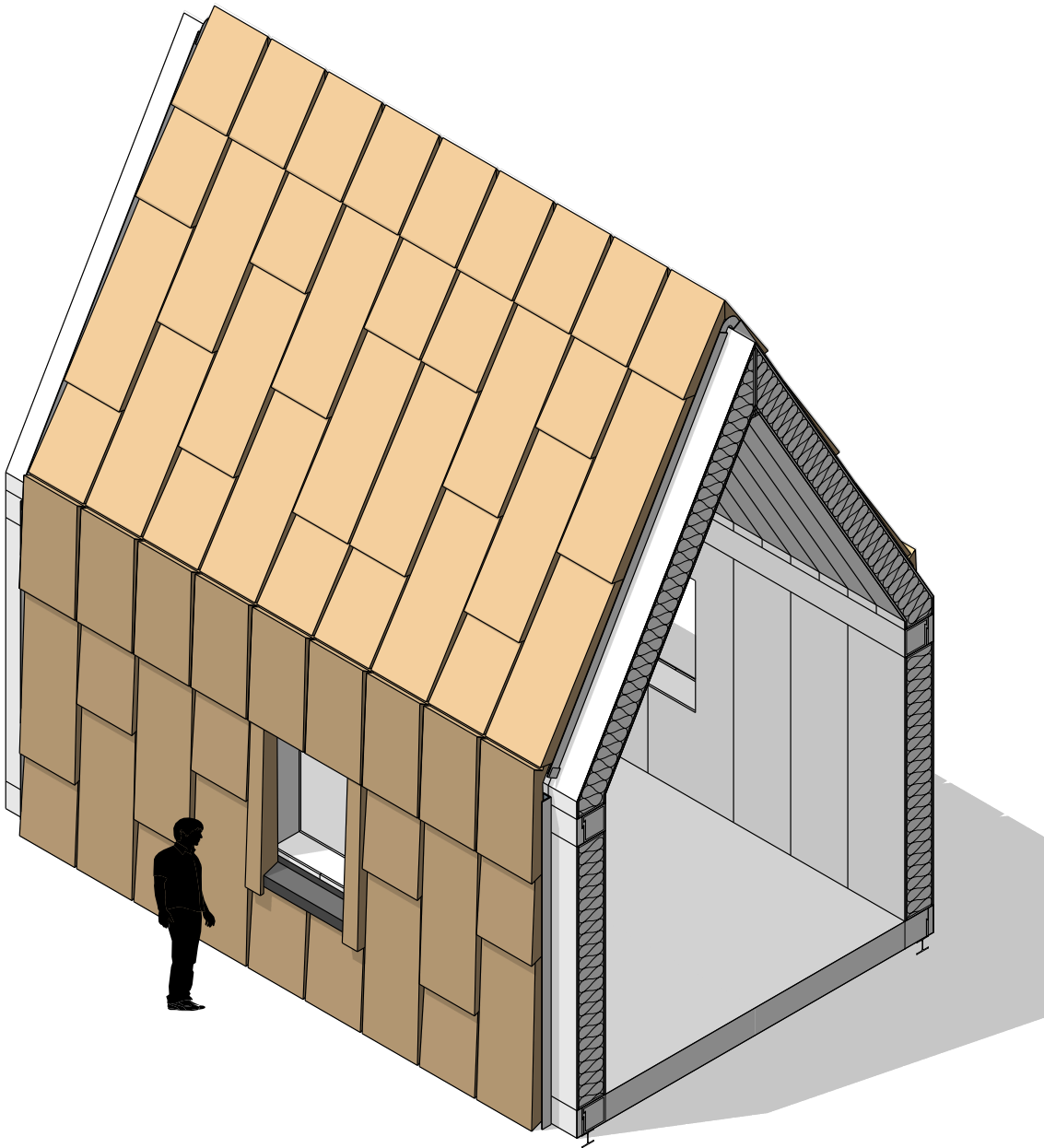
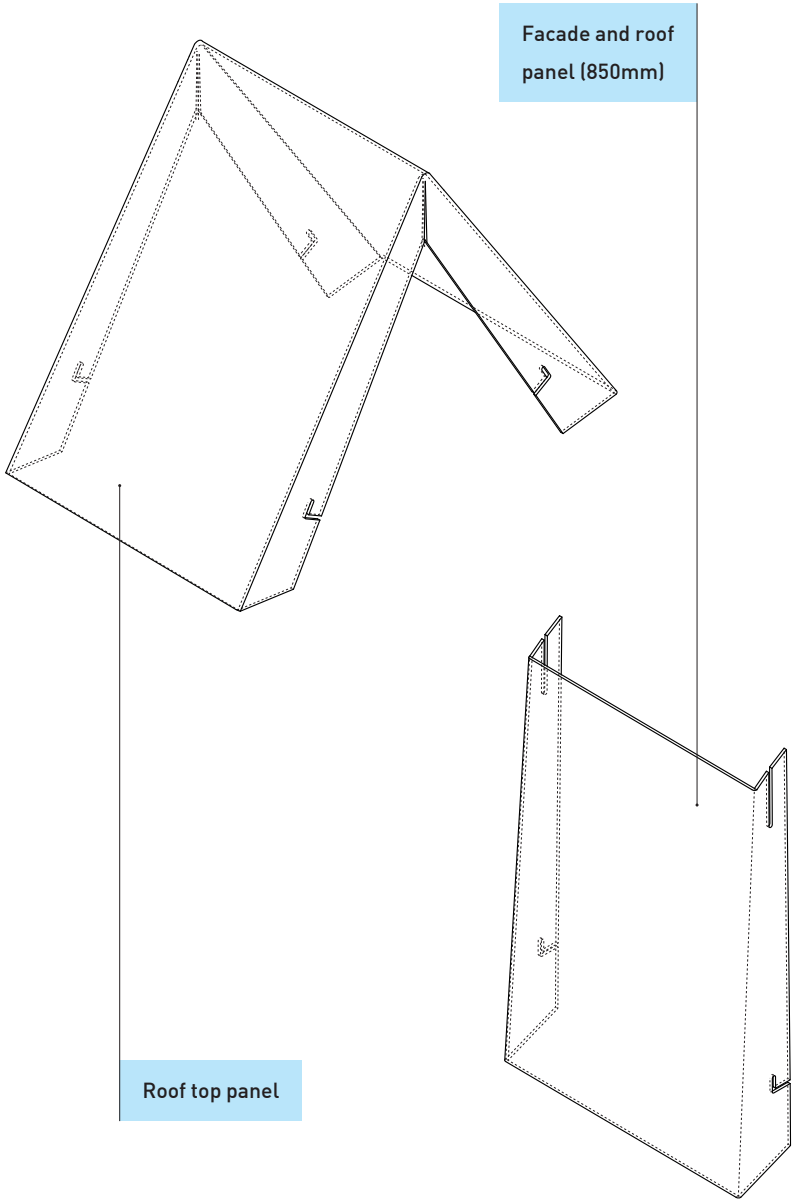
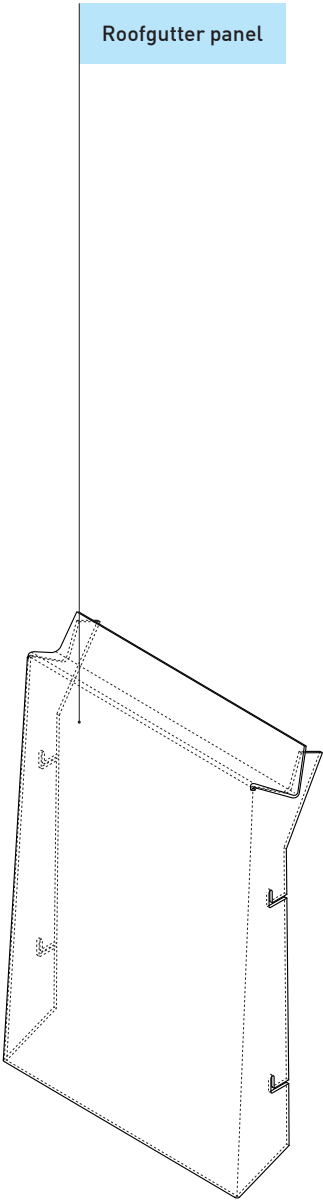
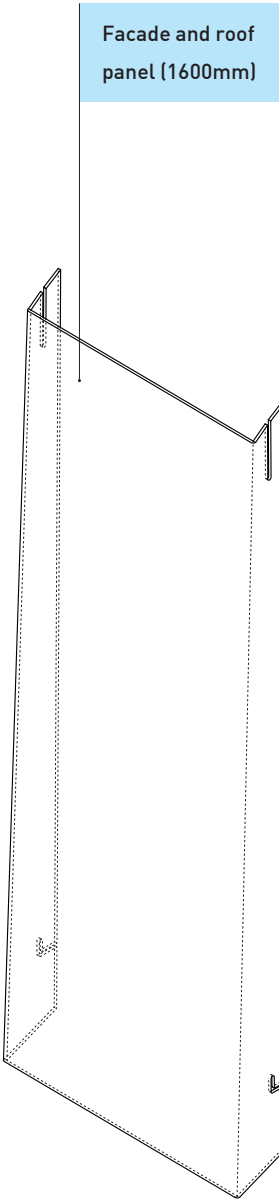
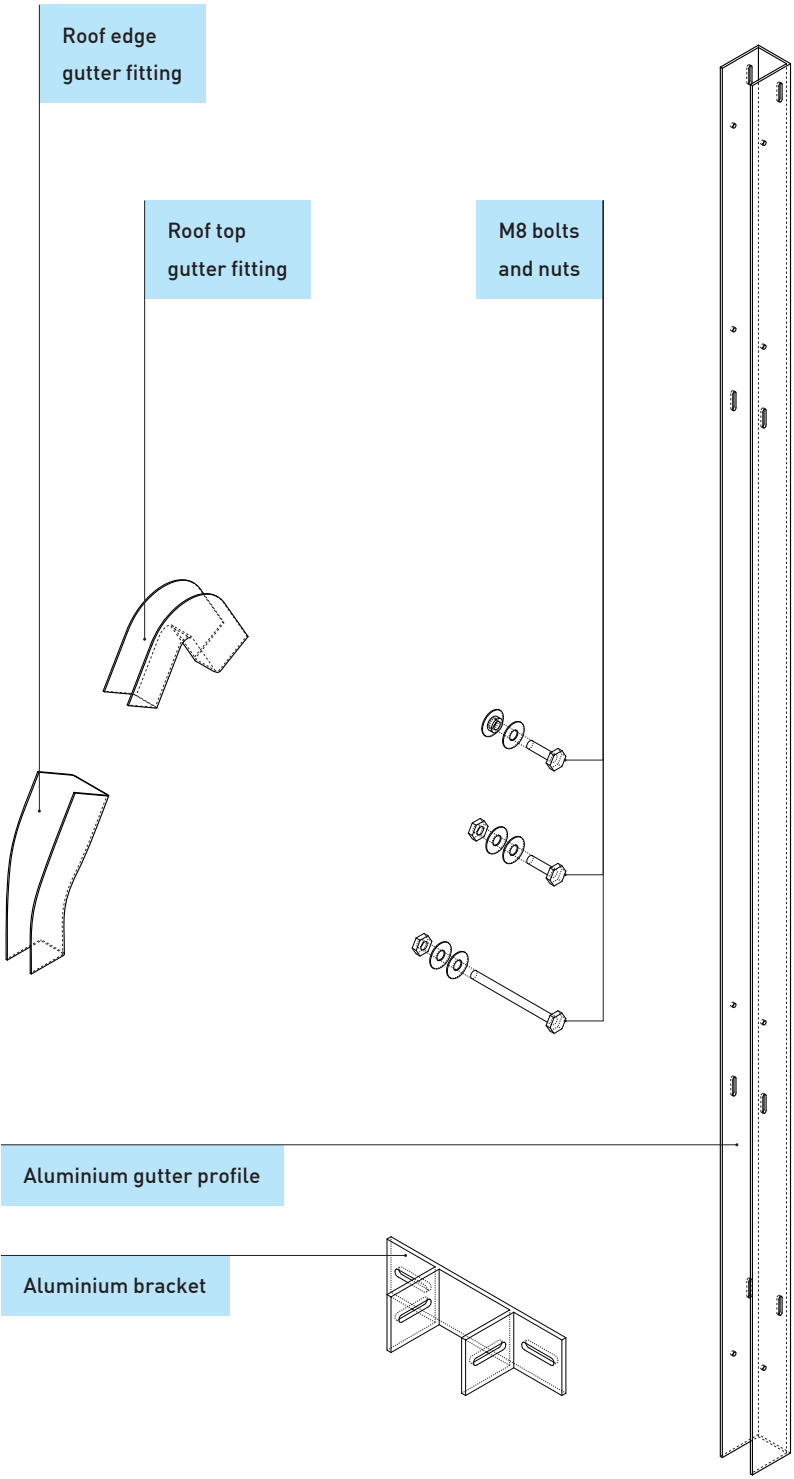


fig. 60. Overview of the final design for the cladding system

6.1 Parts



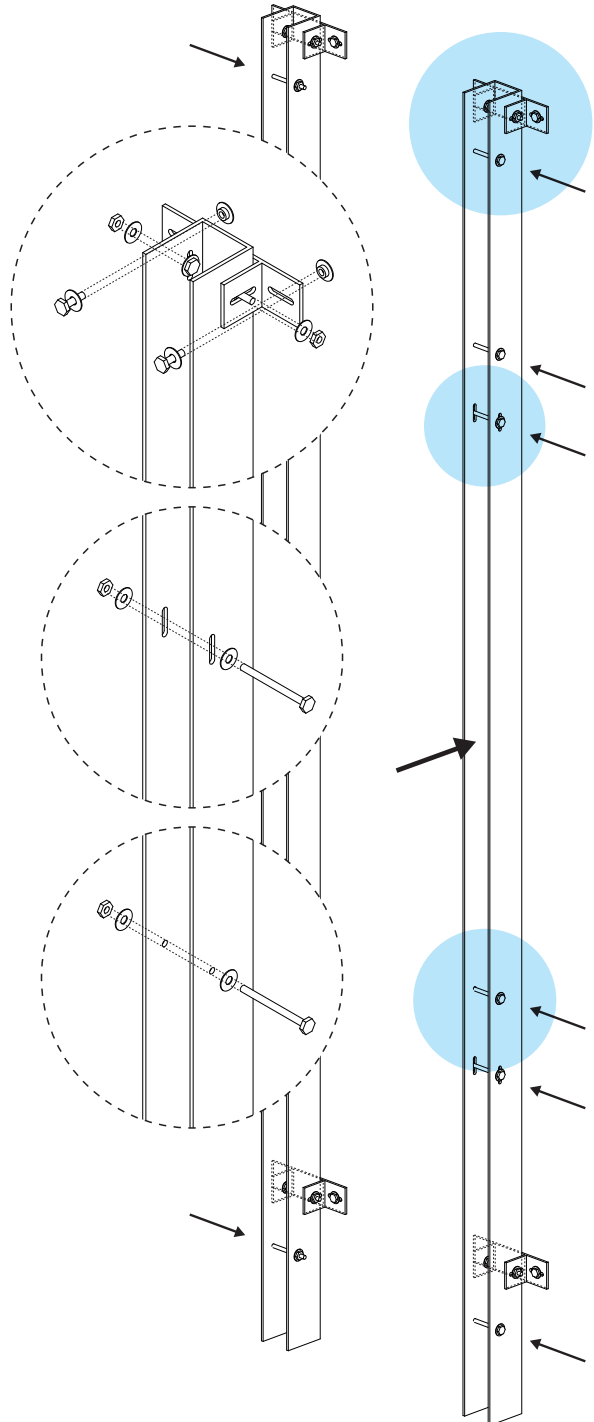




## 6.2 Assembly

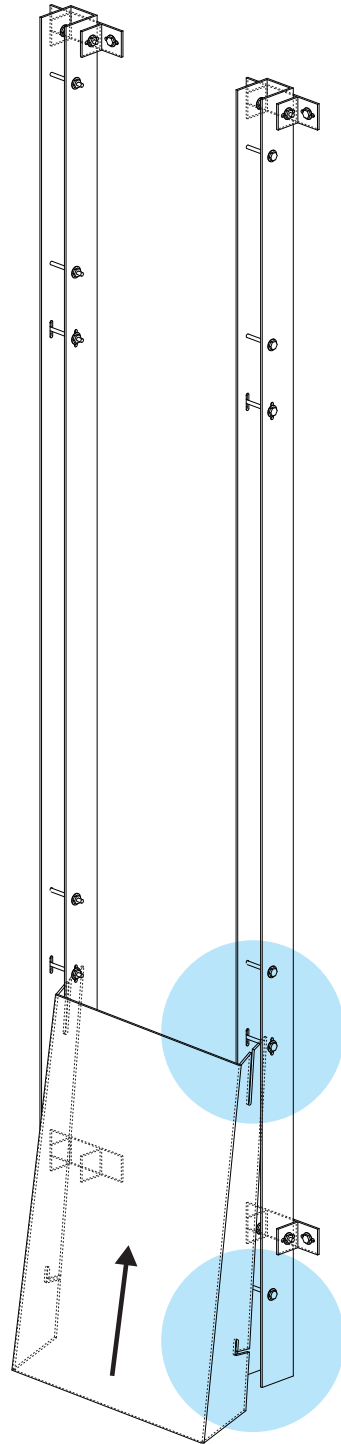
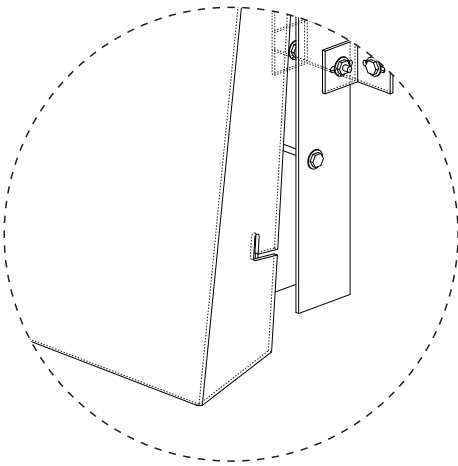
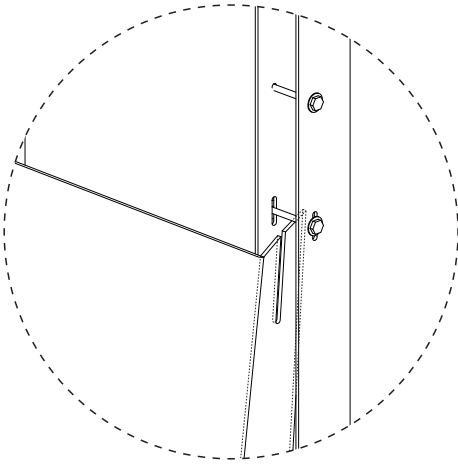
### Step 1.

The aluminium brackets are mounted on the structure of the PD lab. In these brackets, the aluminium vertical gutter profiles are placed and fixed with M8 bolted connections. The slotted holes in the brackets and vertical profiles allow for adjustment.

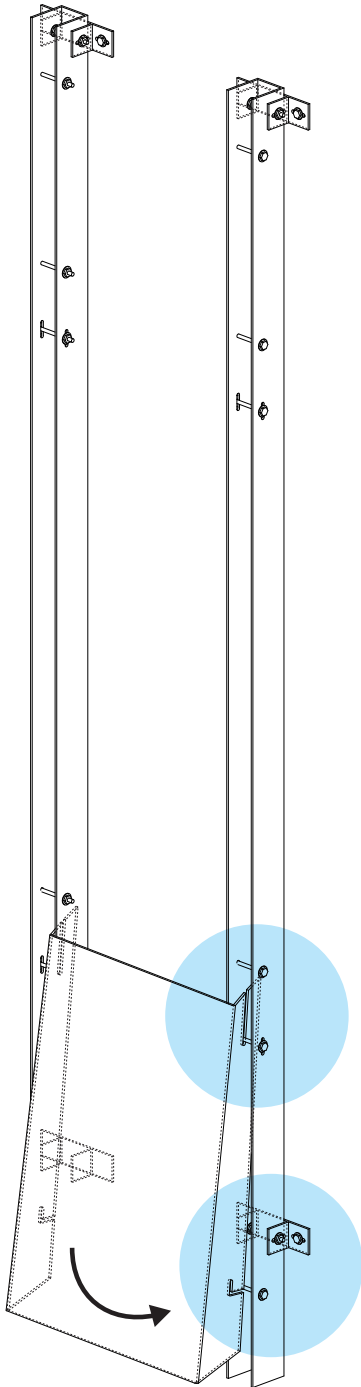


**Step 2.**

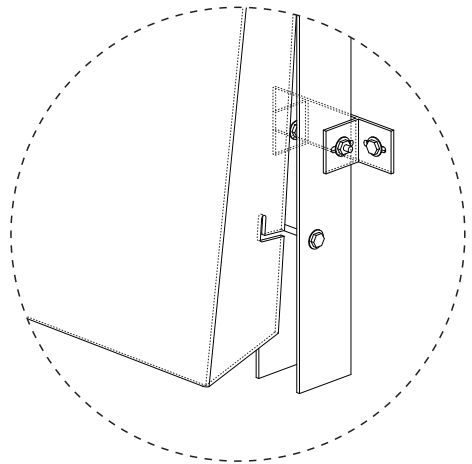
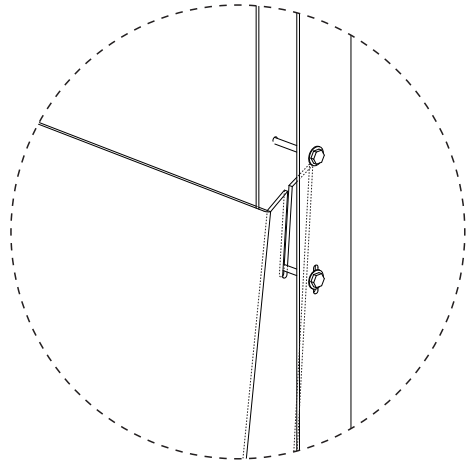
A cladding panel, with vertical slots at the top of the panel, slides over the pin connections.





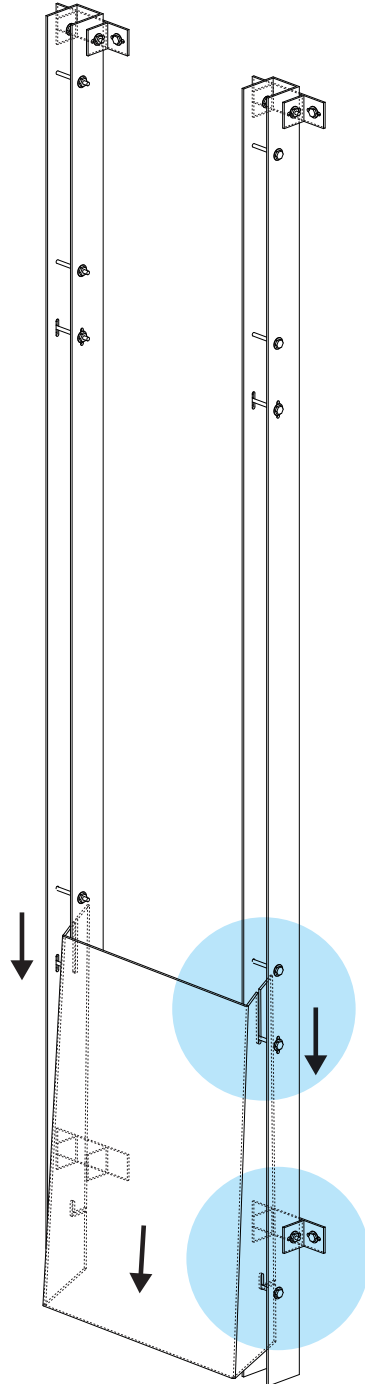
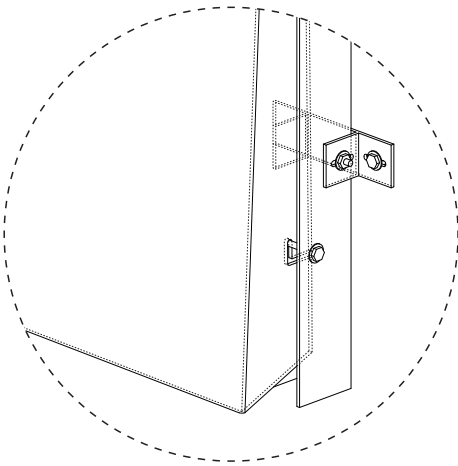
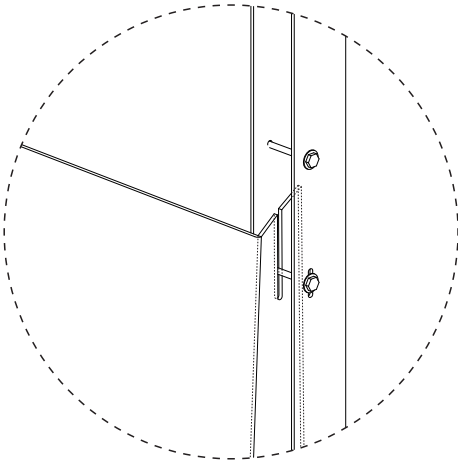
**Step 3.**

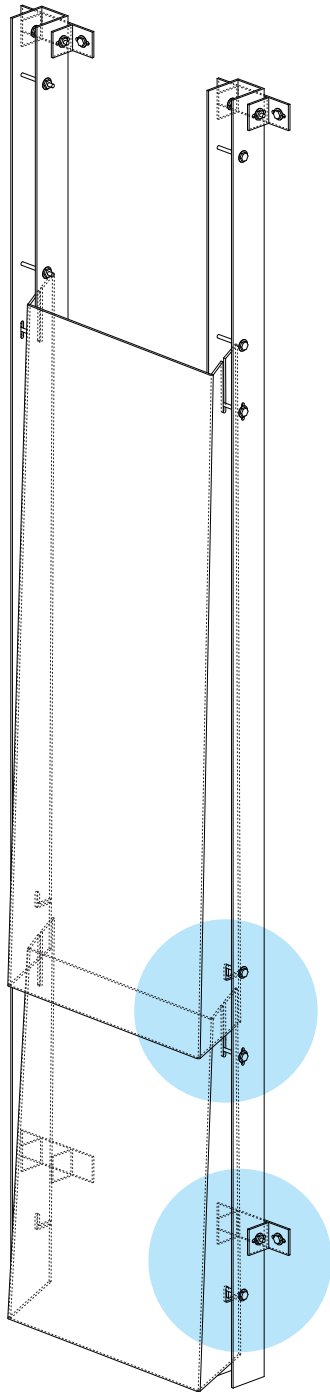
Subsequently, by hinging the panel, slots at the bottom of the panel slide over two other pin connections.



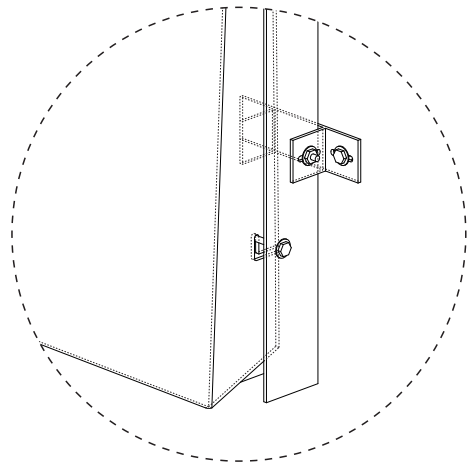
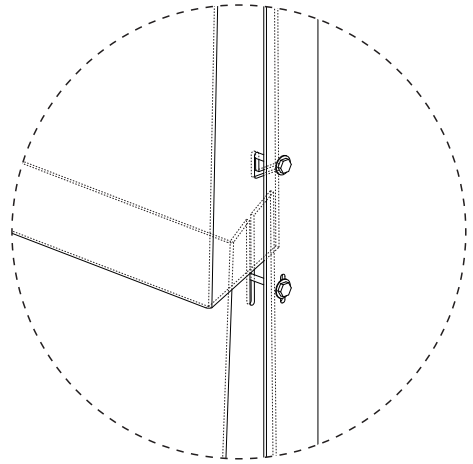
**Step 4.**

Finally, the panel is lowered to its final position. In order to prevent the panel from coming loose, the two top pin connections are adjusted downwards.



**Step 5.**

Steps 1 to 4 are repeated to assemble the panel above.



6.3 Detailing

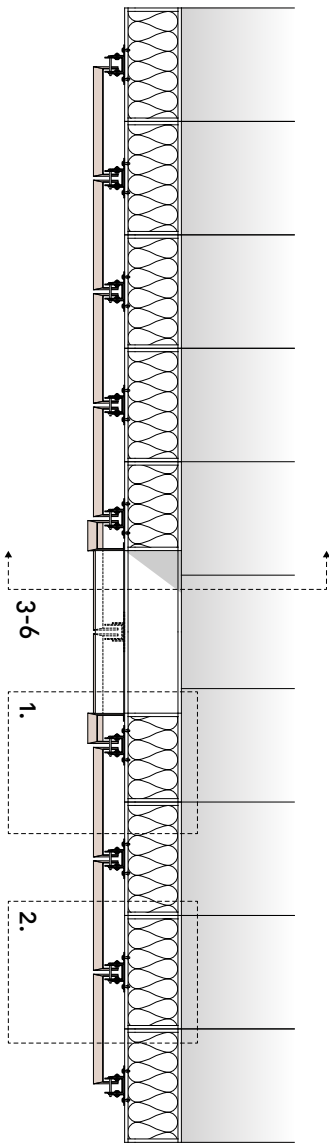


fig. 61. Horizontal section of the facade (scale 1:40)

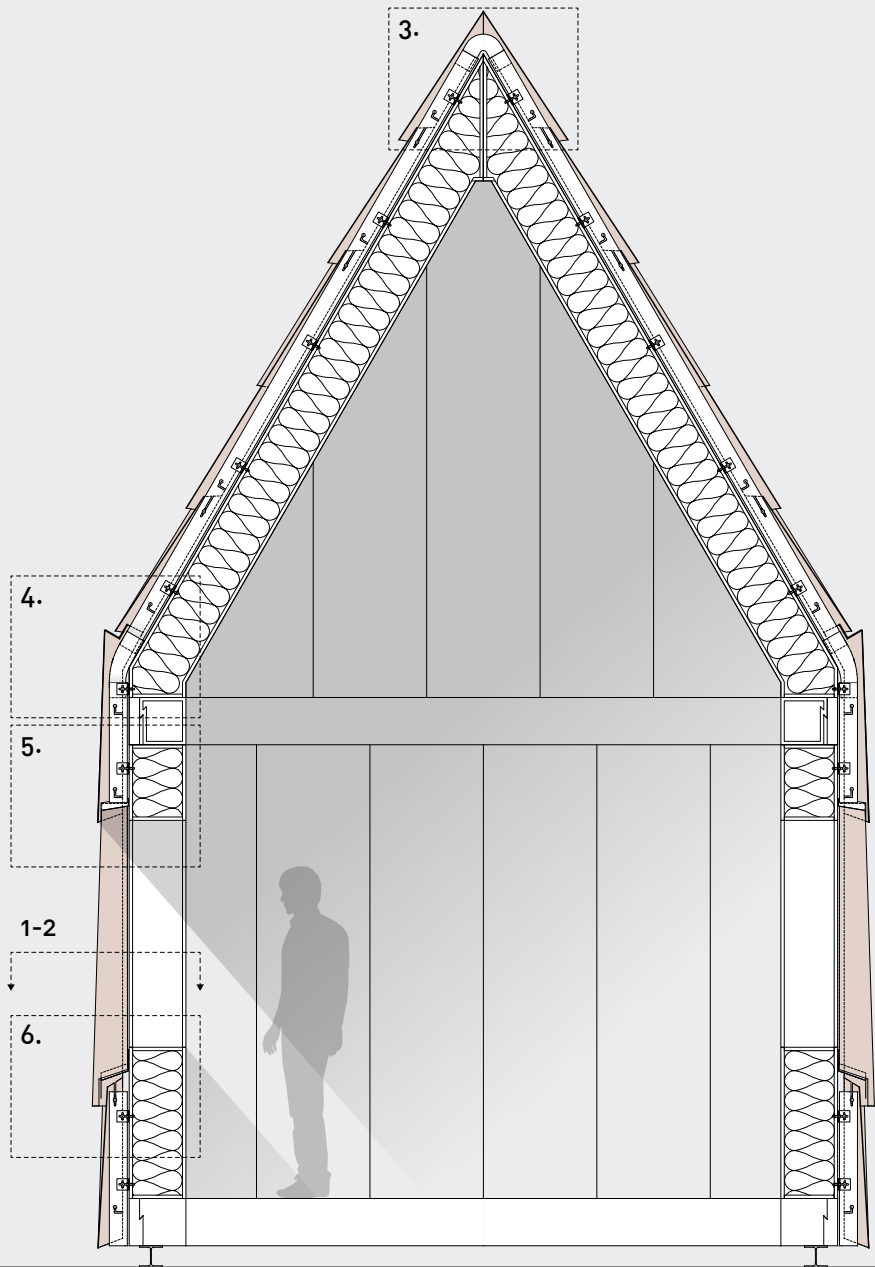
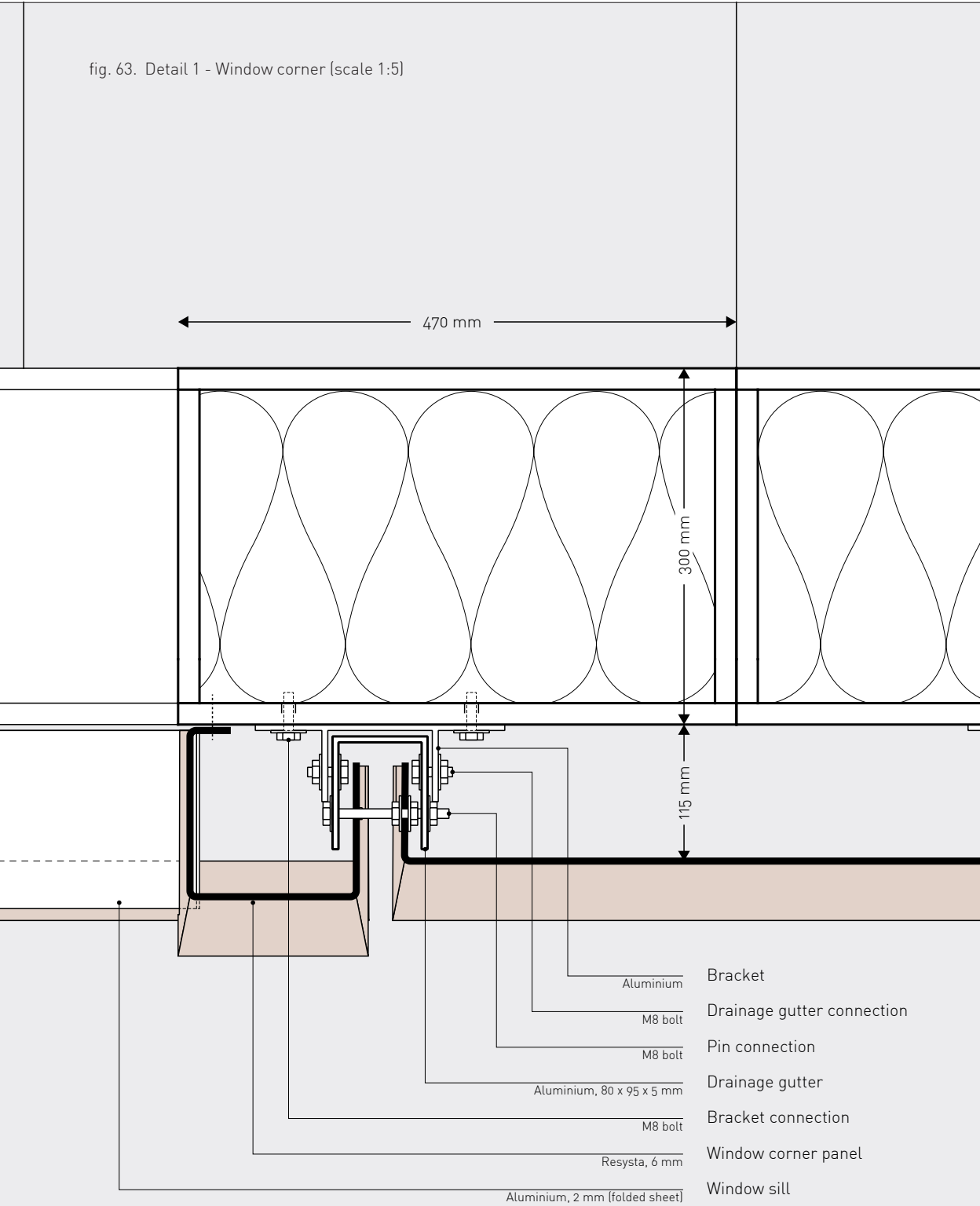


fig. 62. Vertical section of the facade [scale 1:40]

fig. 63. Detail 1 - Window corner (scale 1:5)



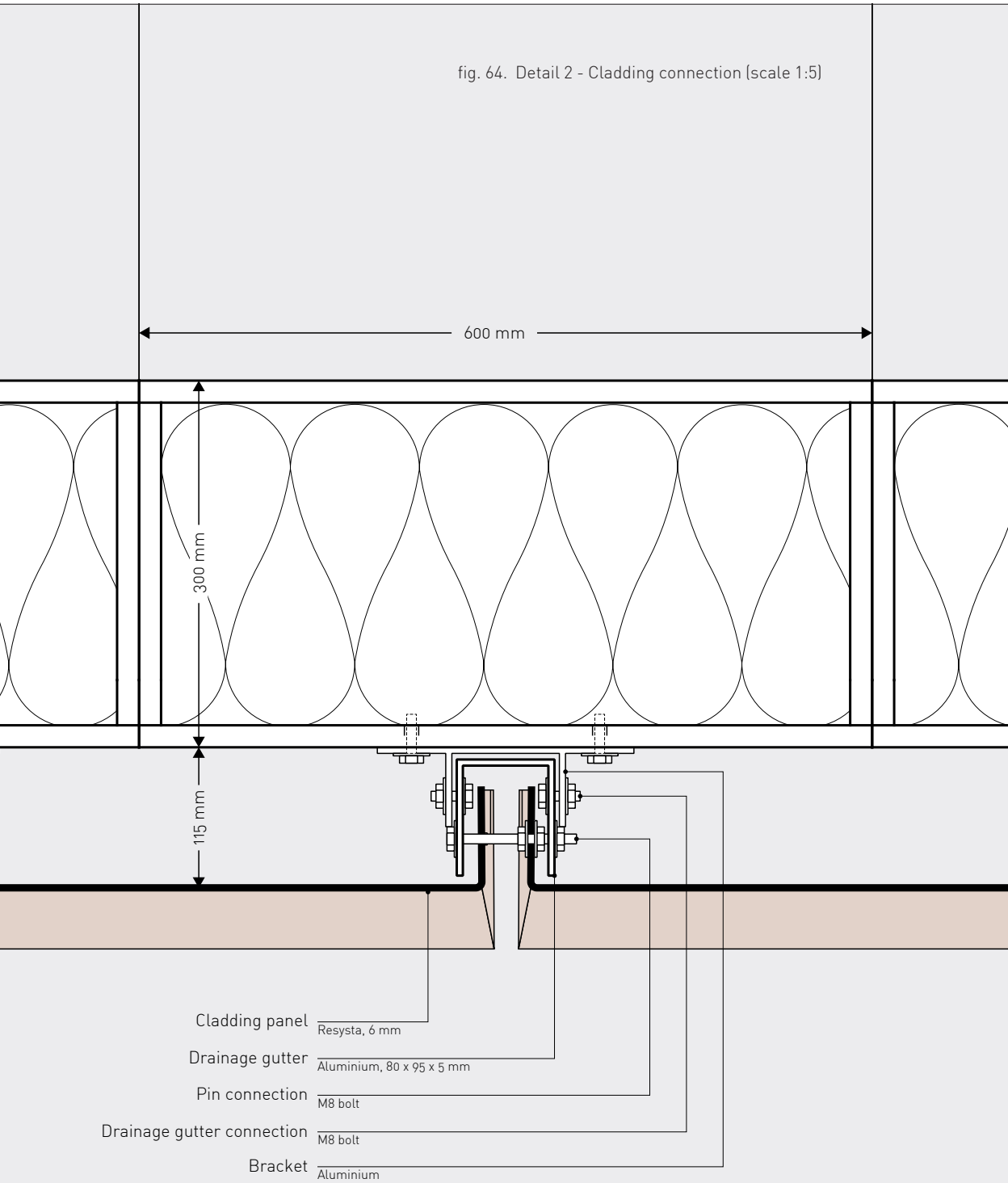
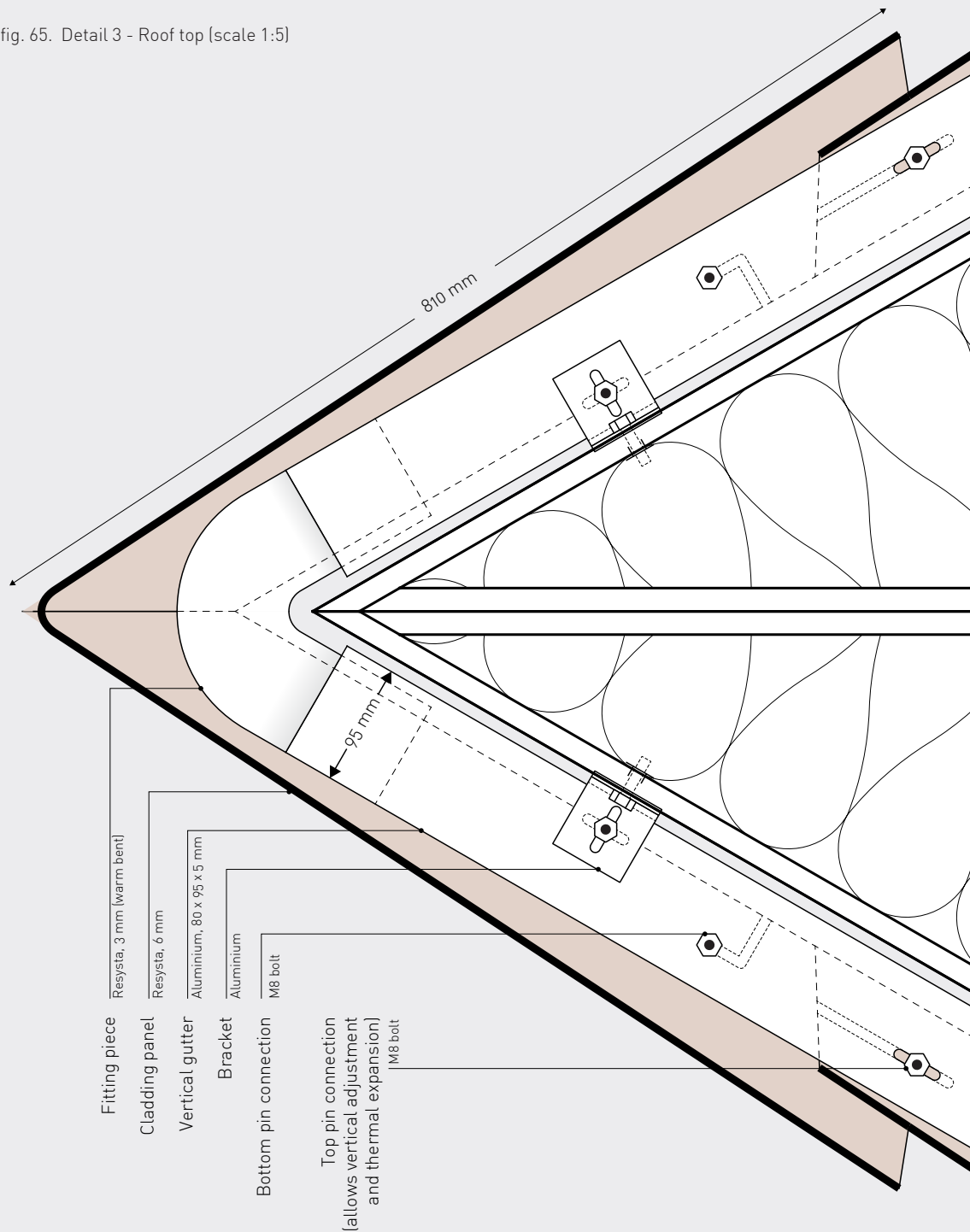


fig. 65. Detail 3 - Roof top [scale 1:5]





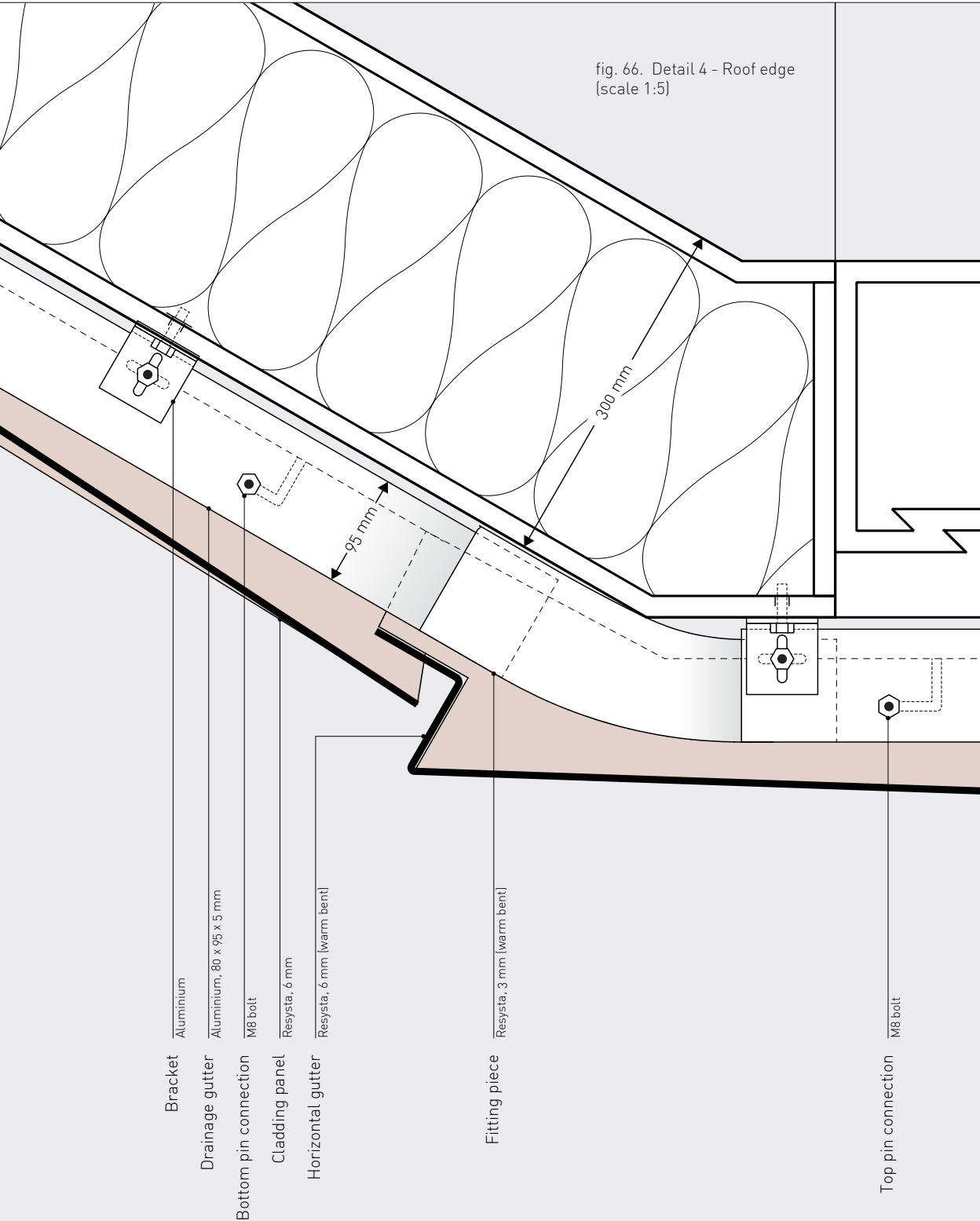


fig. 67. Detail 5 - Window top (scale 1:5)

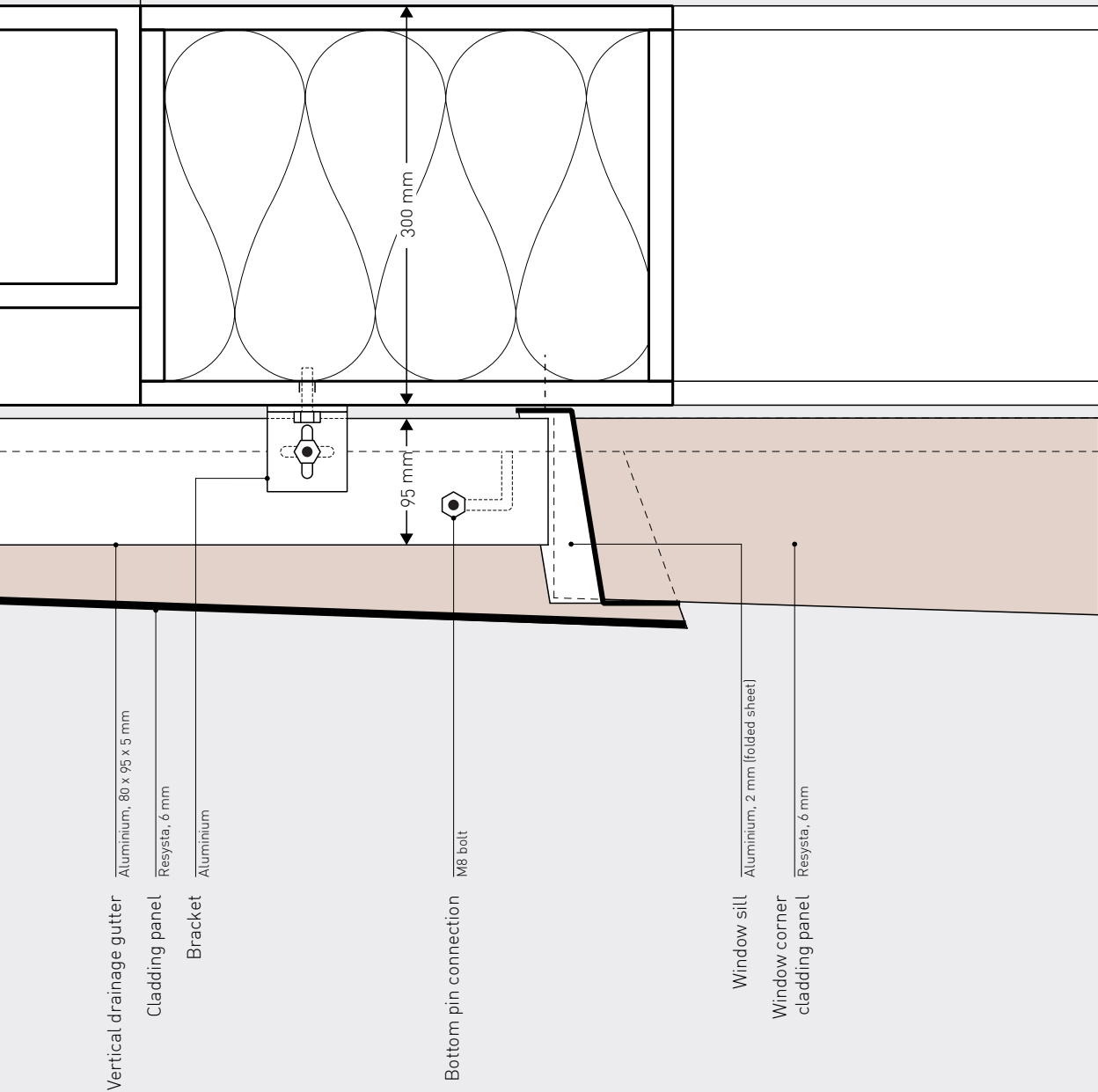
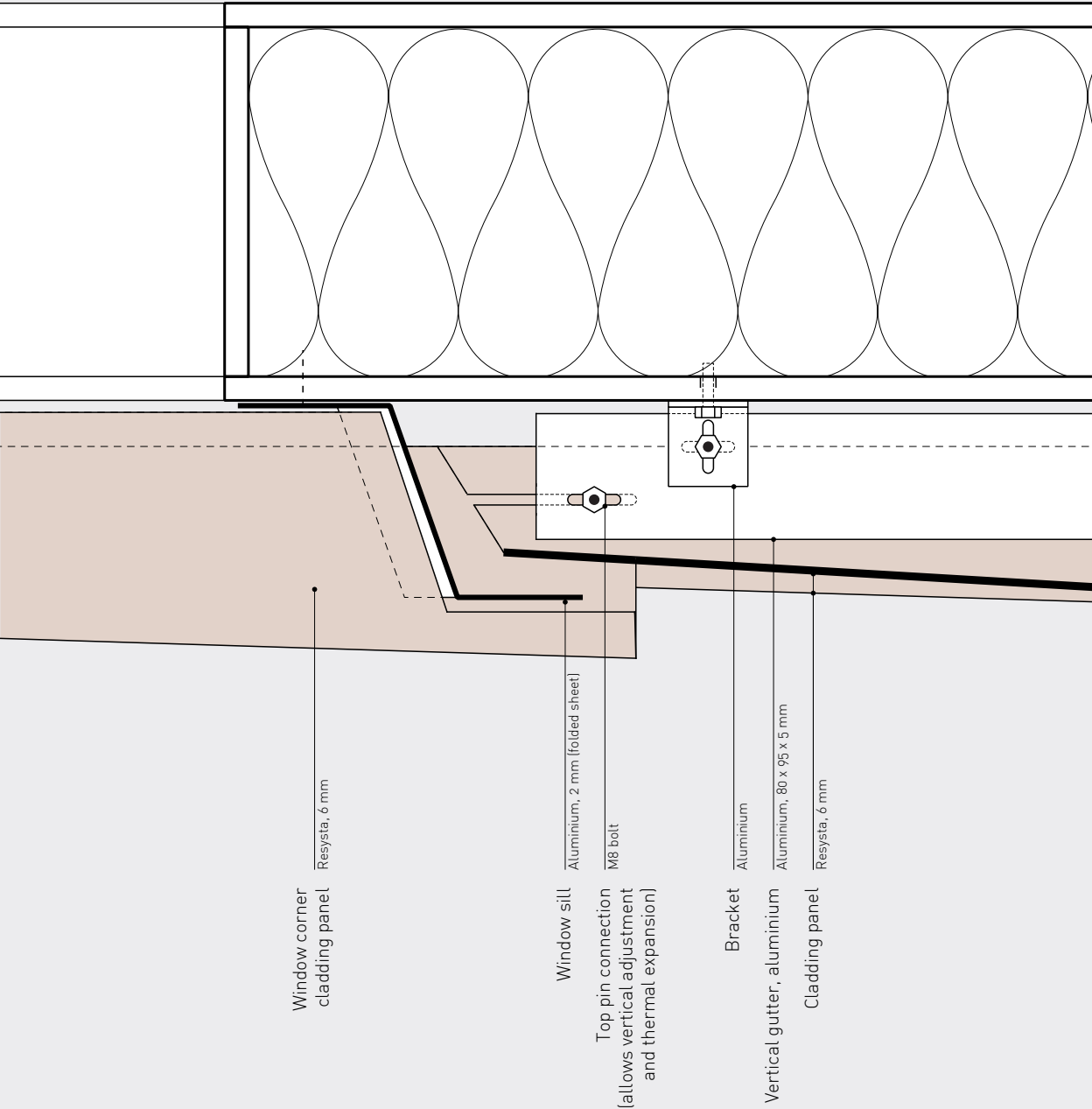


fig. 68. Detail 6 - Window bottom (scale 1:5)



## 6.4 Comparison with the current cladding system: Design

An interesting question to ask at this point is how the design of the proposed Resysta cladding system compares to the design of the current Reynobond cladding system. To do so, they are assessed using the same criteria as in the total concept assessment.

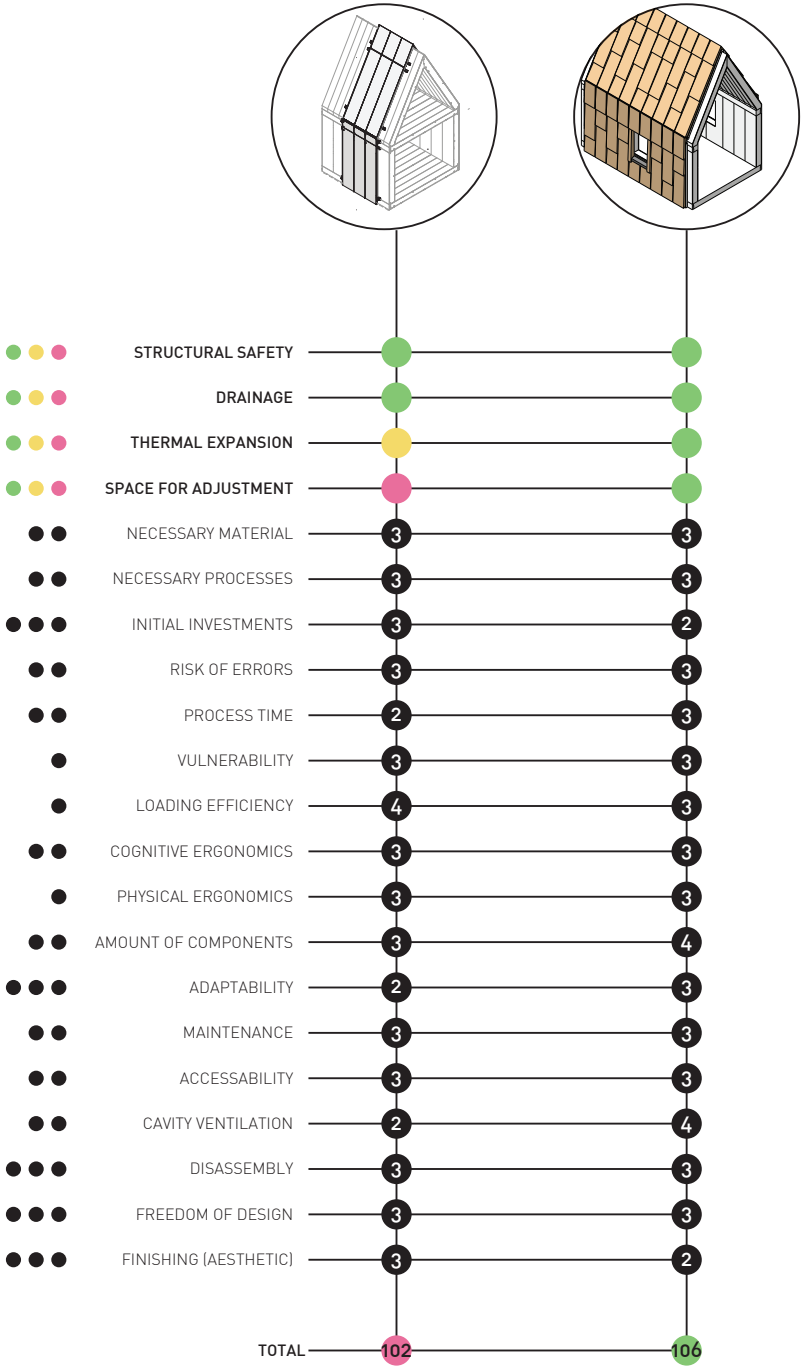
The design process started with the analysis of the PD test lab and the design problems that occurred during the construction of the cladding system. The three main problems were the lack of space for adjustment, the vulnerable points in the drainage and the way of hinging assembly that conflicted with the scaffolding. Although the proposed design uses a similar assembly method, design solutions were found for the space for adjustment and the vulnerable points in the drainage.

If looked at the assessment of the current and proposed cladding system design, the almost equal total score is what strikes most. Although a completely different type of material was used, the systems show quite some similarities in terms of aspect concepts. The largest differences can be found at the boundary conditions, which show again what design problems followed from the current cladding system.

Furthermore there are differences in criteria scores. The current cladding system has a higher score on initial investments, since the proposed cladding system required an extra processing technique: warm bending using a bending press. It also has been given a higher score on finishing, since the seams of the current cladding system are less wide.

The proposed cladding system has a higher score on process time, since it demands less milling time due to its simpler geometry. Since the design does not work with male and female panels, the amount of components has been reduced. This also has an effect on the adaptability, since the cladding system can be expanded per 600mm without having to take the difference between the male and female panel into account.

fig. 69. Assessment of the current and proposed cladding systems



6.5 Comparison with the current cladding system: Environmental impact of the material

The environmental impact of a product or material during its life cycle can be analysed by making a LCA, which stands for Life Cycle Assessment. LCA are reported in EPD's, which are Environmental Product Declarations for specific products. In this case, the EPD's of Reynobond and Resysta will be compared to see what the differences are between these two materials in terms of environmental impact.

In LCA's and EPD's, the environmental impact is measured on the basis of the following seven categories:

GWP (Global Warming Potential)	[kg CO2 equiv.]
ODP (Ozone Depletion Potential)	[kg CFC11 equiv.]
AP (Acidification Potential)	[kg SO2 equiv.]
EP (Eutricification Potential)	[kg (PO4)3 equiv.]
POCP (Photochemical Ozone Creation Potential)	[kg ethene equiv.]
ADPE (Abiotic Depletion Potential non-Fossil Resources)	[kg Sb equiv.]
ADPF (Abiotic Depletion Potential Fossil Fuels)	[MJ]

6.5.1 Calculation rules

System boundary

The life cycle of a product can be seen as a system with many inputs and outputs such as material use, energy consumption, waste generation and gas emission. In a LCA, this system is divided according to the life cycle stages of the concerning product (see Table 2). Since not all LCA reports include all stages, a system boundary is needed to show which stages are and which are not included. For each included stage, the seven environmental impact categories mentioned earlier are measured.

SYSTEM BOUNDARIES (X = INCLUDED IN THE LCA; MND = MODULE NOT DECLARED)																
Product stage			Construction process stage		Use stage							End-of-life stage				Benefits and loads beyond the system boundary
Raw material supply	Transport	Production	Transport	Assembly	Use / Application	Maintenance	Repairs	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction	Transport	Waste treatment	Landfilling	Re-use, recovery or recycling potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
X	X	X	MND	MND	MND	MND	MND	MND	MND	MND	MND	MND	MND	MND	MND	X

table 2. LCA system boundaries in an EPD

In the LCA reports of Reynobond and Resysta not all stages are present or are calculated based on a different system boundary. Therefore, they will only be compared on the basis of stages A1-A3 (product stage).

Functional unit

The functional unit of a LCA shows on what basis environmental impacts are calculated. It describes the function of the product while expressing it in a certain unit. The functional unit of a coffee machine, for example, would be: making 1000 cups of coffee. It explains the main task it has and expresses it in a measurable value by connection a certain unit to it. By expressing the function in a certain unit, the data can be compared with the LCA's in EPD's of other product. In the case of a cladding system, the functional unit would be: 1m2 of cladding material X with stiffness Y. The stiffness allows to compare materials with different structural properties.

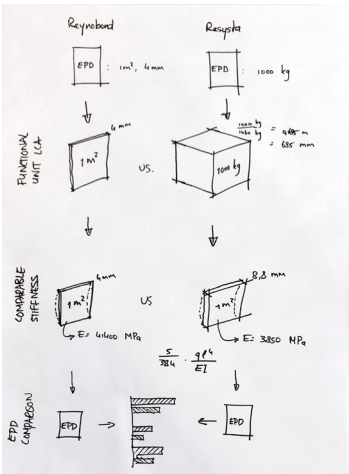


fig. 70. Explanation of the functional units conversion

The used data from the EPD's of Reynobond and Resysta only applies to the materials as semi-finished product, so not applied in a cladding system yet. Since calculating the environmental impact of these two differently manufactured cladding system is very elaborate and deserves a completely new LCA, this comparison will only focus on the materials that were used in the current and proposed cladding system.

Property	Unit	Symbol	Reynobond 4mm	Resysta 4mm	Resysta adjusted thickness
GENERAL					
Weight	kg/m²	m =	5,6	5,8	12,9
Section width	mm	b =	1000,0	1000,0	1000,0
Section thickness	mm	h =	4,0	4,0	8,8
SITUATION					
Span	mm	l =	1000,0	1000,0	1000,0
Load (wind)	N/mm²	q =	1,6	1,6	1,6
STRUCTURAL					
Youngs Modulus	MPa	E =	41400,0	3850,0	3850,0
Moment of inertia	mm⁴	I = bh³/12	5333,3	5333,3	57350,6
Stiffness		EI =	2208,0x10⁵	2053,3x10⁴	2208,0x10⁵
RESULTS					
Deflection	mm	d = 5/384 x q l⁴/EI	94,4	1014,6	94,4

table 3. Calculation of needed panel thicknesses to achieve an equal deflection (=stiffness)

The functional unit states that the Reynobond and Resysta panel should have the same stiffness. This can be measured by calculating their deflection as a result of a wind load of 1,6 kN/m<sup>2</sup>. The current cladding system, made from Reynobond, serves as a benchmark. The calculations in Table 3 show that a Resysta 1m<sup>2</sup> panel needs a thickness of 8,8mm to achieve the same stiffness/deflection as the Reynobond 1m<sup>2</sup> 4mm panel. This means that a conversion factor of 2,2 will be used to compare the LCA data.

## 6.5.2 Results

Data from the EPD's of Reynobond (Institut Bauen und Umwelt, 2013) and Resysta (BRE Global, 2017) can now be compared. The data from the EPD of Resysta is multiplied with a factor 2,2. This results in the values shown in Table 4.

Parameter	Unit	Reynobond	Resysta
Weight	kg	7,04	12,89
Surface	m <sup>2</sup>	1,00	1,00
Thickness	mm	4,00	8,83
Lifetime	year	70,00	70,00
GWP	[kg CO <sub>2</sub> equiv.]	3,70E+01	2,69E+01
ODP	[kg CFC11 equiv.]	8,10E-07	5,23E-09
AP	[kg SO <sub>2</sub> equiv.]	1,70E-01	1,04E-01
EP	[kg (PO <sub>4</sub> ) <sub>3</sub> equiv.]	1,00E-02	1,28E-02
POCP	[kg ethene equiv.]	1,20E-02	1,07E-02
ADPE	[kg Sb equiv.]	2,10E+05	7,91E-05
ADPF	[MJ]	5,50E+02	6,09E+02

table 4. Results of the EPD comparison

### Data normalization

The table above shows the normalized data. For every environmental impact category, the largest value becomes reference value '1' while the other, smaller value is expressed as a share of it. As can be seen, Reynobond scores better on two environmental impact categories: EP and ADPF. Resysta scores better on the other five categories.



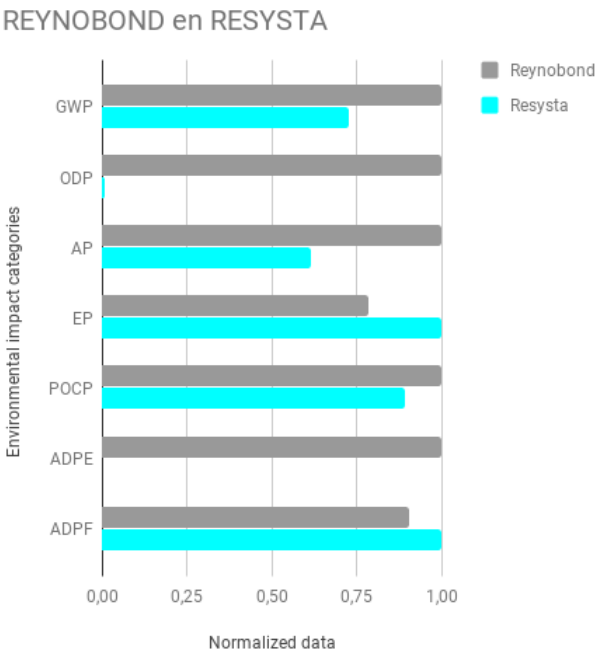


table 5. Results of the EPD comparison

6.5.3 Discussion and conclusion

Although Resysta scores better on five of the seven environmental impact categories, the differences are not that big. This might be a result of the limited focus on the production stage of the material itself, leaving out the production of the actual cladding panels and the influence of the end-of-life phase.

Overall, this environmental impact comparison is done in a very general way, since making a full LCA would deserve a graduation research on itself. This is caused by the fact that, in order to make a complete LCA, a lot of very specific data is needed which is not always readily available. It is possible to make so-called 'fast-track' LCA's which are based on using characteristic values from databases. However, without a good understanding of the complete life cycle of the concerning products with all of its inputs and outputs, which is a time consuming process, the results will not be very accurate.

So, LCA's remain complex and time consuming analyses to make. The key of making fast LCA's lies in the availability of necessary data. If data can be collected fast, the LCA can be made fast as well.

## 7. CONCLUSION

### Research questions

In this research, the following research questions were used:

How can biobased materials be applied to develop a modular and demountable cladding system for the PD lab?

- What are biobased materials, how can they be categorized and which biobased materials are available as market (cladding) products?
- How can suitable biobased materials be selected for further development in a cladding system for the PD lab?
- Which concepts for the cladding system of the PD lab can be developed with the selected materials?
- How can suitable concepts be selected for further design development?

### PD lab

The Product Development lab (PD lab) is an experimental platform that researches the potentials of a new building system that uses industrial production techniques, flexible production processes and flexible and demountable components. This way, a transition of the building industry towards a circular economy is promoted. In this research, the PD lab functioned as the case for which a new cladding system, made of biobased materials, was developed.

### Biobased materials

Biobased materials are materials that consists completely or for a significant part of renewable organic substances, either in their sourced format or resulting from modification or treatment. There are six categories of biobased materials to be distinguished: Wood, paper/cardboard, leather/hide, plastics, composites and textiles. From these six categories, only wood, plastics and composites in their basic form are suitable as cladding material.

The discussion of the three selected material categories shows that wood is the traditional choice, while plastic and composites are relatively as building materials. This also means that wood has less possibilities for innovation than biobased plastic and composites. Bio-plastics and bio-composites show some overlap, since bio-composites are often made of bio-plastics that are reinforced with natural fibres. Due to its design flexibility, high strength to weight ratio, corrosion resistance, fatigue resistance and little thermal expansion, bio-composites are most suitable for application in a cladding system.

Within the category of bio-composites, the following market products are discussed and assessed: Trespa, N8010 and Resysta. Based on the assessment and the interesting processing technique it enables, Resysta is chosen for application in the biobased cladding system.

**Concept development**

The chosen material is the starting point of the concept development. The used design methodology is based on the idea of dividing a problem into sub-problems, after which sub-solutions and a main solution can be found. In this case, the problem of developing a cladding system is divided into seven sub-problems called 'aspects' which together define the cladding system. These seven aspects are: assembly, connection, horizontal joints, vertical joints, sub-construction, panel stiffness and processing technique.

For every aspect, multiple concepts are generated and subsequently assessed according to various design criteria. By combining the most suitable aspect concepts, five total concepts were generated and assessed again. Initially a choice was made for the extruded panel concept. However, due to critical limitations encountered later on in the design process, a different total concept is chosen. Due to the ease of production, design freedom and relatively low initial investments, the tapered panel total concept is chosen for further design development.

**Design development**

The tapered panel total concept has several incorporated functions: drainage, cavity ventilation, aesthetics, assembly, space for adjustment and thermal expansion. In the further design development, design solutions for these functions are found and integrated into the complete cladding system design. The production of the cladding panels takes place by CNC-milling and warm bending.

**Final design**

The final design of the cladding system consists of panels with warm bent edges. These edges are connected to the structure of the PD lab via vertical gutters with pin connections. The vertical gutters not only function as sub-construction, they also function as vertical drainage gutters. Due to the tapered shape of the cladding panels, they allow for cavity ventilation and a dynamic appearance of the façade. Finally, the proposed cladding system allows for adjustment and thermal expansion in multiple directions.

## 8. RECOMMENDATIONS

With every research, questions are answered and new ones are raised. In this chapter, recommendations are made for topics that were already discussed in this research but deserve further research.

**Biobased materials**

With the renewed interest in biobased materials, many innovative materials are being developed in this field at the moment. The industrial application of bio-composites in building composites is still fairly new, which means there are many possible innovations ahead. At the moment, the majority of biobased materials have a low water resistance, which makes them unsuitable for application as a cladding material. Based on this research, an interesting question to research is if and at what term a bio-composite can be developed that fully consists of biobased ingredients, has a thermoplastic behaviour and is suitable as a cladding material.

**Development of critical parts**

The final design that was proposed in this research consists of a cladding system that covers a sectional profile of the PD lab. In order to cover the complete PD lab, further research is necessary to develop special parts that cover critical points such as the front and back edges. Although the development of these parts is challenging due to their more complex geometry, the total concept that was used for the sectional profile part has the potential to provide design solutions for the critical parts as well.

**Processing techniques**

During the elaboration of the extruded panel total concepts, several limitations of the extrusion processing technique were encountered. This could have been prevented, if there would have been more knowledge of processing techniques. Since industrial processing techniques are a cornerstone of the PD lab, processing techniques deserve more research.

**Challenges regarding integration in the circular economy**

This research started with the goal of designing a cladding system that would fit in a circular economy. Although several criteria regarding circularity were taken into account during the design process, there is still a lot of research that has to be done in order to overcome economic, environmental, behavioural, societal, technical and governmental challenges and that way truly integrate the cladding system in the circular economy.

## 9. REFLECTION

Reflecting on a research process and in particular on the used methodology is very interesting, since it provides valuable lessons for future research on related topics. The methodology (see fig. 71) will be reflected by discussing the decisions that were made during the actual design process (see fig. 73). This way, the questions of 'how' and 'why' did the methodology (not) work can be answered. Finally, the future use of the methodology, together with the relevance of the research beyond the PD lab will be discussed.

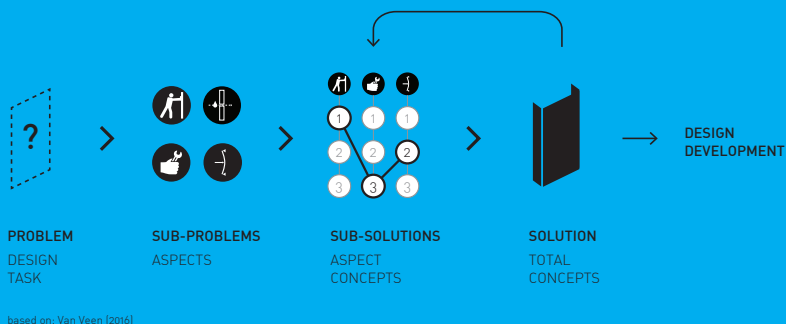


fig. 71. Design methodology



## 9.1 Decision making during the design process

### PD lab

In this research, the PD lab functioned as a case for which a new, biobased cladding system was developed. Previous research on the development of a cladding system provided a design methodology, including design criteria, aspects to take into account and a method to assess aspect concepts. However, this design methodology did not include a material selection method yet.

### Material selection

The challenge of the material selection was to find out how the philosophy of the PD lab could be translated into material criteria and a material assessment method. This turned out to be quite hard, as comparing materials get very elaborate very quickly. This made the development of a material assessment method come to a halt and that way the whole research process. After discussing this problem with mentors and a holiday trip far away from the research, the realization came that the material assessment simply had to result in a suitable material choice, instead of the best material choice. To continue with the research process, a provisional material choice was made for the thermoplastic bio-composite material Resysta. Later on, based on extra criteria that followed from the concept development, a definitive choice could be made.

### Concept development

The design methodology that was used in previous research on the development of a cladding system, used five aspects of a cladding system as a starting point for the concept development. After generating aspect concepts, the most suitable were combined into concept: the rectangular panel concept. This concept was

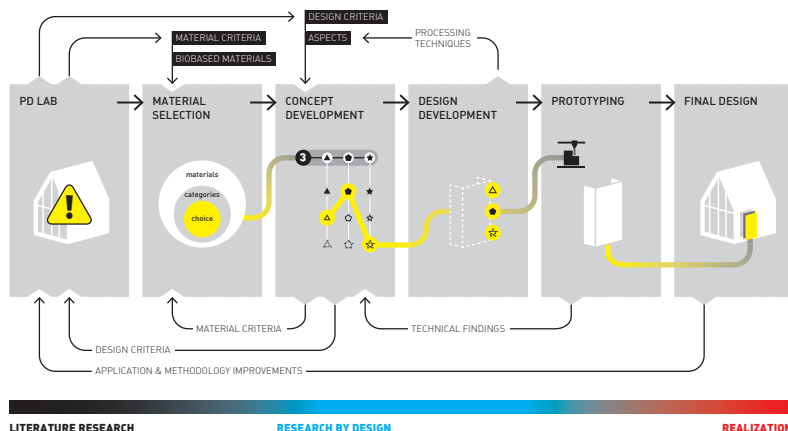


fig. 72. Research methodology

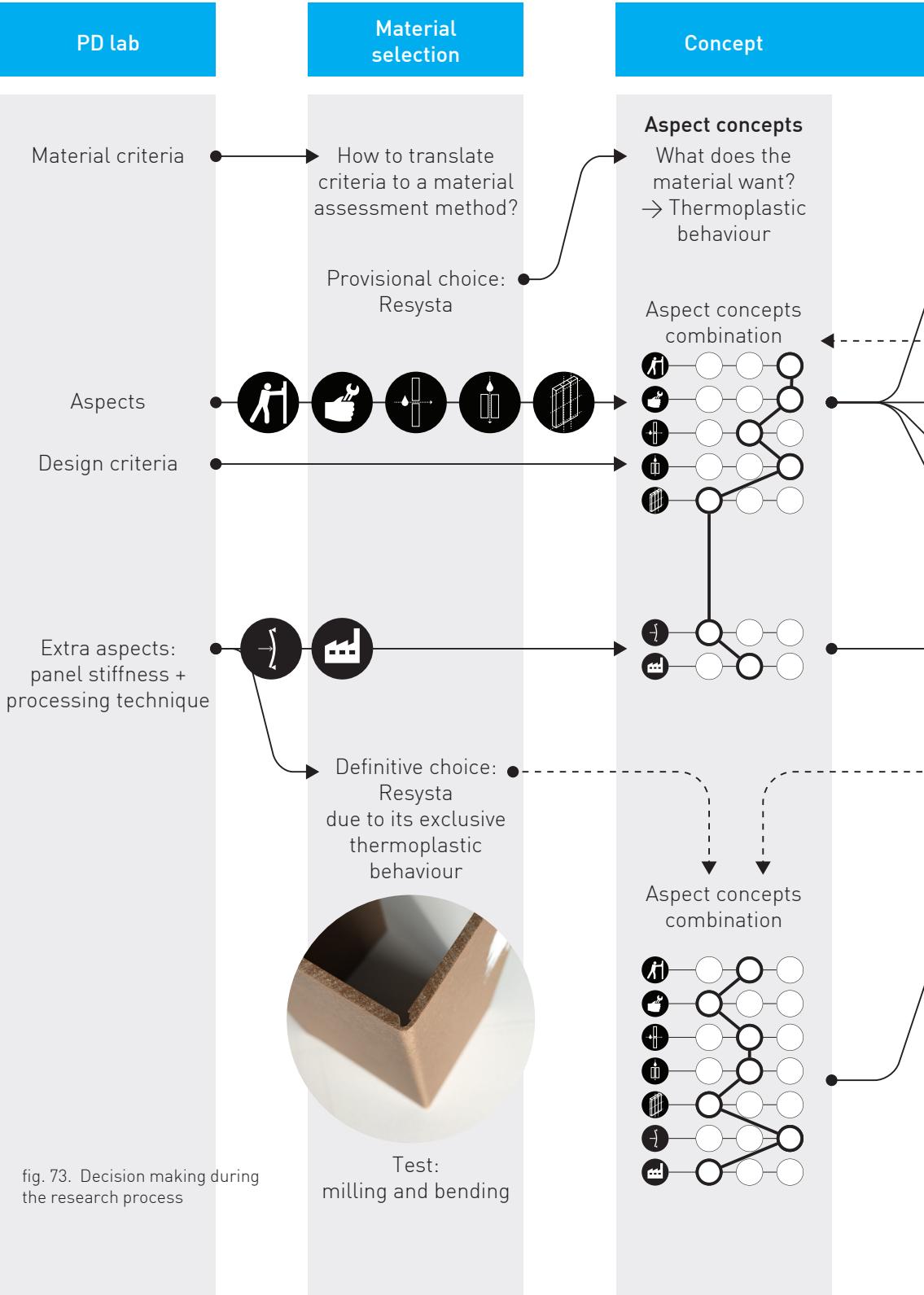
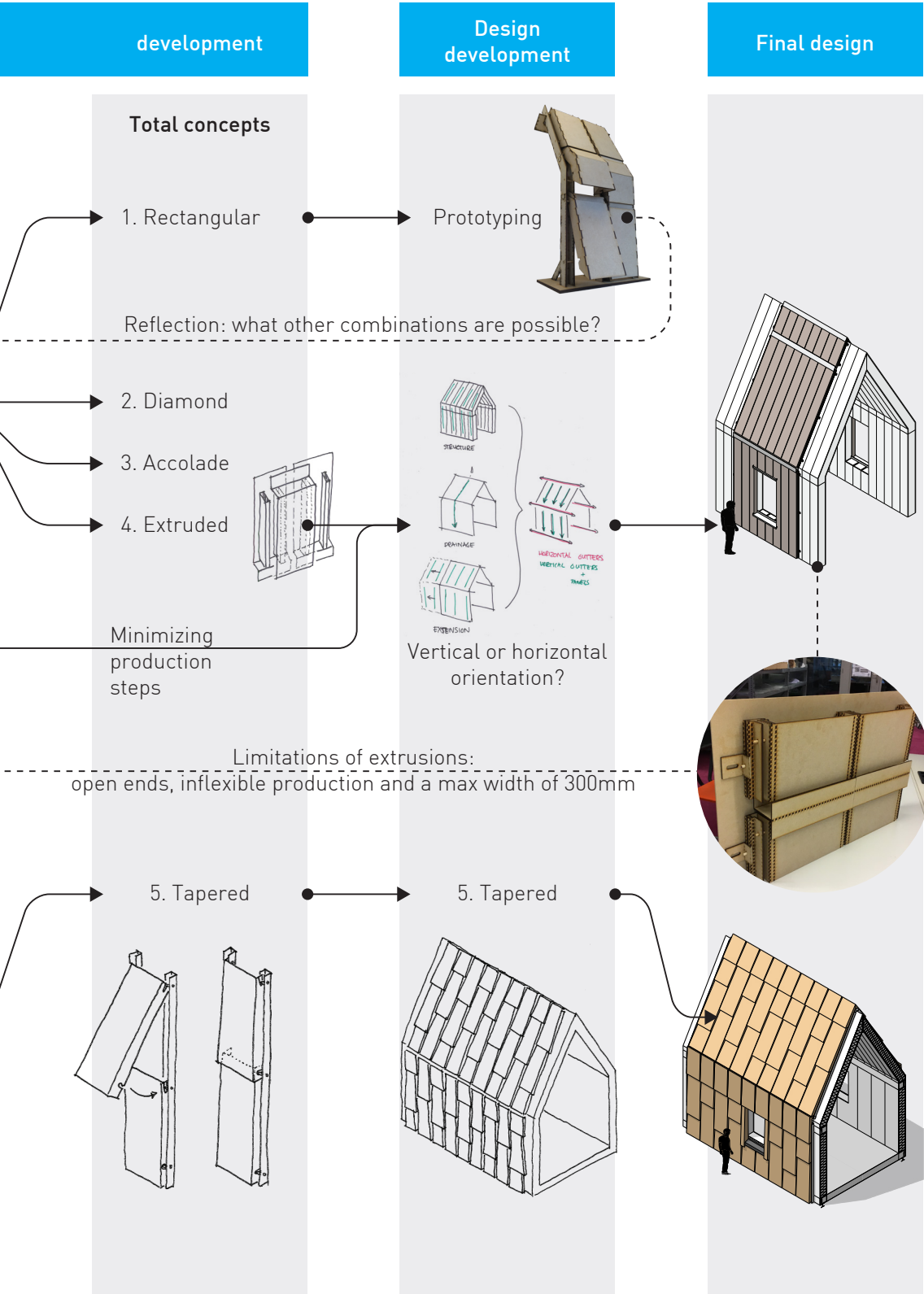


fig. 73. Decision making during the research process



elaborated towards a complete system and prototypes were made, but the advice was given to look for other aspect concept combinations as well, before completely elaborating this concept. This way, it was found that the methodology lacked an extra concept level, since a cladding system is more than the sum of the aspect concepts. Therefore, total concepts were introduced into the methodology. By making different aspect concept combinations, three extra total concepts were generated besides the rectangular total concept: diamond panels, accolade panels and extruded panels.

### **Design development, prototyping and final design**

The fourth one, the extruded panel total concept, was chosen for further elaboration because of the processing technique of extrusion and the seemingly large design freedom and fast and continuous production it allows. This total concept was elaborated towards a final design that was presented at the P4. However, the final design and a 1:1 prototype made very clear that extrusion is a processing technique with critical limitations for the design of a rainscreen cladding system. These limitations were: open ends, inflexible production on a maximum width of 300 mm. Furthermore, the proposed final design did not perform optimal in terms of tolerances and assembly.

As a result of the found limitations and the comments after the P4, a search for a new design with less complex details started. However, the design problems were strongly related to the processing technique on which the fourth total concept was based. Therefore, the decision was made to return to the concept development stage.

However, instead of choosing one of the other total concepts, a fifth total concept was generated. Interestingly, the aspect combination that led to this total concept had already passed a lot earlier in the design process. Due to doubts regarding the aesthetic performance of this concept, it was not elaborated at that moment. Apparently, the aesthetics criterion unconsciously weighed much heavier than the other criteria in the assessment of the various aspect and total concepts. When this realization came, together with the many potentials it had, this fifth total concept eventually was chosen and further elaborated towards a second final design.

## **9.2 Functionality of the methodology**

Although there were quite some moments during the research process at which a significant amount of time could have been saved, this was never caused by a wrong approach of the methodology itself, but rather a result of the fact that the methodology is not complete and needs further development.

Just like the material assessment and total concept assessment were added to the methodology during this research, it would be of great use if the methodology would focus more on the implementation of the building system in a circular economy. This could be done by adopting criteria regarding the economic, environmental, behavioural, societal, technical and governmental challenges that come with the transition to a circular economy.

Additionally, it would be good to find a way to make the methodology more objective. At the moment, the assessment of the concepts and the weighing for the criteria is quite subjective. This was part of the cause that the total concept choice had to be revised, since the assumptions appeared to be incorrect or incomplete later on in the process.

Furthermore, it was found that a change in material has far reaching consequences for the design, production of a product and its implementation in a circular economy. Because of this and the fact that the PD lab is based on industrial production, the methodology should focus more on processing techniques. More knowledge of the opportunities and limitations of different processing techniques would be of great use for future use of the methodology, as more optimal design results could be achieved in a shorter time.

Finally, it remains important to not lose the complete system out of sight, since development of a complete building system is ultimately the goal of the methodology. Besides the standard components, the critical components should be taken into account at a very early stage of the design process. This could be achieved by adding an system concept level, above the aspect and total concept levels.

### 9.3 Relevance of the results beyond the PD lab

Although the resulting cladding system design was developed for a specific case project, the relevance of this research goes beyond the PD lab. In terms of biobased materials, it shows the potentials of the industrial application of bio-composites in building composites. Furthermore, by explaining the importance of the circular economy and the technical consequences it has for the design of a building component, the transition of the building industry towards such an economy is brought a step closer.

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## Interviews

Willem Böttger (NPSP), 7th of February 2017, Questions regarding N8010  
Joost Vogtländer (TU Delft), 27th of November 2017, Life Cycle Assessment

## Conference visited

The Biobased (R)evolution, 12th of May 2017, Tilburg

# 11. APPENDICES

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Appendix A - Material criteria

Appendix B - Design criteria

Appendix C - Panel stiffness assessment

Appendix D - Extrusion total concept elaboration

Appendix E - Project flyer

## Appendix A - Material criteria

TOPIC	CRITERION	WEIGHT
BOUNDARY CONDITIONS	MARKET PRODUCT	● ● ●
	BIOBASED >50%	● ● ●
	WATER RESISTANT	● ● ●
DURABILITY	WATER ABSORPTION	● ● ●
STRUCTURAL PROPERTIES	DENSITY	●
	FLEXURAL MODULUS	● ●
DESIGN FREEDOM	SUITABLE PROCESSES	● ● ●
	AVAILABLE COLOURS	●
SUSTAINABILITY	BIOBASED %	● ● ●
	RECYCLING RATE	● ● ●
SAFETY	FIRE SAFETY CLASS	● ●
	MAX SERVICE TEMPERATURE	●
COSTS	COSTS	● ●

### Boundary conditions

#### Market product

This research is not focussed on the development of a new material. To keep the material selection compact, this assessment will only focus on materials that are already further developed and available on the market.

#### Biobased →50%

Due to the main focus of this research, the majority of the material's ingredients should be biobased.

#### Water resistant

One of the most important functions of a cladding material is to protect the layers of the building underneath against water.

## Criteria

### **Water absorption [mass.%]**

The amount of water absorbed by a material specimen as a percentage of its mass.

### **Density [g/cm<sup>3</sup>]**

Mass per unit volume.

### **Flexural modulus [MPa]**

The flexural modulus indicates the bending stiffness of a material.

### **Suitable processes [-]**

Indicates which processing technique categories (cutting, deforming, machining and moulding) can be used to process the concerning material.

### **Available colours [-]**

The number of colours in which the material can be delivered by the manufacturer.

### **Biobased % [vol. %]**

The share of the material that is based on organic, renewable ingredients.

### **Recycling rate [vol. %]**

Indicates what percentage of the material can be recycled into a product of similar quality.

### **Fire safety class [-]**

Fire safety classification according to DIN 4102.

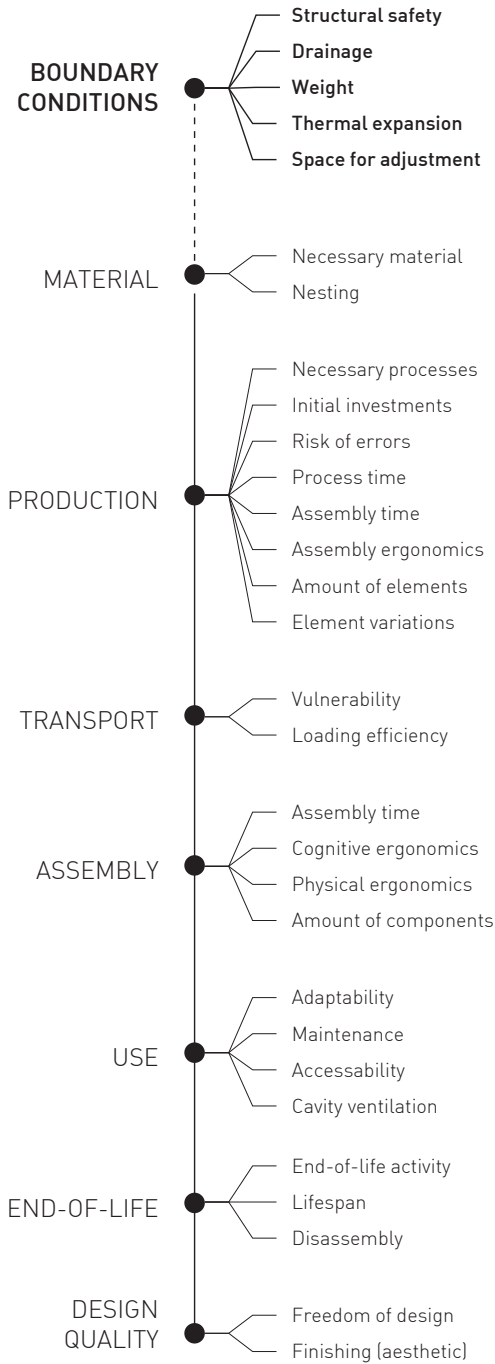
### **Max service temperature [°C]**

Highest temperature at which material can be used for an extended period without significant problems, such as oxidation, chemical change, excessive creep, loss of strength, or other primary property for which the material is normally used.

### **Costs [EUR/m<sup>2</sup>]**

The costs of a 1m<sup>2</sup> panel expressed in euros.

Appendix B - Design criteria



## Boundary conditions

### Structural safety

The cladding system should be safe under circumstances corresponding to wind area 1 within the coastal area, with a height of 10 m above ground surface. As the cladding system is part of a modular building system it should be able to operate in various settings and surroundings to accommodate varying location and user needs.

### Drainage

The cladding system should perform as a rainscreen for the underlying structure. The used material must be able to cope with climatological circumstances of wind, rain, UV and varying temperatures. The system has to be able to drain rain and snow down via the cladding layer. Water that penetrates the cladding layer must be able to escape from the cavity to the outside.

### Weight

The building system has to have the ability to be built with two persons. The cladding system has to follow this requirement. This means the components may not exceed a weight of 50 kg each. This comes from building regulations, where one person is allowed to carry 25 kg and two persons are allowed to carry 50 kg as long as the components are convenient in handling.

### Thermal expansion

The materials used for the cladding system can have a varying thermal expansion coefficient and may conflict with the underlying structure. The system should be designed in such a way it can cope with the thermal expansion of the cladding system and that of the underlying structure.

### Space for adjustment

In order to correct small inaccuracies in dimensions, building components have to allow some adjustment.

## Material

### Necessary material

The environmental impact of the design has an impact on the entire life cycle of the material needed. This includes the energy needed for all phases in the life cycle, toxics that are released during production, use and after its end of life and the ability to recycle the material at the end of its life.

**Nesting**

Nesting describes the efficiency with which a CNC-milling machine cuts out parts from a plate. Complex elements or component shapes can lead to nesting inefficiency. Protruding parts or curved objects are difficult to nest efficiently.

**Production****Necessary processes**

The number of necessary processes has a large influence on production time, costs and freedom of design.

**Initial investments**

The investment costs necessary to start up production.

**Risk of errors**

Errors in the production phase can lead to delay and material loss. And therefore should be avoided. Errors are often initiated by problems with the vacuum. Plates are kept in place by a vacuum while they are milled. When plates bend or slide due to the vacuum being not strong enough, a complete plate has the risk to be unusable. Small parts and large holes have a high negative influence on vacuum strength and should therefore be minimized.

**Process time**

Time needed to process the whole component before assembling it. This is the total milling time that is required. Including the production of nonmilled parts. Milling time may increase by using a special drill bits, large pockets or complex shapes with a high amount of corners.

**Transport****Vulnerability**

Protruding or fragile parts may be vulnerable for damage during transport and increase the chance of damage or asks for extra protective packaging around these parts.

**Loading efficiency**

Inefficient loading due to odd shapes or parts can lead to residual space in trucks or containers.



## Assembly

### Assembly time

The building speed depends on several aspects and is therefore also included as individual criteria. It resembles the total duration of on-site assembly.

### Cognitive ergonomics

The obviousness and ease of assembly, and the handling and understanding of the components assembly.

### Physical ergonomics

Amount and complexity (electric tools, costs, weight, force to be applied) of the tools that need to be used. Also the weight of the components itself can be optimized.

When these have a maximum weight of 25 kg they can also be handled by just one person.

### Amount of components

The amount of components required to assemble the building. These are milled elements, but also components or elements of other materials that are required to finish the building for different reasons. (foil, tape, etc.)

## Use

### Adaptability

The amount of adaptability can vary from a concrete building that needs to be demolished completely as one particular part is not sufficient anymore, until a building that can be taken apart in multiple pieces when they turn out to be outdated or damaged.

**Maintenance**

The possibility to replace broken components or parts of it.

**Accessibility**

The possibility and ease of the accessibility of essential elements for modifications, additions or partial disassembly by the user.

**Cavity ventilation**

The cladding material needs sufficient ventilation in the cavity to prevent accumulation of moisture and warping as a result.

**End-of-life****End-of-life activity**

The level of possible end-of-life activity (landfill, combustion, recycle, re-manufacture, reuse) of the module elements and the components as a whole.

**Lifespan**

The lifespan of the elements relative to the complete module lifespan. Elements and components should be able to survive at least one building lifespan. If the lifespan of single elements exceeds that of the component that it is part of, easy disassembly is desirable.

**Disassembly**

The ease, speed and possibility of disassembly of the components from the complete building as well as of disassembly of the components itself.

**Design quality****Freedom of design**

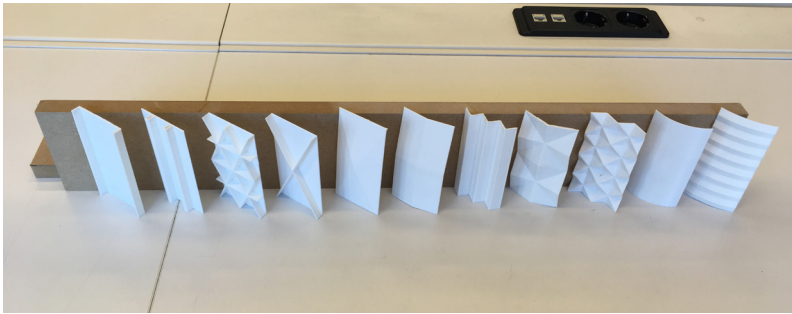
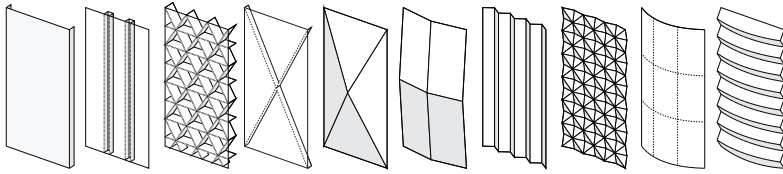
The influence of an alternative to the design freedom of the whole system. Starting from a building system which can create simple building forms, until a building system which can have more, and more complex configurations.

**Finishing (aesthetic)**

The level of finishing/detail of the cladding system depends on the detailing design. The cladding system needs a high level of finishing to give a high-tech appearance, e.g. preferably no visible screws. And searches for innovative solutions.

## Appendix C - Panel stiffness assessment

The purpose of the panel stiffness aspect is to find the most efficient shape. This means: the smallest deflection with the least amount of material. To find the most efficient shape, several conceptual panel shapes are 3D printed (same material, thickness and external dimensions), loaded and compared in terms of deflection.



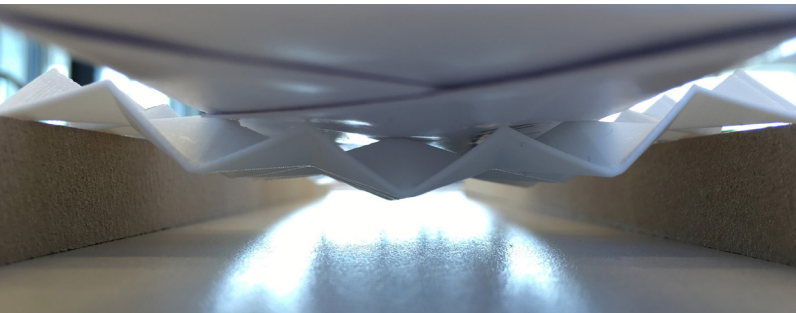
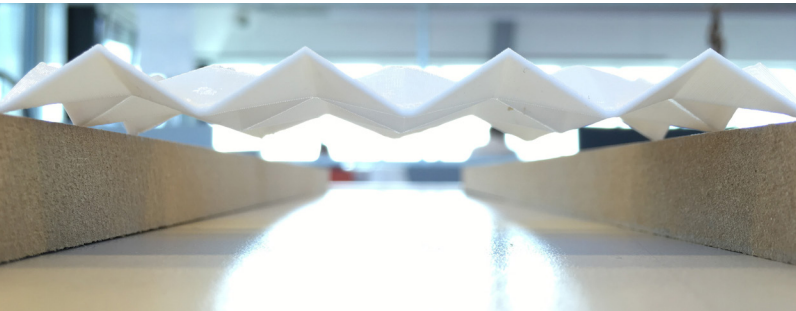
To say anything about the stiffness of a panel related to its weight, a stiffness-mass ratio will be used. The stiffness of a panel can be found by calculating or measuring its deflection under a certain load. The mass calculation will be reduced to area surface calculation, since the used material and thickness are the same for all test specimens.

Support

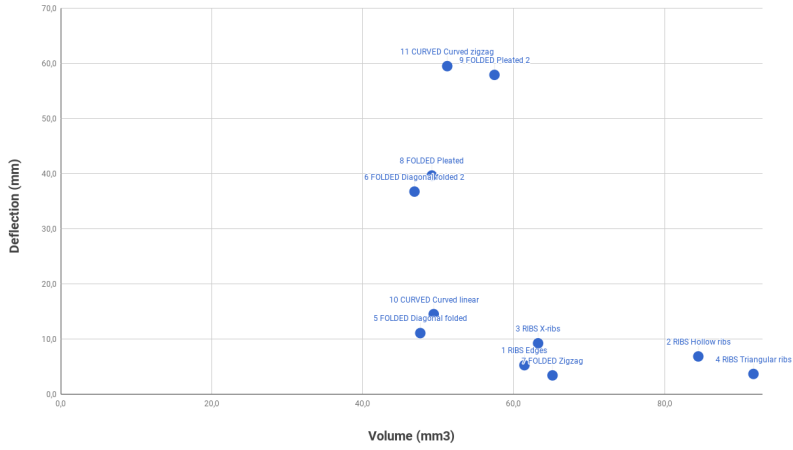


Results

The results of the deflection tests are visible in table 1. Since both a minimal deflection and minimal amount of material (indicated by the surface area) are desired, a minimal product of the deflection and the surface area, which is shown in the last column, is desired as well.

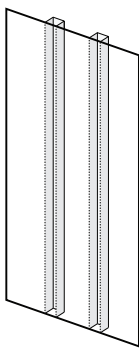


Panel shape		Deflection [mm]	Volume [mm3]	Deflection x volume	Normalized scores
Folded	Zigzag	3,4	6516	22	4
Ribs	Edges	5,3	6144	33	4
Ribs	Triangular	3,7	9179	34	4
Folded	Diagonal	11,1	4764	53	3
Ribs	Hollow ribs	6,9	8448	58	3
Ribs	X-ribs	9,3	6325	59	3
Curved	Curved linear	14,6	4942	72	3
Folded	Crossed	36,8	4687	172	2
Folded	Pleated	39,7	4917	195	2
Curved	Curved zigzag	59,5	5121	305	0
Folded	Pleated 2	57,9	5747	333	0

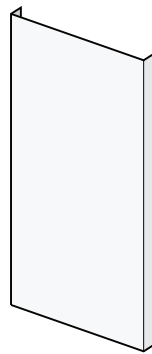


By looking at these products, some panel shapes stand out by their minimal product and thus their optimal shape in terms of stiffness and weight. The graph in above illustrates the difference in surface area (x-axis) and deflection (y-axis) even better.

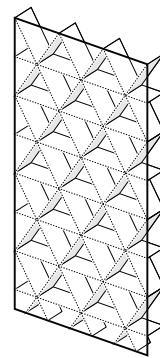
Eventually, the following three panel shapes are most optimal due to a minimum deflection x volume product value:



Folded Zigzag [22]



Ribs Edges [33]



Ribs triangular [34]

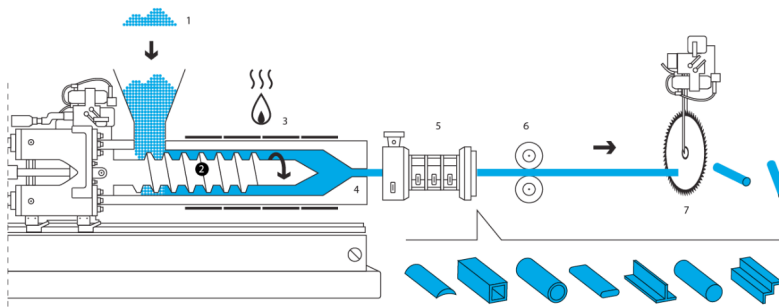
## Appendix D - Extrusion total concept elaboration

This appendix shows the initial design elaboration of the extrusion total concept. As explained, critical limitations were found which caused the shift to a different total concept.

### Extrusion

#### Processing technique

Extrusion is a processing technique that can be compared with pressing clay through a mould. As can be seen in the figure below, extrusion is done by melting material and pushing it through a die. This die has a specific shape and determines the cross-section of the resulting extrusion.



Source: Kula, Ternaux, Hirsinger, de Boer-Schultz & van Leeuwen, 2013

In order to design for extrusion and make optimal use of this technique, the essence should be defined first. When looked at an extrusion, it is clear that there is a lot of design freedom in the 2D plane of the cross-section, which is determined by the shape of the die. This enables for interesting design opportunities for the cladding system, such as the integration of the drainage or connections. On the other hand, however, designing for extrusions is limited in the sense that there is little design freedom in the linear direction. Therefore, a closer look should be taken at the orientation of the extruded panels.

### Points of attention

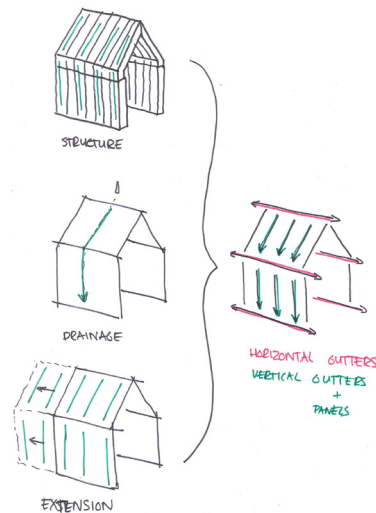
Just like every processing technique, extrusion has its own characteristics. One of them is the linearity in the direction perpendicular to the cross-section. While there is great design freedom in the 2D cross-section plane, the 3D shape is always linear as a result of the essence of extrusion: creating objects with a fixed cross-section. This has consequences for the possible joints between separate panels in the linear direction.

Another point of attention is the maximum width and height that can be achieved in the cross-section. For most extrusions, including those of Resysta, the maximum width and height is 300 x 100mm.

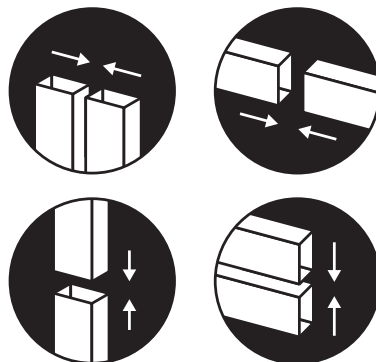
### Panel orientation

Since extrusions have a clear orientation as a result of the way they are produced, a decision has to be made whether to position the cladding panels vertically or horizontally.

When looked at the structure of the PD lab, a clear vertical orientation of components is visible. This also determines the direction in which a possible extension can be added. A vertical orientation would be advantageous for an integrated drainage system as well, since rainwater has to move from top to down by definition.

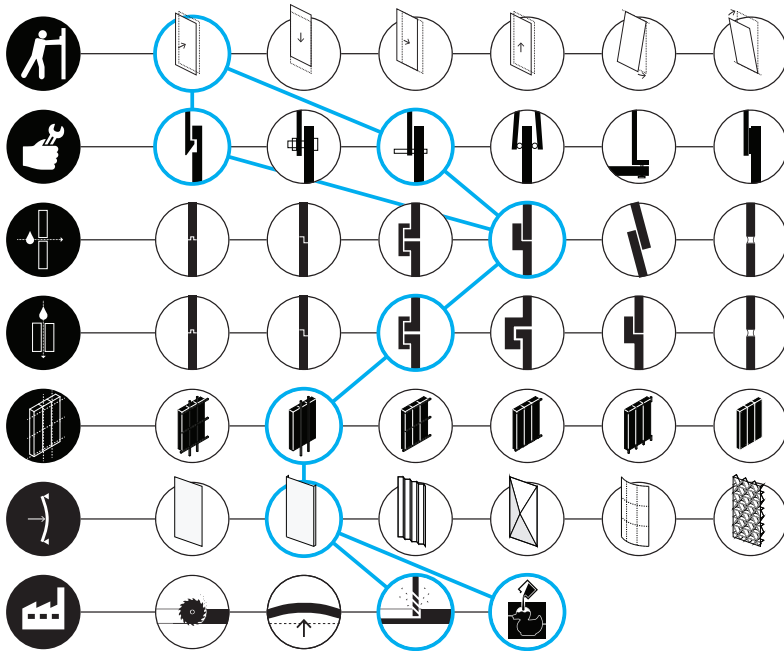


Therefore, the cladding panels will be vertically oriented and will be joined at the roof top, roof edge and bottom with horizontal profiles and gutters. The main challenge of a vertically oriented cladding system will be achieving a watertight horizontal joint in between the panels, since a vertical oriented extrusion has an 'open' top and bottom.



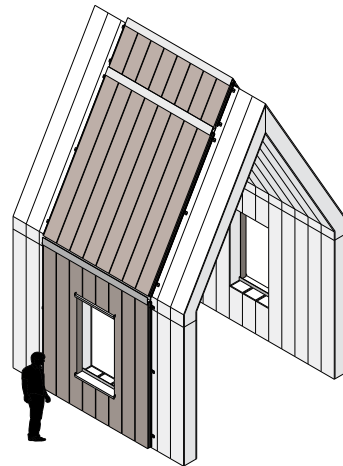
### Aspect concept combination

With the extra information about extrusion found in the last sections, a new total concept is combined from the aspect concepts. As explained earlier, the main challenge of a cladding system with vertically oriented panels is making a good horizontal joint between separate panels. This will be done by covering the open ends of the panels with a horizontal element.



### Final design

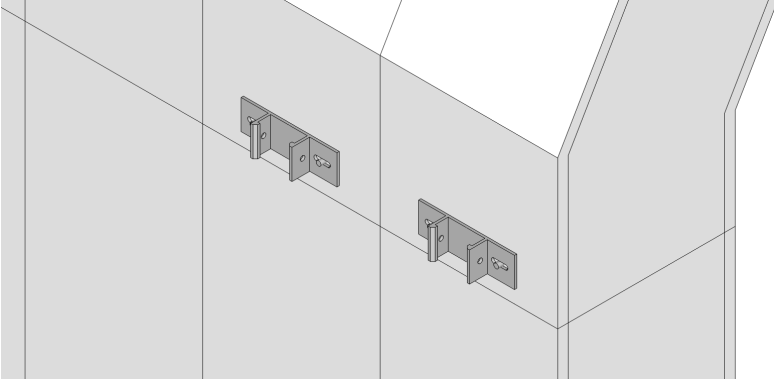
The final design consists of all the parts that together cover a principle section of the PD lab. Based on the orientation that was determined earlier, the system consists vertically oriented panels, which cover the largest part of the building, and horizontal gutters, which collect the rainwater let it flow into the vertical gutters underneath.



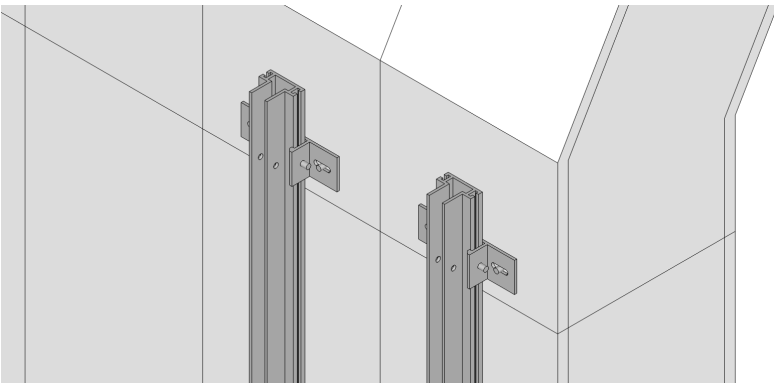


### Assembly

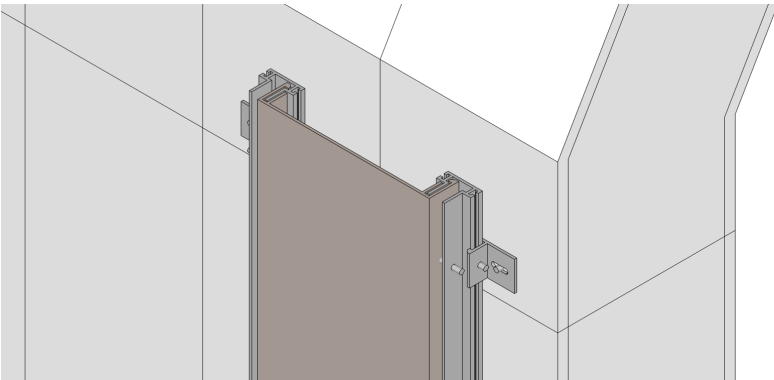
1. Aluminium brackets are mounted on the structure



2. Vertical gutter profiles, made of Resysta, are clicked into the brackets and fixed with T-bolts

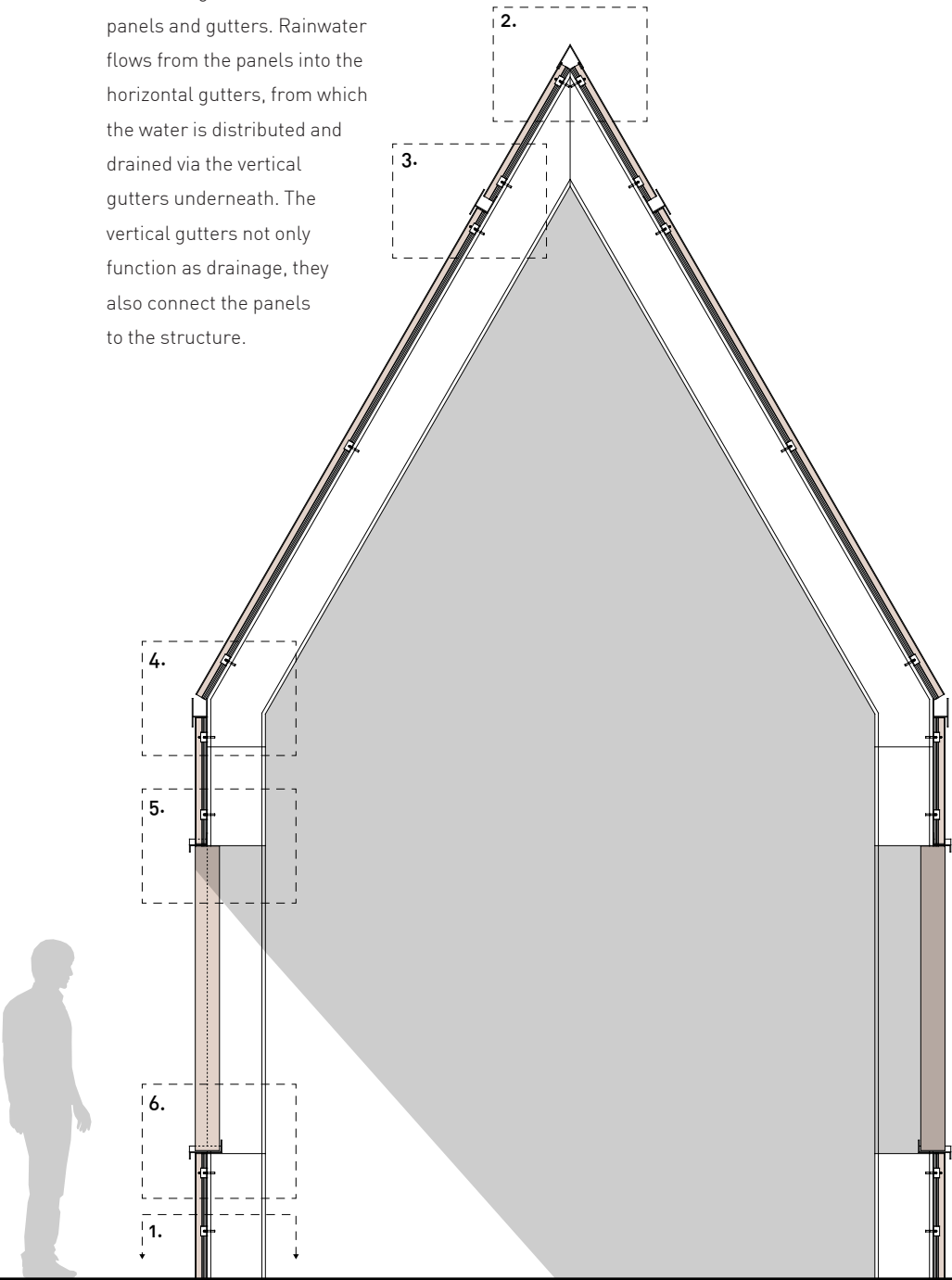


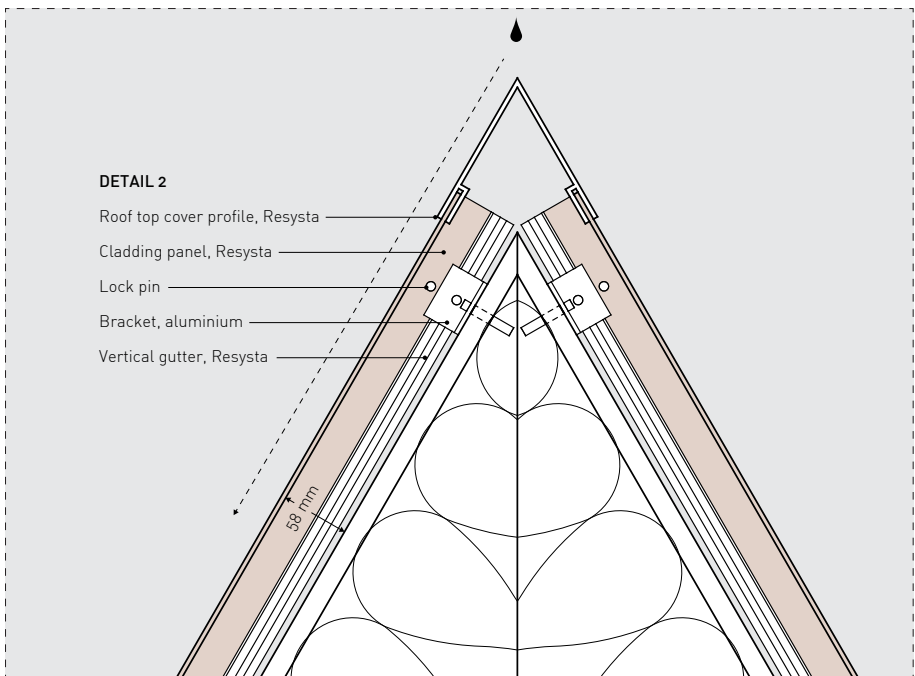
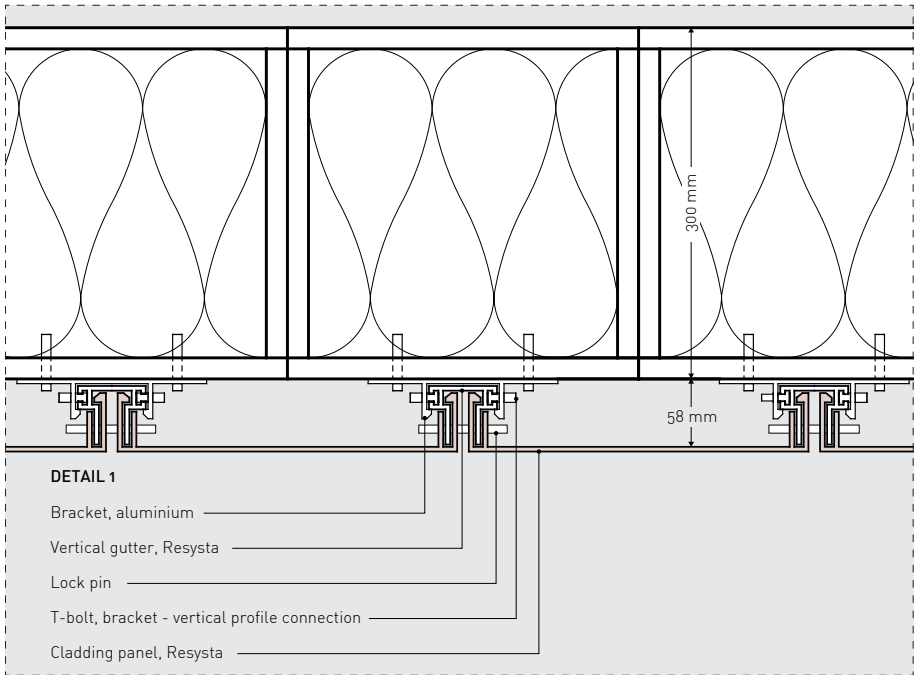
3. The extruded panel, made of Resysta, is clicked into the vertical gutter profiles and fixed in the vertical direction with a lock pin.

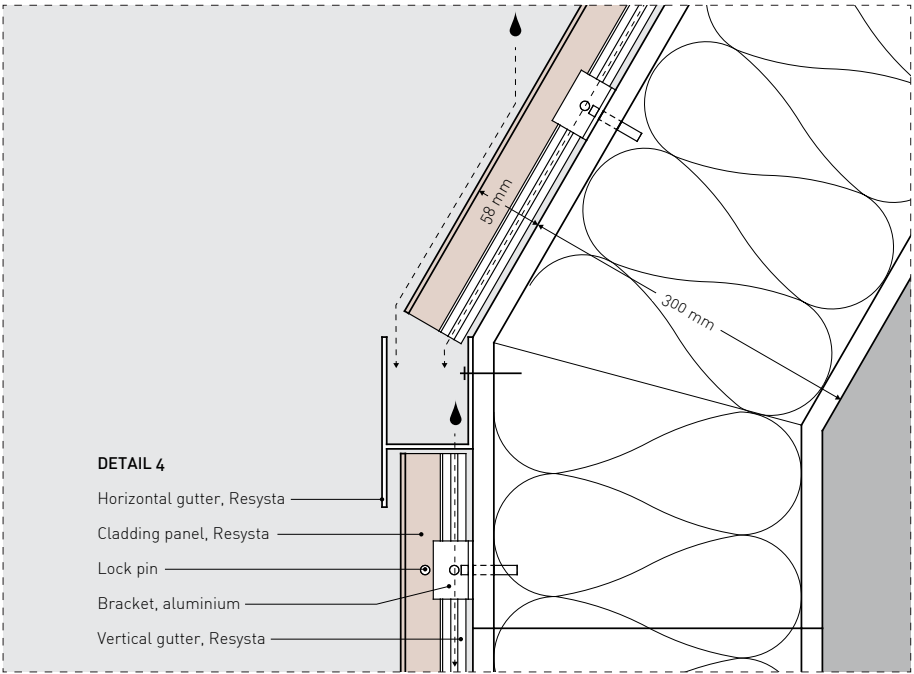
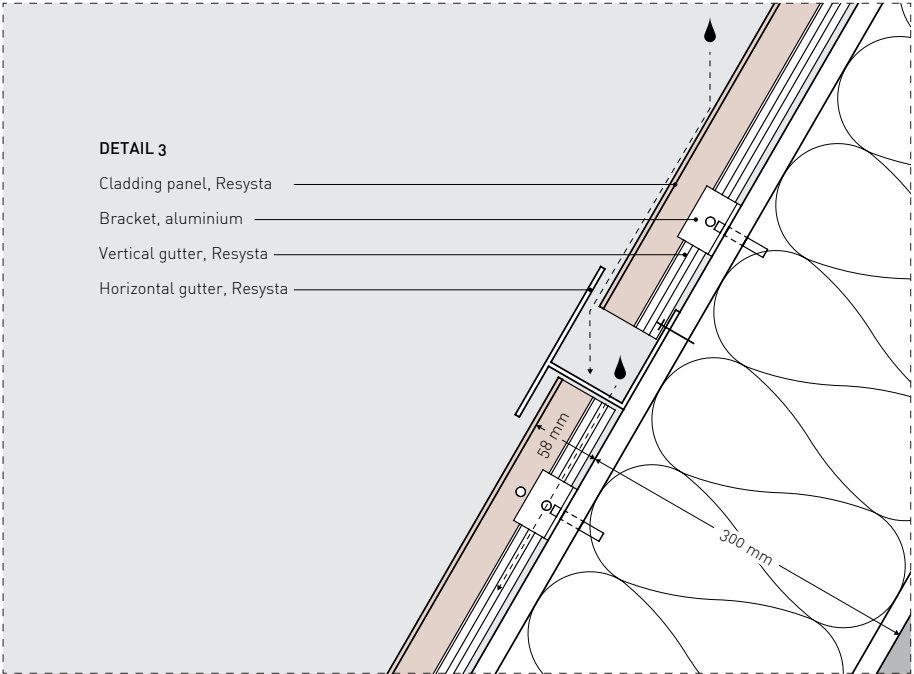


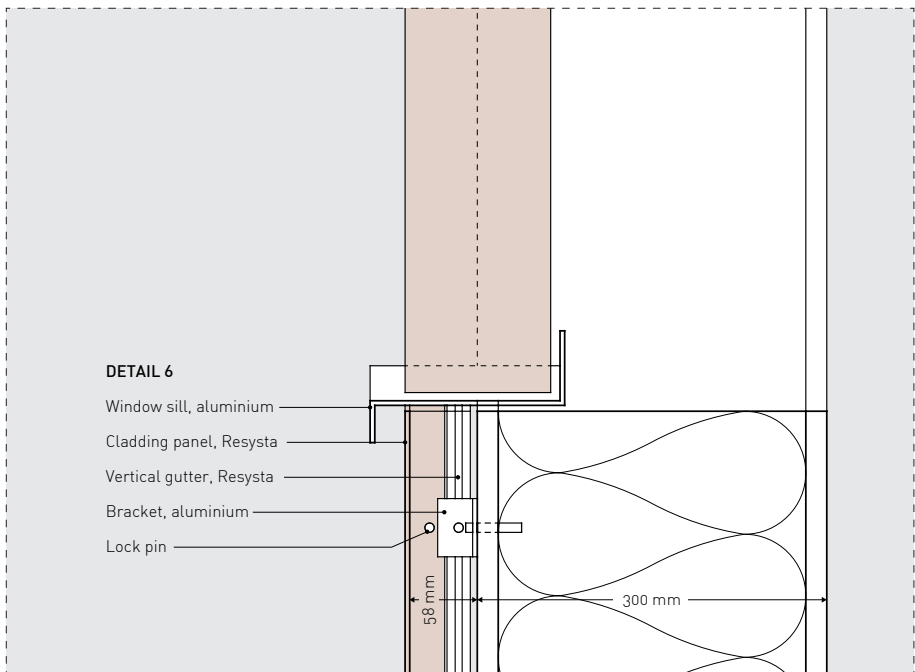
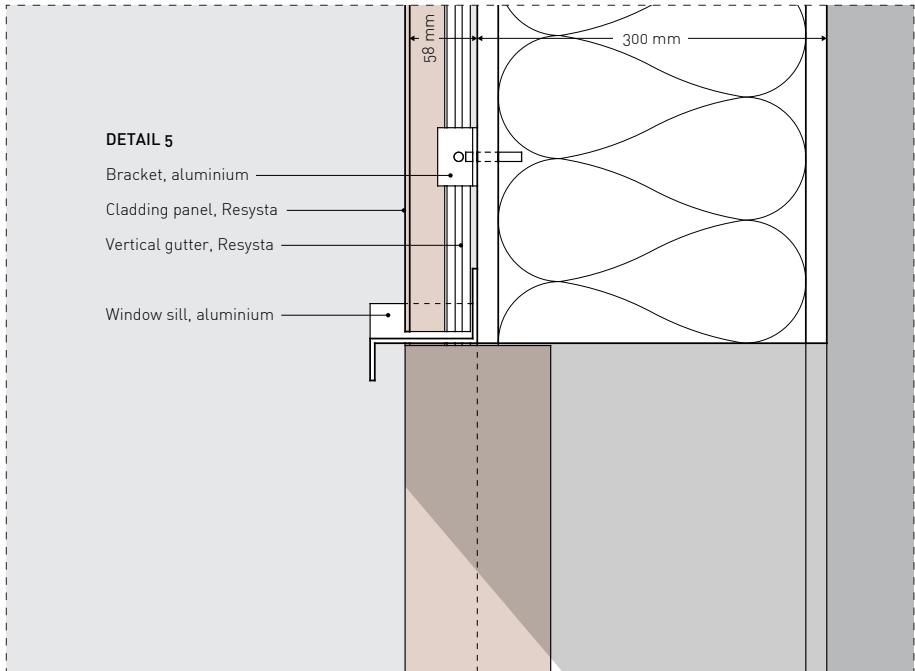
**Detailing**

The cladding system consists of horizontal gutters and vertical panels and gutters. Rainwater flows from the panels into the horizontal gutters, from which the water is distributed and drained via the vertical gutters underneath. The vertical gutters not only function as drainage, they also connect the panels to the structure.





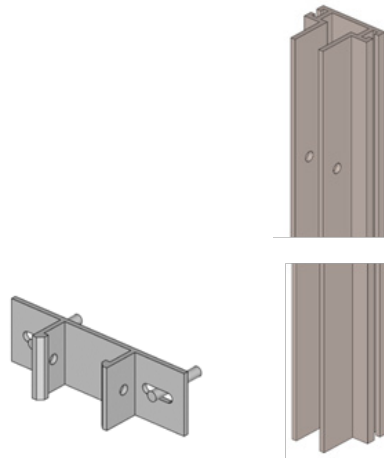




## Parts

Vertical profiles (cropped) and aluminium bracket

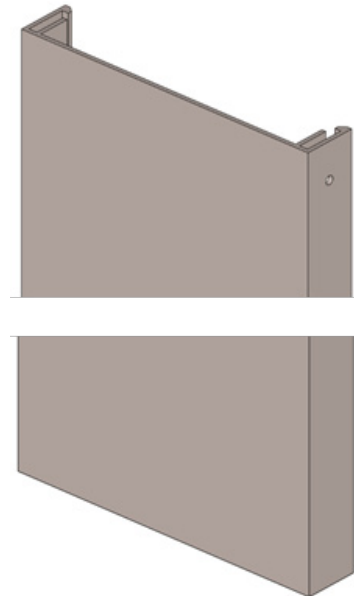
The vertical profiles are made of Resysta and function as vertical drainage. The standard profiles are 2900mm in length and have a cross-section of 50x58 in width and length. Standard available aluminium brackets are used to mount the vertical profiles to the structure. Together, they connect the cladding panels to the structure.



## CLADDING PANEL (CROPPED)

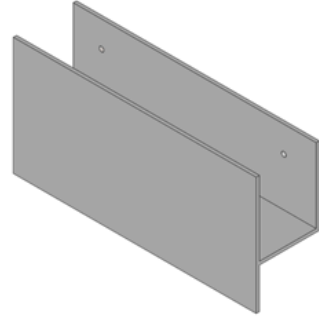
The cladding panels are extruded panels made of Resysta. The standard panels are dimensioned 290x2900 mm and cover the side and lower parts of the roof of the building. At the top of the roof, special dimensioned panels are used.

Thanks to the extrusion processing technique and the freedom of design in the cross-section it enables, a click connection could be integrated in the panel's shape. As shown in earlier, the panels are clicked into vertical drainage gutters and fixed with a lock pin.



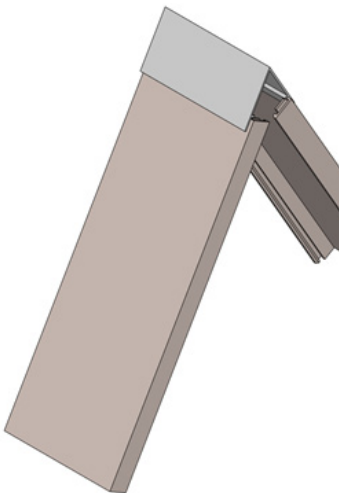
## HORIZONTAL RAIN GUTTER (CROPPED)

The horizontal profiles that function as rain gutter are made of Resysta. The profiles have a cross-section of 78 x 146mm in width and height and are mounted to the structure by screws. Since these profiles not only function as rain gutter, but also cover the horizontal joint between separate panels, a cover flange is added to the bottom (see detail 3 and 4).



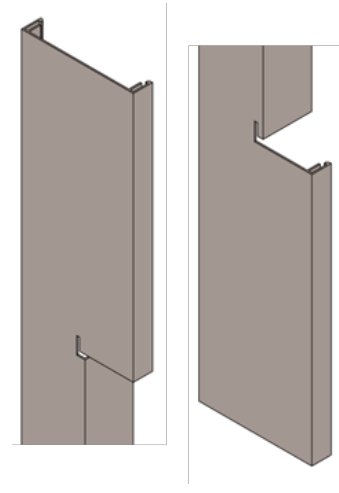
## ROOF TOP: COVER PROFILE AND CLADDING PANELS

Since the roof components of the PD lab are longer than the walls, an extension is needed to cover the full section. This extension is achieved by using cut off standard cladding panels with a cover profile on top. This profile is mounted to the cladding panels by double flanges that slide over the panels.



## WINDOW CLADDING PANELS (CROPPED)

In order to make an opening in the cladding while preserving a good drainage, special cladding panels are used. These panels are made from standard cladding panels. By milling and warm bending a part of these panels, a window cladding panel is made.



## Appendix E - Project flyer

This flyer was used to inform potential sponsors of the Resysta material about both the PD lab and my graduation project.



With sustainability getting more and more relevant, the building industry is looking for building systems that fit in a circular economy.

The Product Development lab is a research platform that connects theory and practice. It researches a new building

system that combines the modularity of Lego, the efficiency of Ikea and the scalability of Wordpress.

Modular and demountable components that are produced using digital manufacturing techniques (such as CNC-milling)

contribute to the sustainability and efficiency of this building system.

**More information:**  
<https://www.tudelft.nl/en/architecture-and-the-built-environment/research/research-facilities/pd-test-lab/>  
<https://www.fabfield.com/>

Digital manufacturing



Modular



Demountable





# Graduation project

**The development of a new biobased  
cladding system for the PD lab**

Within the PD lab platform, this graduation project focusses on the development and realization of a new cladding system made of a biobased material.

Thanks to the focus on theory and practice, this project will provide the participating company with valuable information regarding the application of the material in an innovative cladding product and its performance in practice.

Biobased  
material

Design  
development

Prototyping +  
Realization

Theory

Practice

## Graduate student

## Supervisors

Department of Architectural Engineering +Technology



**Mitchell Mac-Lean**  
MSc student  
Building Technology



**Prof. dr.ir. Tillmann Klein**  
Building Product  
Innovation



**Dr. David Peck**  
Climate Design and  
Sustainability



**Ir. Pieter Stoutjesdijk**  
Architectural  
Engineering



**Dr.ing. Marcel Bilow**  
Product  
Development





# Abstract

The building industry consumes a lot of energy, uses a lot of materials and generates a lot of waste. In order to achieve sustainable development, it has to change its focus from merely the use phase to the complete life cycle of buildings. The PD lab is an experimental platform that does so, by setting its aim to develop a modular and demountable building system that fits in a circular economy. In the spring of 2017, a prototype of the PD lab was built: the PD test lab. The cladding system that was applied, is made of an aluminium sandwich material, which is non-renewable, difficult to recycle and therefore not optimal for application in the circular economy. Biobased materials however are organic, renewable materials and might fit better in a circular economy.

This thesis researches the potentials of biobased materials for application as cladding material by developing a rainscreen cladding system for the PD lab. Based on a material assessment, the bio-composite material 'Resysta' is chosen as a starting point for the concept development. For seven aspects of the cladding system, which are: assembly, connection, horizontal joints, vertical joints, sub-construction, panel stiffness and processing technique, concepts are generated. The most suitable aspect concepts are then combined into five total concept. Initially, the total concept of extruded panels is elaborated. However, critical limitations of extrusion are encountered later on in the design process. These limitations are: open ends of the extruded panels and a processing technique which is inflexible, demands high initial investments and allows a maximum panel width of 300 millimeters. Instead, the tapered panel total concept is elaborated. Based on the design problems that were found during the construction of the aluminium sandwich cladding system, special attention is given to the functions of drainage, cavity ventilation, aesthetics, assembly, space for adjustment and thermal expansion. Eventually, a biobased cladding system for the PD lab is achieved that fulfils these functions.

In order to bring the PD lab and its cladding system to the next level, further research is necessary on biobased materials, the development of critical cladding parts, processing techniques and the integration of the system in the circular economy.