A CIRCULAR BIOBASED COMPOSITE FACADE

Research on a high performance and circular application of biobased composite on a facade

Marijn Flore Verlinde

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Marijn Flore Verlinde
4076982

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First mentor: Ir. Arie Bergsma
Second mentor: Ir. Rafail Gkaidatzis
External mentor: Ir. Christiaan de Wolf

Faculty of Architecture &
the Built Environment
Julianalaan 134
2628 BL Delft

DGMR Facade Technology
DGMR The Hague
Casuariestraat 5
2511 VB Den Haag

ABSTRACT

The building industry produces 40% of the total amount of waste in the Netherlands and almost all of this waste leads to landfill loading. This has been the start for this research into a circular biobased composite façade.

The question for building materials is expected to increase in the future and some common used materials impend to run out, therefore biobased materials could provide a solution.
Thereby is circularity often called as a solution for the material problems because when materials can keep performing, there is no need to discard them.

This thesis studies a high performance and circular application of biobased composite on a facade. During the research the focus was on office buildings in the Netherlands.

Biobased composite has previously been used for bridge design, and a few façades have been developed of which only one has been built today. These designs regard quite simple facades without windows or insulation, while for office buildings (especially the higher buildings) extensive safety requirements are obliged.

Because biobased composite is a material for which not many tests have been performed, the information, especially regarding safety requirements, is still scarce.

With help of specialists of DGMR a set of requirements has been defined. Besides the safety requirements the research focusses on different production methods and their environmental impact.

For circularity, different scenarios are defined, which are reuse, adaptation and recycling. Especially the connection methods between different parts are very important regarding circularity, because they define whether a part can be reused, adapted or recycled.

To establish the durability of coated and uncoated biobased composite for external use (when exposed to weather conditions as any facade is) two different material tests have been performed. The first test focusses on extreme temperatures while the second test simulates freeze-thaw cycles.

Eventually different common building products and facade typologies are compared to their biobased concept in terms of weight, thermal insulation and shadowcosts.
Thereby the circular scenarios of both the original element as the biobased concept are compared.

Overall it can be concluded that the durability of biobased composite is quite good when a safety margin for the bending stiffness is taken into account. The environmental impact is at this moment not better than that of most common building materials, therefore the shadowcosts require improvement. The materials does offer good options for designers, however requires more research and testing before large-scale application is possible.

The results of the research offers information on biobased composite useful for designers. Different subjects are circular design, a comparison between the environmental impact of common used building materials and manufacturing of biobased composite.

PREFACE

While writing this thesis, I have been very lucky to find many the people enthusiastic to help me.

At first I own a great deal to DGMR for offering the opportunity to perform my graduation research in cooperation with them. I would like to specially thank all the employees of DGMR who helped me finding specific information, and especially the four specialist who I have interviewed: Frank Lambregts, Johan Koudijs, Kevin Lenting and Jean Frantzen.
Furthermore I would like to thank my external mentor Christiaan de Wolf especially for sitting down with me weekly to structure my research, presenting it visually as clear as possible, but most important help me keeping track on the essence without wandering too much.

Thereby I would like to thank my main mentors.

At the TU Delft, Arie Bergsma always had a critical view, and in one hour of talking a hundred new ideas were offered, while always leaving enough space to create my own approach.

Rafail Gkaidatzis offered a lot of help with arranging the recycling and material tests and helped me keeping hope it would eventually be possible to carry them out.

For the material tests, SKG-Ikob offered the possibility to finally start testing the material. When my graduation was almost at its end, they offered their laboratory to carry out the tests and helped me to determine the test plan.

Dorine van der Linden helped me defining the material tests and even provided me with panels of biobased composite to use for test samples. Her prior thesis on biobased composite for bridge design offered a great starting point for this research.

I would also like to thank dr. ir. Fred Veer for helping me with the tensile tests, and explaining me how to interpret the test results.

Before I could test the samples, I needed to coat the material with a toxic two-component lacquer. To do this, Merel van Engelen offered me her artist workplace to coat them, while using her gas mask.

Last, I would like to thank my family for their support during this whole research. Not for the least for being to understanding for hearing not so much from me for the last months.

I would like to thank my father especially, who, as a building engineer himself, always taught me about all the aspects of a building since I was very little, and did this so enthusiastic that I decided to study Architecture.

Finally I would like to thank Samuel Verburg for understanding when I was stressed or busy, and his help and ideas for my thesis layout. And just as important, for providing me occasionally with a healthy meal when I didn`t take the time myself.

I`m very gratefull for all the support, and without everyone mentioned I would not have come this far.

Readers guide

To make the report easy readable, a layout with highlighted elements is used. Key phrases and key elements are given a yellow color to make them stand out.

After every paragraph, a text box is added summarizing the most important conclusions of the paragraph.

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INTRODUCTION

1.1 | PROBLEM DEFINITION

"The building industry produces annually twice as much waste as all the Dutch households together, and is therefore responsible for 40% of the total amount of waste" (SUEZ, 2016).

Constructing a building of 190 m2 nowadays means 3,6 tons of waste (Construction Waste Recycling, n.d.).

"Most construction waste goes into landfills, increasing the burden of landfill loading and operation" (Construction Waste Recycling, n.d.).

Most commonly used building materials require a lot of energy to be produced and cause a lot of CO2 emission during their production and demolition.

Many building materials can only be recycled while down cycling them significantly (down cycling means recycling in such a way that the new product is of a lower quality and functionality than the original product) or cannot be recycled at all which turns them directly into waste.

Just like all other sectors, the building industry needs to change its mind set and processes to play their role in the race against climate shift and environmental pollution. In the current course, materials often have a relative short lifespan regarding the high amount of energy that is used to produce and maintain them.

Problematic is that many resources will run out. Commonly known for running out is petroleum, however some daily used materials will disapear even sooner.

Many building components are constructed out of petroleum products or other finite resources. Petroleum products have in the past years turned out to be cheaper than their natural variant and have therefore often been used as replacement.

Some raw materials often used for building components only last a frightful amount of time, especially if we keep consuming them at the current rate. Some examples are lead, with 8 years, zinc with 34 years and copper with 38 years. Aluminum has a far larger raw materials stock, however is estimated to run out in 510 years (Frechette, 2009).

New material is needed to produce new building products since the building industry does not shrink.
Therefore one option is to expand the raw material market and explore new "infinite" options.

Solutions for building components could also be found in a circular building process. This enhances a smart use of materials, products and goods, so that they can be infinitely reused or recycled and form a closed circuit (Construction Waste Recycling, n.d.).

1.1 | Plastic-soup in the ocean
1.2 | Pre-impregnated flax fabric
1.3 | Pellets of biobased resin

1.2 | RESEARCH GOAL

In this reseach biobased composite is chosen to be further explored because of it`s fast growing fibres and design flexibility. In the past years many designers used composite in buildings, however the current process contains harmfull substances and requires quite some energy.

The aim is to explore whether a more environmental friendly composite material could be offered to designers while retaining the same design options current materials offer.
To do so, the circular possibilties of a facade design mainly constructed out of biobased composite will be explored.

The goal is too establish whether a biobased composite facade can be designed for office buildings in the Netherlands regarding it`s circular properties while designing according to the European and Dutch building standards.

At the same time a new building material is being research, which could possibly be used as a replacement for other building materials wich will soon not be available anymore.

Supportive of the design, several aspects need to be researched:
• The precise meaning of "circularity"
• The best application of circularity
• The properties of the material and the resulting possibilities and restrictions
• The quality demands of a facade
• The production methods and their environmental impact
• Additional materials and their environmental impact and circular possibilities
• General requirements for a facade

The results of the research into these aspects will form the design parameters which are important for the designed concepts.
Different concepts based on exisiting products or designs are developed.
The original elements and the proposed concepts will be analyzed regarding their weight, shadowcosts, insulation value and cirular scenario.

The choice for office buildings was made based on the fact that this group of buildings have very specific requirements regarding their facades, which are for other building types often less strict. Thereby DGMR is predominantly working on office buildings.

The building industry in the Netherlands will need to improve production processes and waste distribution in the next years.

The aim is to explore whether a more environmentally friendly composite material could be offered to designers while retaining the same design options current materials offer.

To do so, existing designs are compared to biobased composite concepts.

1.3 | RESEARCH QUESTIONS

To establish whether a circular biobased composite facade could decrease the environmental impact of the building industry, several research questions were formulated:

“What is possible with biobased composite when used for a circular facade design?”

1. What is biobased composite?

What is biobased composite, for what can it be used, and for what not?

Why application for façade design?

Which types of biobased composites are applicable to a facade design?

What are the first restrictions related to the facade quality demands?

Which production processes are useful to produce a façade?

What would be the best production technique regarding the environmental impact?

What does this mean for the façade design?

2. How can a biobased composite façade be designed circular?

What does circular mean?

How can biobased composite be used in the most circular way?

Which facade typologies are there, and which are most suitable for the design context?

How does this influence the façade design?

3. Final design

Pre-design:
How can the façade be adapted to meet the facade quality demands while keeping the circular aspects and material properties in mind?

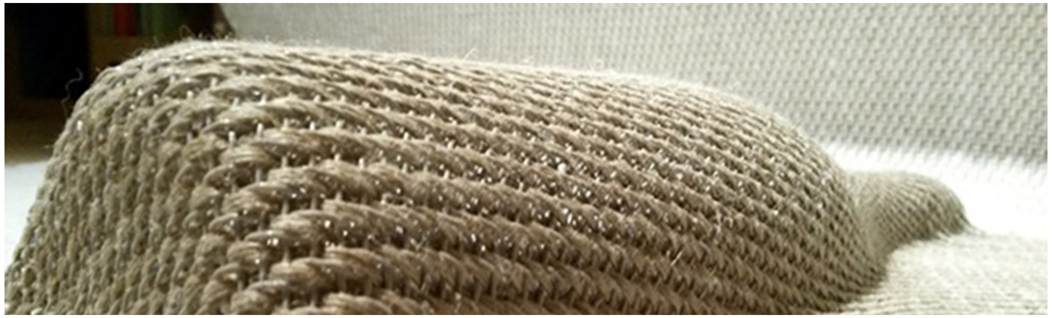
What are the effects of these adjustments for the design?

4. Design

What is the best biobased circular façade design regarding the quality demands?

How can the facade be produced and installed?

How does the façade relate to other facades in terms of lifetime, costs, production time, waste, CO_2 emission and energy?



1.4 | INTRODUCTION INTO BIOBASED COMPOSITES

1.4.1 | What is biobased composite?

Composites are an interesting material group since they are lightweight, strong, stiff, heat proof, have a long lifespan, high chemical resistance, and allow freeform designs. Another benefit from composites, is that by picking the right type of fibre and an applicable resin, the composites can be "customized" to fit a certain application.

Fibre-reinforced composites contain fibres providing the structural strength and a resin bonding the layers together and adding several more beneficial properties to the material (Polyproducts, 2016). The fibres are often placed in differently orientated layers providing strength in different directions. Especially for outdoor purposes a coating is added to provide a certain color, protection (for example against UV-radiation or moisture) and safety, such as fire safety.

At this moment, the waste management of the end of life streams still is a huge challenge.
Commonly used composites are glass fibre reinforced composites and carbon fibre reinforces composites, mainly used in the construction industry and automotive sector because of their high strength and low weight. Only in the Netherlands, already 25.000 boats and lots of military airplanes, predominantly made out of finite source based composites, are waiting to be demolished (Waterrecreatie advies b.v., 2015).

The alternative of finite resource based composites are biobased composites. This is fibre-reinforced material which is partly or completely made from renewable materials. Both the fibres as the resin can have a natural origin, based on natural resources (Wageningen University & Research).

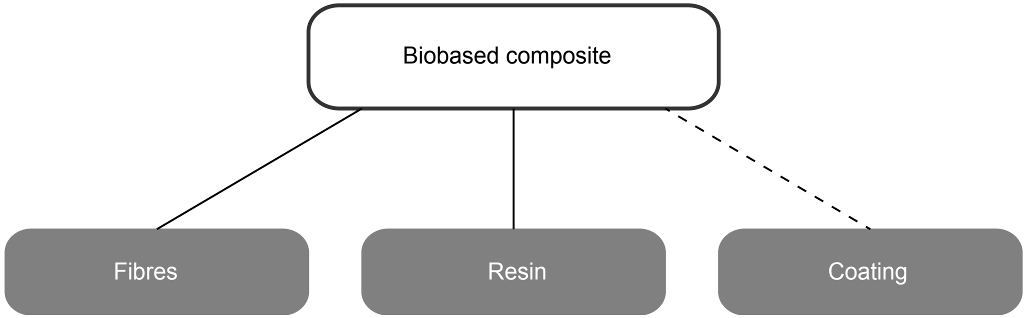
Examples of natural fibres are flax, hemp, silk, cotton and grass. Natural fibres are divided based on their origin, namely whether they are coming from plants, animals or minerals. The main components of natural fibres are cellulose, hemicellulose, lignin, pectins and waxes (John & Thomas, 2007). "The major attractions about green composites are that they are environmentally friendly, fully degradable and sustainable" (John & Thomas, 2007, p. 4).

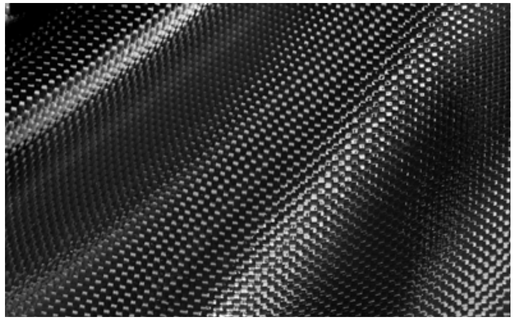
In most work, "green composites" is referred to only for wholly biobased composites, in which both the fibres as the resin are from renewable resources.

Biobased composites can have the same benefits as non-biobased composites but are made from self-growing, infinite, natural resources with low energy demand. Most of the production techniques for non-biobased fibres reinforces composites are applicable for biobased composites.

Biobased composites are fibre-reinforced materials that are partly or completely made from renewable raw materials.

Examples of natural fibres are flax, hemp, silk, cotton and grass.
The major attractions of green composites are that they are infinite and fast growing, have a low energy demand and are therefore much more environmental friendly than their non-biobased variant.





1.4 | Shaped biobased composite
1.5 | Pre-impregnated flax fabric
1.6 | Glass-fibre woven
1.7 | Carbon-fibre woven
1.8 | Concept of biobased composite

1.4.2 | Applications

“Vegetable fibres, extensively explored since 1990 by research institutions and automotive companies as an environmentally friendly alternative to traditional glass fibre reinforcement, are characterized by low density. Moreover they are low costs, and they are intrincically biodegradable”. (Zini & Scabdola, 2011. p. 1).

”At the beginning of this century, polymers reinforced with natural fibres started to be industrially applied, not only in the automotive and building sector, but also in the broad area of consumer goods”. (Zini & Scandola, 2011. p. 1).

The mechanical properties of natural fibres compared to those of glass, carbon and aramid fibres, are lower. However if the difference in density is taken into account, the specific mechanical properties of natural fibres come closer to those of synthetic fibres. Additional advantages of natural fibres are renewability, biodegradability, nontoxity, good insulation properties and low machine wear. (Zini & Scandola, 2011).

Most studies focus on vegetable fibres, and in particular on bast fibres (hemp, jute and kenaf) for their good mechanical properties and the fact that the fibres are easily divided from the cementing fibres in the bast.
However, unlike synthetic fibres, vegetable fibres have significantly greater variability in their mechanical properties as result of different reasons:
- age of the plant
- geographical influence
- climate influence
- harvesting method, etc.

Globally flax and hemp are cultivated dominantly in temperate regions, while in tropical regions jute and kenaf grow better.

There are three different issues to overcome when applying vegetable fibres for industrial application:
- the variability of fibre quality
- changing geographical availability
- their tendency to absorb water

(Zini & Scandola, 2011).
John and Thomas (2007) also set out that the structure, microfibrillar angle, cell dimensions, defects, and the chemical composition of fibres are the most important variables that determine the overall properties of fibres. In general the tensile strength and young`s modulus of fibres increases when the cellulose content increases.

Another positive property of biofibres is, according to John and Thomas (2007), that biofibres are nonabrasive to molding equipments and other machinery necessary for the manufacturing of products. This can positively effect the production costs. However the most interesting aspect is their positive environmental impact.

Biobased composites is applicable to a wide range of applications, and still new applications are being developped.
The application possibilities depend on the exact composition of the material, the fibres, but more importantly the resins define for which purposes the material can be used.

So far, biobased composites are used for:
- Car bodywork parts
- Indoor and Outdoor furniture
- Flower pots
- Panels and cladding for Architectural puposes
- Extruded profiles
- Doors
- Facade panels
- Casing of electronic equipment
- Packaging material
- Sanitary
- Scooter sheeting
- Pedestrian bridges

Composite manufacturer like NPSP and Polyproducts produce biobased composites now, and are expanding their range of products.

1.5.1 | Worlds first biobased composite facade

The first biobased composite facade was designd for a gas receiving station, Argo&Food Cluster Nieuw Prinsenland in Dinteloord (NPSP, 2013).

This was the first biobased composite façade in the world (disregarding wooden facades). It was manufactured by NPSP and designed by studio Marco Vermeulen.
The design concerns a rather simple facade, since the facade presumably has no windows, no insulation or sound of air proving. The composition of the used composite is unknown, as well as the exact structure of the facade and it`s properties.

Since the facade is designed for a gas-receiving station, the panels picture the chemical composition of gas. The panels were made using a mold.

This is the first project made with biobased composite for facade purposes and therefore an important reference for the research. Unfortunately little information on the project is public.

Advantages of natural fibres are renewability, biodegradability, nontoxity, good insulation properties and low machine wear.

There are three different issues: The variability of fibre quality, changing geographical availability and their tendensy to absorb water.

The application depend on the exact composition of the material, the fibres, but more importantly the resins define the application possibilities.

1.9 | Hemp fibre
1.10 | Biobased composite and natural fibre
1.11 | Self-supporting biological composite facade panels
1.12 | Self-supporting biological composite facade

1.5.2 | The BioBuild project

The aim of the BioBiold project was to use biobased composite materials to reduce the embodied energy in building facades by at least 50% over current materials without increasing the costs (Stevensons, 2014).

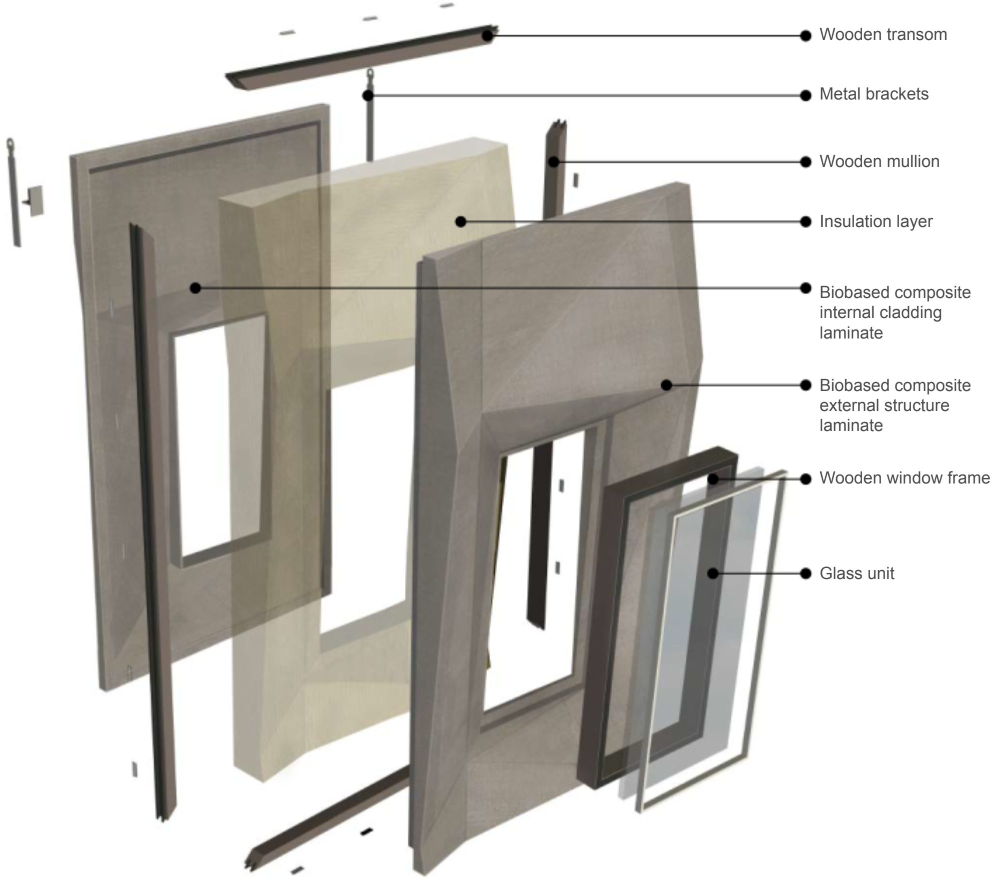
For Arup Germany, the task was to develop four buildings systems as case studies, namely:
• An external wall panel/ unitized facade system
• External cladding kit/ rain screen system
• Internal partition wall/ internal partition system
• Suspended ceiling kit/ architectural ceiling system
For this research, the external wall panel and he external cladding kit are most interesting, therefore these designs are explored further.

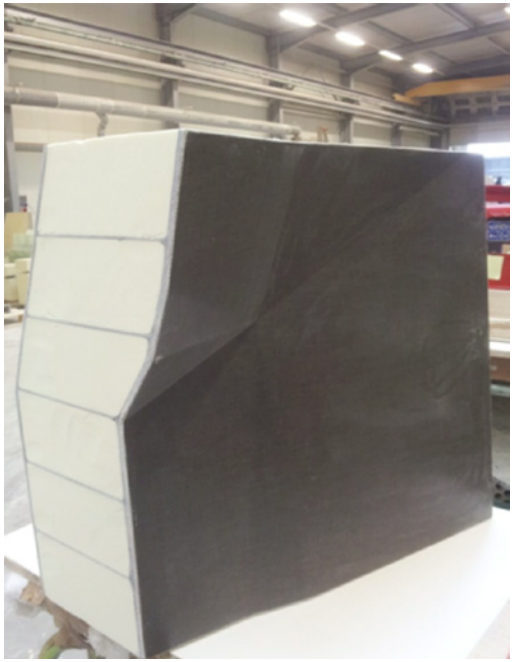
1.5.2.1 | External wall panel

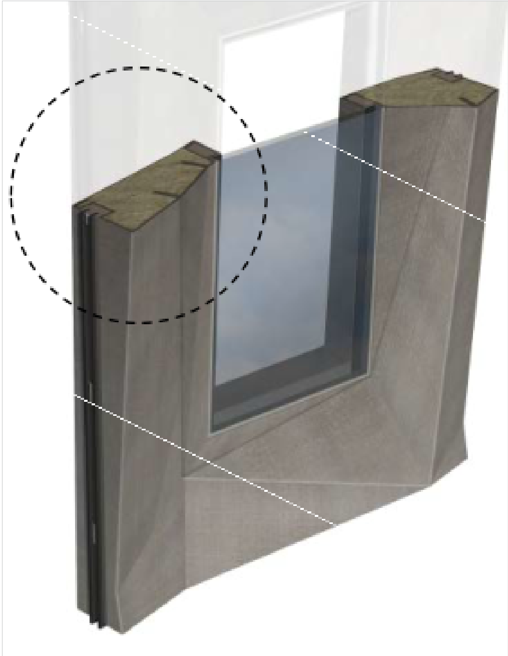
The design concerns a four meter high panel which is self-supporting and has high thermal and acoustical properties. One panel is 2,5 meter wide.

The facade element is made out of flax fibres and biopolyesther (Cardno, 2015).

The panel consists of an exterior structural panel and an interior panel with wood-fibre insulation in between. The panel has a designed life time of 30 years (Carra, 2014).







However, as showed in the mockup, the insulation layer is not made out of wood-fibre insulation but PUR foam. Why the choice was made to design the panel with a non-biobased insulation layer is not clear. It could be linked to the availability, fire-safety or costs.

Unclear is also what will become of the facade elements after this estimated lifetime of 30 years. Since biobased composite is often not biodegradable, the panels can presumably only be thrown away.
Since there are no connections showed, it is likely that all elements are glued together. For the insulation layer it is sure that this material is glued to the exterior laminate and shaped to be strongly connected, see the picture below. If all connections are glued, it will be very difficult to demount the panels. Even if parts of the panel are reusable, recycleable or compostable, the layers are very difficult separatable.

This example shows a more technical developed facade design, however the demolition phase is not designed and this will influence the environmental impact of the product significantly. Besides this, for unclear reasons the insulation layer is not biobased.

1.13 | Impression of the panel
1.14 | Impression of the facade
1.15 | Construction of the panel
1.16 | Part of the mockup
1.17 | Section of the panel

1.5.2.2 | External cladding kit

The external cladding kit exists out of a long-span panel which is lightweight. It is a prefabricated system which reduces the installation time. The metal sub-structure is customized and has the shape of a -profile (Carra, 2014).

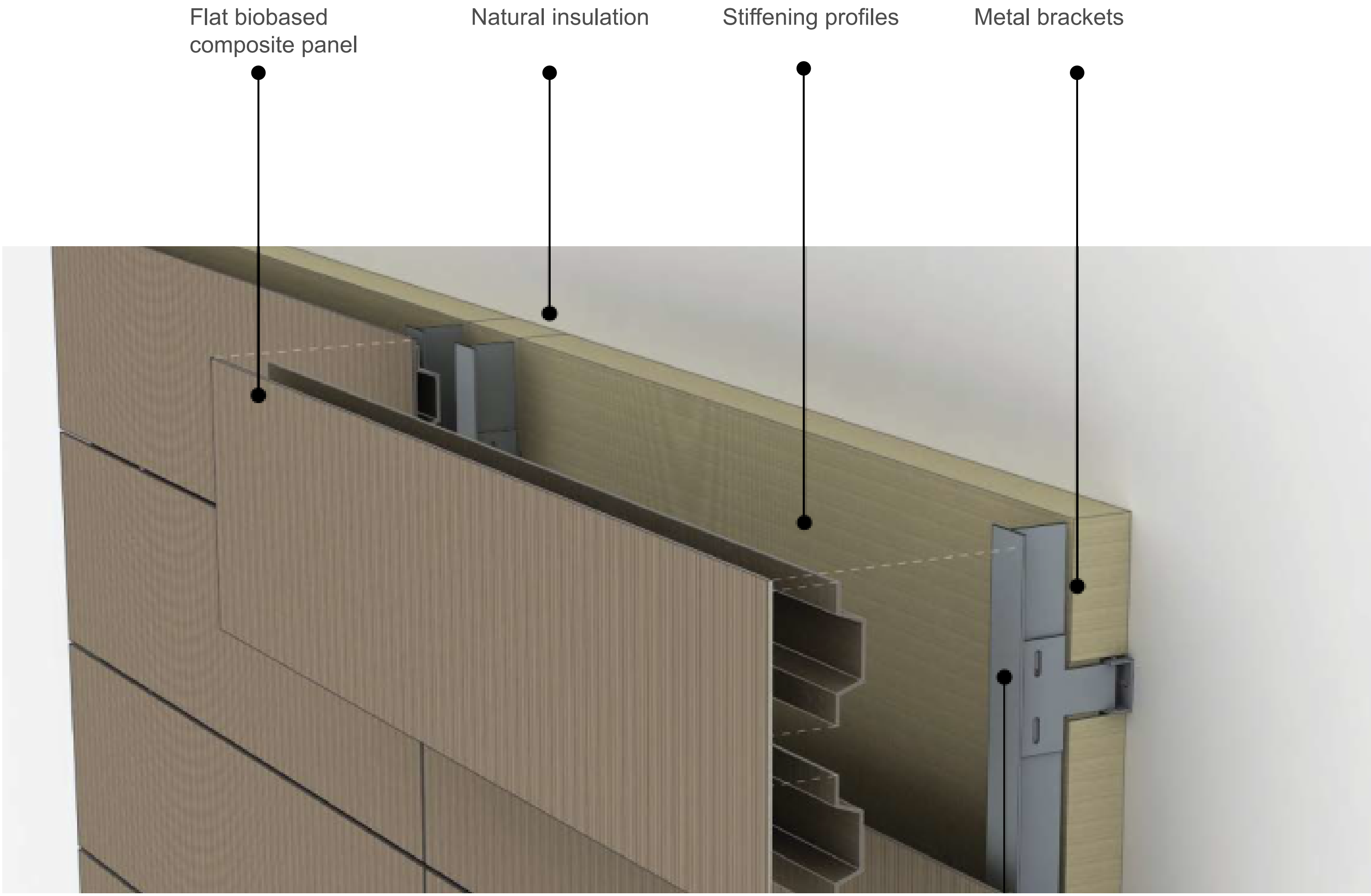
One panel is 2.5 meter wide and half a meter high. It is constructed out of one flat panel with two stiffening profiles behind it. These profiles are attached to the substructure (Carra, 2014).

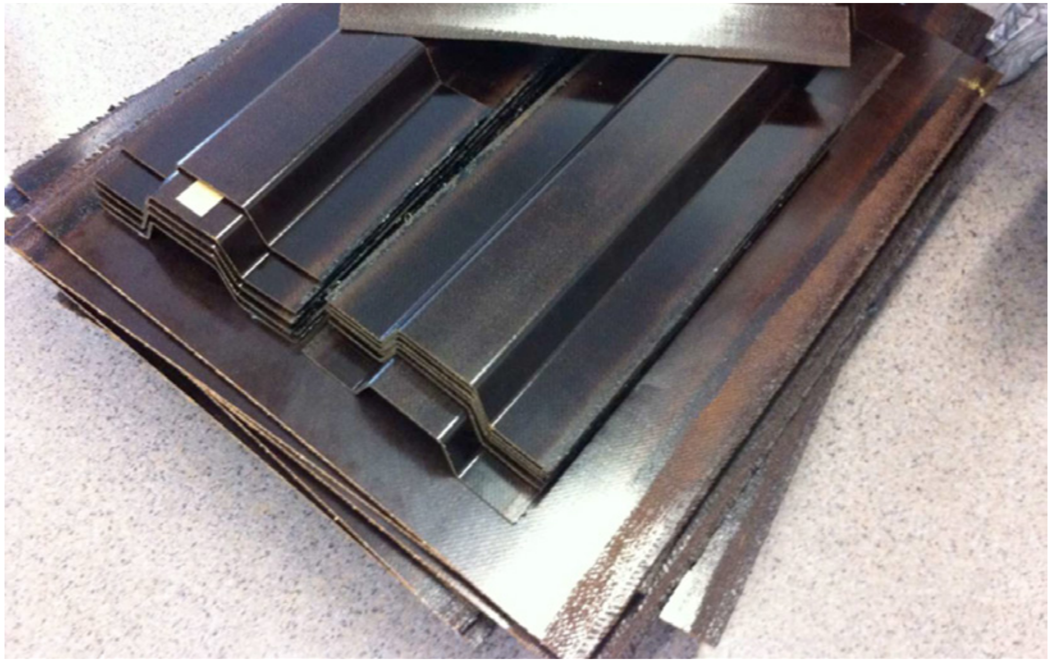
The actual connections are not shown, but the connections between the substructure and the panels need to be a mechanical one, presumably bolted. The connections between the stiffening profiles and the flat panels are presumably glued, since no bolts, screws or rivets are visible.

The natural insulation is now directly behind the panels, which are the first water barrier. This means that the insulation will be confronted with water and moisture. For most natural insulation materials this will mean that they need to be impregnated with environmental harmfull substances or that foils need to be added. Both options are reducing the biodegradability of the construction.

Samples of the profiles have been made, using semi-continuous compression molding. The material for the profiles was a flax textile with a furan resin and a cork core.

Other than the wall panel case, different materials in this design are only mechanically connected. This means that they are quite easily demountable and separable, which increases the possibility to reuse, recycle or compost them.





1.18 | Impression of the cladding kit
1.19 | Used biobased parts
1.20 | Shaping the stiffening profiles
1.21 | Shaping the stiffening profiles

There are some former projects in biobased composite. Little information is known on these designs.

Of all designs, the connections between biobased composite elements and other elements is not clear, however it is likely that the designs are not easily demountable and therefore difficult to re-use, recycle or compost.

1.5.3 | Biobased composite pedestrian bridge

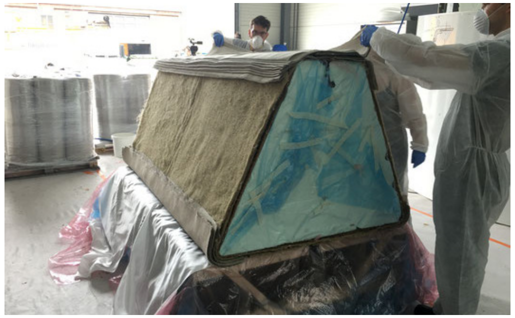
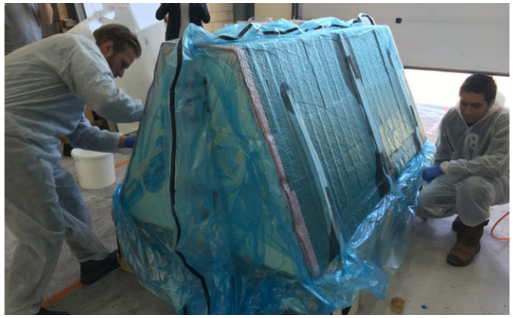
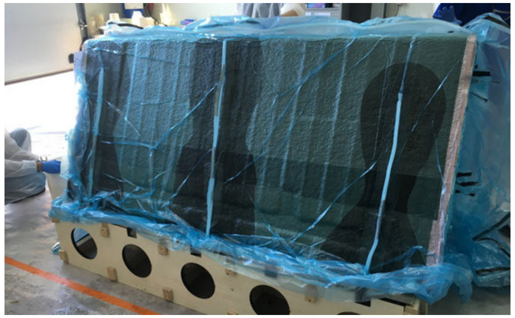
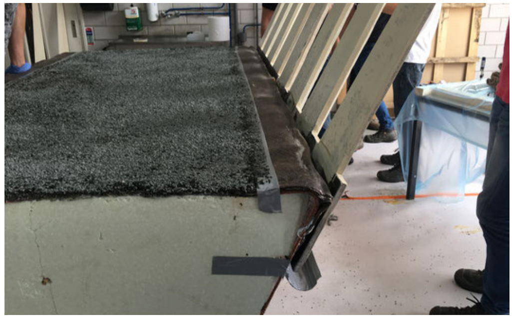
The fully biobased composite pedestrian Bridge was designed and build by a 4TU Lighthouse project. (De Architect, 2016).
The design concerns a fourteen meter self-supporting bridge which is completely built up from biobased materials.

The composite consists of hemp and flax fibres, with a core of biological PLA-foam and cork. PLA or polyactic-acid is a biodegradable and bioactive thermoplastic aliphatic polyester derived from renewable resources, such as corn starch, tapioca roots chips or starch or sugarcane (Wikipedia, 2016).

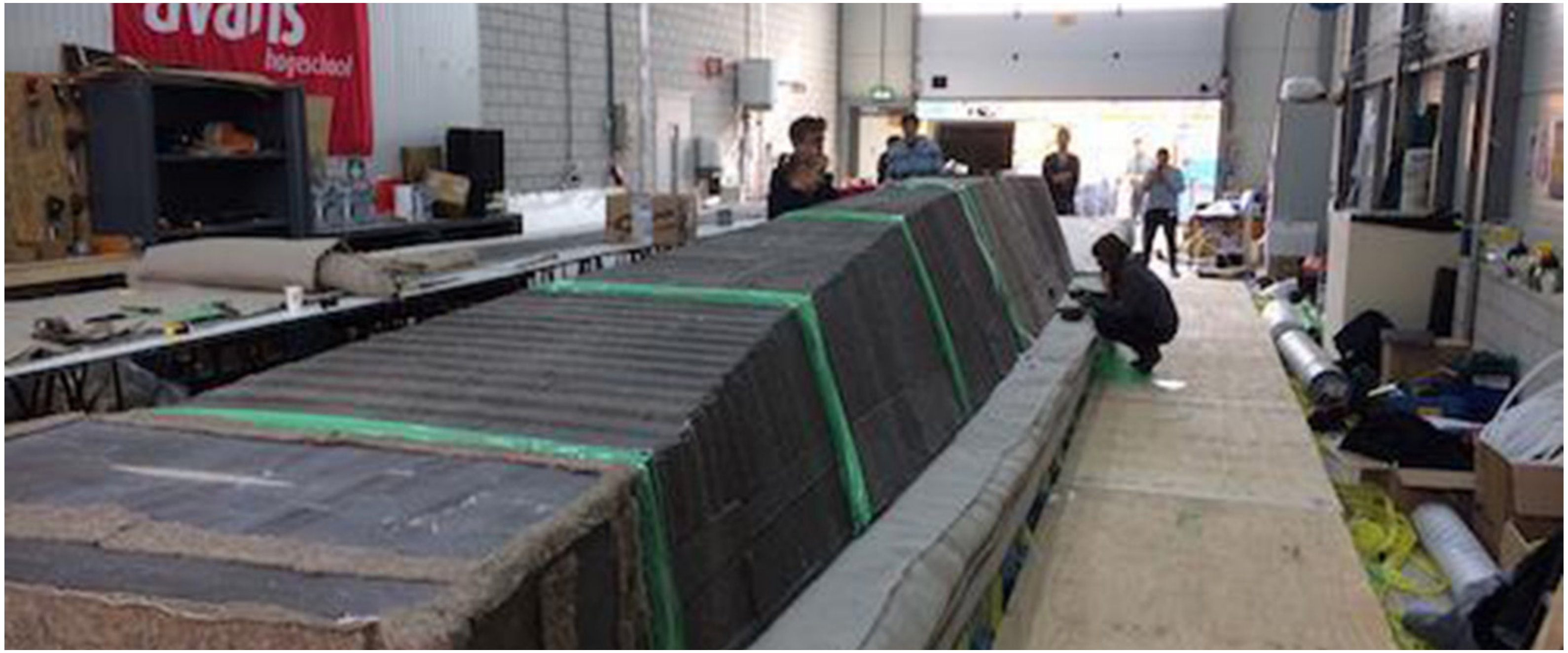
The bridge is placed over a small stream on the campus of the Technical University Eindhoven, and will be monitored for deflection for a whole year.

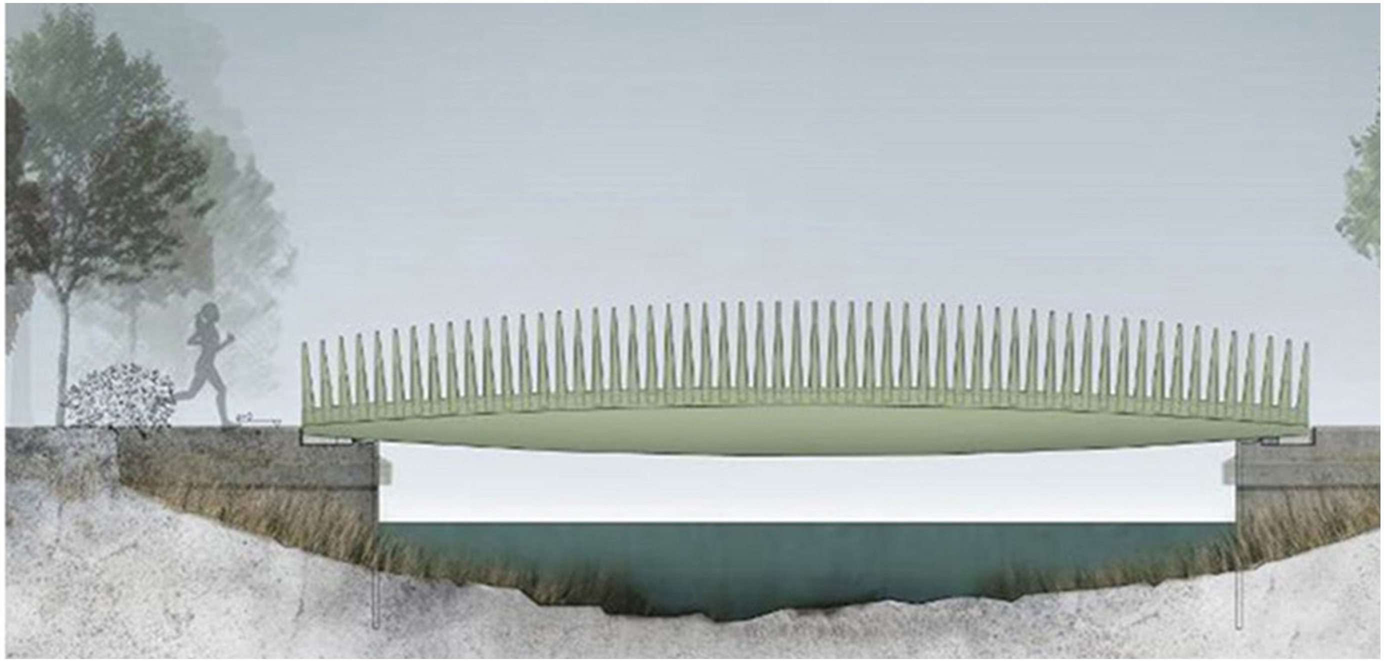
To establish how the bridge should be built exactly, a mochup was made by students prior to the actual construction. On the right some steps of the manufacturing are shown.

This project was a collaboration in which the TU Delft took place, therefore it was an opportunity to actually see such a project and help a little. The bridge is now outside for at least a year and serves therefore as a test to see how the material manages in outside applications.

1.22-1.26 | Construction-steps of the biobased bridge
1.27 | Bridge section and side view
1.28 | Result of the project





2

BIOBASED COMPOSITE

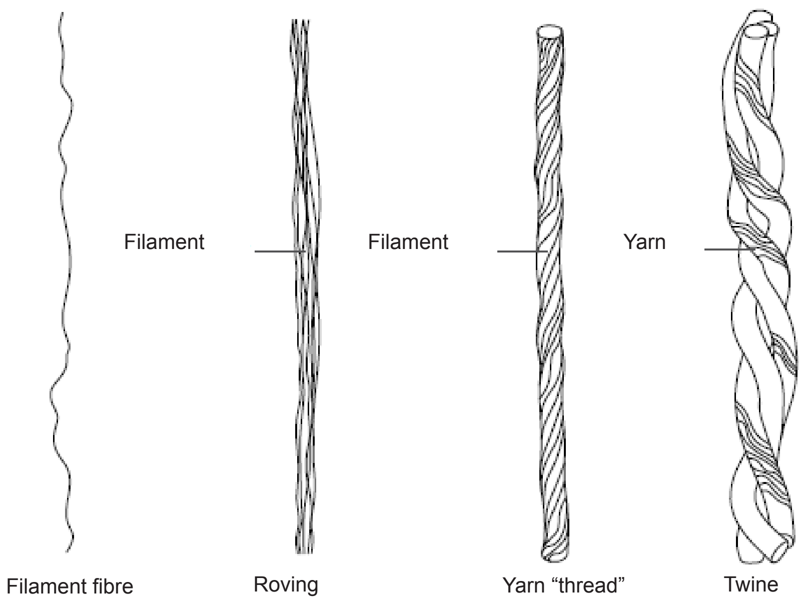
The information about fibres and resins, as well as the production techniques for biobased composites in the next part refers to the extensive explanation in the master thesis “Bio-based FRP structures: A pedestrian bridge in Schiphol Logistics Park” by R. Gkaidatzis (2014).

Fibres can shortly be divided into four parts: Inorganic fibres (glass and carbon), polymer fibres (synthetic), metal fibres and natural fibres. The majority of fibres consists of bundles of tiny fibres.

An individual fibre is known as a filament, whereas a bundle of parallel filaments is known as a roving. When the bundle of the fibres is twisted, the result is a yarn (or thread). A twine is made from several twisted yarns.

Natural fibres
Plant fibres are obtained from various parts of plants, such as the seeds (cotton, kapok, milkweed), stems (flax, jute, hemp, ramie, kenaf, nettle, bamboo), and leaves (sisal, manila, abaca), fruit (coir) and other grass fibres.

Animal fibres can be either fur/wool taken from hairy mammals, silk fibres secreted by glands of insects during the preparation of their cocoons or feather fibre like avian collected from birds. Mineral fibres are naturally occurring or slightly modified fibres procured from minerals and they can be categorized into asbestos, ceramic fibres and metal fibres.



2.1.1 | Plant fibres

Bast/Stalk fibres

Bast fibres are in general preferred in the building industry for their high mechanical properties. The fibres are concentrated in the outer skin of the stalks, supporting the conductive cells and providing strength to the stem. The filaments are made of cellulose and hemicellulose bonded together by a matrix which can be lignin or pectin.

2.1.1.1 | Kenaf
Kenaf is a relatively new crop growing in the United States. The plant comes originally form Africa and Asia and can reach a height of four meters. Kenaf shows good potential for use in biobased composites.

2.1.1.2 | Hemp
Hemp grows just like flax in temperate regions. These fibres are mainly used as special cellulose for composites and insulating materials.

2.1.1.3 | Jute
Jute has the highest production volume and the lowest price compared to the other natural fibres. Jute grows best in the countries China, India and Bangladesh.

2.1.1.4 | Flax
Flax is one of the oldest fibre crops existing. Flax grows in cooler regions and is the most commonly used fibre in the composite area.

2.1 | Build-up of fibres
2.2 | Hemp fibres
2.3 | Jute rope
2.4 | Flax fibres

2.1.2 | Leaf fibres

Leaf fibres are hard, coarse fibres obtained from thick and fleshy sword-shaped leaves of plants (flowering plants such as grasses, lilies, orchids, and palm. The fibres are mainly used to make ropes.

2.1.2.1 | Sisal
Sisal is made from the agave plant growing in East Africa and South America. Fibres are extracted out of the leafs, and are mainly used to make ropes and twine.

2.1.2.2 | Abaca
Abaca is made from the banana plant, and the best quality is produced in the Philippines and Ecuador. Abaca is resistant to moisture, sea water and is very durable.

2.1.2.3 | Pineapple leaf
Pineapple leaf fibres are extracted from the pineapple plant which grows in tropical climates, mainly Indonesia, India, Brazil and China. The fibres contain much cellulose and it is relatively cheap, since the leaves are a by-product.

2.1.2.4 | Oil palm
Oil palm is mainly produced in South East Asia. The empty fruit bunches contain cellulose fibres, since these are a waste product they are cheap. The fibres are hard and tough, and the surface is porous. Therefore they are useful for mechanical interlocking with matrix resin for composite fabrication.

2.1.3 | Fruit/seed fibres

Seed fibres are produced out of the seeds of plants. Most commonly known is cotton, but also kapok, floss from milkweed, dandelion, and thistle fibres are produced out of plant seeds. Seed fibres normally are light, hairy and relatively shorter compared to other fibre types.

2.1.3.1 | Coconut
Coconut fibre is largely available in tropical regions. The fibres are extracted from the outer shell of the coconut fruit. The brown fires are thich, strong and have a high abrasion resistance. The white fibres are smoother and finer, however weaker.

2.1.3.2 | Cotton
Cotton is the most common seed fibre. The fibre is soft, fibrous and grows spherical around the seed. The cotton plant grows in tropical and subtropical regions. Cotton is rather weak, absorbs moisture up to 20% and of its own dry weight.

2.1.3.3 | Wood/Paper
Wood fibres mostly refer only to the tracheid cells of wood, which forms the largest part of a tree. These fibres are roughly of a tubular shape and their dimensions can vary significantly.

2.1.3.4 | Grass
Grass contains bundles with elongated fibre cells, mainly in the leaves and stems. Most usable are Ryegrass, Trefoil and Lucerne. Grass fibres are most used for domestic goods or handicraft items like hats and baskets.

2.5 | Abaca fibre
2.6 | Pinepple leaf fibres
2.7 | Oil palm fibres
2.8| Cotton fibre
2.9 | Wood fibres
2.10 | Grass fibres

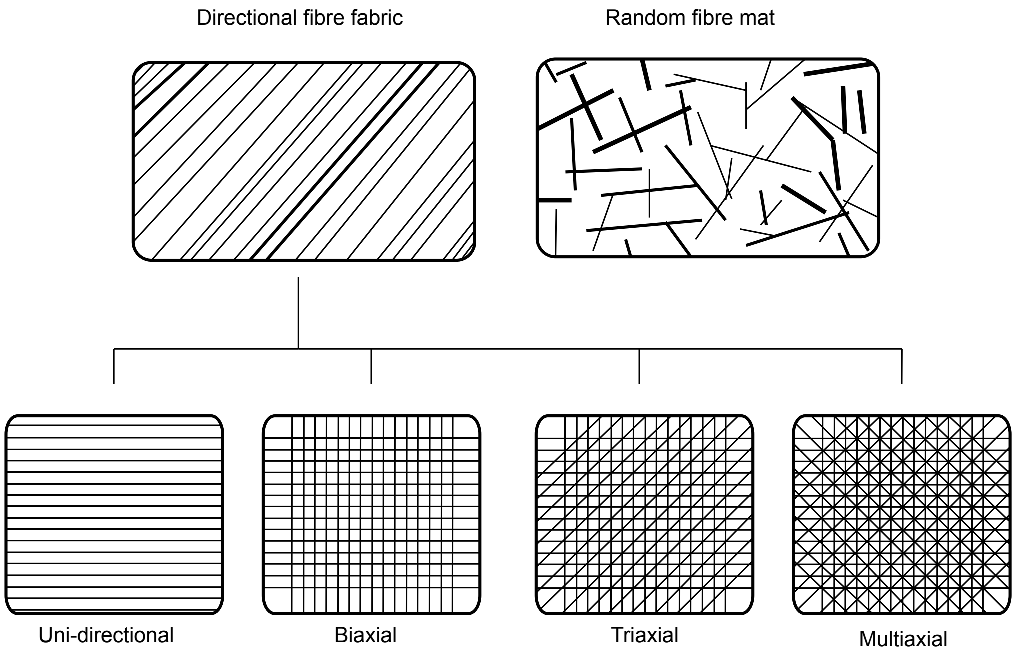
2.1.4 | Fabrics

The information on fibre fabrics is mainly based on the information set out in the thesis “The Application of Bio-Based Composites in Load-Bearing Structures” by Van der Linden (2017).

The most common process to make separate fibres suitable for use in biobased composite is to make technical fibre fabrics.

There are several different types of fabrics. The most economical is a random oriented fibre mat, because the production is relatively easy and fast. The random orientation makes it less suitable for structural use. For structural applications it is preferable to know the exact orientation of the fibres because this influences the strength.

Fabrics can be produced out of yarns or loose fibres.



The amount of fibre per square meter is a parameter producers can vary. Besides this, there is a variety of actual weaving patterns. Some of the possible weaving patterns are shown in the diagram below.

To get an idea of the possible fabrics, a couple of them are shown on the right.

2.1.4.1 | Flax fabric 550 gram/m2
Woven flax yarns, produced by Lineo.

2.1.4.2 | Flax fabric 150 gram/m2
Woven flax yarns, produced by Lineo.

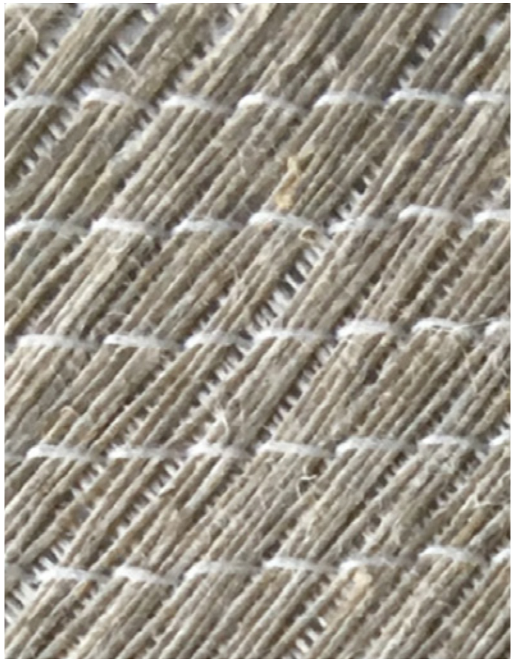
Both 2.1.5.1 as 2.1.5.2 are woven flax fabrics, however the fibre density is different. In 2.1.5.1 the flax yarns are thicker than the yarns applied in the fabric of 2.1.5.2.
These are just two examples, there are more different fabrics on the market.

2.1.4.3 | Hemp fibre mat
350-2000 gram/m2, **r**andom oriented hemp fibres, produced by Hempflax.

Hemp fibres are only available in non-woven, random orientated mats. Due to the random orientation, the structural properties in different directions are difficult to establish. Therefore hemp fibre mats are often used to increase the thickness of a composite instead of the actual strength.

2.1.4.4 | Unidirectional flax fabric
180 gram/m2, produced by Lineo.

This is a non-woven fabric, just as the one on the right (2.1.5.4) in which the fibres are all oriented in one direction. The stich in between functions to keep the fibres together. Because the fibres used in these fabrics are usually of a higher quality than those used in yarns, these fabrics are more expensive.



2.1.4.4 | Flax fabric 45º /-45º
300 gram/m2**,** produced by Lineo.

Besides these examples, there are more fabrics available. They usually differ concerning the types of fibres or amounts of fibres per square metre.

Yarns are also available to be used in for example filament winding or pultrusion.

Besides the dry fabrics and yarns, so called “pre-pregs” are available. This are fabrics impregnated with a resin.

2.11 | Different possible fabrics
2.12-2.13 | Flax fabric
2.14 | Hemp fibre mat
2.15 | Unidirectional flax fabirc
2.16 Flax fabric 45º /-45º

Fibres can shortly be divided into four parts: Inorganic fibres (glass and carbon), polymer fibres (synthetic), metal fibres and natural fibres.

Fabrics can be divided based on the orientation of the fibres as well as the density of the fabric.

Random oriented fibres are economical advantageous, however due to the random orientation the specific structural properties cannot be established.

2.2 | RESIN

“Most commercially available biobased resins are biobased up to a maximum of 50%. Increasing this percentage while retaining useful properties requires adapting the biobased raw materials and/ or applying alternative chemical reactions” (Blaauw, n.d.).
“Well-known (synthetic) resins are polyester resins, epoxy resins, phenol formaldehyde resins and polyurethane resins” (Blaauw, n.d.).

Polymers are mostly categorized based on the bonding of their organic molecules, since this type of bonding affects the physical properties. Polymers can be divided into three groups: Thermoplastics (thermosoftening plastics), Thermosets (or thermosetting plastics) and Elastomers.

Most researches on composite materials use only a division into thermoplastics and thermosets, since elastomers can be both a thermoplastic as a thermoset polymer. The differences will shortly be analyzed.

2.2.1 | Types of polymers

2.2.1.1 | Thermoplastics

In thermoplastics the molecules are not cross-linked. Therefore they become moldable when they reach a specific temperature, and turn solid again when cooled down and are therefore remoldable. They have a relatively low strength. Common thermoplastic polymers include nylon, polyethylene, polypropylene, polystyrene, polyvinyl chloride and Teflon.

2.2.1.2 | Elastomers

Elastomer polymers are viscoelastic and cannot be melted again, since the molecules are cross-linked. The raw material for elastomers is tough crude rubber, which is made elastic by cross-linking. However, as they have low young’s modulus they are inappropriate for structural applications and thus they are preferred to be used as seals in joints, adhesives or bearing pads in constructions. Elastomers can both be thermoplastic or thermoset.

2.2.1.3 | Thermosets

In thermosets the molecules are even denser cross-linked, and have therefore higher strength, better durability and can be highly heath resistant.
Like elastomers, they cannot be melted down after curing. The material starts liquid and when heated up to a certain temperature the material becomes permanently solid, and is therefore not recyclable.

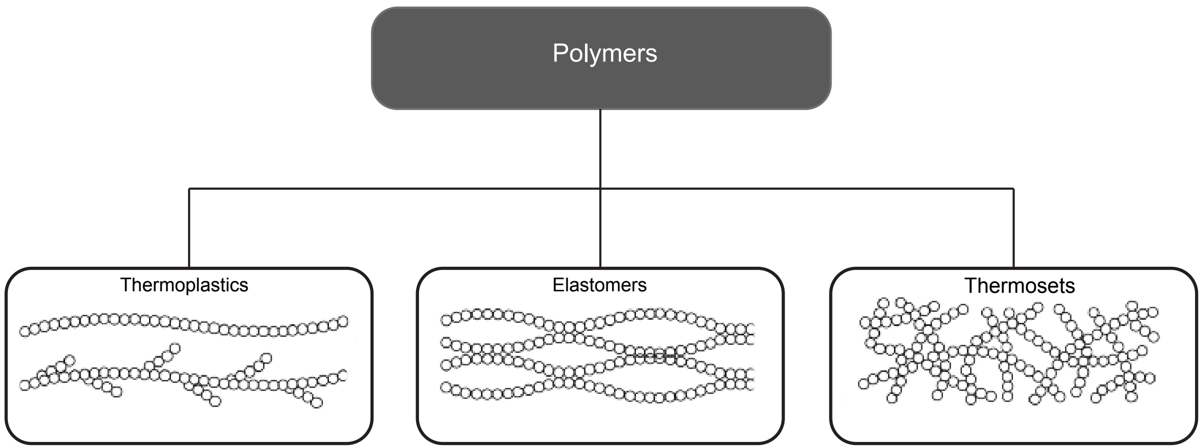
2.2.2 | Biopolymers

Biopolymers (bio-based polymers or organic plastics) are synthetic materials produced from renewable raw material. Biopolymers are also known as biodegradable plastics when their compostability has been verified by the Europe-an Standard EN 13432.

Bio-based plastics can be produced in three different ways. The first is directly from natural biopolymers such as cellulose or starch through modification. Another method is to compose them out of polymerized monomers of renewable raw materials, such as of agricultural waste. The last option is to produce them from petroleum raw materials. This can be done as long as the chemical structure of the polymer allows for biological degradability. In the same way like conventional polymers, biopolymers are categorized in thermoplastics, elastomers and thermosets and they can be processed and machined with the same machinery.

Not all biopolymers are biodegradable. Compostable biopolymers are mainly used for packaging and other temporary purposes, while long-lasting biopolymers are not- or hardly compostable due to their long-lasting properties.
Although thermoplastic biopolymers absorb more moisture than petroleum-based polymers, the percentage of this absorption, apart from the case of thermoplastic starch, remains below 1%.

One of the advantages of thermoplastic biopolymers compared to conventional polymers is their lower rate of shrinkage, which affects the high precision of the components during the production positively.
Additives are also important in improving the durability of bio-resins.



2.17 | Molecular structure of thermoplastics, elastomers and thermosets

These are the most common biopolymers

Thermoplastic starch (TPS)
Starch, which is water-soluble is mixed with a water-repellent, petroleum-based polymer and the plasticizer glycerin. The material is in the building industry mainly used for insulation but in a limited scale because the material's absorbs moisture up to 4%.

Cellulose (tri)acetate (CA, CTA)
Cellulose acetate derives from the chemical reaction of natural cellulose with acetic acid. It is characterized by its shiny surface which allows light transmission and by its high resistance to scratches due to high surface elasticity. Additives can reduce its flammability or make it weather resistant.

Polylactide (PLA)
PLA is a lactic acid synthetic polymer consisted of natural monomers and produced by bacteria from starch or sugar. This biotechnical method of production allows for developing the chemical structure of the polylactide and thus adjustment of its properties. Therefore, the properties of PLA are comparable with those of PP and PET. Polylactides are scratch-resistant, waterproof and transparent and show good mechanical properties.

Polyhydroxybutyrate (PHB)
PHB is a high-crystalline thermoplastic polymer with a smooth, shiny and highly waterproof surface. It is resistant to UV radiation and is stable between -30°C to +120°C. However, because of its high production costs it is one of the most expensive biopolymers in the market.

Furan
Furan (polyfurfuryl alcohol) is a recent addition to the thermoset resins. Furan is produced from pentose sugars. Furfural, the raw material for furfuryl alcohol, is produced from the hemicellulosic part of agricultural wastes. Technically, furfural can be produced from any raw material which contains pentose, making it a renewable and CO2-neutral chemical. This furfural can be converted into furfuryl alcohol (FA) by a low cost derivatization process and this furanic monomer can be easily polymerized into polyfurfuryl alcohol (PFA). PFA based-resins have found a range of useful applications in the foundry industry, wood adhesives and binders, polymers concretes and fibre-reinforced plastics.

Durable bio-based plastics that are used as resins in composites are modified polylactic acid (PLA), polyhydroxy alkanoates (PHBV), industrial starch and resins based on castor oils which is produced from agricultural waste, such as furan. Besides these, a big number of existing resins (PEBA, copolyester TPEs, TPUs and even acrylics) are modified to include a part of renewable content.

2.18 | Different polymers
2.19 | Furfuryl alcohol
2.20 | PLA
2.21 | PLA raw particles

Natural fibre-reinforced PLA (thermoplastic)
Although the mechanical properties of PLA are similar or even superior to petrochemical polymers, PLA shows low toughness because of its brittle nature, but also has much lower molecular weight compared to conventional polymers. In order to overcome the brittle nature of PLA, natural fibres are embedded into the polymer matrix. Plasticizers can be used during processing.

Lignin-bonded natural fibre composites (thermoplastic)
Lignin is one of the most common naturally occurring biopolymers and its function is to give stability between the cellulose fibres in all plants and wood. This biopolymer has a dark brown colour, absorbs UV light almost totally and is difficult to be decomposed either biologically or chemically. It is also known as liquid wood as in combination with natural fibres it becomes a composite material with the positive properties of naturally grown wood and the unrestricted moldability of a thermoplastic. Therefore, the composite shows similar mechanical and thermal properties to those of wood which makes it suitable as a connecting component in timber construction.

Polymers can be divided into three groups: Thermoplastics (thermosoftening plastics), Thermosets (or thermosetting plastics) and Elastomers.

They are classified based on how their molecules bond. Thermoplastics can be molded again while heated, while thermosets cannot be melted after curing.

Not all biopolymers are biodegradable.

2.3 | COATING

A coating consists of the following parts:
- Pigment, also referred to as filler
- Solvent
- Binder

In order to improve the properties, additives can be added.

The binder ensures that the pigments (coloring substances) and the substrate are mutually connected. The choice of binder is very important because this determines the thickness of the coating, and therefore the application potential. Coatings can be divided into two groups: aqueous and solvent-based.

The solvent in the coating determines the rheology and the extent to which the surface coating cross links with the surface it is applied on.

The most widely used coatings are aqueous coatings, because solvent-based coatings are generally more expensive and require additional machinery.

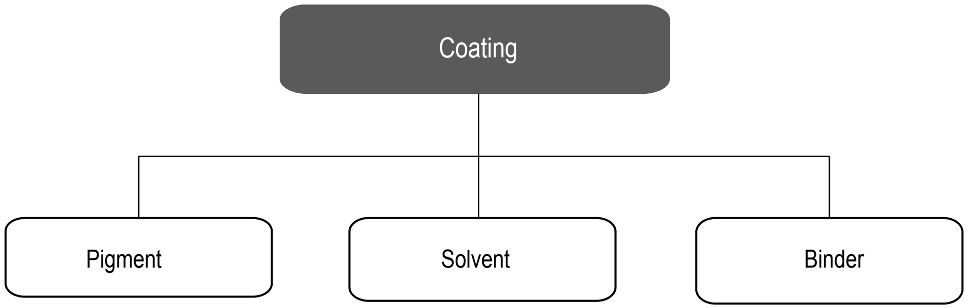
A coating machine applying solvent-based coatings must be explosion-proof build and the air which is used for the drying of the coating, must be special post-treated because the solvent in the air must be incinerated or absorbed.
Typical examples of the solvents used are water, acetone, alcohol (ethanol) and isopropanol.

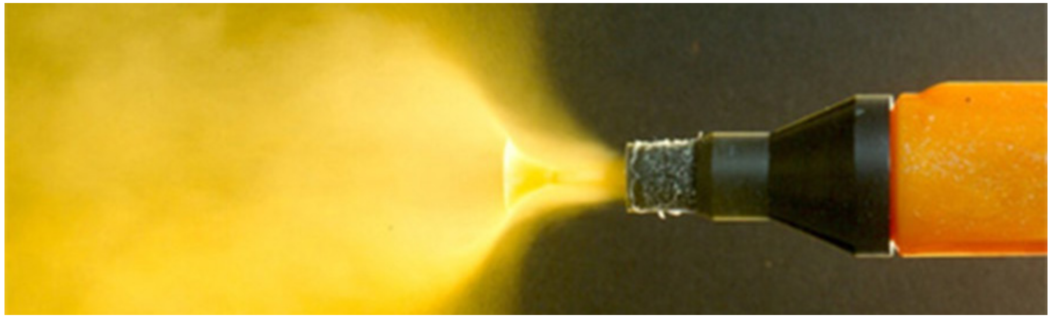
Rubber coatings have been used for years worldwide, especially in infrastructure and industrial projects. This is mainly due to their protecting and waterproofing properties. Rubber coatings are often fully adhesive flexible coatings. The advantage is that they are cold applicable and environmentally friendly (Wikipedia, 2016).

2.3.1 | Organic coatings

Organic coatings are complex mixtures of various substances. Components include polymers or resins, volatile organic compounds (VOCs), pigments, and additives.

Polymers and resins, commonly called binders by the coatings industry, form the continuous film that adheres to the substrate, binds other substances in the film together, and imparts film strength and durability. Pigments impart color, opacity, and other visual effects to the coating film. Additives enhance the properties of the final product and include dispersants, colorants, and rheology modifiers (Wool & Sun, 2005, pp. 285-291).





“Most coatings used on an industrial scale are based on synthetic materials because these are easy to work with and exhibit good resistance to environmental influences” (Knippers, Cremers, Gabler, & Lienhard, 2011, p. 57).

Generally coatings are classified based on the binders they contain, however, since many products contain more that one binder they will be categorized based on their application or function (Knippers, Cremers, Gabler, & Lienhard, 2011).

2.3.2 | Protective coatings

“Coatings can be used to protect surfaces of materials which are susceptible to corrosion caused by water, UV radiation, carbon dioxide, dissolved de-icing salts or petrol” (Knippers, Cremers, Gabler, & Lienhard, 2011, p. 57).

As fibres generally are not corrosion resistant, there are two ways to protect them. One is to encase them in a polymer, producing a fibre-reinforced matrix.
Polymers themselves usually do not need any protective coating on their surface because the material in combination with the fillers normally can comply with the technical and visual requirements.
Another method is to coat the fibres with a synthetic material.

2.3.2.1 | Fire protective coatings

Fire protective coatings are based on their intumescent function. When a certain temperature is reached (200°C) the blowing agent in the coating starts swelling up to 120 times its original size. This is shown on the picture on the right.

This type of coating does not comply with some sorts of fibre-reinforced polymers. For example, before the intumenscent mechanism starts the reaction temperature is already too high for glass fibres to keep their mechanical properties (Knippers, Cremers, Gabler, & Lienhard, 2011).

Another method for fire protection is to add specific fire retardant powders to the coating. An example of paint containing fire retardant powder is shown on the picture below on the right.

2.3.3 | Decorative coatings

Besides the protective functions of a coating, additional paint or lacquer finishes are sometimes used on polymers for decorative reasons.

2.3.3.1 | Paints

Most paint finishes are dispersions. They are mixtures of two or more substances and usually consists of pigments, binders and solvents. Dispersion paints are permeable to water, except for latex, which is less permeable to water because of its higher proportion of binder.
These paints can be applied with simple tools and are relatively cheap.

2.3.3.2 | Synthetic resin finishes

Synthetic resin finished consist of a dispersion paint and a siliceous aggregate, which improves the capacity to be formed into different shapes.
These coatings are therefore more elastic and more waterproof than mineral coatings.

2.3.3.3 | Lacquer systems

A lacquer system consists of several components. The top coat is responsible for the properties of the surface.
For fibre-reinforced materials it is sometimes necessary to apply a leveling layer when a smooth surface is demanded. To do this a filling compound is used to compensate for uneveness`s. Then a primer is applied to ensure a good bonding. Last the final coat is added which determines the appearance and protection.
A metallic coat is applied in a base coat which holds the metallic pigments and a lacquer top coat protecting the base coat to mechanical and chemical effects.

2.3.4 | Coating methods

Usually paint is applied with brushes or rollers. Lacquer is mainly prayed on. Dip coating uses a tank of lacquer in which the element is dipped.
Coil coating enhances an even application using rollers, giving it an uniform appearance.

2.22 | Composition of a coating
2.23 | Waterproofing coating
2.24 | Spray coating
2.25 | Intumescent coating
2.26 | Fire protective coating

A coating consists of the following parts: Pigment, solvent and binder.

Fibres can be protected by encasing them in a polymer or by coating them with a synthetic material.

For fire protection both a blowing agent or a fire retardant powder can be applied.

At this moment the market offers little information on coatings for biobased composite. Even less information is available about biobased coatings or biodegradable coatings.

When designing the biobased bridge, the team analyzed different coatings and tested a linseed based coating in the mock-up of the bridge.

Van der Linden (2017) stated in her master`s thesis that one important test result from the mock-up of the biobased bridge is that this biobased paint turned out not to be suitable. The paint did not dry properly and stayed sticky for more than a month.

Unfortunately, there were no other bio-based paint options, so a regular petrol based coating is used on the biobased bridge.

Another conclusion from this thesis is that the flammability of bio composites dependents on the type of fibre and the type of polymer. Natural fibres are highly flammable, and most polymers are flammable as well.

The best method to reduce the flammability could be to add a flame retardant powder to the biobased composite. Unfortunately, most flame-retardant substances are petrol based.

Promising on this matter, is an announcement Sicomin has made on the “Composites Europe 2016 exhibition”. The company announced a 30 percent bio-based fire resistant coating (Van der Linden, 2017, p. 61).

2.3.5 | Previous tests on coatings

Van der Linden tested a set of samples of biobased composite for accelerated weathering in a QUV accelerated weathering machine.

These tests were performed on flax fibre-reinforced samples with two types of resins:
• FormuLITE 2501A & 2401B hardener
• Greenpoxy56 & SD4770 hardener.

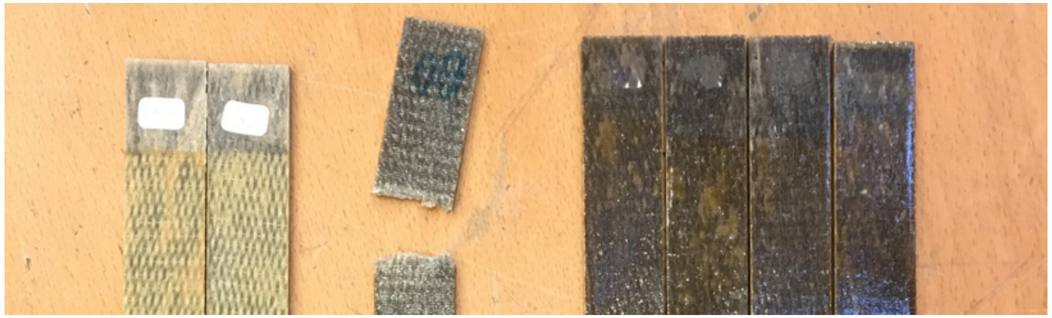
The shape and size of all test samples were equal, namely 250*20*3 mm.

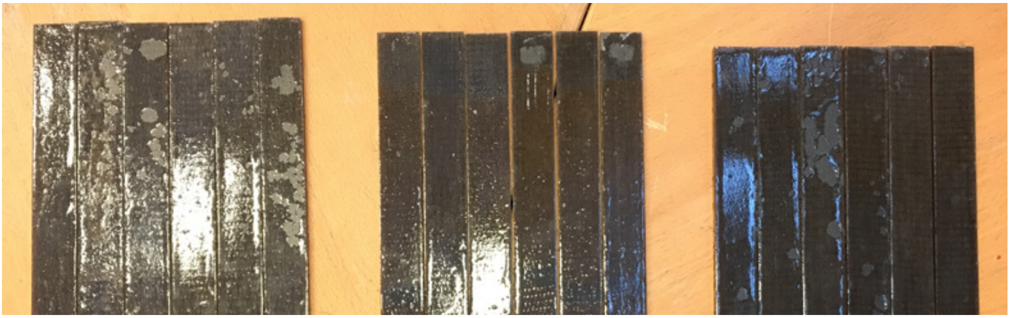
A large part of the test specimen were tested with a clear UV coating. About this, Van der Linden sais:
“The assumption is that all samples are coated with a clear UV-blocking coating, because, in reality, this would happen as well.
There is chosen to use the same coating as used in the bio based bridge, one layer of two-component polyurethane coating with UV blocker” (Van der Linden, 2017, p. 81).
The coating needs to protect the bio-based composite from water, ultraviolet lighting and other harmful environmental factors.
NPSP advises to always use a coating when biobased composite is applied outside.

Two tested samples were not coated while accelerated weathered, these are the two samples on the left on the left picture below.

One difficulty while comparing the results of the non-coated samples with those of the coated samples is that they have been weathered shorter than the coated samples. The coated samples have been weathered for 808 hours, when the non-coated samples have been weathered for 500 hours due to a mistake.

2.27 | Test samples by Van der Linden
2.28 | Test samples by Van der Linden
2.29 | Test setup tensile tests Van der Linden
2.30 | Test setup tensile tests Van der Linden





The results of the non-coated weathered test should be taken as an indication, since not enough test specimen have been tested to draw conclusions on reliable average values.

The table shows a degradation of 8,8% in tensile strength between the weathered coated sample and the non-weathered coated sample of Greenpoxy 56. A 15,9% degradation occurs on tensile strength between the weathered coated sample and the non-weathered coated sample of Formulite.

The average maximum tensile strength of the non-coated samples is 241Gpa. Since these samples were made using Greenpoxy resin, they will be compared to the coated Greenpoxy resin.

Coated Greenpoxy samples have a maximum tensile strength of 258Gpa. Non-coated Greenpoxy samples have therefore a 6.6% lower maximum tensile strength than their coated equivalent.
Coated non-weathered samples have a maximum tensile strenght of 284Gpa. This is 15,1% higher than the weathered non-coated samples.

For the youngs modulus, non-coated elements have a higher value than coated elements, both weathered and non-weathered.

Drawing conclusions on these results, non-coated elements degrade (regarding their tensile strength) more than coated samples, with a 6,6% lower maximum tensile strength than coated and weathered samples. These numbers could be even higher regarding the fact that the non-coated elements have been weathered for 500 hours and the coated elements for 808 hours.

Based on the available test results, it seems wise to apply a coating to prevent the fibres from degrading too fast. NPSP also advises to always apply a coating if biobased composite is used outside.

Table 2.1 | Results tensile tests Van der Linden

Weatered (500 hours)

Uncoated 1	Measured	Number	Unit
	Maximum tensile strength	250	Mpa
	Elongation at break:	3,2	%
	Young`s Modulus:	12,6	GPa

Uncoated 2	Measured	Number	Unit
	Maximum tensile strength	232	Mpa
	Elongation at break:	3	%
	Young`s Modulus:	12	GPa

Weathered (808 hours)

Coated 1	Measured	Number	Unit
FormuLITE 2501A +2401B	Maximum tensile strength	230	Mpa
	Elongation at break:	3	%
	Young`s Modulus:	11,4	%

Coated 2	Measured	Number	Unit
Greenpoxy56 & SD4770	Maximum tensile strength	258	Mpa
	Elongation at break:	3,4	%
	Young`s Modulus:	12,1	GPa

Non-weathered

Coated 1	Measured	Number	Unit
FormuLITE 2501A +2401B	Maximum tensile strength	273	Mpa
	Elongation at break:	3,7	%
	Young`s Modulus:	11.9	Gpa

Coated 2	Measured	Number	Unit
Greenpoxy56 & SD4770	Maximum tensile strength	284	Mpa
	Elongation at break:	3,8	%
	Young`s Modulus:	12	GPa

Sicomin recently announced a 30 % bio-based fire resistant coating.

Test results show that fibres degrade (in terms of their tensile strength) faster than coated elements. Therefore it can be concluded that a coating is needed for outdoor applications.

These testresults however are not directly comparable to each other due to a different accelerated weathering time.

2.4 | FIBRE TREATMENT

The aim of fibre treatment is first of all to reduce the water uptake or hygroscopicity. Because of hygroscopicity, fibres swell and shrink as a result of water uptake, see the picture below. If much water is taken up, the fibres swell to such a volume that microcracks can appear, eventually degrading the composite significantly.

Besides hygroscopicity and the following effects, biodegradation can take place, which means a biological attack such as fungal decay.

The physical degradation, for example UV radiation can also be prevented or reduced.

Specific fibres could also improve the intrinsic strength and flame retardant properties of fibres.

2.4.1 | Fibre treatments

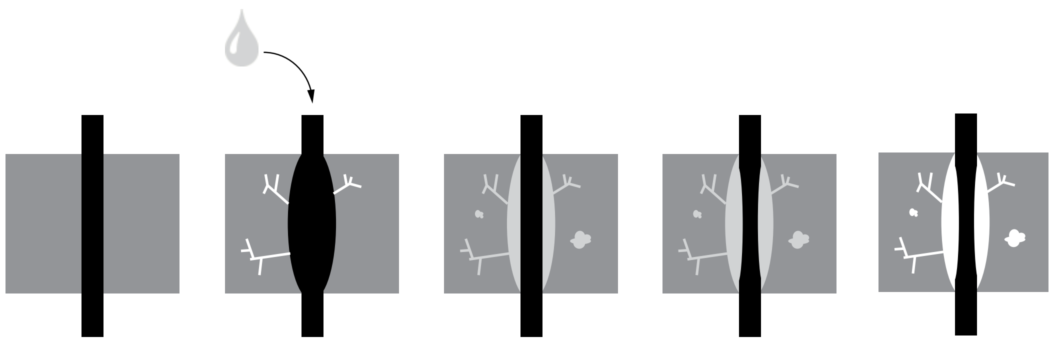
In the BioBuild project, several fibre treatments are examined:

- Acetylation: A reaction that introduces an acetyl functional group into a chemical compound.
- DMDHEU: Dimethylol dihydroxyethyleneurea
- Bio resin/ furan
- NaOH: Sodium Hydroxide
- Plasma surface treatment.
- Fire retardant treatment

(Tjeerdsma, 2014).

Eventually Acetylation was tested. A fibre board made out of jute and Bio-PE was tested for water uptake/swelling in a boiling test. The mass gain and swelling were measured. The results are shown in the graph below (Tjeerdsma, 2014).

2.31 | Possible water uptake by fibres
Graph 2.1 | Effects of fibre treatment



Stage 1

No moisture has been in contact with the composite

Stage 2

Moisture is introduced and absorbed in the fibre. The fibre swells, which causes microcracks in the polymer around the fibre.

Stage 3

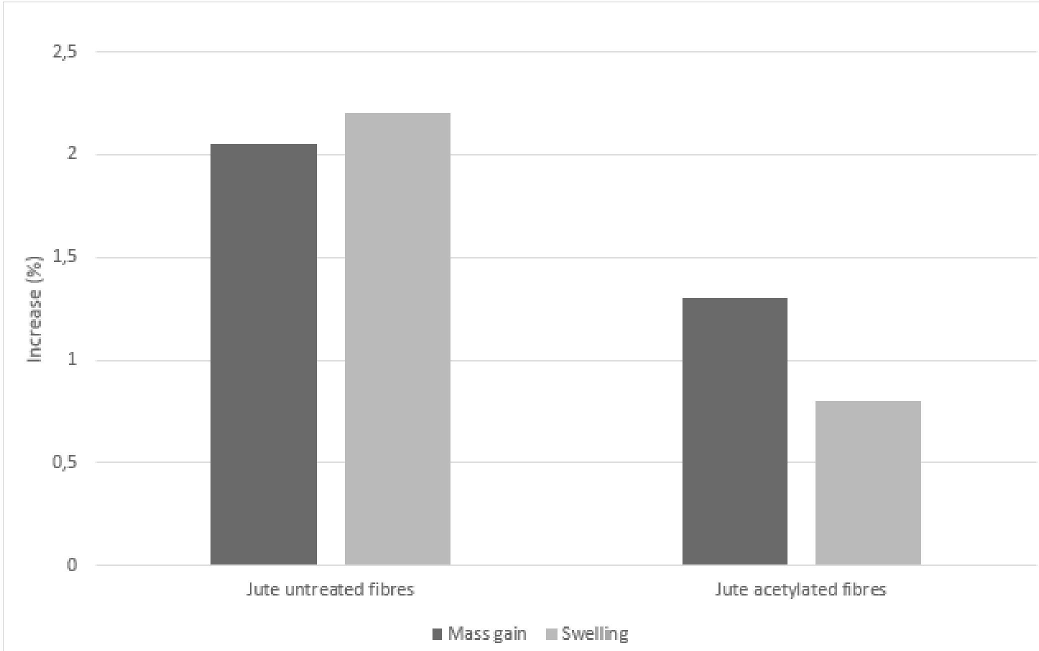
Moisture diffuses through the polymer matrix, getting into the microcracks.

Stage 4

Water-soluble substances from the fibre dissolve in the moisture between the fibre and the polymer matrix.

Stage 5

Moisture evaporates from the composite, leaving the fibre-polymer matrix damaged and debonded.



2.5.1 | Test

Information on fire-safety was very difficult to find. For one reason because almost no test have been carried out. One test, in cooperation with TNO turned out to be confidential.

One test that was found, was an indicative test on mass loss of composite boards in a presentation for the biobased project by Tjeerdsma (2014). In this test different materials where exposed to a “little flame test” in which the materials were being weighted and exposed to the fire after which they were weighted again. The results of the decrease in weight indicated the material loss during an actual fire.

The graph below shows the results from two test which were performed with the same set of materials:

• Flax/ BioPE
• Flax/ BioPe + White intumescent coating
• Jute/ Furan
• Jute/ Furan + White intumescent coating
• Jute/ BioPE
• Jute/ Fire retardant BioPE

2.5.2 | Result

Based on the results of this indicative tests, some small conclusions can be drawn. These are just indications.

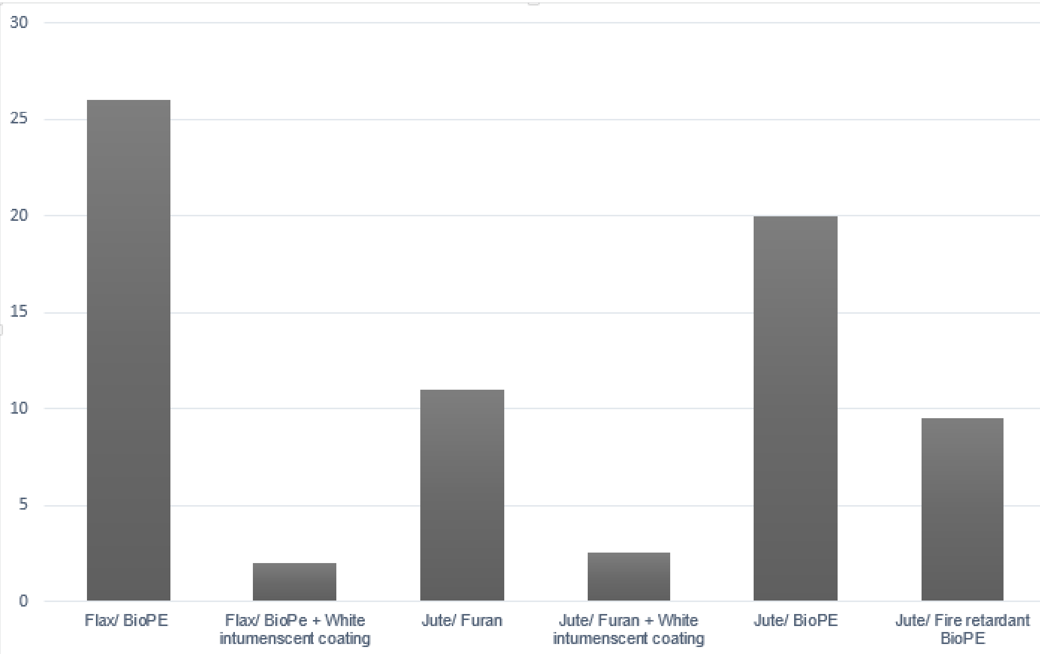
• There is a difference in material losses due to incineration between different resins.
• There is a difference in material losses due to incineration between coated and uncoated elements.
• Coated elements with white intumesent coating lose up to 90% less material
• Applying fire retardant BioPE instead of a normal BioPE reduces the material loss by 52.2%

2.5.3 | Fire-safety Precautions

The found results show that white intumesic coatings decrease material loss due to incineration significantly. The expectation is that a complete fire-safety test will result in similar results, however in this stage this can only be assumed.

Another method is to apply a fire-retardant resin. Unfortunately the information source was not specific on the composition of such a resin, but it is expected that fire-retardant powders are mixed to the resin.

When the fire-safety precautions turn out to be insufficient, there is a chance that the material cannot be applied to all type of buildings. The specific requirements for fire-safety depend on the buildings function. Thereby the typo of building can require more specific precautions, such as for high-rise buildings is the case.



Graph 2.2 | Percentage mass-loss in (indicative) fire test of composite boards.

An indicative test for weight loss after incineration was found. The test regards different fibre-resin matrices of which some are coated and some are uncoated.

The test shows that white intumesent coating decrease the weight loss up to 90%. Applying a fire retardant coating can reduce the material loss by 52,2%. These results are just indications.

2.6 | REQUIREMENTS

As with every facade, the design should meet several requirements to both meet the designed quality demands as well as the Dutch building regulations.

Because the time for the research is limited, not all requirements can be researched, let along tested. This chapter shows which quality demands are the most interesting to research, or the most urgent to solve.

At first several critical parts of the Dutch building regulation were researched. These do very little specific statements on facades, therefore the regulations were not included in the report. Besides the Dutch building regulations, the European standards for non-movable facades were studied, see table 1. This table points out which main demands there are to comply. The last column summarized to what extend they can be met, and what the approach should be. Most of these standards relate to a complete facade, including the connections. Since it will not be possible to build and test the complete facade, it will not be possible to make statements about these standards. In consultations with the mentors and specialists from DGMR assumptions should be made on these standards.

The next step was to interview specialists from DGMG, regarding fire safety, facade technology, acoustics and sustainability.
Within these interviews, after a brief explanation about the research subject and a overview of the properties of the average properties of biobased composite, the specialist were asked what the main issues of such a facade would be, regarding their direction of specialization. Besides this their opinion on the application of the European standards to this design was asked. The setup of the interview and the results are shown on the next pages.

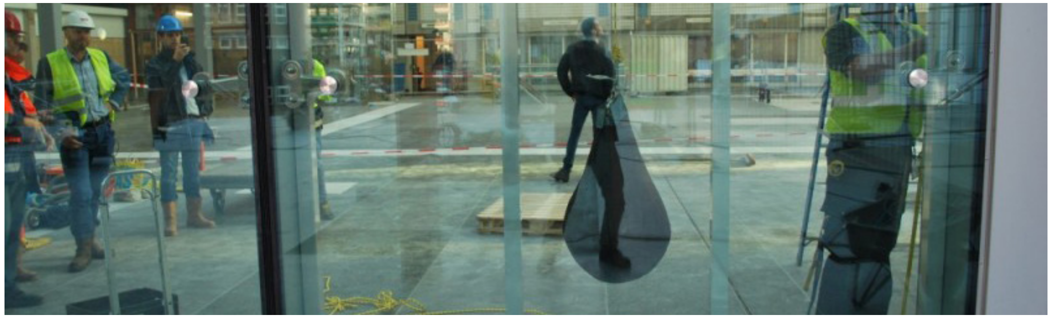
Properties for which classification is required	Short description	Standards	Requirement/Approach
4.1 Resistance to wind load	The curtain walling shall be sufficiently rigid to resist the declared wind loads for serviceability (5.2.3. c), both positive and negative, when tested in accordance with EN 12179. It shall transfer the declared wind loads to the building's structure, safely, via the fixings intended for that purpose. The declared wind load results from testing in accordance with EN 12179.	NEN-EN 13830; 2003, chapter 4.1. NEN 8700.	Under the declared wind loads the maximum frontal deflection of the curtain walling's framing members shall not exceed L/200, or 15 mm, whichever is the less, when measured between the points of support or anchorage to the building's structure, in compliance with EN 13116. This standard focusses mainly on the connection details. Since these will not be tested, they need to be designed in a way that it is plausible that they will meet the requirements. Mentors and/or DGMR specialists can be consulted for this. The for wind load resisntance tested sample will make clear what the bending under windload of the material is, and calculation can be made on the necessary thickness of the material.
4.2 Dead load (Self-weight)	The curtain walling shall sustain its self-weight plus any attachments incorporated into it by original design. It shall transfer the weight to the building structure, safely, via the fixings intended for that purpose. Self-weights shall be determined in accordance with EN 1991-1-1.	NEN-EN 13830; 2003, chapter 4.2. NEN 8700.	The maximum deflection of any main horizontal framing from vertical loads shall not exceed L/500 or 3 mm, whichever is the less. This cannot be tested, therefore an estimation should be made on the connextions (if they will be designed).
4.3 Resistance against impact	Where specifically required tests shall be performed in accordance with EN 12600:2002, clause 5. The results shall be classified in accordance with prEN 14019. Where glass products are concerned they shall comply with EN 12600.	NEN-EN 13830; 2003, chapter 4.3.	Since it will not be possible to test the whole element, the facade should be designed robust, making it plausible to be able to resist certain impact. To make a substantiated assumption the mentors and/or DGMR specialists can be consulted.
4.4 Air permeability	An air permeability test shall be carried out in accordance with EN 12153. The results shall be expressed in accordance with EN 12152.	NEN-EN 13830; 2003, chapter 4.4.	The air permeability is mainly determined by the connections. These cannot be tested but can be designed in a properly functioning manner. The air permeability of the material itself can be tested, and statements on the efficiency can be made.
4.5 Watertightness	A water-tightness test shall be carried out in accordance with EN 12155. The results shall be expressed in accordance with EN 12154.	NEN-EN 13830; 2003, chapter 4.5. NEN 2778.	The water tightness is mainly determined by the connections. These can not be tested but can be designed in a properly functioning manner. The air permeability of the material itself can be tested, and statements on the efficiency can be made.
4.6 Airborne sound insulation	Where specifically required, sound insulation index shall be determined by test in accordance with EN ISO 140-3. The test results shall be determined in accordance with EN ISO 717-1.	NEN-EN 13830; 2003, chapter 4.6. NEN 5077.	The sound proofing is to a large extend determined by the connections. These can not be tested but can be designed in a properly functioning manner. The acoustical insulation of the material itself can be calculated, and statements on the efficiency can be made.
4.7 Thermal transmittance	Methods of assessment / calculation of thermal transmittance of curtain walling and appropriate methods of test are defined in prEN 13947.	New construction and renovation according to the Dutch building regulations. NEN-EN 13830; 2003, chapter 4.7. NEN 1068.	The thermal transmittance is to a large extend determined by the connections. These can not be tested but can be designed in a properly functioning manner. The thermal insulation of the material itself can be calculated, and statements on the efficiency can be made.
4.8 Fire resistance	Where specifically required the fire resistance shall be classified in accordance with prEN 13501-2.	NEN-EN 13830; 2003, chapter 4.8. NEN-EN 13501-1.	The fire resistance cannot be tested. So far little information is available. In cooperation with DGMR specialist, assumptions can be made, on which fire resistance can be calculated. Also the connections, when designed, should be designed in a way that it is likely that they are fire-resistant.
4.9 Reaction to fire	Where specifically required the reaction to fire shall be classified in accordance with EN 13501-1.	NEN-EN 13830; 2003, chapter 4.9. NEN-EN 13501-1.	See 4.8
4.10 Fire propagation	Where specifically required the curtain wall shall incorporate such fire and smoke stops as are necessary to prevent the transmission of fire or smoke through voids in the curtain wall construction at its abutment at all levels with structural floor slabs in accordance with 4.8.	NEN-EN 13830; 2003, chapter 4.10. NEN-EN 13501-1.	See 4.8
4.11 Durability	Durability of performance of any characteristics of curtain walling is not tested, but is related to the results of the conformance of the constituting materials and finishes to the state of the art, or, where available to European technical specifications specifying the material or finish.	NEN-EN 13830; 2003, chapter 4.11.	The design will be compared to four other facades in terms of environmental impact, CO2 emission,, estimated lifetime and costs, and a rating system will be set up to make statements about the durability. All used materials and production processes will be discussed for their environmental impact.
4.12 Water vapour permeability	Vapour control layers which conform to the appropriate European Standard shall take into account the specified hydro-thermal conditions of the building.	NEN-EN 13830; 2003, chapter 4.12.	The water-vapour permeability of the connections should be checked by specialists, since this cannot be tested. The water-vapour permeability of the material will be clear in the testresults for moisture (the weather tests).
4.13 Equipotentiality	Where specifically required the metal component parts of the curtain walling shall be mechanically connected together with the building structure to provide an equipotential bond to the earth circuit of the building. This is a requirement for all metal based curtain walling installed into buildings with a height greater than 25 m. The electrical resistance of the bond of the curtain walling shall not exceed 10 Ω when tested in accordance with annex A (normative).	NEN-EN 13830; 2003, chapter 4.13.	No specific requirement.
4.14 Seismic shock resistance	Where specifically required, seismic shock resistance shall be determined in accordance with technical specifications or other provisions valid in the place of use.	NEN-EN 13830; 2003, chapter 4.14.	No specific requirement.
4.15 Thermal shock resistance	Where it is determined that a glass resistant to thermal shock is required, a suitable strengthened or toughened glass shall be chosen which conforms to the appropriate European Standard(s).	NEN-EN 13830; 2003, chapter 4.15.	No specific requirement.
4.16 Building and thermal movement	The design of curtain walling shall accommodate thermal and specified building movements without inducing damage to the components or performance. The specifier shall specify the building movements which the curtain walling will be required to accommodate, including movements at joints within the structure.	NEN-EN 13830; 2003, chapter 4.16.	No specific requirement.
4.17 Resistance to live horizontal loads	The curtain wall shall resist a horizontal live load at sill height as specified in EN 1991-1-1.	Dutch building regulations. NEN-EN 13830; 2003, chapter 4.17.	Since it will not be possible to test the whole element, the facade should be designed robust, making it plausible to be able to resist certain horizontal load. To make a substantiated assumption the mentors and/or DGMR specialists can be consulted.

Table 2.2 | Summarized requirements of the NEN-EN 13830; 2003.

2.7 | INTERVIEWS

To get a better idea of the problems and opportunities of biobased composite for a facade application, specialist of DGMR were interviewed.

On the next pages, the interviews are shown including conclusions drawn on the obtained information.



2.32 | Sound measurement
2.33 | Firesafety test
2.34 | Pendulum test
2.35 | Sustainable (roof) materials

2.7.1 | Interview acoustics

Date: 09-12-2016
Interview with: Frank Lambregts (DGMR)
Specialized in: Acoustics

1. What is your first idea of this material regarding your specialization?

For office buildings there are no standards related to acoustics anymore. The former standard from the "Bouwbesluit" 2012 is still often used. This standard indicates that the sound insulation should be such that the sound insulation level will not exceed 40dB(A). This can be found in the "Bouwbesluit 2012" chapter 3 part 3.1 "protection from external noise, new buildings". The sound proofing of the total construction depends on the sound proofing of the different parts, such as glass and ventilation grilles. The area of the different parts and the sound insulating value of these parts determine which part is normative.

2. What do you see as the greatest opportunities?

A cavity wall construction. It might be possible to accomplish enough acoustical insulation using only mass. Some numbers: A massive wall of 100kg/m2 has a Ra value of 38dB. A compact 50kg/m2 wall has a Ra of 30-33dB(A). For 10 kg/m2 this is 24dB(A).

3. What do you see as the main problems?

The bending resistance of the material and the possibilities of acoustic decoupling. Besides this, it is of much influence whether a single- or double gap sealing is applied, and whether there is a ventilation grille or silencer applied.

4. Do you have an idea in which direction I should look for a solution to this problem, or are there comparable projects?

The first solution would be to add mass, however this is in contrast with the material properties, which have a low mass per m_2. Then the solution can be found in a cavity wall construction, or a combination of these two. For adding mass the basic rule is: Doubling the mass means about 5dB better sound insulation. When using a cavity wall construction, it is important to use a resilient core and as little single point supports as possible to prevent resonance, which lowers the sound proofing of the construction. Thereby felt or a similar material can be applied in places where resonance can occur, for example at the single-point supports.

5. What standards are most important to meet?

First the "Bouwbesluit". Then tests should be carried and a calculation using the "GL program" can be used. This former standard which said that the sound insulation should be such that the sound insulation level will not exceed 40dB(A) is not obligatory anymore, however it is a good basis to obtain a healthy indoor environment. In case of industrial, road or traffic noise the "Bouwbesluit" does have requirements, however since the design is not made for a specific situation, this former demand is a good basis rule.

6. How do you suggest to meet these standards, since in most cases testing is not possible and/or specific information about an area is not known?

The proposed design can be tested and simulated in the program Insul. At DGMR the Hague, you can consult Eric Cremers for the program.

7. If possible, what would be interesting to test?

The panel could only be tested sufficiently if the complete panel is fabricated and tested in a laboratory, resulting in a test report.

8. Because the time is limited for this study, I cannot research all aspects of the facade. What do you think is the most important part, to design a credible and qualitative facade?

An estimated Ra- or Rwtr-value and a prediction of the sound proofing, using "Insul" and references. Also a theoretical calculation of the estimated sound insulation.

9. Do you have any other comments?

Besides the external sound insulation, the intern sound insulation regarding the facade is important for the design too. For an office building, the internal sound insulation (Rw,i) should be 39dB. To prevent this noise level from becoming normative, 10 dB should be added. 49dB is the Rw,f value that should be taken into account. A good option is to provide dilatations at the places where the partition walls reach the facade. This is only possible in buildings built according to a fixed size system without exceptions. Another option is to use retention walls, These should run all the way to the next partition.

Conclusion of the interview

For office buildings there are no requirements related to the acoustical insulation of the facade. It is recommended to apply the former requirement which said that the sound insulation should be such that the sound insulation level will not exceed 40dB(A).

This sound insulation can be achieved by adding mass, however using a cavity wall with insulation would be a better solution regarding this material. In the book “Herziening rekenmethode geluidwering gevels” different types of wall constructions can be found, with their mass/surface ratio and established sound insulation value. Some of these pages are shown in picture 1.16 and 1.17.

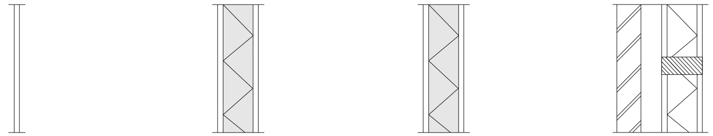
Using a cavity construction, there is always the difficulty of resonance. These drops of insulation value can be seen in the graphs at picture 1.17.

To reduce cavity resonance a few design rules can be set. Use as little as possible single point supports. Use a resilient core material which absorbs sound and if necessary add felt or a similar material in places where resonance can occur.

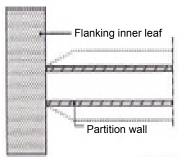
Besides the external sound insulation, the intern sound insulation regarding the facade is important too. For an office building, the internal sound insulation (Rw,i) should be 49dB. A good option is to provide dilatations at the places where the partition walls reach the facade. This is only possible when there is a fixed size system without exceptions. Another option is to use retention walls, These should run all the way to the next partition.

Core	PS foam plate	PUR foam plate	Cork plate	Foamglass
Thickness total construction	50-65 mm	45-75 mm	65-75 mm	45-85 mm
Mass/m2	20 kg/m2	20 kg/m2	20 kg/m2	20 kg/m2
Sound insulation Ra in dB(A) for the standard spectre	27 dB (A)	28 dB (A)	28 dB (A)	28 dB (A)

Massive constructions	Single panel	Panel material with rigid core of mineral wool (150 kg/m3)	Panel material with rigid core of mineral wool (100 kg/m3)	Stony outer leaf and prefabricated wooden inner leaf
Thickness total construction		50-85 mm	50-85	
Mass/m2	10 kg/m2	20 kg/m2	20 kg/m2	200 kg/m2
Sound insulation Ra in dB(A) for the standard spectre	24 dB (A)	22 dB (A)	23 dB (A)	46 dB (A)



Nr.	Detailling	Construction	Rw, f
		Inner cavity leaf filled with massive, non porous constructions	
1		70 mm gypsum blocks 70 kg/m2	39 dB
2		100 mm limestone 175 km/m2	52 dB
3		150 mm limestone 260 kg/m2	58 dB
4		150 mm concrete 345 kg/m2	60 dB
5		≥200 mm concrete ≥ 460 kg/m2	64 dB



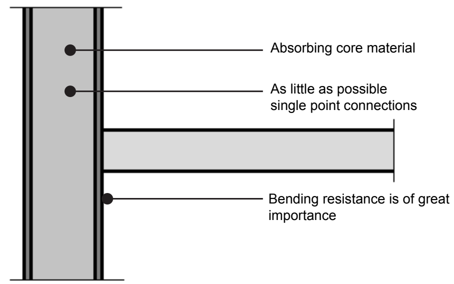


Table 2.3 | Description of the construction (mass per m2)

Table 2.4 | Flanking sound insulation through the facade

2.36 | Requirements regarding sound insulation

The sound insulation should be such that the sound insulation level will not exceed 40dB(A).

A cavity wall with sound insulation would be a good option. It is recommended to use as little as possible single point supports, and a resilient core material which absorbs sound.

The intern sound insulation regarding the facade is important too.

2.7.2 | Interview Fire-safety

Date: 09-12-2016
Interview with: Johan Koudijs
Specialized in: Fire-safety

1. What is your first idea of this material regarding your specialization?

Most fire-safety standards set in the "Bouwbesluit" are height-related. Therefore it is difficult to make assumptions regarding the requirements. Materials need to be tested to be able to say something about their fire-safety properties. Fire-safety relates to both the behavior of materials in their application as to requirements by smoke and fire compartments.

2. What do you see as the greatest opportunities?

The benefits of this material should be found within the biobased feedstock and the circular properties. It is important that the lifetime is based on the estimated use of the facade design.

3. What do you see as the main problems?

There are three types of fire loads: Fire penetration, flash-over and fire propagation, to be found in the standard WBDBO (Weerstand Brand Doorslag Brand Overslag/Standard Fire-penetration and Flash-over) NEN 6068. Fire penetration through floors does not apply to this design. Fire penetration trough the parapet to the floor above is, however, a problem which should be solved, as well as fire penetration through the facade (which spreads at the outside of the facades and penetrates the facade on a higher level, spreading the fire to a higher level). Thirdly the fire propagation through the outer centimeter material of the facade should be slow enough to be able to leave the building safely. The two main problems for fire safety will be fire penetration trough the facade and fire propagation along the facade.

4. Do you have an idea in which direction I should look for a solution to this problem, or are there comparable projects?

A solution for the fire penetration would be to add a fire proof retention wall. For the fire propagation along the facade, the material itself should be fire retardant enough. To classify the fire retardant properties of a material, materials are divided into different classes, namely from A to D, in which D is material like pinewood, and A1 is not able to catch fire. For high buildings, higher than two floors and bigger than one fire compartment (for office buildings, this is maximum 1000m_2), or when calculated using the program "Pintegraal", a class B is mandatory. To classify materials, they are tested according to the European standards for testing (NEN-EN 1364-3), and classified according to NEN-EN 13501.

5. What standards are most important to meet?

The normal procedure for a new facade element starts with a flame test. This is a relative simple test in which a flame is held underneath a material sample, and during the test the flames should spread only limited in the vertical direction. This test assesses the flammability of a product under exposure to a small flame. The next step is to perform a "single burning test". This is a test for the determination of the product classification A1, A2, B, C and D. This test simulates a starting fire, for example, a burning trash bin. By measurement of the oxygen consumption, and the smoke and CO2 production the classification is determined. When for example designing a new product, a cone calori test can be performed in between the flame test and the SBI test. This is a test in which the released power is measured. If there are enough reference tests with a certain correlation, the cone calori test can be used to give a quick insight in the properties of a material. This can for example be used to test different versions of a new design.

6. How do you suggest to meet these standards, since in most cases testing is not possible and/or specific information about an area is not known?

Coatings and additives can increase the fire-safety properties of a product or material. Material suppliers might have information about them.

7. If possible, what would be interesting to test?

It could be possible to perform a flame test with a sample of the material, to be able to say anything about the flammability of the material. The official mandatory test (the SBI test) will not be possible to perform, since this requires a full scale sample of the facade at its exact structure.

8. Because the time is limited for this study, I cannot research all aspects of the facade. What do you think is the most important part, to design a credible and qualitative facade?
This question was not answered in the interview.

9. Do you have any other comments?

There is also a classification for smoke, divided into different classes (S1, S2..) by the results of the SBI test. This is mainly important for smoke free escape routes. For the interior a smoke classification S2 should be applied.

Conclusion of the interview

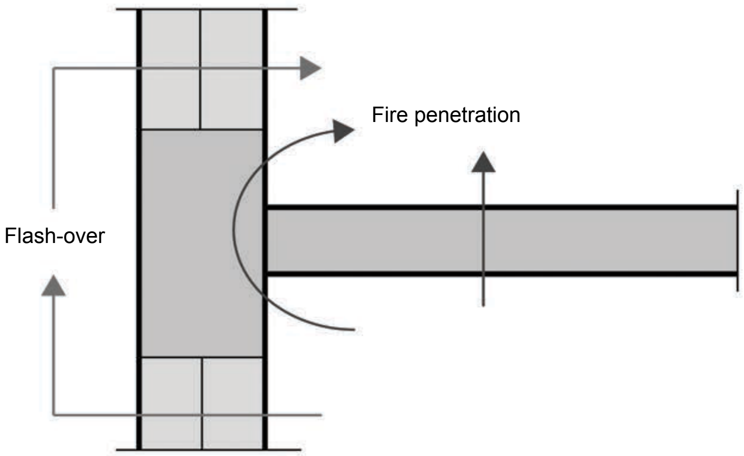
It is difficult to make assumptions regarding the requirements, since most standards are height related. Materials need to be tested to be able to say something about their fire-safety properties.

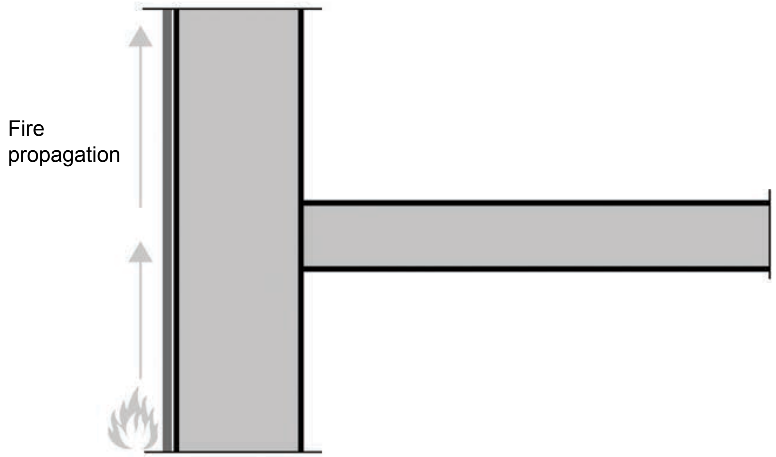
There are three types of fire loads: Fire penetration, flash-over and fire propagation (see pictures 1.18 and 1.19), to be found in the standard WBDBO (Weerstand Brand Doorslag Brand Overslag, Standard Fire-penetration, Flash-over) NEN 6068. Fire penetration through the facade right in front of the floor to the floor above is a problem which should be solved, as well as flash-over trough the facade. Another problem will be fire propagation through the outer centimeter material of the facade.

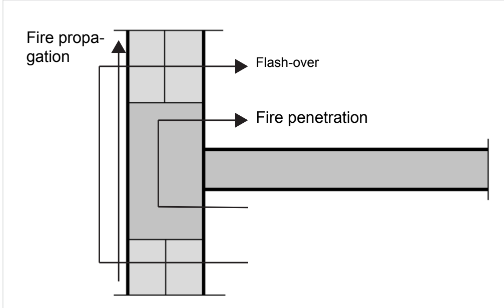
A solution for the fire penetration would be to add a fire proof retention wall. For the fire propagation along the facade, the material itself should be fire retardant enough. For high buildings, higher than two floors and bigger than one fire compartment, or when calculated using the program "Pintegraal", a class B is mandatory. To classify materials, they are tested according to the European standards for testing (NEN-EN 1364-3), and classified according to NEN-EN 13501

Coatings and additives can increase the fire-safety properties of a product or material.

It could be possible to perform a flame test with a sample of the material, to be able to say anything about the flammability of the material. The official mandatory test (the SBI test) will not be possible to perform, since this requires a full scale sample of the facade at its exact structure.







2.37 | Different ways of fire spreading: Fire penetration and flas-over
2.38 | Schematic image of fire propagation along the facade
2.39 | Three different options of fire spread

There are three types of fire loads: Fire penetration, flash-over and fire propagation.
For the fire propagation along the facade, the material itself should be fire retardant enough.

Coatings and additives can increase the fire-safety properties of a product or material.

2.7.3 | Interview Facade technology

Date: 15-12-2016
Interview with: Kevin Lenting
Specialized in: Facade Technology

1. What is your first idea of this material regarding your specialization?

If you use vacuum injection and add fire retardant substances, this makes the resin more viscous. The problem is that this makes it more difficult for the resin to reach all corners and the curing of the resin starts too soon, before the resin has reached all necessary places. It will be an option to make the core recyclable, but presumably the finishing will still be chemical because you need to meet the requirements of the Dutch building industry. I`m convinced that the Dutch building industry requires a sysnthetic layer to meet the quality standards.

2. What do you see as the greatest opportunities?

A cavity wall construction. It might be possible to accomplish enough acoustical insulation using only mass. Some numbers: A massive wall of 100kg/m2 has a Ra value of 38dB. A compact 50kg/m2 wall has a Ra of 30-33dB(A). For 10 kg/m2 this is 24dB(A).

3. What do you see as the main problems?

When used vacuum injection, it is difficult or even impossible to disassemble an element. It is an option to saw the core material out of the other elements. It does not specially matter for the facade out of which type of composite (resin) it is fabricated, however it should be resistant to moisture and UV radiation. It will probably be relatively simple to solve any structural problem, for example by adding fibres or material at specific places. If the element is completely made out of pressed material, the resistance against UV-radiation might be quite good, however water resistance will definitely be a problem.

4. Do you have an idea in which direction I should look for a solution to this problem, or are there comparable projects?

Coating the biobased composite would be a solution. Adding a waterproof layer will be necessary, for example a thin layer against the penetration of water into the facade. This could be the finish layer of the facade.

5. What standards are most important to meet?

NEN 2778 Penetration of moisture: Penetration of moisture through material. Since this is a smooth surface, the surface itself could obstruct a lot of moisture. Water resistance is regarded in relation to the whole element, therefore we use a method using test tubes for normal tests. Standards to follow in relation to moisture are the “Bouwbesluit” and NEN 2778 on moisture.
I should advise not to concentrate on the connections of the facade.

Secondly NEN 1068 Insulation and ISO 6948 are concentrating on insulation calculations and associated methodologies to calculate insulation. This standard holds the methods to calculate the insulation value, based on measurement (thermal transmittance measurement) and indicated with the lambda value. The total insulation value can be calculated using the standard. For the construction the “Euro code standards” should be applied. Using AFM or a similar program materials with their corresponding e-modules etc. can be calculated according to the European standards.

Solico is a company which is specialised in these calculations for composites. There is a publication of the SRB about the structural applications of composites, explaining about the calculation values for different composites. The connections of the facade can also be calculated using such a calculation method.

6. How do you suggest to meet these standards, since in most cases testing is not possible and/or specific information about an area is not known?

If a material or product is not applied in the conventional way (for which it has been tested), then new tests have to be performed, or it can only be estimated. The focus should be on water tightness. The construction issues can be solved by additional reinforcements or adding resin at specific places. Foils are usually tested and divided into different classes. If a similar test is performed for this material, equivalence can be demonstrated.

7. If possible, what would be interesting to test?

Water penetration. (Water container test).

8. Because the time is limited for this study, I cannot research all aspects of the facade. What do you think is the most important part, to design a credible and qualitative facade?

The water tightness. When it is an element out of one piece, delamination can be an problem. How do you know that the product will not disintegrates?

9. Do you have any other comments?

The building industry is fairly traditional.
In project concerning sustainability, sometimes there is space for experiments, however mainly when it doesn`t costs money and when there are no risks. I’m curious about the result of your graduation.

Conclusion of the interview
Vacuum injection with fire retardant substances makes the resin more viscous and this makes the resin more difficulty reach all necessary places. Presumably the finishing need to be chemical to meet the requirements of the Dutch building industry.

When using vacuum injection, it might be impossible to disassemble an element. The facade material should be resistant to moisture and UV radiation. It will probably be relatively simple to solve any structural problem, for example by adding fibres or material at specific places. If the element is completely made out of pressed material, the resistance against UV-radiation might be quite good, however water resistance will definitely be a problem.
Adding a waterproof layer will be necessary. This could be the finish layer of the facade.

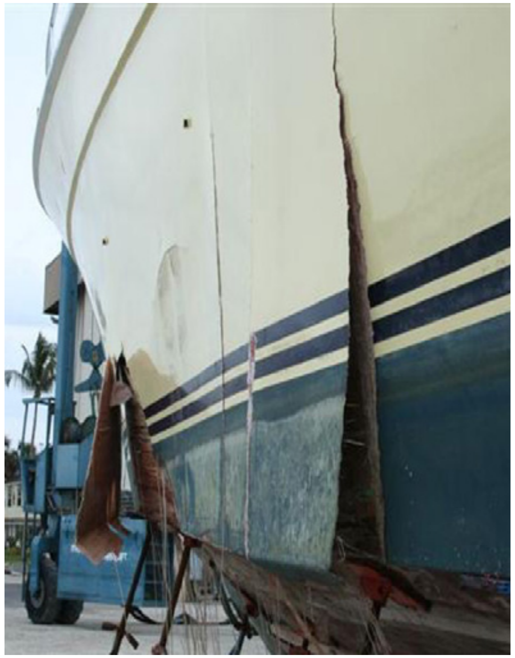
Important to meet is NEN 2778 Penetration of moisture: Since this is a smooth surface, the surface itself could obstruct a lot of moisture. Standards to follow in relation to moisture are the “Bouwbesluit” and NEN7078 on moisture.
Secondly NEN 1068 Insulation and ISO 6948 are concentrating on insulation calculations and associated methodologies to calculate insulation. This latter standard holds the methods to calculate the insulation value, based on measurement (thermal transmittance measurement) and indicated with the lambda value. The total insulation value can be calculated using the standard.
For the construction the “Euro code standards” should be applied. Using AFM or a similar program materials with their corresponding e-modules etc. can be calculated according to the European standards.

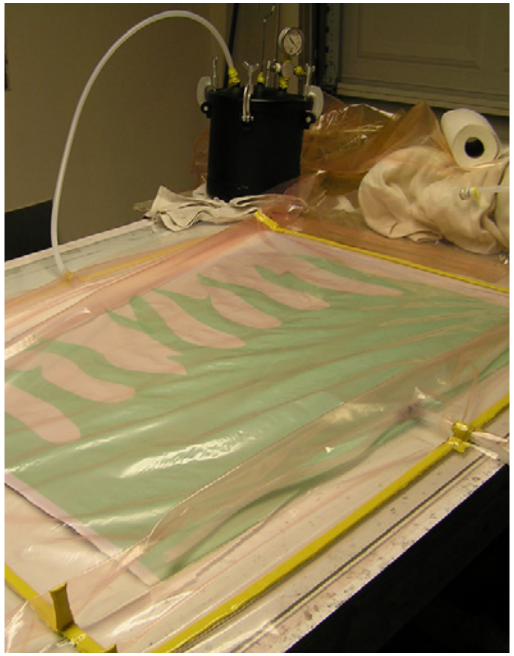
If a material or product is not applied in the conventional way (for which it has been tested), then new tests have to be carried out, or only estimations can be made. The focus should be on water tightness.

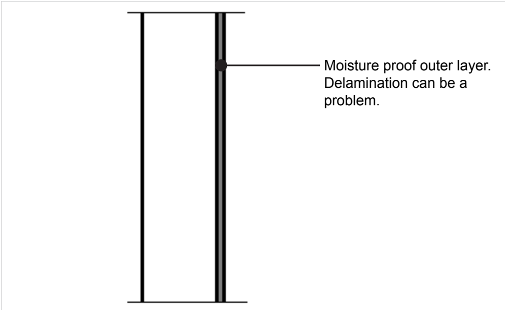
Foils are usually tested and divided into different classes. If a similar test is performed for this material, equivalence can be demonstrated.

The most interesting test (by its test results) would be a water penetration test (Water container test).

The water tightness is the most urgent problem. Another problem can be, for an element out of one piece, delamination.







2.40 | Delamination of a composite ship
2.41 | Vacuum injection of a composite sheet
2.42 | Important design aspects

When using vacuum injection, it might be impossible to disassemble an element.

The focus should be on water tightness, Therefore the most interesting test (by its test results) would be a water penetration test.

Delamination could also be a problem.

2.7.4 | Interview Sustainability

Date: 15-12-2016
Interview with: Jean Frantzen
Specialized in: Sustainability

1. What is your first idea of this material regarding your specialization?

An example of fully biobased elements are wood panels impregnated with latex, which are therefore bio-based and water-repellent. This type of coating from Pavatex probably has been tested. When using foils to make the facade waterproof and breathable, it is no longer biobased. You can use a timber frame construction element and finish it with a waterproof plate. Then you get a box of a timber frame construction which is waterproof. The finishing of the facade has then no influence on the technical functioning and this can be a moisture permeable construction. It is better to prevent the necessity of foils on the inside. When the outer layer of the facade is moisture permeable, the inside need to be moisture proof, ensuring a descending U-value, to avoid problems with moisture.

2. What do you see as the greatest opportunities?

I have performed research at the TU Delft on the field of recycling timber frame constructions which can easily be mounted together and disassembled. In this way you can disassemble a complete house and reassemble it again later. The size of elements should be uniform, because standardized elements can easily been applied again. If an element does not meet the quality demands anymore, you can disassemble it, upgrade the components and apply them again, this is re-use at element level. If all the material is completely organic, the elements can be put on a compost pile. Another possibility is put the elements through a shredder and use the granulate for new fibre boards. There are many different recycling options.

3. What do you see as the main problems?

The material requires good detailing and good awareness among the designers and contractors. For example a while ago there was a flooding river somewhere in Germany. A lot of houses with foils in the timber frame constructions had major damage, because they could not dry by the moisture proofing of the foils. Judges of insurance companies said that because they did not have to make the construction moisture proof, they did not compensate for the damage. Moisture permeable building is only done on very small scale in the Netherlands. Market parties who are applying this are small and have difficulties profiling themselves. They are more competing among themselves that they work together.

4. Do you have an idea in which direction I should look for a solution to this problem, or are there comparable projects?

This question was not answered in the interview.

5. What standards are most important to meet?

The CE markings. Insulation materials must have a certain R-value. The Dutch standards which determine the insulation value for renewable materials are not so favorable. For this the CE marking is beneficial.

6. How do you suggest to meet these standards, since in most cases testing is not possible and/or specific information about an area is not known?

The proposed design can be tested and simulated in the program Insul. At DGMR the Hague, you can consult Eric Cremers for the program.

7. If possible, what would be interesting to test?

This question was not answered in the interview.

8. Because the time is limited for this study, I cannot research all aspects of the facade. What do you think is the most important part, to design a credible and qualitative facade?

I think it is interesting to discuss with an architect (since your external mentor is one) the possibilities of a wooden facade (wood/ biocomposite on the outside, wood/biobased composite on the inside with a bio-based PUR foam in between) Just like the sandwich construction CEPEZED uses made out of steel. Adding sheets (tiles) to conventional facade would be quite easy.

9. Do you have any other comments?

The R-value is important. At this moment the problem is that the existing market (mainly the concrete industry) has been working very hard to ascertain how they are environmentally rated in database models. Sometimes they indicate a thick concrete facade as durable as a wooden facade. For renewable materials there are now unfavorable calculations used.
Therefore it is better to arrange the certification at product-level. Usually in timber frame constructions a gypsum plane is used at the inside and at the outside a material which is also classified in the mandatory class for fire-safety, for example Pavatex.
Interesting is also the way the material ages. Most natural materials have a nicely looking way of ageing, however this is a more technical material than for example wood. Another option is to use the facade as a “food source” for moss and algae. This comes from the Biomimicry: Sustainable Innovation by learning from nature. Their belief is that it is better to work together with nature than to conquer nature, using heat, beat and treat.

Conclusion of the interview
An example of fully biobased elements are wood panels impregnated with latex, which are therefore bio-based and water-repellent. When using foils to make the facade waterproof and breathable, it is no longer biobased.

An option is to use a timber frame construction element and finish it with a waterproof plate.

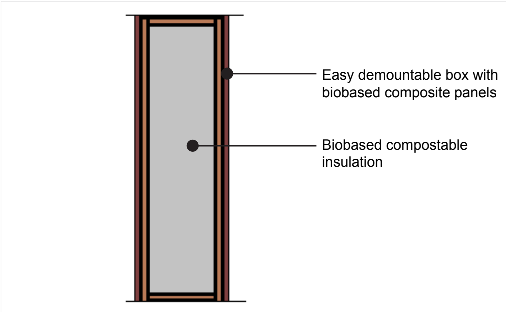
It is better to prevent the necessity of foils on the inside. When the outer layer of the facade is moisture permeable, the inside needs to be moisture proof, ensuring a descending U-value, to avoid problems with moisture.

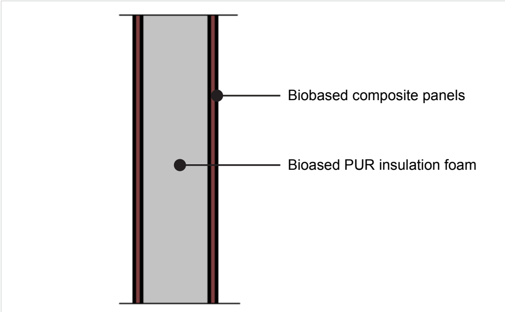
An opportunity in the field of recycling is the use of timber frame constructions that can easily be mounted together and disassembled. In this way you can disassemble a complete house and reassemble it again later. If all the material is completely organic, the elements can be put on a compost pile. Another possibility is put the elements through a shredder and use the granulate for new fibre boards. There are many different recycling options.

The material requires good detailing and good awareness among the designers and contractors. Moisture permeable building is only done on very small scale in the Netherlands.

The CE marking requirements are the most important to meet. Insulation materials must have a certain R-value. The Dutch standards which determine the insulation value for renewable materials are not so favorable. For this the CE marking is beneficial.

A sandwich construction, now often made out of steel, could possibly be made out of biobased composite (biobased composite on the outside, biobased composite on the inside with a biobased PUR foam in between).
Interesting is also the way the material ages. Most natural materials have an nicely looking way of ageing, however this is a more technical material than for example wood.
Another option is to use the facade as a “food source” for moss and algae.





2.43 | Prefabricated timber frame construction element
2.44 | Application of moisture-proof foil
2.45-2.46 | Possible design solutions

Sustainable options are to use an adaptive timber frame construction and to avoid foils on the inside.

Recycling options are disassembling, composting and shreddering.

The CE marking requirements are the most important to meet.

Interesting is also the way the material ages.

3 CIRCULARITY

3.1 | DEFINITION CIRCULARITY

Circularity refers in this report to circular building principles. In the past years, regarding the immense waste stream the building industry produces, research into the possibilities of circular building materials and processes has started. Since then, a number of studies have been carried out regarding the building industry, and a couple of these researches specifically regard the facade industry.

The building industry will be just one sector in a circular economy. The circular economy is a rather recent way of looking at sustainability, based on thinking in circular supply chains, maximizing the value of materials in which products can be re-used, remanufactured and/or recycled (Ellen MacArthur Foundation, 2012).

According to Geraetds and Prins (2015, pp. 1-2): The need to adapt buildings and to reduce environmental footprints becomes more and more pressing over time as global concentrations of carbon dioxide increase. Besides this, the dynamic worldwide process of unlimited growth, characterized by rapid urbanization and fast consuming economies will in the next decades lead to an explosive demand of construction materials (Van Timmeren 2013, Schoolderman 2014).

At this moment, in the Netherlands 50% of the national raw material consumption is caused by the construction industry and 40% of this amount refers to demolition waste (Geraetds and Prins, 2015, pp. 1-2).

To enhance the shift from a “take-make-waste” or “cradle-to-waste” pattern into “closed loop thinking”, products should be adaptable, meaning that if they no longer deliver the requested performance, they can be adapted to a higher quality, instead of disposing them (Geraetds and Prins, 2015, pp. 1-2).

This adaptive capacity of a building includes all characteristics that enable it to keep its function during the technical life cycle in a sustainable and economic profitable way, withstanding changing requirements and circumstances (Geraetds and Prins, 2015, pp. 3).

Within this circular building proces, Duffy (1998) and Brand (1994) defined six different loops, of which the skin is one:

- Site: Urban location,
- Structure: Foundation, load bearing elements,
- Skin: Exterior finishing,
- Services: Installations,
- Space plan: Interior layout,
- Stuff: Furniture,

presenting six functional levels within a building, with different changing life cycles and their own technical, functional and economic lifespan.

According to Geldermans (2016) “Circular building demand for flexible and adaptable buildings in order to facilitate change without loss of material quality. However, for circular building the focus lays on the materials used and their quality, recyclability and health”.

The cradle-to-cradle principle has put forward the idea of buildings as material banks. In this way waste can be regarded as resource.

“Cicularity-values emerge at the intersection of specific intrinsic properties (material and product characteristics) and relational properties (building design and use chracteristics), whilst combining multiple parameters” (Geldermans, 2016, pp. 1).

In a recent study Geraedts, Remoy, Hermans, & Van Rijn (2014, p. 1) state that the increasing interest in flexible building is caused by high structural vacancy of buildings, the economic crises and the increased awareness of and interest in sustainability issues and the circular economy.

3.1 | Growing flax
3.2-3.3 | Excavation of raw materials

“Adaptive capacity is not the goal itself, but the means to ensure the future use of building” (Geraedts et al., 2014, p. 2).

In beyond sutainability Luscuere, Geldermans, Tenpierik, and Jansen (2016, p. 29) made clear that of all available top soil approximately 50% has been lost during the last 150 years. The herefore responsible linear material- and product processes do not relate well to a finite planet. The so called solution for this probles is called Circularity: We must endlessly renew all natural resources. “We are consuming in a irresponsible rate, like we have been doing with our fossil fuels (Luscuere et al., 2016, p. 29).
“The depletion of resources is more imminent and potentially more disruptive than the fossil energy depletion alone” (Luscuere et al., 2016, p. 30).

“The only sustainable way forward is developing improved recycling and upcycling techniques” (Luscuere et al., 2016, p. 34).
To apply a positive footprint to the resource “materials” in the built environment, materials should be brought in a biological or technological cycle so that they can be reused indefinitely (Luscuere et al., 2016, p. 33).

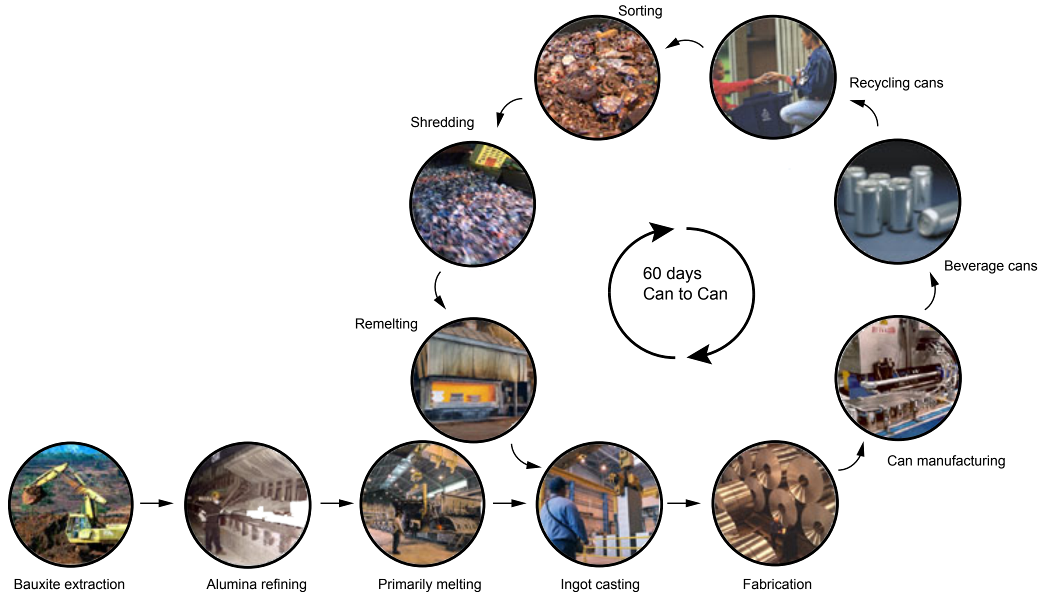
Biological materials are renewable by definition: They grow. Dramatic efficiency improvements can be achieved in the cultivation of biological materials by choice of different crops and harvesting techniques (Luscuere et al., 2016, p. 33).

In addition, Luscuere et al. (2016, p. 35) warns for the competition between energy and material cycles on one hand, and the production of food on the other, as a situation which should by all means be avoided.

Biological routes are labelled as:
• Bio-cascades: reuse at significant lower grade of biological application,
• Bio-feedstock: Providing direct nutrition`s for the soil,
• Multiple technical routes: Maintenance, redistribution, refurbishment, remanufacturing and recycling.
(Luscuere et al., 2016, p. 40)

Upcycling (bringing a material or product to a higher quality, keeping it useful) is the opposite of downcycling (use a material or product in a level lower that its original designed for).

Using upcycling, a material can be kept in the circle unlimited, because the quality of the material will not degrade. This seems a contradiction regarding the effect of entropy, however in this process it is allowed to add energy to the system (Luscuere et al., 2016).



3.4 | (Circular) Life cycle of an aluminum can

To conclude, the circular building principle has the purpose to keep materials and products “performing” as long as possible, avoiding discarding them, while in the same time products or materials are used as “material banks” to avoid the scarcity of raw materials.

Reuse of materials can be applied at several different qualities. The higher quality a material can remain at, the highest chance exists that it can be reused or adapted to useful products or material again.

By keeping materials or products adaptive, the maintenance, redistribution, refurbishment, remanufacturing and recycling can be done much easier.

Different methods to apply circularity to this design are explained in the next paragraph.

The circular building principles enhance “closed loop thinking”, adaptive design and upgrading.

The aim is to keep materials and products “performing” as long as possible, avoiding discarding them while at the same time products or materials are used as “material banks”.

3.2 | CIRCULAR DESIGN WITH BIOBASED COMPOSITE

One method already in 1961 described by Habraken concerns a division between the support level of a building (providing this with a long lifespan) and the infill level, giving this a significant shorter lifespan (Habraken 1961).
This approach makes it efficient to replace materials or products at certain levels, whilst keeping others (the support level) for a long time.

In "the CE meter", the dismountability of a facade is weighted as a "number three out of three", the same as nine other factors out of seventeen, giving it a high importance regarding the adaptivity of buildings (Geraetds and Prins, 2015, pp. 1-2). See the table on the right page.

In "the adaptability of buildings" some of the assessment values regarding the facade are:

• "The more the layout of a building is equilateral and regular, the easier a building can be rearranged".

• "The more project independent, demountable and replaceable construction components have been implemented, the easier a buiding can be rearranged or transformed to other functions".

• "The smaller the size of the horizontal measuring grid of a facade, the easier buildings can be arranged or transformed to other functions".

• "The more facade components are easily dismountable the easier a building can be rearranged or transformed to other functions".

• "The more a facade is self-supporting and is not taken part of the load bearing structure of the building the easier a building can be rearranged or transformed to other functions".

• "The higher the exchangeability of the infill construction components, the easier a buiding can be rearranged or transformed to other functions".
(Geraedts et al., 2014, p. 11-14).

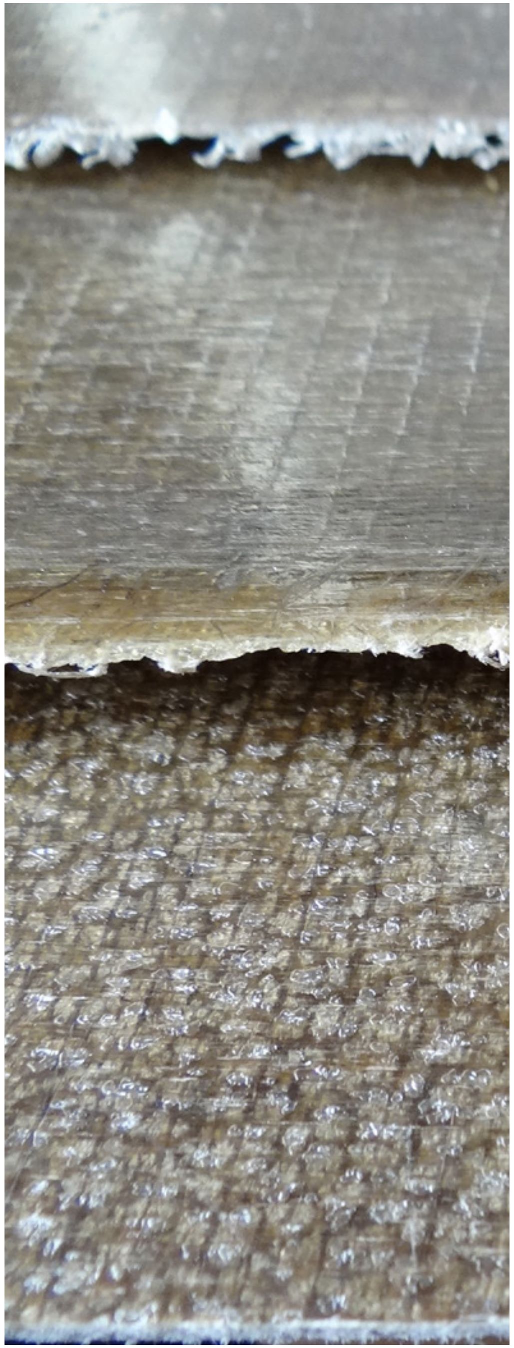
According to "Design for change and flexibility" there are four demands to a circular material.
It should be:
1. Of high quality,
2. Of sustainable origin,
3. Non-toxic,
4. Consistent with the biological cycle and cascade, or one or more technical cycles.

Besides these intrinsic properties, a material or product should relate to the design and use of buildings.

Technically this can be defined by the:
• Dimensions (dynamic capacity demands),
• Connections (dry and logical),
• Performance time (defining the life span),
Geldermans, 2016.

The NSS (new stepped strategy) introduced by Geldermans (2016) to specify the link between the material- and product cycles and the building design is based on three steps:
1. Reduce resource,
2. Reuse resource,
3. Apply regenerative (circular) solutions.

In "Beyond sustainability" the following is proposed:
"Bring materials in a biological or technological cycle so that they can be reused indefinitely" (Luscuere et al., 2016, p. 33).
Furthermore healthy material use and anticipated disassembly and reuse routes are mentioned.



Flex light 2.0					
Layer	**Sublayer**	**Flexibility Performance Indicator**	**Weighting**	**Example assessment**	**Score**
1 Site/ Location		Surplus of site space	1	3	**3**
2 Stucture	Measurements	Surplus of building space/ flooring space	2	2	**4**
		Surplus of floor height	3	4	**12**
	Access	Access to building: location of stairs, elevators, core	2	1	**2**
	Construction	Surplus of loadbearing capacity of floors	3	3	**9**
		Extendible building/ unit horizontal	3	2	**6**
		Extendible building/ unit vertical	1	1	**2**
3 *Skin*	*Facade*	*Dismountable facade*	*3*	*4*	***12***
4 Facilities	Measurements & control	Customisability and controllability of facilities	2	1	**2**
	Dimensions	Surplus facilities shafts and ducts	2	1	**2**
		Surplus capacity of facilities	3	1	**3**
		Disconnection of facilities components	2	3	**6**
5 Space plan/ finishing	Functional	*Distinction between support -infill (fit-out)*	3	2	**6**
	Access	Access to building: horizontal routing, corridors, gallery	1	2	**2**
	Technical	*Removable, relocatable units in building*	3	1	**3**
		Removable, relocatable interior walls in building	3	3	**9**
		Disconnecting/ detailed disconnection interior walls hor/vert.	3	4	**12**
					95

Class table	**Score**
Adaptivity Scores	**Range**
Class 1: Not adaptive	17-54
Class 2: Hardly adaptive	55-92
Class 3: Limited adaptive	93-130
Class 4: Good adaptive	131-168
Class 5: Excellent adaptive	169-204

3.5 | Flax growing
3.6 | Biobased composite panels
Table 3.1 | Example of “The CE meter”: the most important indicators.

3.2.1 | Conclusion

To start with, a division between load bearing elements and infill elements can be made, giving load-bearing elements a long lifespan and infill elements a short lifetime and design them to be easily replaced.

Summarizing the information of different scientific resources, to be adaptable a facade should be designed:
• Dismountable,
• Project independent,
• Replaceable,
• Equilateral and regular,
• With a small horizontal measuring grid,
• Self-supporting,
• Of high quality,
• Of sustainable origin,
• Non-toxic,
• Of well thought dimensions,
• Have dry and logical connections,
• With an appropriate performance time/life span.

For circularity the quality, origin and non-toxicity of materials are important. Three main rules of circular building are:
• Reduce the resources
• Reuse the resources
• Apply regenerative circular solutions.

It is important to make a division between load bearing elements and infill elements, and adjust their lifetime to their application.

For the aspects of an adaptable facade, see the summarizing above.
The quality, origin and non-toxicity of materials are important and the main rules are “reduce the resources, reuse the resources and apply regenerative circular solutions.

Recycling of biobased composite is at this moment still in it`s infancy, Several chemical test have been performed, however they only include the decomposition of the composite, and not the analyses of the residual products.

Avans university Breda has performed different solvolysis reactions both on carbonfibre reinforced composite and biobased composite material. In his research "Recycling of fibre reinforced composites" Klok (2016) performs solvolysis`s using different solvents.
The method of the research is, very roughly, to boil the sample (biobased composite) in a strong alkaline environment and visually analyse the result.
These tests showed that the epoxy resin dissolves and the fibres remain visually intact. However, the weight of the fibres before and after the reaction are not measured, and the fibres are not being tested for mechanical strength, therefore the degradation of the fibres is not made insightful.

3.3.1 | Results previous tests

In the research of Klok (2016), the bio epoxy composite dissolves almost completely when heated for two hours in one of the three solvent mixtures being Sodiumhydroxide-Diethylene glycol (NaOH/DEG), Potassiumhydroxide-Diethylene glycol (KOH/DEG) or Sodiumhydroxide-Polyethylene glycol (NaOH/PEG 300).

The picture below shows the resulting fibres of the NaOH/DEG solvolysis before the solvolysis (left) and after the solvolysis (right). The fibres seem to be intact, however the decrease in weight or the degradation of strength was not measured.

3.3.2 | Proposed test

To test whether a coated sample can be recycled using solvolysis as well, a test plan was written to test three different samples. The plan was to test coated and uncoated samples which have been or haven`t been tested for accelerated weathering (in a QUV machine for 808 hours by Van der Linden, 2017). The three options were:

- Unweathered and coated
- Weathered and coated
- Weathered and uncoated

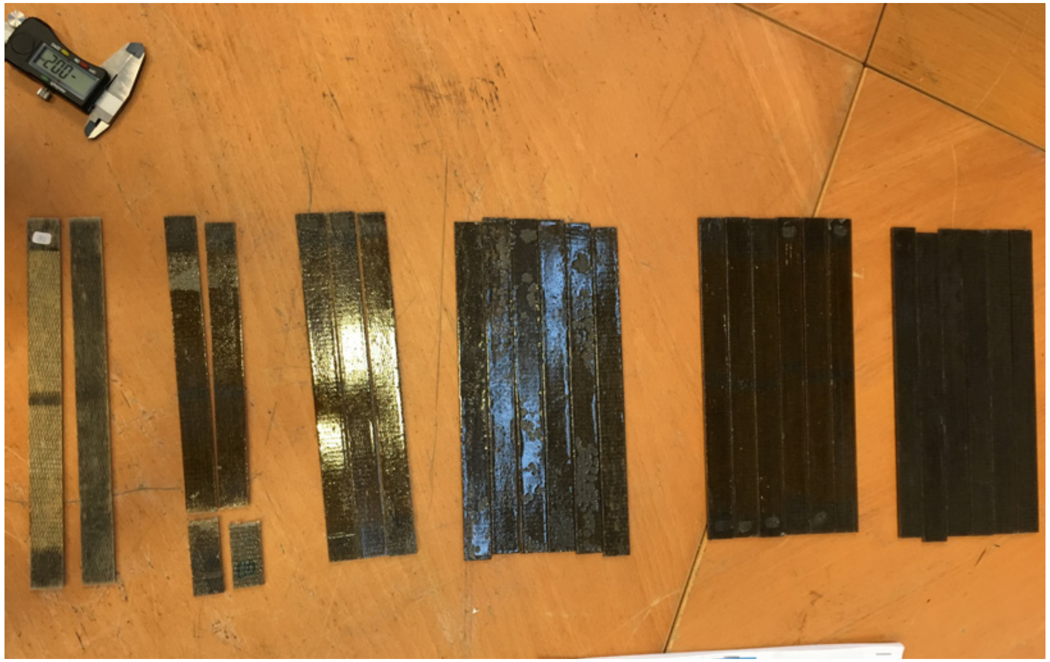
The three samples were to be decomposed using solvolysis with one of the three mixtures used in the research at Avans university Breda. After approaching different institutions with this plan, a meeting with chemist ing. D. Bosma at the faculty of applied science of the TU Delft showed that the background of the research turned out to be far more complex. The following information is based on the discussion with ing. D. Bosma.

The substances used in the research of Avans university are relatively aggressive and can therefore attack the fibres as well. In general epoxies are dissolved in alkaline environments, when the temperature is high enough. It would be interested to test less aggressive substances to see whether the same effect is achieved.

Epoxy is the worldwide most commonly used glue due to its strength, and therefore difficult to dissolve. Regarding the circularity, it can be recommended to design the resins taking the recycleability into account.

Besides the weight, the structural properties of the fibres could decrease due to the solvolysis. The strong alkaline environment and the high temperature will very likely affect the composition of the natural fibres. Since the filaments of natural fibres are made from cellulose or hemicellulose and the matrix is usually lignine or pectine, the fibres probably undergo an amorphous transition during the solvolysis.

3.7 | Result of the test performed at Avans university Breda before and after the solvolysis



3.8 | Coated and uncoated samples tested for tensile strength after 808 hours in an QUV accelerated weathering machine

For starch, a common component of natural fibres, this transition occures already at 60-70°C, while for cellulose the reaction only starts at 320°C and a pressure of 25 MPa (250 bars). Cellulose was proven to melt at 467°C (Wikipedia, 2017).
How the fibres react in a strong alkaline environment has not been researched yet. The expectations are that the fibres degrade at a lower temperature and at a lower pressure than the 250 bars. Therefore it is recommended to create a most mild reaction environment to protect the fibres as much as possible.

Another discussion is if it is necessary to protect the fibres. This is mainly important when the concerning fibres are expensive or scarce. Because biobased composite regards fast growing fibres, it might be beneficial to not protect the fibres and just compost them. The actual recycling will in this case regard only the resin, and when applied the coating.

Another point of attention is recovering the catalyst. The solvent used will remain mixed with the resin after dissolving it. Many solvents can be distilled out of the mixture, however this only applies when the solvent has a relatively low boiling point. When the solvent can be made solid, it might be possible to remove the substance using a sieve.

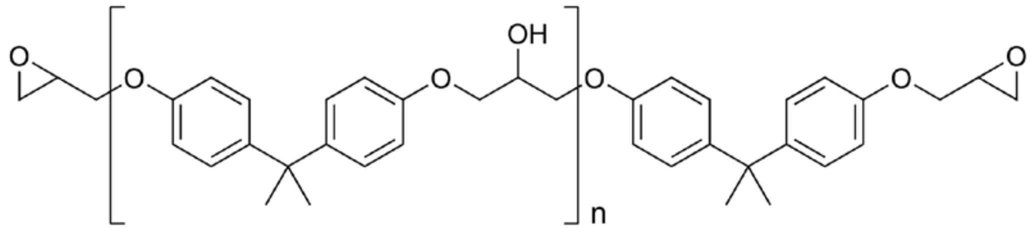
In the Experiment at Avans, Klok (2016) used DEG and PEG in combination with the actual solvent (NaOH or KOH) because these substances reach a higher boiling point than for example water. The same experiment can therefore also been performed with water, however only under higher pressure than the average atmospheric pressure of one bar, because water can then reach higher temperatures. Autoclaves could be used to perform this recycling process. Autoclaves exist in a wide variety of sizes, however the very large ones (picture below on the right) are scarce and very expensive.

Which substances are applicable to dissolve epoxy resins and or epoxy coatings requires further research. Since this research will be extensive and (bio)chemical knowledge is required, this cannot be performed by the author.

Therefore a strong recommendation exists for biochemical students or researchers to further explore the possibilities to recycle biobased composites.

3.3.3 | Recycled resins

The epoxy resin forms usually strong cross-linked bonds which are broken due to the high temperature and alkaline environment. This process is called “transesterfication”, however how the process takes place at molecule level is not known yet. Therefore it is also not known to what extend these bonding`s can be recovered, and what the properties of the epoxy resin will be afterwards.



3.9 | An autoclave
3.10 | Epoxy polymer

3.3.4 | Recycleable coatings

3.3.4.1 | Epoxy

Epoxy coatings will presumably dissolve just as good as the epoxy resin. The additional problem is that the remaining liquid contains the resin and solvent as well as the dissolved coating. Recapturing the resin will therefore become even more difficult.

3.3.4.2 | Waterglass/ Sodium-silicate

A commonly used impregnation method for outside applications is “waterglass” or sodium silicate. This substance is a white powder untill dissolved in water.
Dissolved in water, the substance is frequently mixed with the glue used to stick poster on outside walls, since the substance protect very good against water.
Another application of waterglass for biobased composite can be to impregnate the fibres with the waterglass before applying the resin, to make the fibres better water-resistant.

3.3.4.3 | PVC

PVC coatings are petrochemical based, however they offer possibilities regarding recycling. PVC coatings protect materials for outside applications very well, and after the lifetime of the product the coating can be removed afterwards (dissolving it) and the product can be recycled further or coated again.

3.3.5 | Future recycling options

3.3.5.1 | Ammonia

Ammonia can induce the same alkaline environment as for example sodiumhydroxide. The benefit of ammonia is that it can be distilled out of the mixture due to its low boiling point. However, the ammonia vapor produced is highly toxic, especially for the lungs. This process requires therefore different specialistic safety precautions.

3.3.6 | Conclusion

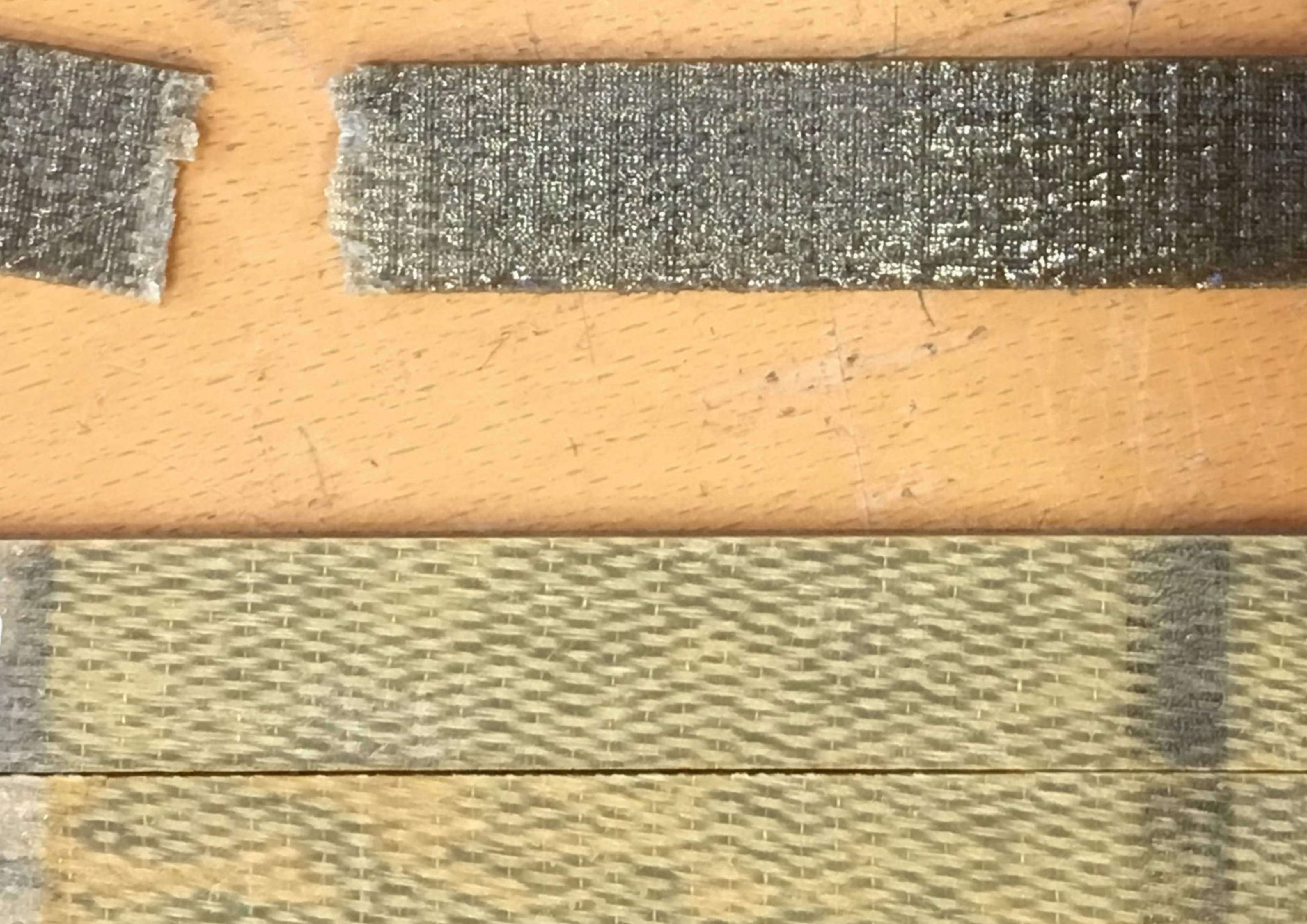
At this moment, the biobased composite can be decomposed into the fibres and the resin, which provides opportunities for recycling or composting. The fibres are presumably degraded, however it is not clear yet to what extent.

Because the fibres are biobased and fast growing, at this moment it seems best to concentrate on recapturing the resin. The ability to do this depends on the used solvent, and the ability to reuse the dissolved resin since the bonding`s are damaged. Both aspects require further research.

The catalyst (solvent) should preferably be as environmental friendly as possible and/or 100% reusable. The process should, specifically when performed on large scale, be harmless for the environment and people performing it. Many solvents are toxic, therefore it is expected that several safety precautions need to be taken.
Regarding the environment it seems more beneficial to use water instead of PEG or DEG, however when water is used a higher pressure is required. If the process is performed on large scale, the high pressure caused by an autoclave requires a significant amount of energy. To make clear whether it is more sustainable at an industrial scale to use a chemical or water under pressure requires further research too.

3.11 | PVC coating
3.12 | Distillation of ammonia

The recycleability of biobased composite is still at it`s infancy. Biocomposite can be decomposed into fibres and resin, when the resin is dissolved using a solvent.
Two problems still need to be solved while doing this:
• The fibres might degrade due to the solvent and the high temperature
• The resin (and coating) are mixed with the solvent and recapturing need further research.
Also the bonding`s in the resin are destroyed.



4 PRODUCTION

4.1.1 | Composite manufacturing

The complete product manufacturing can be divided into four steps, according to the book "Composite manufacturing" (Mazumdar, 2002):

Forming
Feedstock is changed into a desired shape and size. These processes are described in paragraph 4.2 about production techniques.

Machining
Examples are drilling, cutting, turning and grinding. These operations are used to remove extra, undesired material. For composites, different tools and conditions are required than for metals.

Joining and assembly
Joining and assembly is performed to attach different components. More on this subject will be described in paragraph 4.3 on connections.

Finishing
Finishing operations are carried out for different reasons, for example to improve the outside appearance, to protect the object against environmental degradation or to provide wear-resistance as explained in paragraph 2.3 on coatings.

Not all steps are necessarily performed at one manufacturing company.

4.1.2 | Design for manufacturing

To make a product more cost-effective, Mazumdar (2002) defines 9 design rules. These are defined for composites used in the airline industry, however they can also be applied on biobased composite designs. It is important to keep in mind is that these design rules have to do with cost effectiveness and not specifically with circularity.

Minimize part counts
Composite materials offer a good potential for part integration, which minimizes the need for assembly, inventory control, storage, inspection, transportation and servicing.

Eliminate threaded fasteners
Avoid the use of screws, nuts, bolts and other mechanical fasteners. These mechanical connections increase the inventory costs (driving a screw into a material costs 6-10 times more than the screw itself) and make assembling more complicated, besides, threaded fasteners can come loose over time.

Minimize variation
Nonconformities and defects are mainly caused by dimensional variations and property variations. Therefore it is wise to avoid the use of special parts and try to use off-the-shelf components. While using parts of the same size, the same assembling tool can be used. This will also increase the inventory control and interchangeability.

Easy seviceability and Maintainability
Products should be designed in such a way that parts are easy accesible for assembly, demontation and inspection.

Minimize assembly directions
While designing a product, it is important to think about the operations needed to attach different parts. It is preferable to use one direction assembly operations, this also minimizes part movement and the need for different assembling workshops.

Consider ease of handling
For smooth assembly and ease of handling, parts should not be heavy and not have too many curves. Last mentioned reduces the potential for entanglement. The assembly locations should be easy to acces. Symmentric parts are easier to orient, and features can be added to help guide the part to its location.

Design for mulitfunctionality
When the idea of the design is clear, parts can be designed multifunctionally. Built-in features like self-alignment, self-locating or mounting can be added.

Design for ease of production
Each production technique has its own strengths and weaknesses. A design should profit from the strengths of the production technique. A design should be simplified as much as possible to ease manufacturing and assembly, and be easier understandable for workers.

Prefer modular design
If a product contains standardized modules, each module can be independently designed and improved without affecting the others. Besides this, replacement and assembly will be easy.

Not all design rules explained by Mazumbar (2002) are applicable to a circular composite design.

For example the use of screws, bolts and other mechanical fasteners make parts much better demountable than adhesive connections.
The downside of these connections, such as the chance that parts can come loose, should be taken into account.

Minimizing the part counts depends on the manufacturing techniqe. Using molds, it is important to design the mold as efficient as possible, keeping the explained aspects such as variation and ease of handling in mind.
However, when extrusion is used, the element will be constructed out of connected profiles. Therefore the named aspects do not apply to all production methods and produced parts to the same extend, and need to be applied appropriately.

4.1 | Autoclave molding
4.2 | Composite mold for a yaught

Different steps in composite manufacturing are forming, machining, joining and assembly and finishing.

To make a composite products (not necessarily a circular product) more cost-effective, 9 design rule can be applied.

4.2.1 | Basic manufacturing steps

The basic steps in composite manufacturing (Mazumdar, 2002):

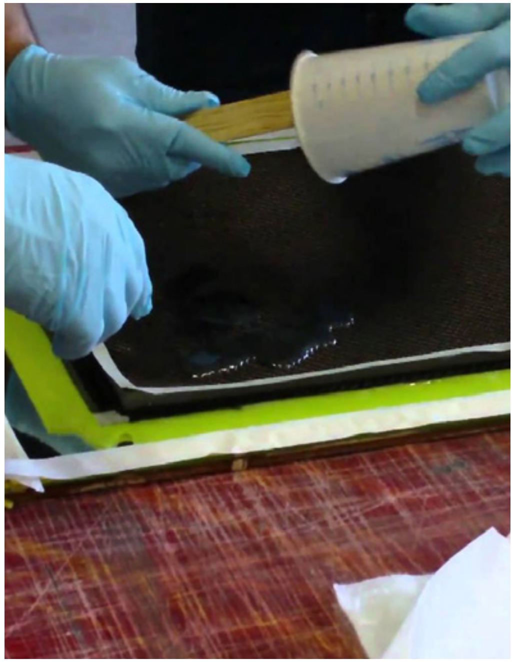
Impregnation
This is the step in which fibres and resin are mixed together, to make sure the resin flows trough all the fibres. This process is mainly influenced by the viscosity, surface tension and capillary action.

Lay-up
Composite laminates are formed, by placing fibre-resin mixtures at the desired angles at the right places. The desired thickness is reached by placing layers on top of each other.

Consolidation
In this step, the goal is to remove all air trapped between the layers. This is an important step since poorly consolidated products contain voids and dry spots.

Solidification
Solidification takes for thermoplastics only a very short time, while for thermosets this can take up to 120 minutes. If necessary, vacuum or pressure is applied during this process.

In this chapter, a division is made between production methods for thermoset and thermoplastic resins, since these vary based on the properties of the polymers.



4.2.2 | Processing thermoset polymers

The benefits of thermoset resins:
• Processing a thermoset is easier than a thermoplast resin, because the resin is in a liquid state.
• It is easier to wet the fibres, therefore fewer voids and porosities occur.
• Less heat and pressure is required, which provides energy savings.
• A low cost tooling system can be used.

The disadvantages of thermoset resins:
• Thermoset composites require a long curing time, therefore the production rate is not very high.
• Cured parts cannot be melted again.
• Recycling of thermosets is an issue.
(Mazumdar, 2002).

The information on the production techniques refers to the extensive explanation in the masterthesis “Bio-based FRP structures: A pedestrian bridge in Schiphol Logistics Park” by R. Gkaidatzis (2014).

4.2.2.1 | Manual lay-up techniques

Hand lay-up

Hand lay-up or wet lay-up is the most widely used and one of the oldest techniques of making composite parts. It is simple and allows for design flexibility and is therefore more suitable for components with irregular shapes in small batches or elements with large dimensions that cannot be produced with automated plant. The first stage is the application of a gel-coat on the mold. Then the reinforcement is laid on by hand and the liquid resin is applied and pressed. Additives such as flame retardants and inert fillers can be mixed to improve the mechanical and physical properties. The process is repeated layer by layer. In general, the application of the hand lay-up method is limited to the thermosets as resins need to be low in viscosity to be workable by hand. Hand lay-up is a relatively cheap process as equipment and tooling cost are low and as only one open (single) mold is needed.

4.3 | Impregnation
4.4 | Hand lay-up
4.5 | Hand lay-up
4.6 | Vacuum bagging
4.7 | Vacuum bagging process

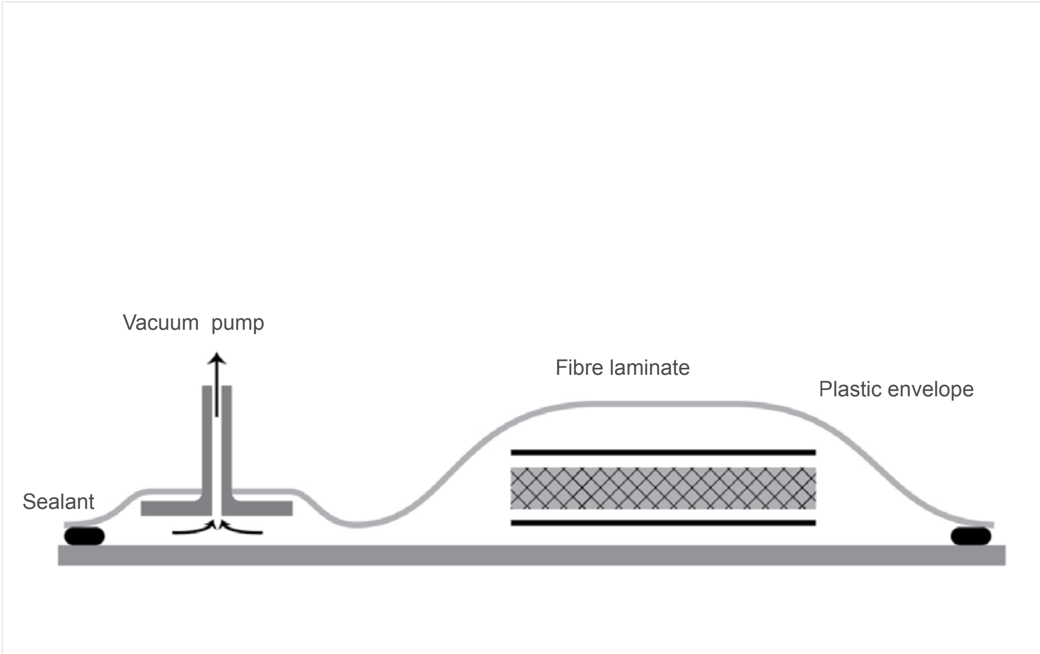
Vacuum bagging

Vacuum and pressure bagging are basically an extension of the wet lay-up process with the difference that pressure (either by air extraction or by pressing) is applied to the laminate in order to improve its consolidation and hold the resin-coated component in place until the polymer cures.

Components that are mainly produced by these two processes include shapes with high surface area to thickness ratio, so they are preferred for large one-off components such as boats or racecars.

In the vacuum bagging process the reinforcement and the resin are applied on the mold manually or by the spray lay-up technique. Then the laminate is sealed within an airtight envelope that consists of an airtight mold on one side and an airtight bag on the other. When the bag is sealed to the mold, air is evacuated by a vacuum pump from the inside of the envelope.

The continuous, firm and evenly distributed atmospheric pressure over the entire surface, allows for a wide range of types and combinations of materials in laminates with a superior bond between them. Concerning health and safety issues, as vacuum bagging is a closed process the emission levels during the cure are low.



Autoclave molding

Autoclave molding is a process similar to vacuum/pressure bagging with the difference that autoclave machinery is used for curing the composites. The autoclave machine is basically a large oven that subjects materials to high pressure, temperature and vacuum. In the same way with vacuum bagging, the reinforcement and the resin are applied on the mold by conventional hand or spray lay-up techniques.

The laminate is again covered with a porous film and a layer of glass-fibre cloth or paper to absorb any excess resin. The laminate will then be covered with a flexible bag which is clamped on a table.

The wet laminate and the mold are then placed inside the autoclave and subjected to high pressures of about 0.55 MPa and temperature which causes the plastic bag to compress the laminate.

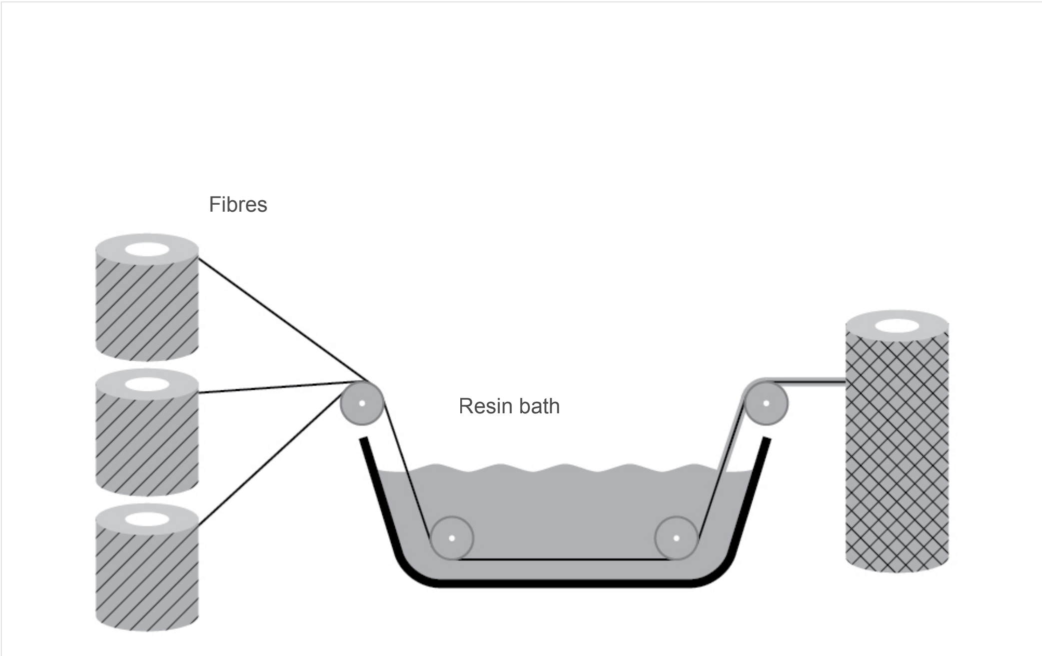
With the subjection of the material to elevated pressures and temperatures, higher fibre-to-resin ratios and removal of all voids (less than 2%) can be achieved, which leads in a maximization of the performance of the thermoset composites. Therefore, autoclaves are used for the fabrication of high quality advanced components such as high strength aircraft and aerospace components.

4.2.2.2 | Automatic lay-up techniques

Filament winding

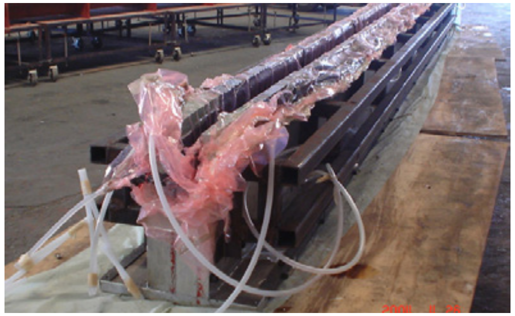
Also known as wrapping, this is a process in which continuous rovings, tows or tapes are wound over a rotating mandrel. Despite the shape limitations very large parts can be produced. Filament winding is ideal for producing axisymmetric hollow parts such as pipes, tubes, tanks and pressure vessels, turbine blades or rocket noses.

As a process it requires less capital investment, compared to other autoclave processes or automated tape lay-up. However, the cost of large mandrels can be high. In general it is an economic process with normal cost for large quantities as the material costs are relatively low.



4.2.2.3 | Resin transfer molding techniques

RTM
Resin transfer molding (RTM) processes are a family of closed mold low-pressure processes in which the dry reinforcement and the resin are mixed within the closed mold. Dry reinforcement in form of fibre mats is laid on the first mold together with other fabric layers, such as a release fabric and a breather. Then a second mold is clamped over the first, and a low viscosity resin (usually epoxy or polyester) is injected into the airtight cavity between the two molds. During the injection, pressure difference is created inside the closed cavity which forces the resin to flow through the reinforcement. The composite is allowed to cure at room temperature.
RTM is an easy process for manufacturing complex shapes without high cost tooling. Another advantage is that both sides of the component have a smooth surface finish. Although the relative cost per unit is low, the fabrication of the two parts of the double mold can be expensive.

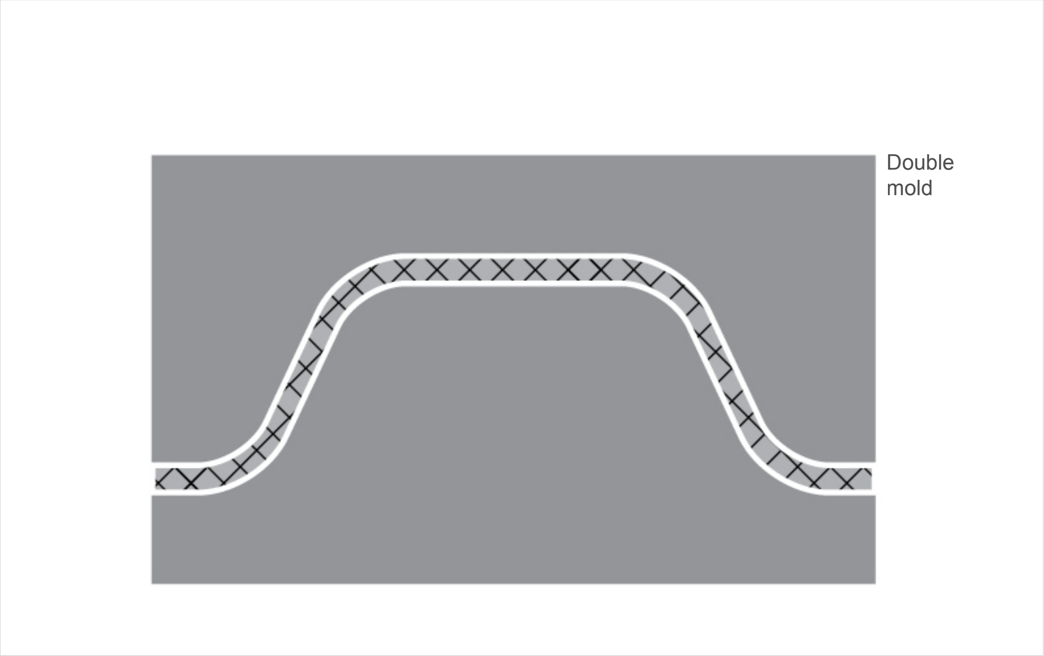


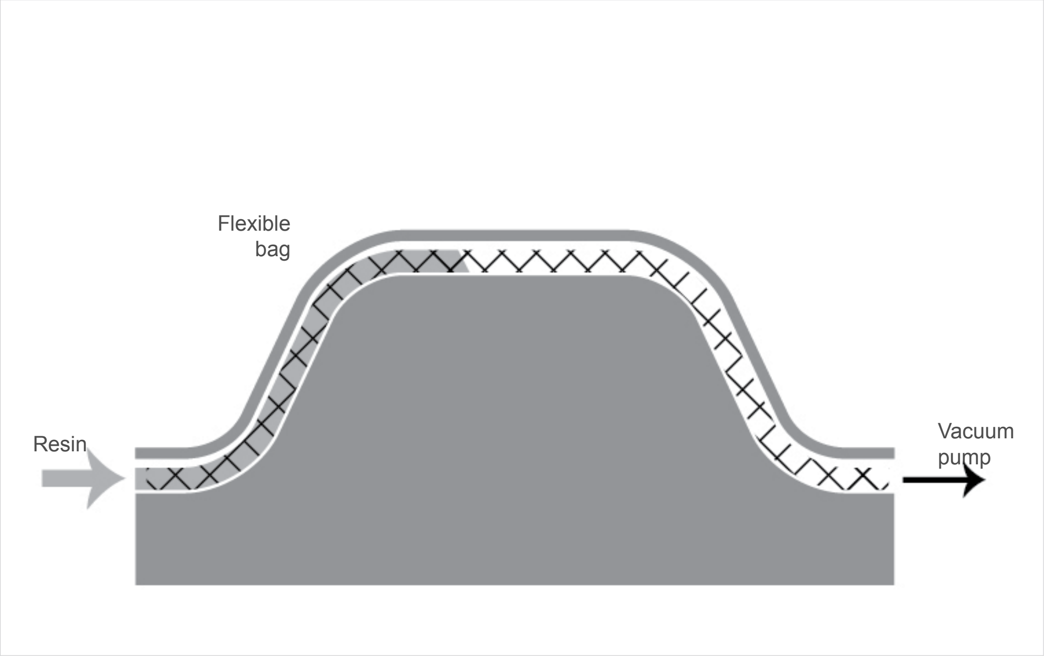
VARTM
Vacuum assisted resin transfer molding (VARTM) or vacuum assisted resin injection (VARI) is another alternative process based on resin transfer inside an airtight closed mold.

The process is similar to typical resin transfer molding with the difference that the mold is a single part with a flexible bag clamped airtight on it, instead of a second solid mold.

Since only one mold is used, the major advantages of VARTM is that it is an economic process for small batches while it retains the good quality of resin transfer processes.

4.8 | Autoclave molding
4.9 | Filament winding
4.10 | Filament winding process
4.11 | RTM
4.12 | RTM process
4.13 | VARTM
4.14 | VARTM process





4.2.2.4 | Compression molding techniques

Compression molding is a wide family of processes that includes several different technologies in which molding compounds are formed and cured in metal molds under heat and high pressure.

BMC molding

Bulk molding compound (BMC) method is a compression mold process in which the molding compound is a sticky dough premixed material that includes the optimum portions of resin, fibre-reinforcement and additives. The compound is placed in the heated mold cavity and then pressed into the desired shape. As the fibres are oriented randomly and not continuous, they cannot be oriented to certain load directions, and thus the composite products have low mechanical properties.

SMC molding

Sheet molding compound (SMC) method is a similar alternative of BMC. The only difference here is that the premixed compound is in the form of sheets, which are placed into the mold after being cut to the desired dimensions.

4.2.2.5 | Continuous techniques

Continuous processes are manufacturing techniques for mass production of high-length components, in which the composite is continuously produced.

Pultrusion

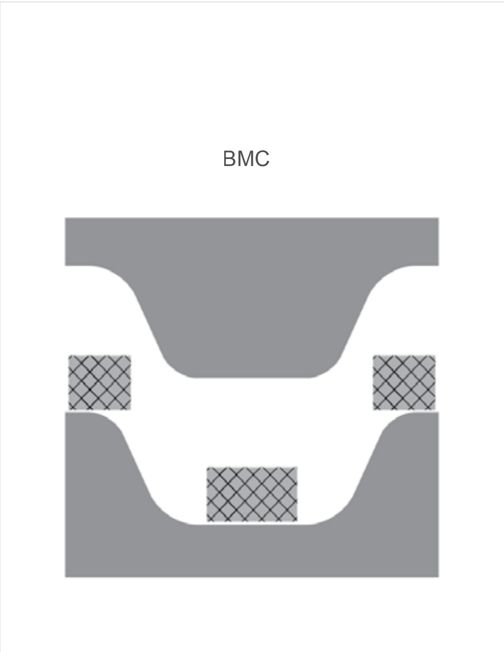
Pultrusion is a well-known continuous manufacturing method for producing constant cross-sectional profiles.

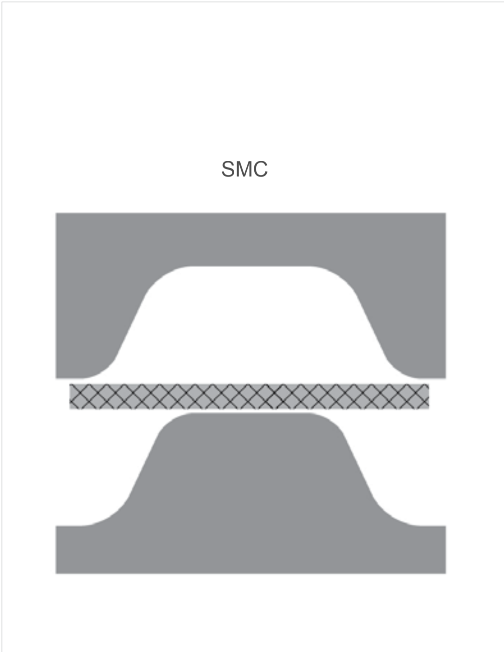
The dry fibres or fabrics are pulled from a series of creels and proceed through a resin bath before continuing to the forming dice.

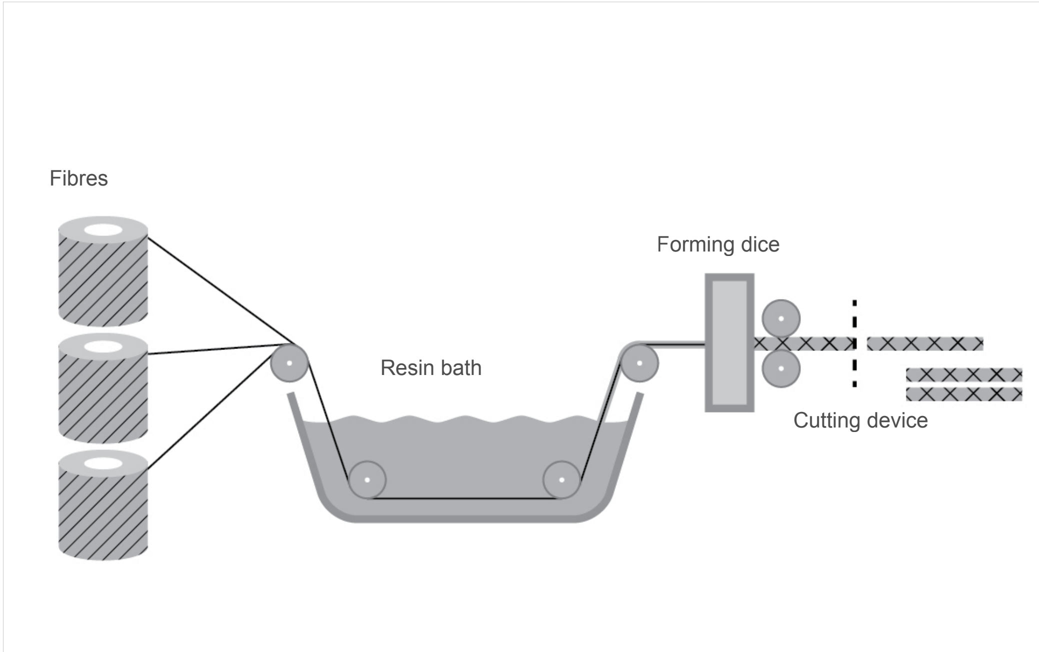
After passing the dice a heated steel starts curing of the resin at high temperatures. A special cutting device cuts the product to the desired length.

The speed of the process depends on the viscosity, thickness and curing of the resin. The cross-sections produced, have thin walls and constant profiles that gives a variety of shapes. Tubes, rods, channels, hollow rectangles, I-beams or angles are common extruded profiles. The process also allows for continuous encapsulation of core materials inside the composite, such as foam, wood or wire.

Pultrusion requires low labor intensity but a high degree of mechanization, with high startup costs. Therefore this method is applied only for large quantities that exceed at least 1000 production meters.







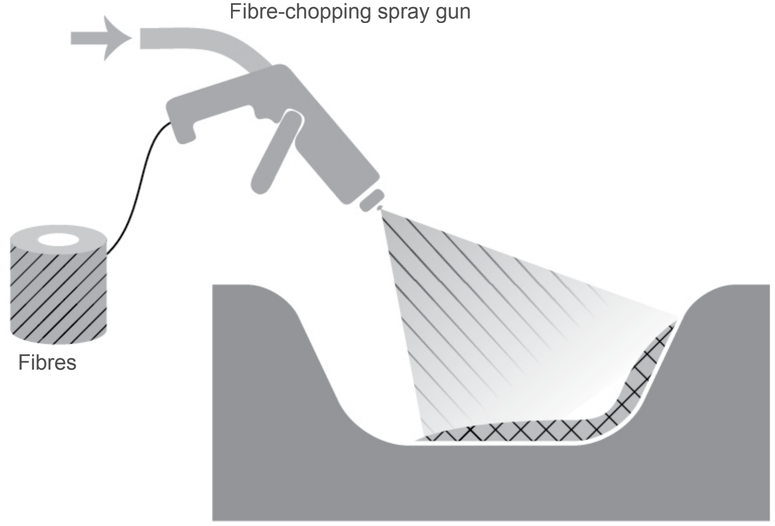
4.2.2.6 | Spraying techniques

Spray-up

Spray-up is a simple and inexpensive method for large parts with complex geometries. The method is based on spraying a mixture of short chopped fibres and resin on the surface of the mold. The process requires a single mold and the necessary equipment that includes a hand-held spray gun and rollers.

The reinforcement is installed in the spray gun as a continuous roving which is chopped in short fibres inside the gun. Prior to spraying the mixture on the surface, a gel coat is applied on the mold as in hand lay-up. Spray-up is suitable for shapes with high surface area to thickness ratio.

The process is low labor intensive, requiring only the minimum amount of work. Spray-up is an open mold process and therefore the styrene emissions are high. Besides, the low viscosity resins that are used are typically more hazardous than other thicker resins.



4.15 | SMC molding
4.16 | SMC molding process
4.17 | BMC molding process
4.18 | Pultrusion
4.19 | Pultrusion process
4.20 | Spray-up
4.21 | Spray-up process

Thermoset resins can be easier processed and the chance on porosities and voids is lower. Less pressure and heat is required and a low tooling system can be applied compared to thermoplast resins.

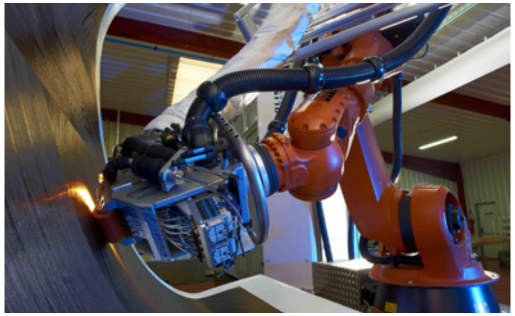
Production techniques for thermoset resins are hand lay-up, vacuum bagging, autoclave molding, filament winding, resin transfer molding and vacuum assisted transfer molding.

4.2.3 | Processing thermoplast polymers

The benefits of thermoplast resins:
• The process cycle is short, because there is no chemical reaction during processing.
• The resins can be reshaped while applying heat and pressure.
• Thermoplastic composites are easy to recycle.

Disadvantages of thermoplastic resins:
• Thermoplastics require heavy and strong tooling. Therefore the tooling costs are high.
• Thermoplastics are not easy to process, and often require sophisticated equipment (Mazumdar, 2002).

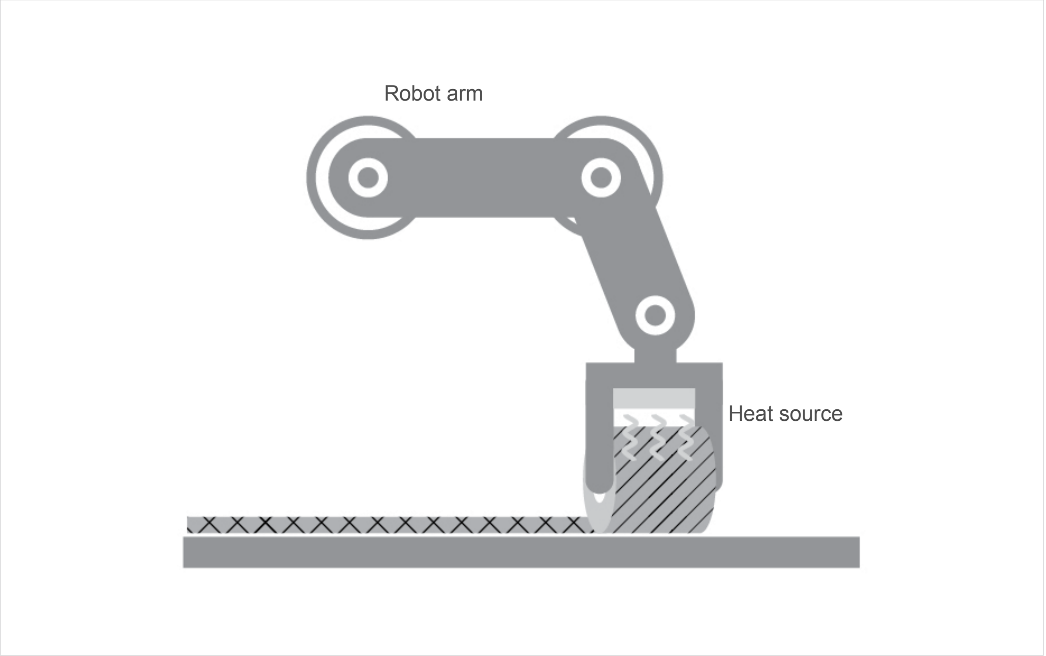
4.22 | Automated tape placement
4.23 | Automated tape placement process
4.24 | Themoforming
4.25 | Themoforming process
4.26 | RFI process
4.27 | Continuous lamination
4.28 | Continuous lamination process



4.2.3.1 | Automatic lay-up techniques

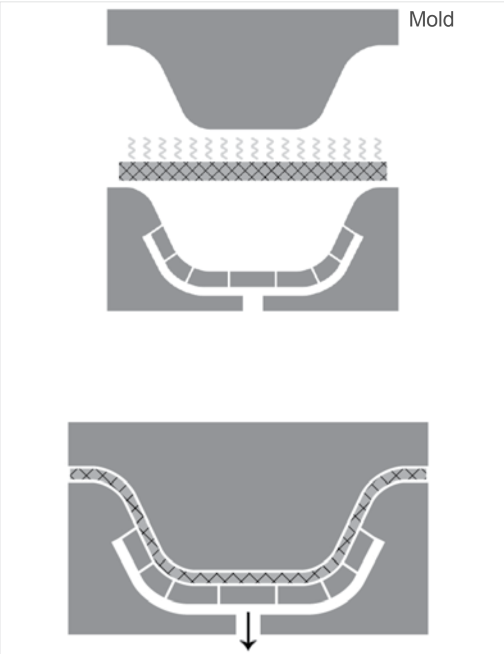
Automated tape placement

Automated tape or tow placement (ATP) is a non-autoclave manufacturing process for advanced composites, based on lamination by layering pre-impregnated fibres in the form of tape. During this process a pre-preg tape or tow is deposited by a laying head, carried by a numerically-controlled multi axis machine. Pre-preg tapes consist of reinforcement fibres in form of unidirectional strands that are impregnated with a resin.
The matrix, which is usually an epoxy resin, is only partially cured and stored in cool conditions in order to avoid complete curing.
Since heat accelerates complete polymerization, only during the process the tape is heated using a laser tool right on the moment it is being applied on the surface. The process is used for large scale productions of large, simple to moderate complex parts that require excellent quality and strength.

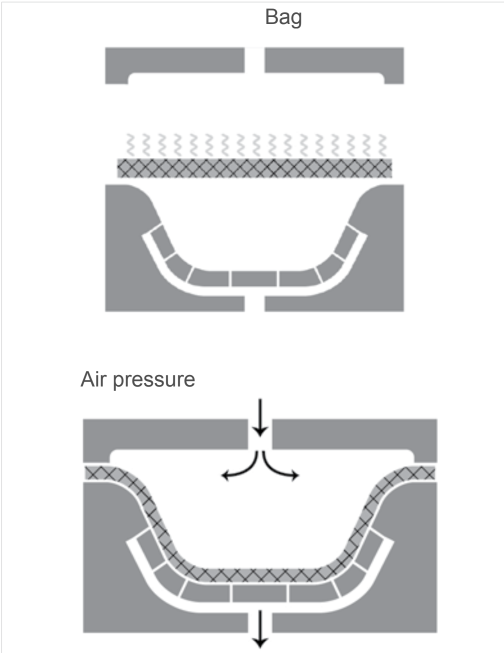


4.2.3.2 | Resin transfer molding techniques

Thermoforming
Being limited only in thermoplastic resins, the process is mainly based on heating and pressing the composite in two different stages.
First a premixed compound (fibrous fibre and thermoplastic resin) in form of sheet is cut into shape. The laminate is first heated inside an infrared heater or hot air autoclave until it has reached the forming temperature. Then it is transferred into the double compression mold were it is pressed to the desired shape. After forming, the laminate is cooled under the pressure of the matched press until it is set.



Resin film infusion (RFI)
Resin film infusion is a typical vacuum/pressure bag process, the only difference is that the resin is applied on the laminate as semi-solid film which is supplied on a release paper.

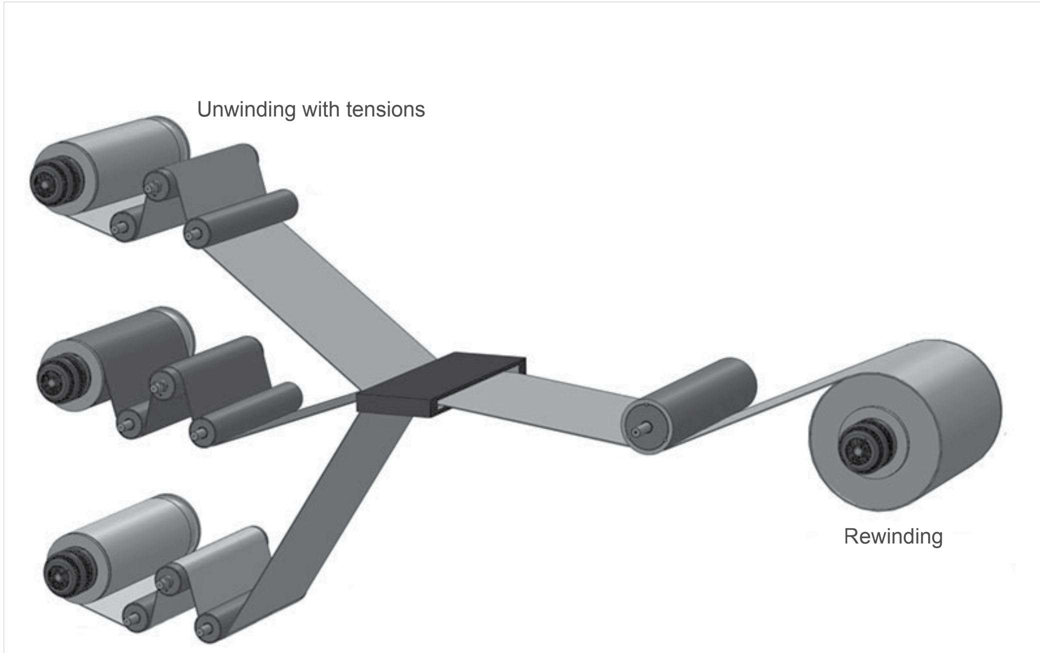


4.2.3.3 | Continuous techniques

Continuous lamination
In continuous laminating the reinforcement is mainly in form of fabrics or mats instead of fibre rovings.
The production process is similar to that of pultrusion, except that curing takes place in an oven.

The process which is limited to sheets, is used for producing flat and corrugated architectural panels.

Besides these processes, SMC and autoclave molding can be performed with thermoplastic resins as well.



Thermoplast resins have a short processing cycle. The resin can be reshaped when heat and pressure is applied, which makes them easy to recycle.

Production techniques for thermoplast resins are automated tape placement, thermoforming, resin film infusion and continuous lamination.

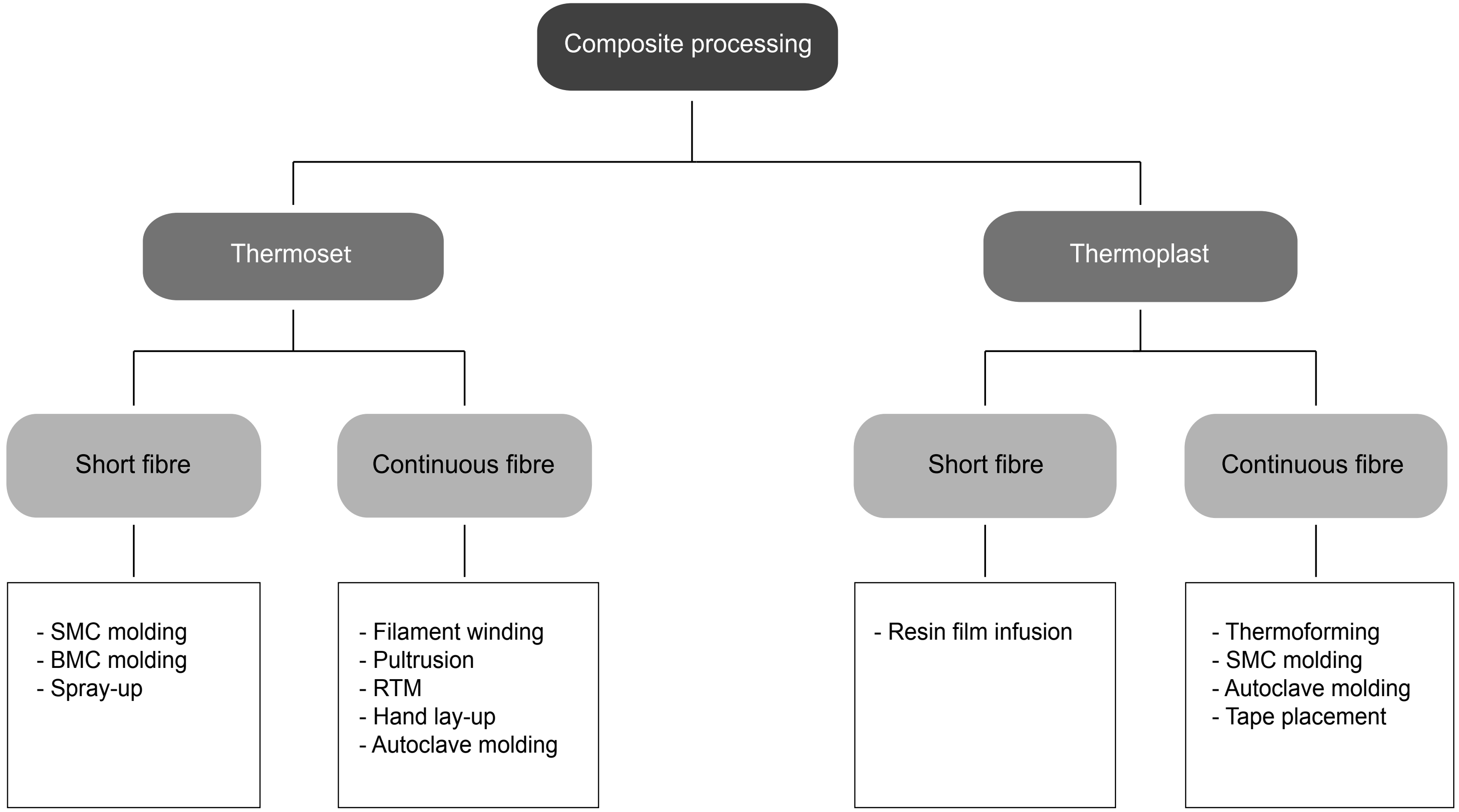
4.2.4 | Selection criteria

For composites, the suitable production technique depends to a large extend on the resin used for the composite. Not all processes are suitable for all materials. On the right you can see a graph dividing the processes based on the materials they are suitable for. The choice of process is based on whether the resin used is a thermoset polymer or a thermoplast polymer. Right now, in biobased composites usually thermoset polymers are used. Besides this, the length of the fibres used is of importance.

Other aspects production processes differ on, are the need of a mold, the need of pressure and whether heat is needed to cure the composite.

Heat and pressure are usually applied by the use of an autoclave. This is a pressure chamber in which pressure and temperature can be adapted to the necessary level. Autoclaves use a lot of energy. The total amount of energy needed for a process is dominated by the need of an autoclave.

The table below on the right shows for which shape which production process is best fitting. Shapes are categorized as flat sheet, dished sheet, hollow 3D shapes, solid 3D shapes, circular prismatic shapes and non-circular prismatic shapes.



4.29 | Composite processing
Table 4.1 | Processing shapes
Table 4.2 | Economical batch size and production rate
Table 4.3 | Process properties

Selection criteria for a production process are production rate, costs, performance (strength), size and shape (Mazumdar, 2002).

To select the best performing production process, the techniques are compared based on the production speed, costs, the strength of the product, the maximum dimensions and the economical batch size.
The results are gathered from the book “Composite Manufacturing” by S.K. Mazumdar (2002) and by using the material selection program CES.

CES provided the available production techniques for composite materials, as welll as the economical batch size and production rate. Since CES could not provide this specific information about all the applicable techniques, the table on the right contains details of most of the techniques. More data were analysed using CES, such as the surface roughness and production tolerances. However the differences were very small and all properties were tolerable for this design, therefore the data were not taken into account.

The search for information about the amount of harmfull emissions released during a production process, and the necessary energy for a process was complicated.
There are no databases available providing information on these subjects.

The energy consumption can easily be estimated, since the use of an autoclave is the highest energy consuming aspect in a production process.
Large machinery, for instance used for pultrusion also consumes lots of energy, however the production is eventually very efficient.

The required additional material should be taken into account as well. Molds are both expensive and need workmanship and man hours to be built.

Besides this, material is needed to built the mold.
Logically, the man hours, energy and material are as good as doubled when a double mold is applied.

Finally, emissions evaporating out of the composite can be harmfull both for the enviroment as well as for the workers. Closed mold techniques, vacuum techniques and autoclave methods avoid the emission from spreading, therefore open mold processes are more polluting.

All aspects influencing the properties of a production process are shown in the table on the right below.

Regarding production processes, three properties are of influence on the environmental impact of the process.

The used energy, this is mainly decided by the use of an autoclave.
The necessary additional material, like molds, vacuum bags, etc.
The emissions evaporating during the process. Closed mold and vacuum processes perform better on this aspect.

Flat sheet	Lay-up methods | Vacuum infusion | Autoclave molding | RTM | VARTM | SMC molding | Pultrusion
Dished sheet	Lay-up methods | Vacuum infusion | Autoclave molding | RTM | VARTM | SMC molding | Thermoforming | Pultrusion
Hollow 3D	Lay-up methods | Autoclave molding | Filament winding | RTM | BMC molding | Pultrusion
Solid 3D	BMC molding | Pultrusion
Circular prismatic	Lay-up methods | Filament winding | RTM | BMC molding | Pultrusion
Non-circular prismatic	Lay-up methods | Filament winding | RTM | BMC molding | Pultrusion

Process	Ec. batch size	Production rate (/hr)
Filament winding	1- 10 000	0.12-2
Hand lay-up	1-5000	0.1-0.5
Automated lay-up	1-5000	0.1-0.5
Spray-up	1-5000	0.1-3
RTM	500-5000	1-8
SMC molding	5000-10 000	12-60

Process	Speed	Costs	Strength	Size
Filament winding	slow-fast	low-high	high	small-large
Pultrusions	fast	low-medium	high (longitudinal)	small-medium CS
Hand lay-up	slow	high	high	small-large
Automated lay-up	slow	medium	medium-high	medium-large
Spray-up	medium-fast	low	low	small-medium
RTM	medium	low-medium	medium	small-medium
SMC molding	fast	medium	medium	small-medium
Injection molding	fast	low-medium	low-medium	small

In most composite products, several thousand parts are assembled. Ideal, a product consists out of one piece.
Mazumdar (2002) summarizes the following disadvantages of joints:

1. Around every joint, stresses concentrate. This creates a discontinuity in the stress transfer.

2. Creating joints is labor intensive because a special process is necessary. Besides this sometimes the materials used are harmful for the worker.

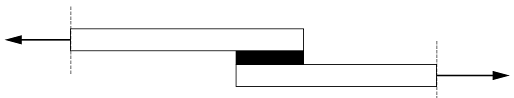
3. Joints add manufacturing time and costs to the fabrication process.

In joints for composites, two classes can be defined:

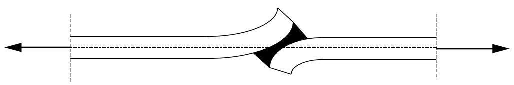
• Adhesive bonding, this is the most common type of joining in composite manufacturing,

• Mechanical joining, these are roughly the same joints as used for metal joining.

For temporary structures, which includes demountable and re-usable structures, it is important to consider the detachability of the connections.



Undeformed joint



Deformed shape under extreme loading

4.3.1 | Adhesive bonding

The definition of adhesive boding is that two substrate materials are joined together by a type of adhesive.

An adhesive is a substance which is capable of holding at least two materials together in a strong and permanent manner (Yarkoni, 2015).

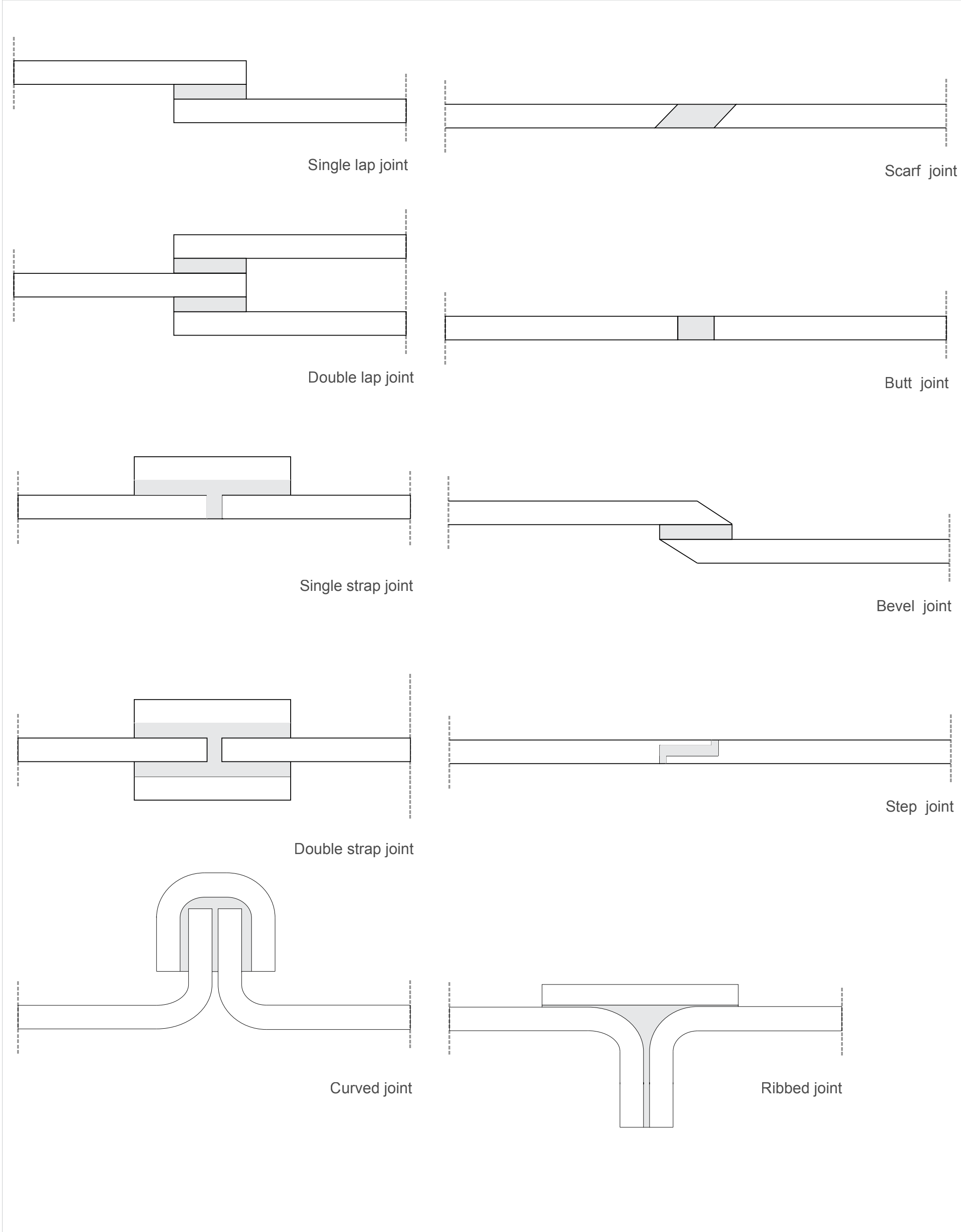
“Glued joints result usually in connections with a high loadbearing capacity. Therefore adhesive bonding should always be preferred over mechanical joining, however, not for all application adhesive bonding is approved” (Knippers, Cremers, Gabler & Lienhard, 2011). Especially regarding the detachability of the design, this does not apply is all cases.

The most common type of adhesive joint is the single lap joint, since this joint is very easy to manufacture. In this joint, stresses are transferred from one adherend to the other by shear stresses in the adhesive. Because the loads are off center, the bending action creates normal stresses in the direction of the thickness of the adhesive. The combination of these forces reduces the strength of a single lap joint.

To overcome the problems of an single lap joint, a double lap joint can be made. In this joint, the bending stresses are eliminated, and therefore the normal stresses. The strength of this joint is therefore higher.

More strength is provided by strap joints (single and double) and scarf joint. Both of these joints are however much more difficult to manufacture. Last mentioned also applies to bevel joints and step joints.

Since the load in adhesive bonded joints is transferred by shear stresses, the adequate test to test the strength of an adhesive joint is an shear test (Mazumdar, 2002).



An adhesive bond should be aligned parallel with the direction of the loads. The area of the bonded surfaces should be as large as possible. This can be achieved by allowing the overlap of the parts to-be-joined sufficient large.
The peak stresses at the edge determine the strength of the bond, therefore larger overlapping parts cannot enlarge the strength of the bond endlessly (Knippers, Cremers, Gabler & Lienhard, 2011).

Polymers can be glued to materials like steel, glass and concrete, however a flexible adhesive should be applied to overcome the changing dimensions due to the different thermal expansion of the joined materials.

Advantages of adhesive bonding

1. In adhesive bonded joints, the load at the joint interface is distributed over a larger area (instead of concentrated at one point).

2. Adhesive bonded joints are better resistant to flexural, fatigue and vibrational stresses, because the stress distribution is uniform.

3. There is almost no extra weight added, in contrast to mechanical joining.

4. Adhesives directly seal the joint, which prevents galvanic corrosion between similar adherend materials.

5. Irregular surfaces can be quite easy bonded together.

6. Smooth contours can be made, and no chance in the dimensions of the product need to be made.

7. Usually less expensive compared to mechanical joining,

Disadvantages of adhesive bonding

1. The surface usually need preparation before adhesive bonding can be applied.

2. Heat and pressure are often necessary during the bonding process.

3. Some adhesive material need a long curing time.

4. Health and safety can be an issue.

5. It is difficult to inspect an adhesive joint.

6. The adhesive bonding process needs more training and rigid process control than mechanical joining.

7. The joint is permanent and does not allow disassembly.
(Mazumdar, 2002).

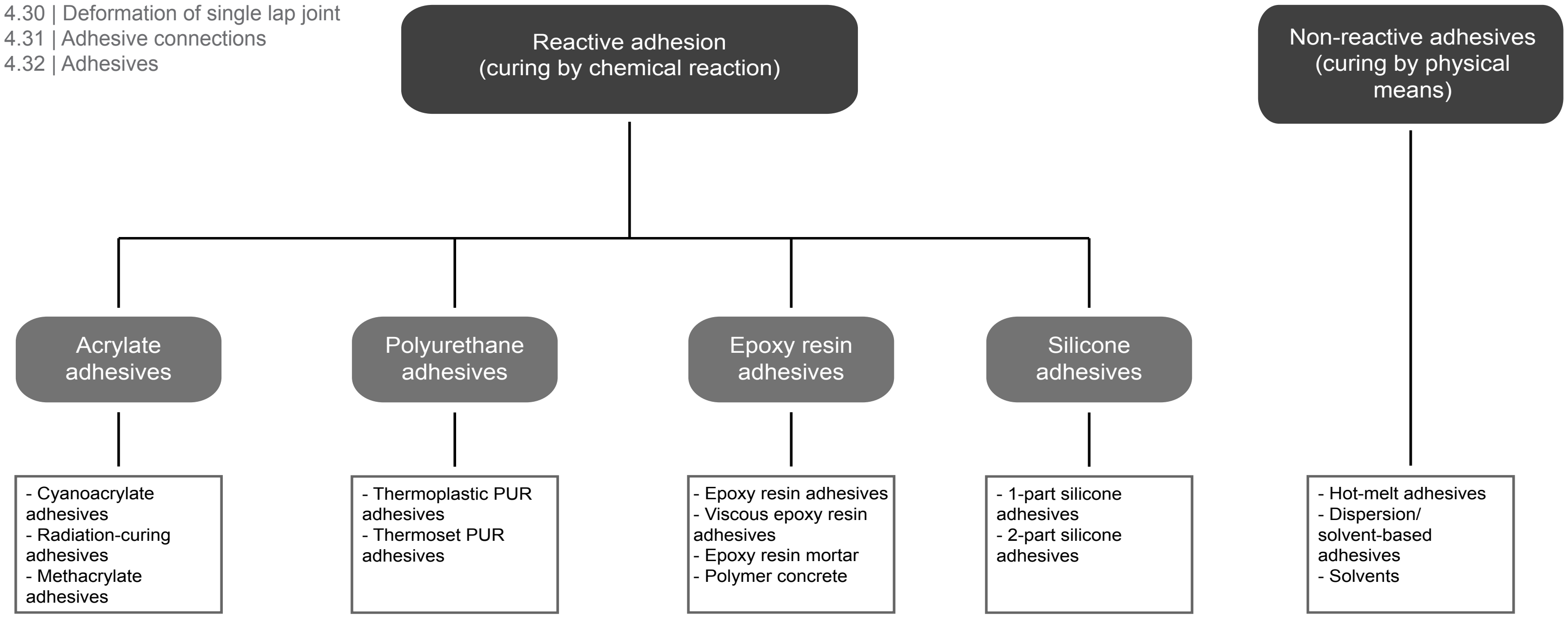
4.30 | Deformation of single lap joint
4.31 | Adhesive connections
4.32 | Adhesives

4.3.1.1 | Types of adhesives

The graph below shows the available (petrol-chemical based) adhesives, categorized based on their chemical structure.
The most important division concerns the way the adhesive cures: This can be either by a chemical reaction the adhesive starts itself, or by a physical condition, such as adding heat.

On the bio-based market, adhesives based on renewable components such as soy-protein, starch-esters, polyactide and polyamine are being developed.

The focus in the market is mainly on hot-melt adhesives. These solid materials with a fast bonding strength are less hazardous and less toxic, since they do not contain volatiles. Besides this they can be decomposed when heated continuously (Yarkoni, 2015).



4.3.2 | Mechanical joints

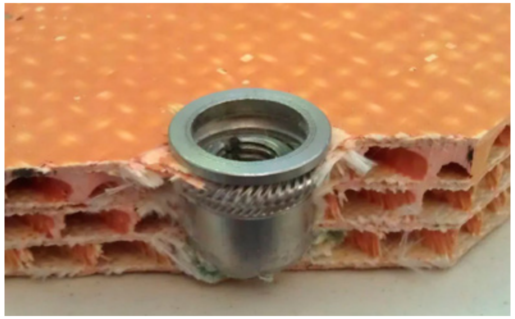
Mechanical joints are worldwide most used to join metal components. Similar to metal joints, composite components are also joined with metal parts, such as bolts, pins and screws.

Polymers can be cut and drilled, however cutting through fibre-reinforced polymers means that the protective outer layer is interrupted, and therefore water can be absorbed by the cut edges. These need to be sealed again (Knippers, Cremers, Gabler & Lienhard, 2011)

In most cases an overlap is required, through which a hole is created. Bolts or rivets can be placed in this hole to connect the parts. There is a wide range of connection methods, they are briefly drawn on the right.

Connections can be made using screws, bolts, rivets and slice plates. Thereby, also steel reinforcement parts can be added in the composite, to strengthen the load transfer between the composite and the mechanical joint. Stainless steel is a good option, because it matches the corrosion-free properties of the composite.

All connecting elements will be briefly analyzed in response to their explanation in “Construction Manual for Polymers + Membranes” (Knippers, Cremers, Gabler & Lienhard, 2011).



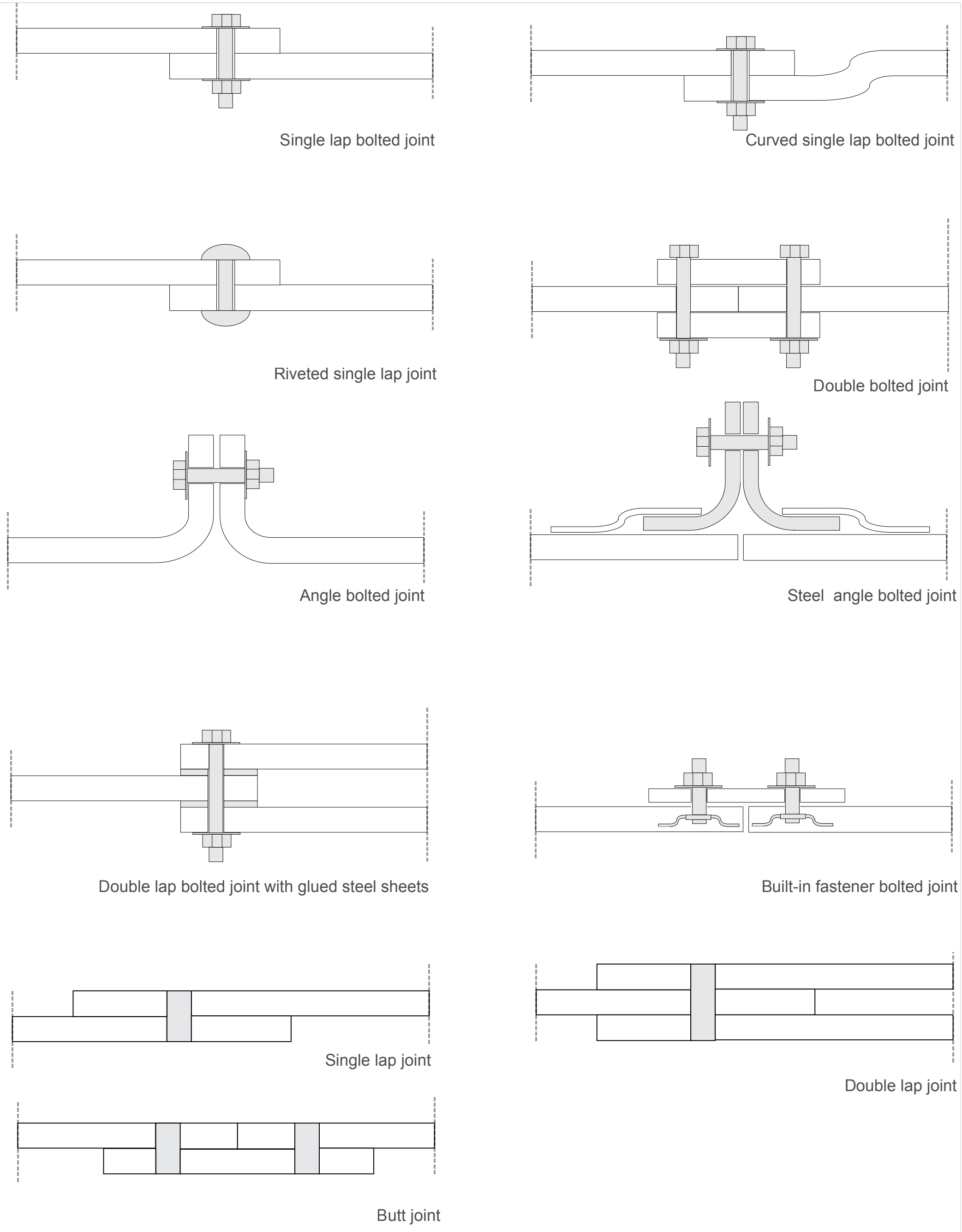
Screwed

If screws are used in a composite material, usually metal inserts are placed to compensate for the weak shear force of threads in composite material (Mazumdar, 2002).

Bolted

Bolted connections carry the loads via shear stresses. The thickness of the bolt relates to the thickness of the components which are being joined.

In single lap joints, the bolts are loaded eccentric, therefore a bending moment appears, as shown in the picture on the previous page.



To avoid this, double bolted joints can be made using splice plates.

Other options are to bend the edge and/ or apply metal angles at the end, like in the drawings of the angle bolted joint and the steel angle bolted joint.
In bolted joints, nuts, blots and washers are applied. Also single lap, double lap or butt joints can be applied.

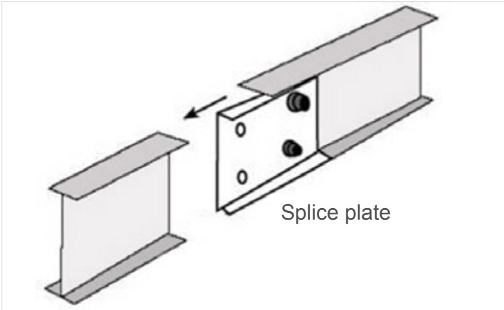
Splice plates
Especially sections can be connected using steel or aluminum splice plates. Because steel transfers the loads better than the composite material, usually thin plates can be applied, however, relative large numbers of fasteners are needed.

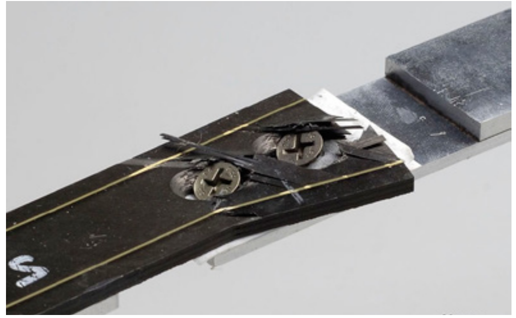
Advantages of mechanical joints

1. Mechanical joints allow repeated assembly and disassembly, for example for repairs or maintenance.

2. They offer easy inspection and quality control.

3. They require little to no surface preparation.





Riveted
In riveting, metal rivets are applied. The load bearing capacity is comparable to those of bolts. However, since the diameter of most rivets is smaller than the diameter of most bolts, they are applied more often.
A positive side effect of applying rivets is that they increase the load-bearing capacity of the fibre-reinforced material they are joining, because the interlaminar shear strength increases by the pressure the rivets apply. At close spacing`s, rivets achieve quite homogenous load transfer, however since their heads are so small, they have a low tear-through resistance.

Disadvantages of mechanical joints

1. The metal parts add weight to the product.

2. The holes create stress concentrations.

3. Potentially they can create galvanic corrosion problems. Some aluminum or steel fasteners do not combine very well with carbon-epoxy composites. Metal connectors can be coated with nonconductive materials.

4. At the location of the hole, fibre discontinuity is created.

4.33 | Metal insert
4.34 | Mechanical connections
4.35 | Rivet
4.36 | Splice plate
4.37 | Lap-joint
4.38 | Tested lap-joint

Connection between composite parts can both be adhesive as mechanically joined.

Adhesive bonded joints have the benefit that no holes need to be drilled which avoids interrupting the fibres and producing stress concentration.

Mechanical joints can be much easier disassembled and inspected.

4.4 | CORE MATERIALS

The information about core materials is based on the chapter "Cores" in the master thesis "Bio-based FRP structures: A pedestrian bridge in Schiphol Logistics Park" (Gkaidatzis, 2014, pp. 61-65). When other sources have been used they are referred to in the text.

"Core materials are lightweight materials that are used for composite components, but primarily for sandwich elements" (Knippers, Cremers, Gabler, & Lienhard, 2011, p. 72).

4.4.1 | Sandwich element

A sandwich element consists out of two thin stiff and strong layers which are separated by a lightweight and thick core. The core has usually a low strength since its main task is to keep distance between the two outer layers. This distance increases the moment of area without increasing the weight too much. The result is a low-density structure with high bending and buckling resistance.

Shear forces in the structure are taken by the core material, thereby the outer layers are also supported by the material. A core material should therefore be lightweight with enough shear and axial stress.

When the shear accumulation of the material is too low, the outer layers will bend.

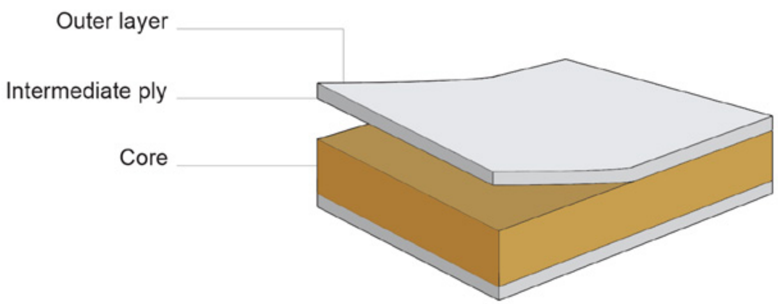
If the axial stiffness is too low, this causes buckling.

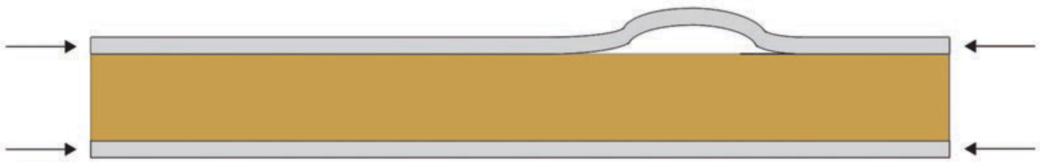
It is important to choose the right materials for the core and the outer layers, but when well composed this results in a material with a high stiffness to weight ratio.

It is also important to know that the three layers of a sandwich panel are glued together, and that a strong adhesive material is used to avoid separation of the core material and the outer layers.

When the adhesion between the layers is not effective, separation of the layers can occur as shown in the drawing below. This does effect the mechanical properties of the sandwich panel since the shear stresses cannot be transferred properly and the outer layer is not supported sufficient.

For circular use and recycling means, glueing poses a serious restriction since the elements cannot be (easily) separated again.





4.4.2 | Core materials

For core materials, both synthetic materials as biobased materials are available. In the scheme below you can see the classification of core materials according to Knippers et al, (2011, p. 72).

4.4.2.1 | Synthetic polymer foams

Polymer foams are formed mixing a solid polymer and a gas. They can be divided into closed-cell and open-cell materials. In open cells, air is allowed to flow through the cells since the edges are partly open. These foams are more flexible, while closed cells are usually more rigid.

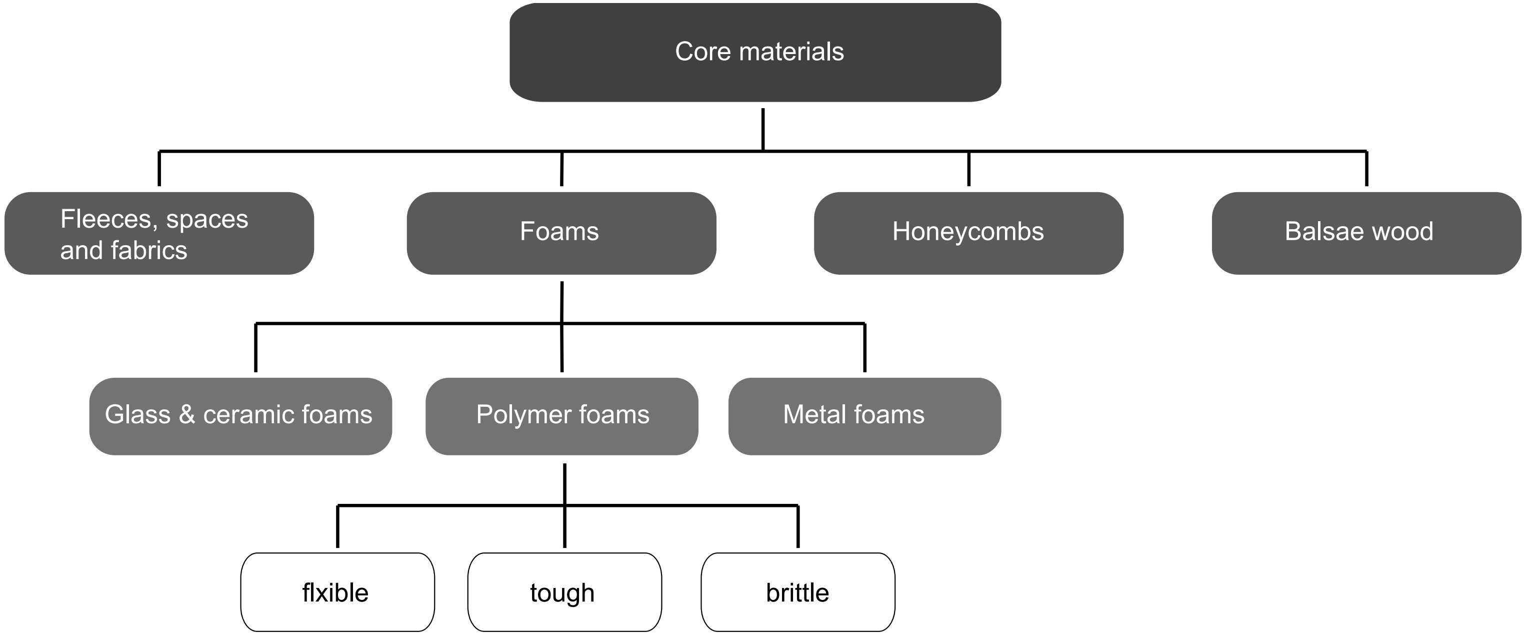
Foams can be divided into thermoplastics and thermosets, which can further be divided into tough, brittle and flexible foams (Knippers et al., 2011).

Thermoplastic foams can usually been broken down and recycled, while for thermosets this is more complicated due to their strong cross-linking. Besides the recyclability, polymer foams induce environmental issues regarding flammability and the effect of blowing agents on the environment. Chemical blowing agents release water vapor, nitrogen, carbon monoxide and/ or ammonia. If these foams are given an interior application, the risk of emitting gas over time appears, which can cause health risk (Knippers et al., 2011).

Often used foams are PU (polyurethane), PS (Polystyrene), PET (polyethylene) and PVC.

4.4.2.2 | Biodegradable polymer foams

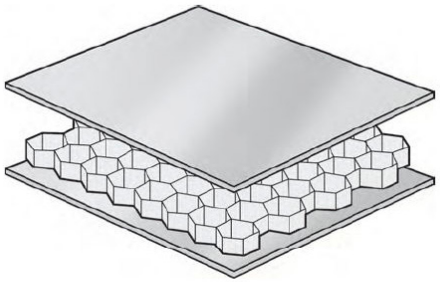
Biodegradable polymer foams have been elaborated to offer an environmental friendly solution to the traditional, non-compostable or non-recyclable polymer foams and as a biobased option to avoid material scarcity.
These foams have similar properties as biobased resins and natural fibres and are therefore sensitive to humidity, in contract to petroleum-based foams. Biobased materials which can be used to produce biodegradable foams are for example ethylene vinyl alcohol, polyvinyl alcohol, polycaprolactone, polyactiv acid and starch. It is important to know that thin sheets of biodegradable foam are difficult to manufacture.



4.39 | Sandwich element
4.40 | Core delamination
4.41 | Sandwich elements
4.42 | Core materials

A sandwich element consists out of two thin stiff and strong layers which are separated by a lightweight and thick core. The core has usually a low strength since its main task is to keep distance between the two outer layers.
The three layers of a sandwich panel are glued together.

Polymer foams are often synthetic, but can be biodegradable.



4.4.2.3 | Honeycombs

Structures consisting out of an array of hollow columnar cells which are formed by thin vertical walls in a hexagonal shape are called honeycombs. The shape of the material allows a very low density, while the out-of-plane compression and the out-of-plane shear are relatively high. This reduces the amount of used material.

For this purpose a wide range of materials can be applied. For sandwich constructions, aluminum, thermoplastics and fibre-reinforced plastics are preferred. Thermoplastic honeycombs are being produced using extrusion, while other materials are manufactured in a continuous process of extrusion and corrugation.

4.4.2.4 | Aluminum foam

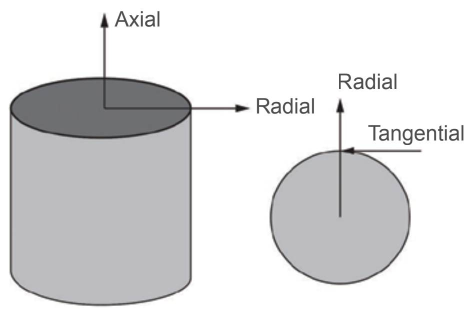
Of metal foams, aluminum is most used. The foam consists of solid aluminum, however with a large volume fraction of gas-filled pores. These foams exist both in closed cells and open-cell foams in which an interconnected network appears.

Closed-cell metal foams are used as high-impact absorbing materials. Different from polymer foams, metal foams remain in their deformed shape after impact.
Metal foams can reach a porosity of 75-95% which makes them ultralight.

4.4.2.5 | Balsae wood

Balsae wood is produced from the balsae tree, which is a fast growing tree making this an environmental friendly alternative for foam. The density of balsae is low, average around 160 kg/m3 because the wood contains large cells filled with water, which are empty cells when dried after cutting the tree.

In proportion to the weight, balsae wood has excellent strength and stiffness and good energy absorbing properties in the axial direction. The wood is less stiff and strong in the tangential and radial direction.



4.4.2.6 | Cork

Cork is an impermeable material. Cork for commercial use is harvested from the Cork Oak in the southwest of Europe (mainly Portugal) and northwest Africa. The material is buoyant since it is composed out of Suberin, a hydrophobic substance. The impermeability ensures the buoyant, elastic and fire-retardant properties (Wikipedia, 2017).

The cells of cork are a 14-sided polyhedron which are filled with air. This gives the cork an filling of 89% air, which provides the very low density. The cells of cork, 100x magnified, are shown in the picture on the right below.

The cells have an extremely strong flexible membrane which is waterproof as well as airtight. Different chemicals in the cell prevent it from rotting or degrading. Since cork absorbs dust, the material is ideal for people with asthma or allergies. (Corklink, 2015).

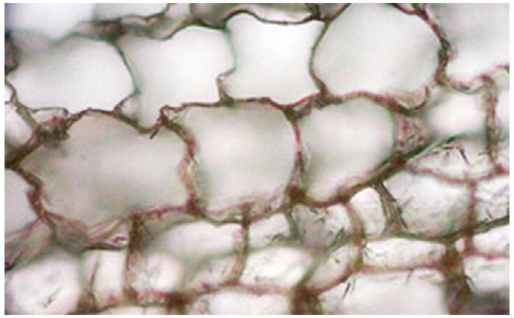
If cork is compressed, the air is not squeezed out. The membranes of the cell keep it inside, for which the cork returns to its former shape after compression.

The thermal transmittance value of corkboard (for example Thermacork) is 0.036 W/m*K. The density is even lower than blasae wood with only 100-130 kg/m3.

4.43 | Honeycomb structure
4.44 | Aluminum foam
4.45 | Balsae wood
4.46 | Axial, radial and tangential load of balsae wood
4.47 | Cork

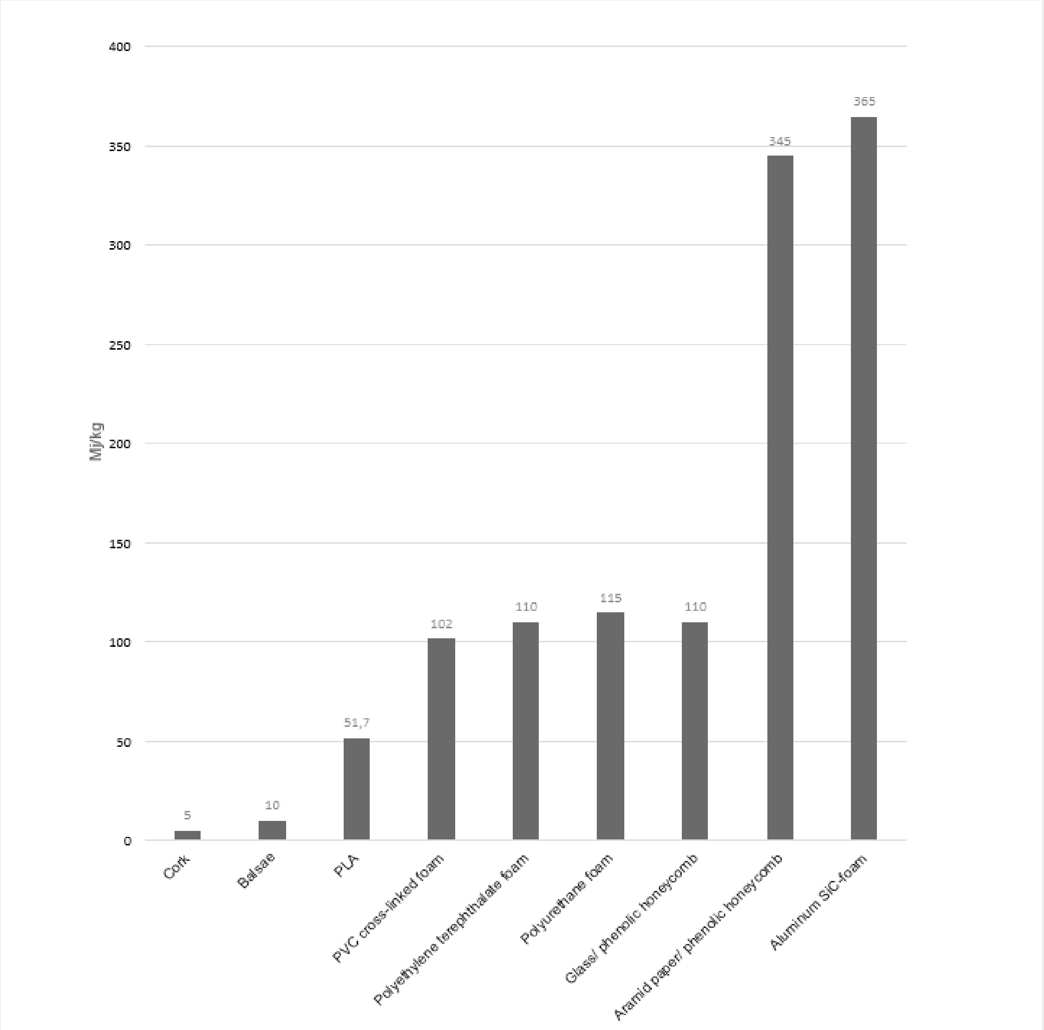
For expanded cork board the density is a little higher, 150 kg/m2.
Its thermal resistance does not decrease over time like man-made foam. It has excellent sound isolation, is dimensionally stable, and resistant to compression (ThermaCork, n.d.).

Every tree produces a few hundred kilograms of cork. One tree can live up to 300 years and be harvested up to 20 times. A tree should be 20-25 years before its harvested at first and from then on every 9 years, the cortex can be removed (Kurk Design, n.d.).



4.4.2.7 | PLA

PLA stands for Poly Lactic Acid. The foam is made from a bio-based raw material, in this case a PLA foam from corn origin (Van der linden, 2017).



4.4.3 | Environmental impact of the core material

In his thesis, Gkaidatzis (2014) has drawn conclusions on the environmental impact of all shown core materials. This analysis is shortly cited.

Conventional core materials are based on non-renewable fossil fuels and the production of polymer foams makes use of volatile liquids. These liquids evaporate, whereby CO2 is produced. Polymer foams are toxic and non-recyclable and the manufacturing process is energy intensive.

The graph on the left shows the embodied energy of all discussed core materials. The embodied energy is “the sum of all the energy required to produce any goods or services, considered as if that energy was incorporated or ‘embodied’ in the product itself” (Wikipedia, 2017).

This graph makes it clear that the embodied energy of cork is the lowest, followed by balsae wood.

4.48 | Cork panels
4.49 | Cork cells
Graph 4.1 | Embodied energy of core materials

Sandwich constructions are materials consist out of two outer layers and one inner core material. These three layers are usually glued together.

For core materials, both synthetic as biobased materials are available. Materials based on non-renewable fossil fuels are usually not very environmental friendly.

Cork, and second best balsae wood have the lowest embodied energy.

4.5 | INSULATION MATERIALS

In this chapter, bio-based and/or bio degradable insulation materials as they are available now are discussed.

4.5.1 | Natural insulation materials

Biobased insulation material has several benefits, of which replaceable resources is the main important one for this research.

Besides the resources, the health risk for the indoor environment is an important aspect. Indoor air can be as polluted as outdoor air, or even more polluted by typical home pollutants such as dust, spores, moulds and those produced by cooking and house-cleaning. “There are no doubts that bio-architecture and bioconstructions can contribute to improving the overall well-being of those who spend a lot of time indoors, and can offer practical help to improve the energy efficiency of buildings” (Miani, 2017).

New insulation materials which are based on plant waste can offer 20% better insulation than traditional materials. These materials are for example straw, clay and grass.

Because the material can be grown close to where it is applied, the energy necessary for transportation can be limited, and because there is little energy necessary for the production and no CO2 is emitted (sometimes even more CO2 is captured by the crops that produced in the process), the total embodied energy can be reduced up to 50%.

Producing biobased insulation material, bio-products such as the stalks and stems of wheat straw are applied, which are normally by-products (Dunlevy, 2015).

4.5.1.1 | Greensulate insulation

Greensulate is an self-growing biobased alternative to usual insulation materials, since it is composed out of paper, rice hulls and mushroom fibres. The roots of the mushroom mycellium have incredible structural and insulating properties, the mushroom requires no power to grow, is flame resistant and compostable.

Mushroom cells are injected into a mixture of starch, hydrogen peroxide, water and minerals. After a couple of weeks the sample is dried to prevent fungal growth (Zinger/Snead, 2010).

The material grows inside a mold in less than two weeks. The optimal conditions are dark and moistly. The molds are disinfected and filled with boiled agricultural waste. After spreading the mushroom seeds, the molds are placed in plastic bags to let the mycelium grow. The last step is to take the material out of the mold and let it dry (González, 2010).

According to Greensulate, the insulation will remain inert as long as it is prevented from getting soaked (Building green, 2011).

An analyzed sample has showed that the sample consists for 95% out of amorphous organic materials, and an organic-textural analysis showed that it is a porous material. Therefore the material is compostable. The material does not contain elements harmful for humans or the environment, and besides this, it releases a certain amount of useful nutrients for plants when it is composted. Unless it is treated and protected, the material has not a very long lifetime for outside applications (González, 2010).

4.50 | Greensulate insulation
4.51 | Greensulate insulation in wall construction




4.5.1.2 | Soybean insulation foam

BioBased 501w Spray polyurethane foam is an open cell and water blown spray with a density of 33.6 kg/m_3. The spray is both sealing and insulating and can be applied walls, ceilings and roof decks in both commercial as residential buildings. The foam is rated a class 1 for fire-safety.

Although the finished foam contains only 3% biobased material, the foam is installed using water as a blowing agent. The use of foam is ideal to insulate hard-to-reach area`s and this foam adheres to almost every surface (Kodiak, n.d.).

The BioBased 502 insulating foam is the second generation open-cell water blown sprayfoam which has a biobased content of 12% and a thermal transmittance value of 0.021W/m*K. The foam is based on a 96% soybean-based polyol. The product is BRE-certified, therefore meets the appropriate standards (EcoBuilding, 2010).

4.5.1.3 | Biofib Hemp

Biofib'hemp is a natural and ecological insulation made by layered hemp fibres, especially applicable for wood-frame houses. It can be applied in rolls or semi-rigid mats. A benefit of this material is the natural moisture control of hemp, which is provided by the fibres assimilating moisture and releasing it in dry periods.

The material does not rot or degrade over time and is recyclable. Because there are no proteins in the material, rodents and insects are not attracted by the insulation.

The reaction to fire of this insulation has not been tested (BioFib, n.d.).

4.5.1.4 | Sheep wool insulation

Wool is a natural, renewable and therefore sustainable material. Sheep wool insulation consists only out of Wool and an anti-insect protection. To apply the material no protecting clothes and no specialized equipment is needed. The insulation does not cause health risks since it doesn`t irritate eyes, skin or lungs. Because wool consists out of natural fibres, the mats can absorb and release moisture. Wool fibres are hygroscopic by nature, meaning the can absorb up to 35% of their own weight from the surrounding atmosphere depending on the humidity, helping to preserve the surrounding timbers.

Sheep wool does not settle because of the high elasticity. Wool has a high fire resistance compared to cellulose and cellular plastic insulation. The inflammable point is at 560°C because of a high amount of nitrogen's. Multiple layered wool fibres effectively reduce airborne sound transfer

The premium class has a thermal transmittance value of 0.035W/m*K.

4.5.1.5 | Wood fibre insulation

Wood fibre insulation consists out of wood fibres, polyamide (as a binding fibre) and ammonium phosphate which acts as a flame retardant (Greenspec, n.d.).

Wood fibre is not irritating, and can therefore be handled without safety precautions. Normal cutting equipment is enough to apply wood fibre insulation.

Because wood is a renewable material, it assimilates CO2 during it`s growth. The material is not as efficient as some petrolchemical-based insulation materials in terms of thermal insulation, but the insulation value is still pretty acceptable (Greenspec, n.d.).

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4.52 | Soybean foam insualtion
4.53 | Application of soybean foam
4.54 | Biofib hemp insulation
4.55 | Sheep wool insulation
4.56 | Wood fibre insulation

4.5.1.6 | Straw

Straw is renewable, and has a low embodied energy. Unlike most manufactured insulation products, straw does not need much manufacturing before it can be used. Besides this, it is non-toxic.

Besides thermic insulation, straw bales provide acoustical insulation as well.

Because no fire-retardants are added, the straw needs to be cut off from oxygen supply. When a building ignites, straw will smolder slowly if the material is compressed and sealed with for example plaster. This gives people in a small home time to leave the building in time, however for high-rise buildings, straw is regarding the fire safety precautions not a very good option (Greenspec, n.d.).

4.5.1.7 | Rice hull bags

Poly bags of 43x76 cm (17”x30”) filled with rice hulls provide 8” (20cm) of insulation. Larger bags can in the future provide even higher insulation values.

Rice hulls are resistant to moisture and to fungal decay. They do not really ignite or smolder, which ensures the fire-safety and meet the building standards of the US. However, to deter mice a small amount of borax, a neurotoxic substance with disinfecting properties, should be added to each bag.

If the bags are not overfilled, they fit next to each other seamlessly (EarthbagBuilding.com, n.d.).

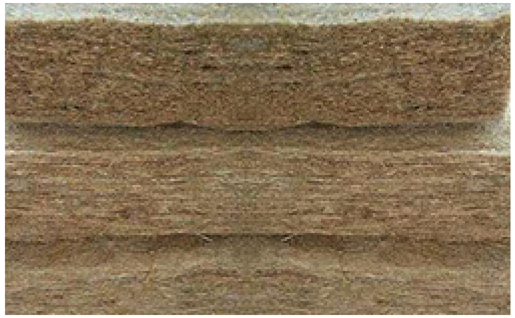
4.5.1.8 | Cellulose

Cellulose insulation is made by grinding old paper. Therefore the material is already a recycled material. Cellulose is available in sheets bonded with the resin which is released during the production, but it is usually used in flocks.

Cellulose insulation lends itself well for renovations because you can fill irregularly shaped and difficult to access areas by blowing the cellulose flocks in using high pressure.

The production of cellulose insulation requires very little energy and because it uses thrown away paper, it is an environmentally friendly material which helps decreasing the amount of waste. Cellulose has good moisture-buffering and sound-insulating properties.
Important is that the cellulose insulation degrades if it remains wet for a significant time. Therefore it is not advisable to use cellulose in high humidity locations.

Borax is added to cellulose (15 to 20 %) to protect the material against fire, mold and pests (Duurzaam thuis, n.d.).



4.5.1.9 | Flax

Flax offers good thermal and acoustical insulation combined with the ability to exhale excess humidity from the facade construction.

The natural fibres form no possible health risk and are biodegradable and disposable.
Flax insulation has a low environmental impacts since is does not pollute air or water.

The regrowing crop is an renewable resource which does not contribute to global warming, but instead converts the greenhouse gas carbon dioxide (CO2) into oxygen (O2) during its growth. Thereby flax insulation does not contain emission of harmful chemicals like formaldehydes, isocyanates, organohalogens, (H)CFCs, like most pertochemical insulation materials contain. Linen (flax) insulation has a natural fibre smell that will diminish over time.

Linen insulation consists out of flax fibre, textile binder fibre and an environmentally friendly flame retardant. The estimated service life is 75 years and it has the NIBE environmental classification: class 1a, which is the best achievable class (Isolina, n.d.).

4.57 | Straw insulation
4.58 | Rice hulls
4.59 | Rice hull bags
4.60 | Cellulose insulation
4.61 | Flax insulation

Insulation	λ (W/m*K)	Rd	d (mm)	Density (kg/m3)	Weight/m2	Rd	d (mm)	Weight (kg/m2)
Rockwool	0,032	4,5	144	150	21,60	6	192	28,80
EPS	0,04	4,5	180	35	6,30	6	240	8,40
PIR foam	0,022	4,5	99	45	4,46	6	132	5,94
PUR foam	0,03	4,5	135	50	6,75	6	180	9,00
Flax panels	0,035	4,5	158	30	4,73	6	210	6,30
Flax rolls	0,038	4,5	171	25	4,28	6	228	5,70
Woodfibre panels	0,04	4,5	180	50	9,00	6	240	12,00
Celluose	0,038	4,5	171	56	9,58	6	228	12,77
Scheepwool	0,035	4,5	158	22	3,47	6	210	4,62
Rice hulls	0,5	4,5	2250	110	247,50	6	3000	330,00
Straw	0,26	4,5	1170	110	128,70	6	1560	171,60
Expanded cork	0,036	4,5	162	120	19,44	6	216	25,92
PLA foam	0,034	4,5	153	50	7,65	6	204	10,20
Greensulate mycofoam	0,039	4,5	176	122	21,41	6	234	28,55
Biofib hemp fibre insualtion rolls	0,04	4,5	180	30	5,40	6	240	7,20
Biofib hemp fibre insualtion panels	0,04	4,5	180	40	7,20	6	240	9,60
Soybean insulation foam open cell	0,022	4,5	99	33,6	3,33	6	132	4,44
Soybean insulation foam closed cell	0,021	4,5	95	33,6	3,18	6	126	4,23

Material	λ (W/m*K)	d (mm)	Rd (m)	Density (kg/m3)	Weight (kg/m2)
Gypsum board 0,95 cm	0,16	9,5	0,0059375	7,62 (kg/m2)	7,62 (kg/m2)
Gypsum board 1,25 cm	0,16	12,5	0,0078125	10,2 (kg/m2)	10,2 (kg/m2)
Steel reinforced concrete per dm	1,7	100	0,06	2400	240
Steel per mm	50	1	0,00002	7870	7,87
Aluminum per mm	200	1	0,000005	2700	2,7
Wood (Fir) per cm	0,18	10	0,06	530	5,3
Balsae wood per cm	0,048	10	0,21	1600	16
Biobased composite (flax-supersap)per cm	0,056	10	0,18	1115	11,15
Biobased composite (hemp-supersap)per cm	0,056	10	0,18	1148	11,48
Fibreglass-polyester composite per cm	0,015	10	0,67	1522,4	15,22
Aircavity (stationary, 15°) per cm	0,026	10	0,38	1,225	0,01
Glass	1,05	4	0,0038095	2500	10
Ceramic	0,8	40	0,05	2200	110

4.5.1.10 | Insulation values

In the table on the left common used insulation materials and biobased or environmental friendly materials are shown regarding their thermal conductivity. Since 2015, for new buildings and large renovations, The thermal insulation of a construction should at least be 4,5 m2·K/W. This is the thermal insulation of the complete wall construction. Since usually the additional materials add very few to the total insulation value, the table shows for these materials the necessary thickness to obtain this insulation value.

Because 4,5m_2·K/W is the demanded minimum, an office building can be insulated better, which decreases the energy consumption of the building. Therefore also for 6,0m_2·K/W the necessary thicknesses are shown.

The table below shows the insulation values of often used building materials. These values will be further used in chapter 7.

Table 4.4 | Insulation materials thickness and weight
Table 4.5 | Thermal insulation common building materials

Both petrochemical based insulation as biobased or more environmental friendly insulation materials are available.

Important is the thermal conductivity of a material, as well as the density of the material. The table shows the necessary thicknesses of insulation materials to obtain a thermal insulation of 4,5 and 6,0 m2·K/W. Besides this, the table shows the consequent weight per m2.

5

DURABILITY

5.1 | TESTPLAN

5.1.1 | Introduction

From the beginning of the research set-up, the aim was to perform material tests to research the weathering of biobased composite further. The previous performed research into biobased composites carried out by Dorine van der Linden showed the ageing under weather influences of biobased composites for (very roughly) 1,5 years. However, for a facade, inconveniences occur often after a slightly longer time than these 1,5 years. Therefore the aim was to perform likewise tests for a longer period. The material for the test (three sheets of biobased composite) were provided by Van der Linden.

However, in the search for a test machine to use, there turned out to be no institute with such a QUV accelerated weathering machine available. This delayed the tests significantly. Eventually, through extensive searching SKG-Ikob offered help with the tests.

SKG-IKOB

SKG-Ikob is an institute which offers quality assurance for the construction and real estate industry. They are specialized in testing materials or elements for all sorts of safety requirements and have a section setting up test plans.

Unfortunately they did not have the exact same test machine, which made it more difficult to compare the test results to the previous found results. However they helped setting up two other tests which led to the results showed on the next pages. By defining the test plan and configuring the machines employees of SKG-Ikob also helped.

5.1.2 | Samples

The tested samples were 250mm long and 20mm wide. The thickness was 3mm.
The samples were built up from 10 layers uni-directional flax fibre and Cardolite 2501A resin with 2401 B hardener. The total percentage of biobased content of the resin with hardener is 34%. The total biobased content of the samples is therefore 64% (Van der Linden, 2017).

In total there were 3 test groups. One group, the “initial” or “control” group, was kept at room temperature while being exposed to as little as possible influences. The second and third group were exposed to the tests as explained on the right.
For each test, there were 3 coated samples and 3 uncoated samples. The samples 1,2,3 (coated) and 11,12,13 (uncoated) formed the control group. In the same way the samples 4,5,6 and 14,15,16 formed the second test group and 7,8,9 and 17,18,19 the third.

5.1.3 | Test plan

After discussion with specialists of SKG-Ikob, two different test were defined. The difficulty with testing a new material is that there are no reliable test methods defined yet. For all new materials the same problem appears; how can you test a material and qualify the results without comparable results from the field?

Because a machine providing UV-radiation was not available, this could not be tested. At this aspect the results differ from earlier carried out tests. However, the material has not before been exposed to extreme temperatures, so this predominantly forms the addition to the knowledge on biobased composite.

Two machines were used for two different type of tests. The first one is a Votch warmth-cold cycle machine and the second machine performs freeze-thaw cycles.

5.1.3.1 | Warmth-cold cycles

The first test ran for 5 days, and preformed temperatures between -20 and 70 °C, as shown on the picture below.
The test is carried out accordingly to the Belgian standard NBN B 62-400: 2016 section 6.2 “Hygrothermal properties of buildings - Determination of the resistance to hygrothermal load of hard cladding adhered to external insulation - Test method” (NBN, 2016).
This test method was chosen because the research concerns a facade material and this test method was decided to be most associated after an extensive discussion with employees of SKG-Ikob. The winter temperatures in the Netherlands hardly reach -20 °C ever, however this is a set temperature in the standards and covers a significant safety margin.

In this test the material is:
• Exposed to 5 cycles of -20 and 70 °C, which all have a duration of one full day (24 hours)

• Heated up to 70 °C in one hour, and kept at that temperature for another 7 hours, which remains in a high temperature exposure of 8 hours in total per cycle

• Cooled down to -20 °C in 2 hours and kept at this temperature for 14 hours, remaining in an extreme low temperature exposure for 16 hours in total

While the maximum temperature according to the standard is maximum 50 °C, for this test it was decided to be raised to 70 °C. The material is, when not coated another colour, very dark brown. Dark materials can heat up in the sun easily, and brown materials can easily reach temperatures like 70 °C.

5.1.3.1 | Freeze-thaw cycles

To perform the freeze-thaw cycles was decided due to the fact that freezing conditions in a wet environment have not been tested for biobased composite, while this is a very important aspect concerning the weather in the Netherlands.

The test was carried out according to the ETAG 004 5.1.3..2.2. “External thermal insulation composite systems (etics) with rendering” (EOTA, 2013).

In this test the material is:
• Exposed to 30 cycles, which all have a duration of one full day (24 hours), therefore the test takes a full month

• Exposed to water for 8 hours. This is done by running the box as shown underneath full of water. The temperature at this time is 23 (± 2)°C.

• Frozen to -20 (± 2)°C in 5 hours and remains at this temperature for another 11 hours.

5.1.3.3 | Sample configuration

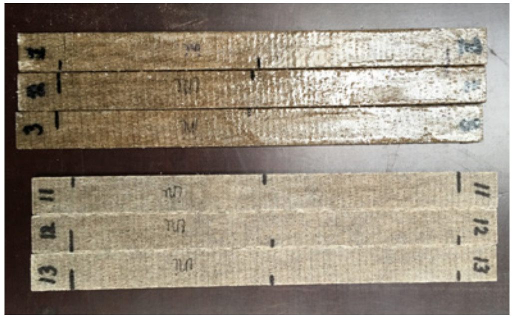
Initially there were 20 samples of the same biobased composite. Half of them was coated, resulting in 10 coated samples and 10 uncoated samples.

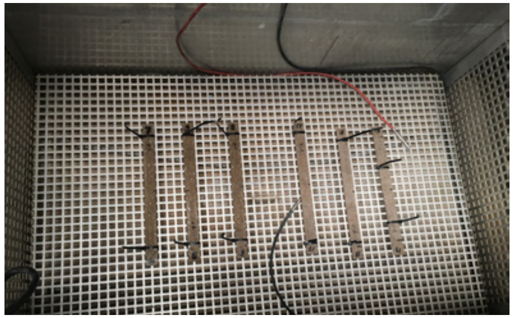
One set of samples was to be kept separate and nor exposed to any weather influences. By comparing the “initial” samples to the tested samples, possible additional influences on the degradation can be kept out of the comparison.

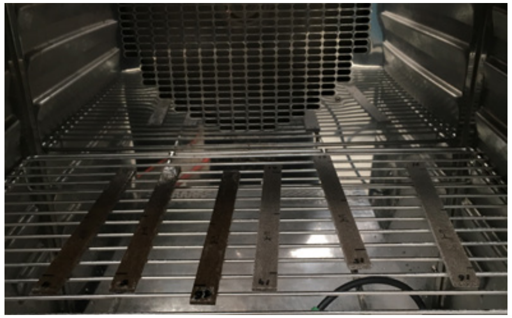
Eventually three groups of samples were made. The aim was to test 5 samples of each type, however due to the choice of two different tests this was not possible. Therefore for each test, and for the initial samples, three coated and three uncoated samples were used. This resulted in a final set of 18 samples being used, and two samples kept as extra.

On the right you see on top the set of samples for the “initial” group.

Before the sampels were tested, they have all been measured for thickness at the bottom, middle and top of the samples. Any increase in thickness (for example by absorbing water) can be measured therefore. For the same reason all samples were weighted before testing.







5.1 | Logo SKG-Ikob
5.2 | Cycle of the Votsch machine
5.3 | Samples in the Votsch machine ready for testing
5.4 | Freeze-thaw machine
5.5 | Samples of the “initial” group
5.6 | Samples in the freeze-thaw machine
5.7 | Samples in the Votsch machine

For new materials there are no test plans defined. Together with specialists of SKG-Ikob two test were defined for biobased composite.

The first test is a warmth-cold cycle test, which performs 5 cycles of 24 hours.
The second test is a freeze-thaw test which performs 30 cycles of 24 hours.

For each test three coated and three uncoated samples are used.

5.2 | TESTRESULTS

5.2.1 | Tensile test

To establish how much the samples have degraded in the accelerated weathering tests, tensile tests were performed at the 3ME laboratory of the Technical University of Delft, under the supervision of dr. ir. Veer.

The idea of a tensile tests is, very roughly, to pull both sides of a sample in the opposite direction while increasing the tensile force and at the same time measure the elongation of the specimen. The test machine monitors the applied force. The breaking point is visible in the dataset, therefore the maximum applied normal force is known and the tensile forces can be calculated.

The youngs modulus can be calculated from the angle of inclination of the stress-strain graph.
The elongation in percentage can be calculated by divining the relative displacement by the total length.

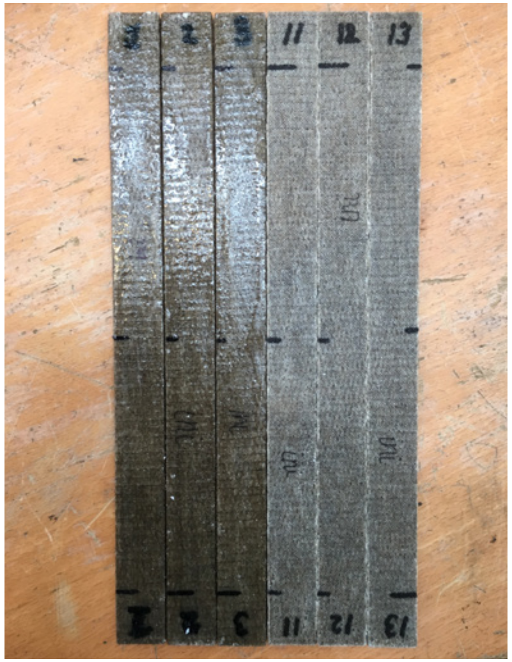
5.2.2 | Results

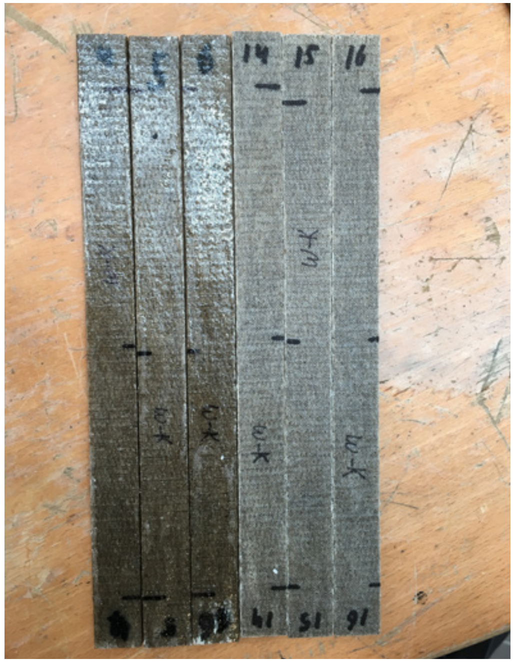
5.2.2.1 | Visual differences
Before the tensile tests the samples have been inspected visually.

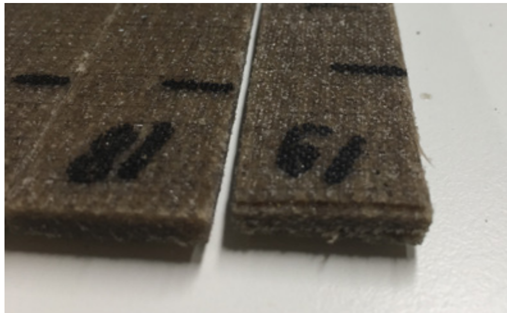
The colour of the samples has not changed to such an extent that visual inspection without any device could determine a difference.

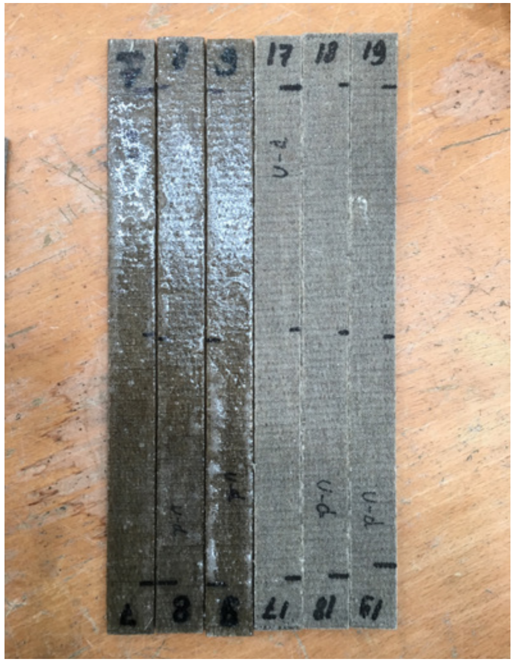
Between the warm-cold cycles tested samples and the control group no differences were seen.

The uncoated freeze-thaw tested samples were wet when they thawed right after the test ended, see the picture on the right page on the right. There was water on the samples which stayed there for a couple of hours. The coated samples did not show any differences with the control group and their surface dried very quickly.
The edges of the uncoated samples were a little more rough, some fibres were sticking out.









5.8 | Test machine
5.9 | Sample in clamps test machine
5.10 | Uncoated freeze-thaw samples just after testing
5.11 | Rough edges of uncoated freeze-thaw samples
5.12-5.13 | Control group before and after testing
5.14-5.15 | warm-cold cycles tests before and after testing
5.16-5.17 | Freeze-thaw cycles group before and after testing

Tensile tests were performed to establish how much the samples degraded under the accelerated weathering tests. Visually there were almost no differences between the samples before and after the tests.

The uncoated freeze-thaw tested samples were wet when they thawed. The edges of the uncoated samples were a little more rough, some fibres were sticking out.

5.2.2.2 | Weight

Thereby they were weighted before the tests and after the tests. Besides this the thickness was measured at the bottom, top and middle of the sample using a calliper.

The weight has increased for all samples. There is no notable difference in weight gain between the test groups. All groups have gained weight between the 12 and 18,5 percent. There is also no notable difference between the coated groups and uncoated groups.

It might be possible that the used scale was not accurate enough.

5.2.2.3 | Thickness

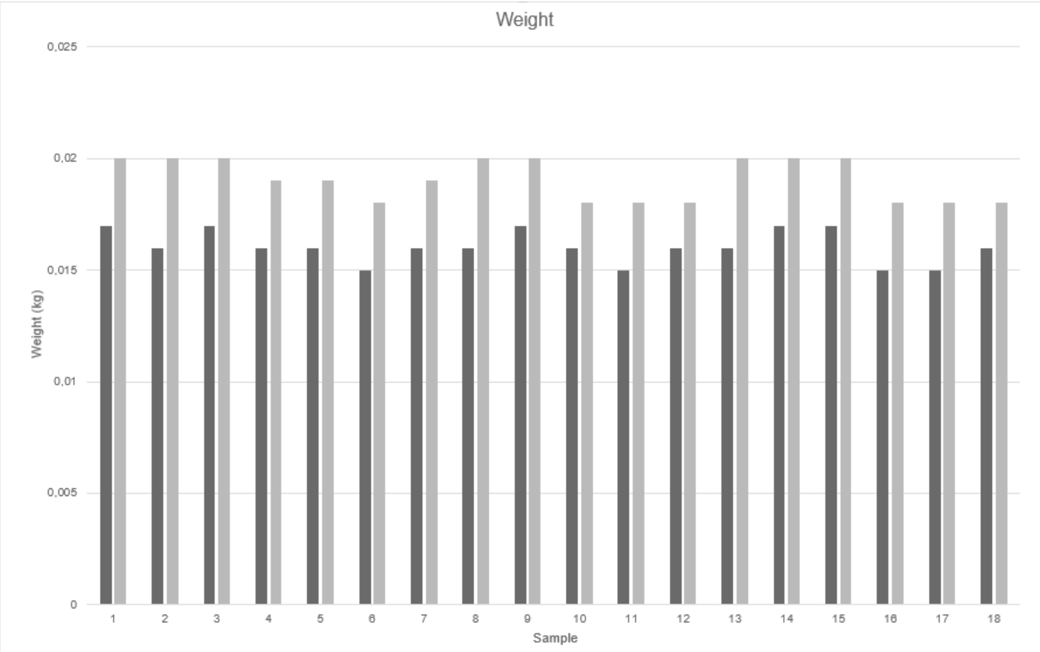
The thickness is increase for all samples. The percentage in which they have increased is for the initial group 0.5% for the coated and 0.75% for the uncoated samples.

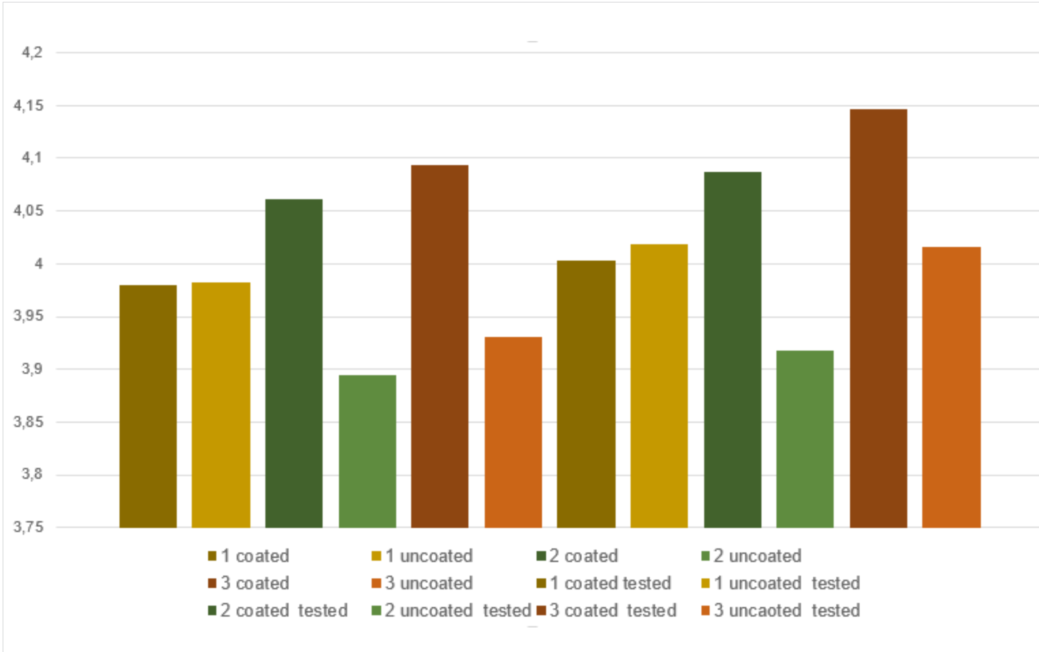
For the warmth-cold group the coated samples increased 0.74% in thickness and the uncoated samples 0.67%.

The freeze-thaw samples increased 1.47% for the coated elements and 2.14% for the uncoated elements.

Between the freeze-thaw cycles tested group samples and the control group, a noticeable difference in the amount of thickness increase was found. The increase was for the coated and uncoated group 2,9 times higher than the thickness increase of the original samples. For the warm-cold cycles tested group this was 1,5 times for the coated samples but a decrease of 0.9 times for the uncoated group.

Graph 5.1 | Weight samples before and after testing
Graph 5.2 | Average thickness per test group
Graph 5.3 | Graph tensile strength-strain of all the samples
Table 5.1 | Nummeric results of the tensile tests





5.2.2.4 | Tensile strength

The tensile strength of the control group is the lowest. The warmth-cold cycli tested group has a slightly higher maximum tensile strength and the freeze-thaw cycles tested group has the highest maximum tensile strength.

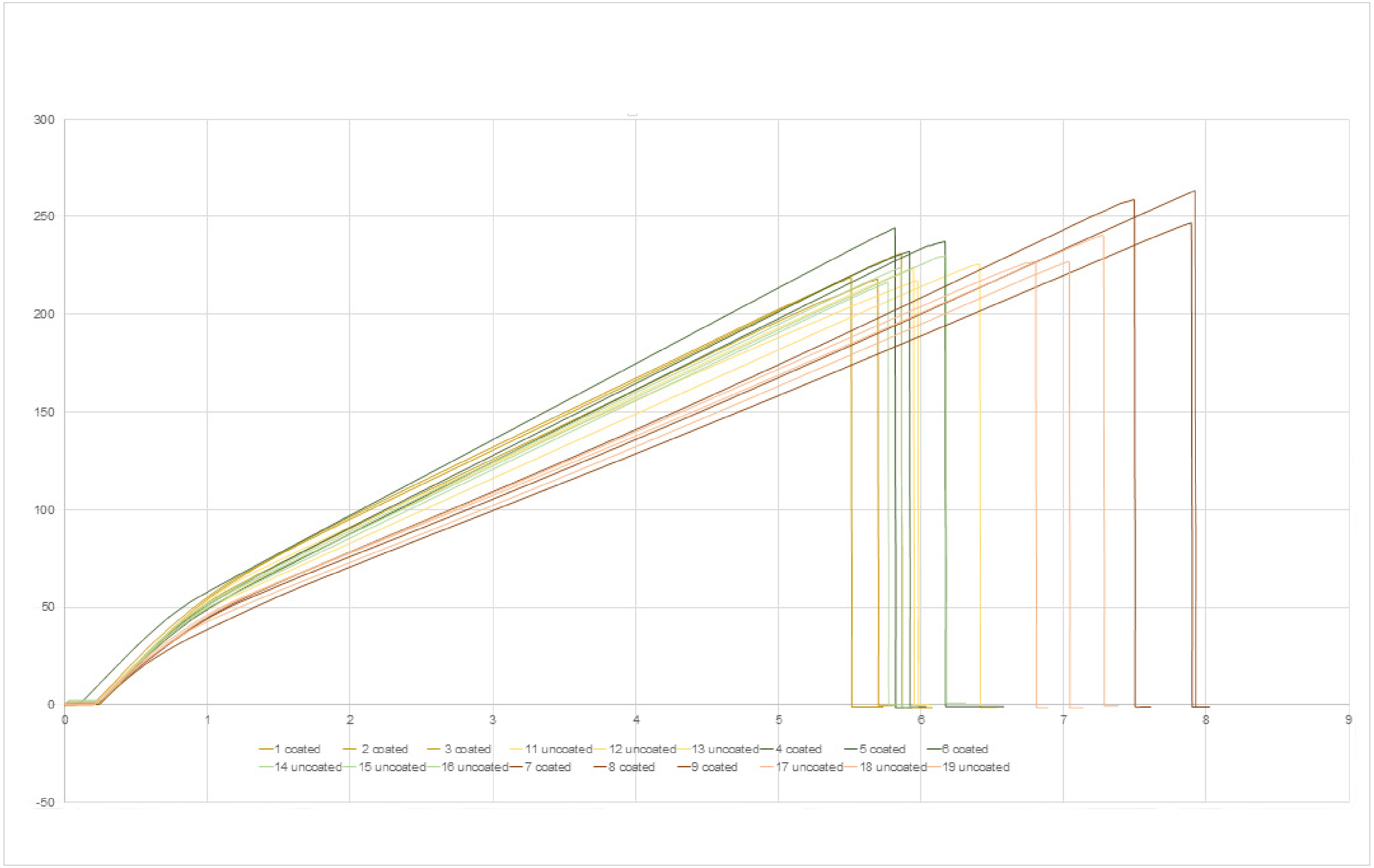
For coated samples the tensile strength increases by 7% and for the uncoated group by 0.77%.

For the freeze-thaw cycles tested group the tensile strength increases by 15% for the coated group and by 4.4% for the uncoated samples.

Based on the results a trend can be noticed. The tensile strength of coated elements increases more when exposed to accelerated weathering than uncoated elements, but all elements increase in tensile strength while being exposed to accelerated weathering tests.

5.2.2.5 | Youngs modulus

The youngs modulus of the control group is higher than those of the tested samples. This is both the case for the coated as for the uncoated samples.
For the warmth-cold cycles tested samples the youngs modulus decreases by 3% for the coated elements and 1% for the uncoated elements. For the freeze-thaw cycles tested samples this is 13% for the coated group and 12% for the uncoated group.



Sample	Youngs modulus (Gpa)	Tensile strength (Mpa)	Elongation at break (%)	Sample	Youngs modulus (Gpa)	Tensile strength (Mpa)	Elongation at break (%)	Sample	Youngs modulus (Gpa)	Tensile strength (Mpa)	Elongation at break (%)
1 coated	19,9	218,8	2,196	4 coated	18,6	237,3	2,352	7 coated	17	263,3	3,052
2 coated	19	231	2,248	5 coated	18,8	232,3	2,268	8 coated	17,3	258,7	2,896
3 coated	19,4	218,1	2,172	6 coated	18,9	244,3	2,28	9 coated	16,4	246,9	3,052
Average	**19,4**	**222,6**	**2,2**		**18,8**	**238,0**	**2,3**		**16,9**	**256,3**	**3,0**
11 uncoated	18,7	224,9	2,476	14 uncoated	19,4	224	2,248	17 uncoated	16,8	226,9	2,724
12 uncoated	19,4	223,4	2,276	15 uncoated	19	229,8	2,36	18 uncoated	16,4	226,9	2,632
13 uncoated	19,8	216,9	2,284	16 uncoated	18,9	216,4	2,204	19 uncoated	17,6	240,6	2,8
Average	**19,3**	**221,7**	**2,3**		**19,1**	**223,4**	**2,3**		**16,9**	**231,5**	**2,7**

5.2.2.6 | Elongation

The average elongation of the samples under tensile force is also showed in the table on the previous page. The elongation of the sample of the control group is 2.2mm and 2.3mm for the uncoated samples.

For the warmth-cold cycles tested group the elongation is 2.3mm and 2.3mm. This means that the average elongation of this group is for the coated samples 4.5% more than for the control group. The uncoated elements have the same average elongation.

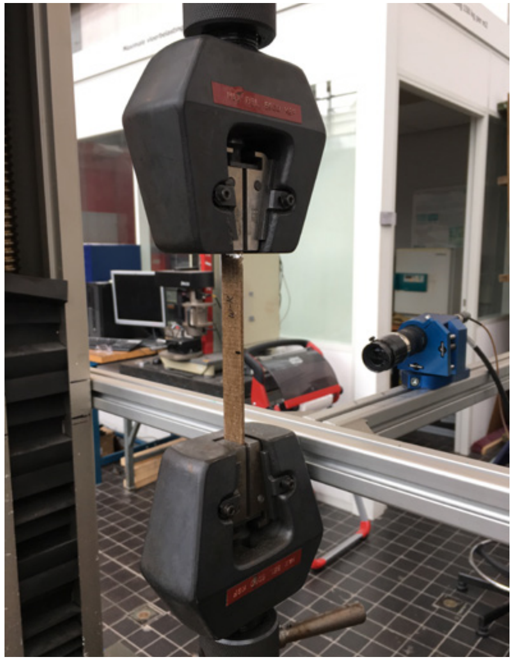
The freeze-thaw cycles tested samples have a far higher elongation. For the coated elements this is 3.0mm and for the uncoated samples 2.7mm. Therefore the elongations are 30% and 15% higher than those of the control group.

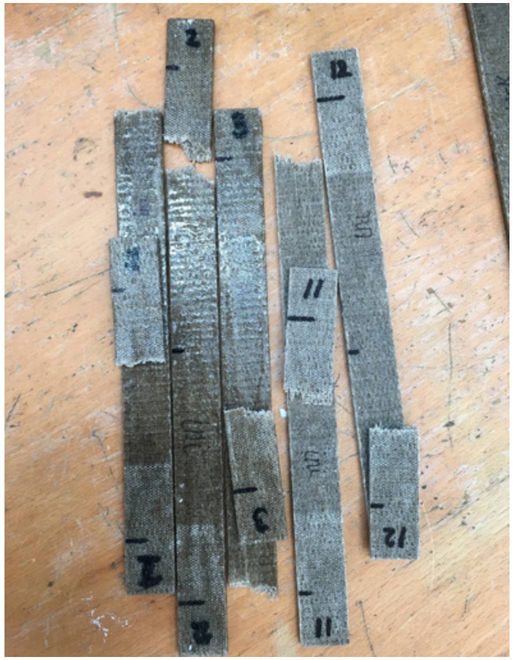
5.2.2.7 | Breaking pattern

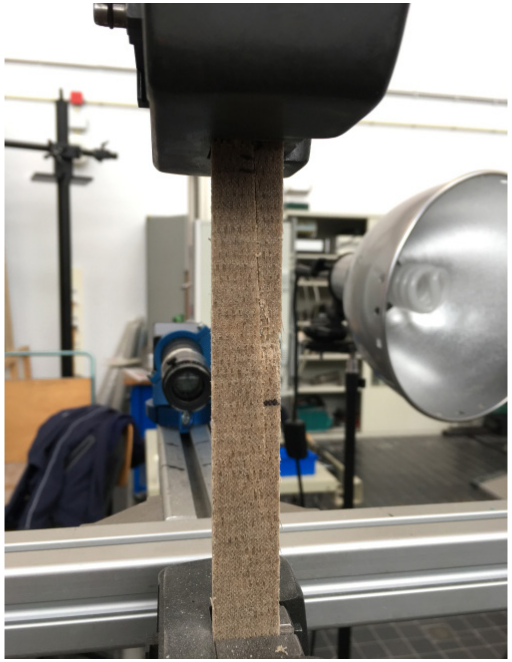
The last remarkable aspect of the test results is the breaking pattern. This is the way the samples break.

For most samples, as is shown on the pictures on top, the breakage is quite linear in the width of the sample. Usually the samples break just before the clamps on the top or bottom side, because the stresses are the highest in these place.
These breaking patterns were found for all test groups except the uncoated samples tested for the freeze-thaw cycles.

This group showed for two of the three samples an unusual breaking pattern. The samples broke in the length of the tensile force, both across the width of the samples as between a laminate layer, see the picture on the bottom.







5.2.3 | Conclusions

These tests must be interpreted as an indication since the amount of samples that have been tested and the test methods are not set-up as a foolproof test. The goal of the tests was to have an indication of the estimated life time of the material and the behaviour of biobased composite in different environments.

The test results can be interpreted as follows:

The initial group of control group shows a smaller elongation than the samples tested by Van der Linden (2017) as well as a far higher youngs modulus and a higher tensile strength.
This could be due to the fact that the material is about one year older, however it can as well be a difference between our calculation methods or a deviation of the samples.

The warmth-cold cycles tested group shows a small increase in tensile strength and a small decrease in youngs modulus. This can be caused by effects of the temperature on the material. For example the resins molecular structure might be changed, which made it more brittle.

The freeze-thaw cycles tested samples showed a large increase in tensile strength and a large decrease in youngs modulus. This means that the samples are stronger when loaded for tensile strength, however their bending stiffness is lower. Also the failure modus of the material is for the uncoated elements different. probably due to water saturation in the laminate, delamination takes place. If this weakens the material to such an extent that this will form the failure modus instead of a breakage at the places where the tension is the highest, this should be taken into account. Another option would be to just coat the elements.

Overall, the samples performed much better as expected. The freeze-thaw cycles test is one of the toughest tests for materials. It tests, accelerated 30 times extreme winter situations. Off course for the Netherlands testing up to -20 is quite extreme, but then at least a safety margin is taken in mind.

From these indicative test, it can be said that over time the tensile strength increases, but the bending stiffness decreases. This should be taken into account when designing. As also recommended by NPSP, a coating should be added, since the uncoated elements showed a more alarming breaking pattern.

The exact lifetime cannot be estimated based on these results, but the expectation is that when the material is coated and the bending stiffness is designed including a safety margin, the lifetime would be similar to other common facade materials.

5.2.4 | Recommendations

The preformed tests were indicative tests. More exact tests should be performed to establish more reliable data. The exact estimated lifetime of biobased composite requires extensive testing and practical results from an actual building situation. This requires more time and investing.

To accurately test the compared aspects, more samples should be tested. At least five samples are required by most test-standards. Since there was a limited amount of material available, these tests were performed with less samples.

To get around deviations caused by the test machines, different machines should be used, for which the results should be compared.

The results of the warmth-cold cycles test are not very different from the control group. For this test, an existing test standards was followed, but when the warmth-cold cycles are performed longer, the results might be more interesting.

The bending stiffness shows a decrease in youngs modulus of 13% for the coated elements.
This test was performed with 30 cycles and in general materials which survival this test in good conditions are estimated to have a lifetime of at least 50 years, according to employees of SKG-Ikob.
Based on these results the estimation can be made that for a facade with an estimated lifetime of 50 years, the bending stiffness should be designed at least 13% higher, however more research and testing is needed to more precise approximate this degradation.

Finally, all tests were performed without UV-radiation. Since this is a very important aspect for accelerated weathering (according to one of the specialists of SKG-Ikob an indispensable aspect) this should be tested more extensively too.

At this moment, the best solution is to apply a UV-radiation blocking coating, but if this is really necessary is not clear. If the exact influence over time is proven, for some applications a coating could be unnecessary, which could decrease the environmental impact.

5.18 -5.19 | “Normal” breaking pattern
5.20-5.21 | Unusual breaking pattern

These tests must be interpreted as an indication.
The initial group of control group shows a smaller elongation than the samples tested by Van der Linden (2017) as well as a far higher youngs modulus and a higher tensile strength.
The warmth-cold cycles tested group shows a small increase in tensile strength and a small decrease in youngs modulus.
The freeze-thaw cycles tested samples showed a large increase in tensile strength and a large decrease in youngs modulus.

6 DESIGN PARAMETERS

6.1 | TYPE OF BIOBASED COMPOSITE

Biobased composite is an anisotropic material, therefore the specific mechanical properties can be adapted to provide the necessary strength in a specific direction.
This can be done by arranging the directions of the fibres. To establish a certain strength and stiffness as well as a specific appearance, the natural fibres and the resin can be varied.

Fibre	Density (kg/m3)	Tensile strength (Mpa)	E-modulus (Gpa)	Moisture absorption (%)
Flax	1400	1150	70	7
Hemp	1480	725	70	8
Sisal	1330	650	38	11
Jute	1460	600	20	12
Ramie	1500	500	44	15
Cotton	1510	400	12	16
Coir	1250	220	6	10

6.1.1 | Type of fibre

The type of fibre also influences the material properties. The table on the right shows the density, tensile strength, elastic modulus and moisture absorption of different fibres.

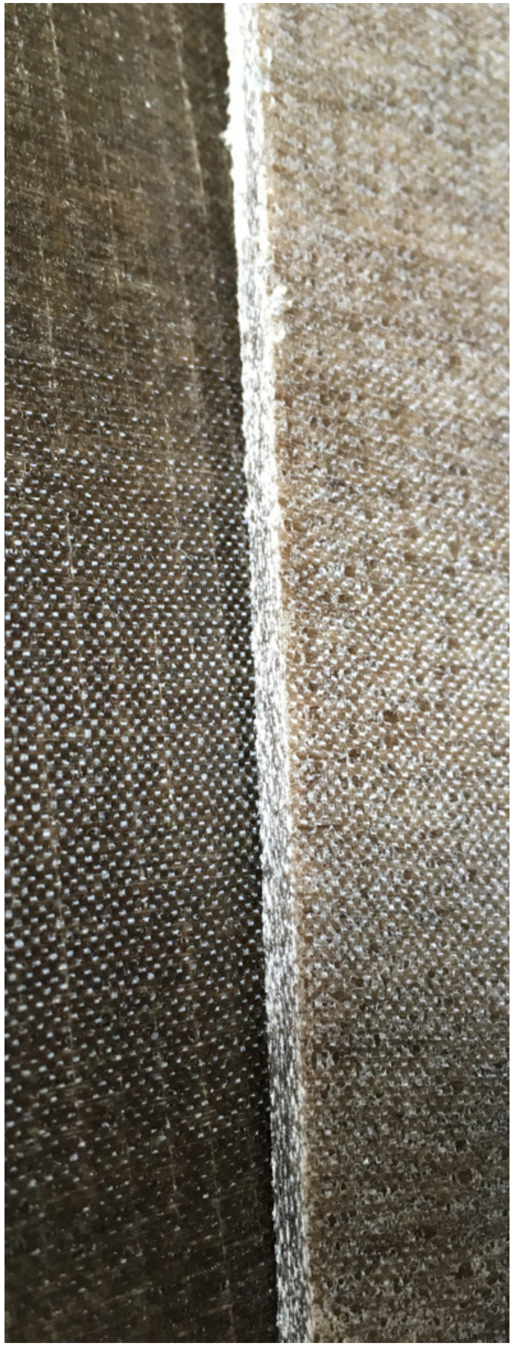
Flax and hemp are on top of the table, because they have the best properties regarding a composite material for facade parts.
For external use, the moisture absorption should be as low as possible to prevent degradation. Even when coated or pre-treated, this minimizes the possibility of undesirable degradation effects. If it turns out that flax fibres can be applied uncoated, this off course decreases the environmental impact.
Besides the moisture uptake, a high tensile strength improves the tensile strength of the composite material.
The elastic modulus defines the amount of bending force the fibres can take up. For facade elements loaded for bending this is an important property.

6.1.1.1 | Choice of fibre

The table shows that for a facade element, the best properties are gathered in flax fibres. They do not even have the highest density while having the best tensile strength and E-modulus. Besides that, they have the lowest moisture uptake.

Thereby most information on biobased composite is provided for flax-fibre composite. The shadowcosts of flax are in the Nibe database, where they aren`t for any other fibres.
Besides that, the material provided to use for the material test was made with uni-directional flax fibres. For the consistency of the research, flax fibre was used for all calculations on biobased composite.

Table 6.1 | Mechanical properties of fibres
6.1 | Panel 10 layer uni-directional flax with Cardolite resin
6.2 | Panels with 10 layer uni-directional flax and different resins
6.3 | Sawn samples, 10 layer uni-directional flax with cardolite resin
6.4 | Sawn, coated and marked samples, 10 layer U-D flax with cardolite resin



6.1.2 | Type of resin

Since epoxy resins usually have a higher biobased-content than biobased polyester resins they are preferred over polyesters (Van der Linden, 2017, p. 69).
Information on resin properties is very limited. To be able to gather the required information, properties of different resins were used. The most common known and best available resins on the market right now are Greenpoxy, Cardolite and Supersap.

From all available resins, Van der Linden has chosen Cardolite and Greenpoxy for their biobased content and processability. For more information see "*The Application of Bio-Based Composites in Load-Bearing Structures" by* Van der Linden, (2017, p. 40-41).
Therefore the main information source on properties of biobased composite, the thesis of Van der Linden, focused on these two resins. Due to a lack of reliable information on other resins, they were maintained during this research.

The benefit of the Cardolite resin (FormuLITE 2501A) is that it is based on Cashew Nut Shell Liquid (CSNL), which is an agricultural rest product, and is therefore not interfering with the food chain (Van der Linden, 2017).

For the density and shadowcosts calculation, Supersap resin was used since this was the only resin for which product specifications on the density were available. The resin used in the test samples is Cardolite.

6.1.2.1 | Choice of resin

The resin choice for calculations was very limited, namely to the only resin for which product specifications were available. For the test samples, Cardolite was used since the test samples made with this resin were available.

Both due to the good properties of flax as the fact that most information on biobased composite was about flax this was chosen to be the fibre used in all calculations. Thereby the provided test samples were made with flax fibres.
The resin used for the density and shadowcosts was Supersap while for other calculations the properties of Cardolite were used.

6.2.1 | Structural demands

The structural demands of a facade depend highly on the typology of the facade. There are three options:
1. The facade is part of the main structure of a building,
2. The facade is self-supporting and spans one or more floors but transfers loads to the floors,
3. The facade is attached to a secondary structure and transfers its own load and weather influences directly to this secondary structure.

In the design, it is most interesting to establish the necessary thickness of the biobased composite to provide the needed strength and stiffness.
In the design concepts, elements will be replaced by biobased composite. Therefore it is important to know how this influences the thickness and weight of the new elements.

6.5-6.6 | Wind pressure and suction on a building
Table 6.2 | Compared mechanical properties of steel, aluminum and biobased composite
6.7 | Schematic display of the addition of ribs
6.8 | Schematic image of curving and double curving

6.2.2 | Thickness

To establish the thickness necessary to transfer all loads, the structural properties of biobased composite were compared to those of steel and aluminum.

The tensile strength of flax-cardolite composite (10 layers of uni-directional flax) is 34% lower than that of . This is the number measured of unused samples in the thesis “*The Application of Bio-Based Composites in Load-Bearing Structures”* (Van der Linden, 2017).

The youngs modulus is much lower than those of steel and aluminum. A low youngs modulus means that a material deformes easily under applied load.

The bending stiffness depends on the youngs modulus (E) and the moment of inertia (I) of an element. The bending stiffness (E*I) results from multiplying the youngs modulus of elastic modulus with the moment of inertia. The actual strength depends highly on the shape and dimensions of the composite, but thereby the exact composition of the composite and the direction of the fibres influences the youngs modulus.

Roughly it can be assumed that the necessary thickness of biobased composite is six times the thickness of aluminum and 18 times the thickness of steel, taking the ratios of their youngs moduli. This does not regard the tensile strength which is far more in proportion to steel and aluminum.

For a facade panel, the flexural rigidity is very important to establish for example the bending stiffness under wind load.
The strength is mainly important at the connections, where the material needs to be strong enough to transfer the loads to the secondary construction.

	Unit	Steel	Aluminum	Biobased composite
Tensile strength	[Mpa]	400	305	273 (unweathered)
Youngs modulus	[Gpa]	210	69	11,4
Density	kg/m3	7800	2702	1185
Schadowcosts	€/kg	0,17	2,65	0,23

6.2.2.1 | Structural loads from weather influences

The main loads on a facade, other than it`s own load, are caused by weather influences. Important loads are caused by wind and the weight of accumulating water or snow.

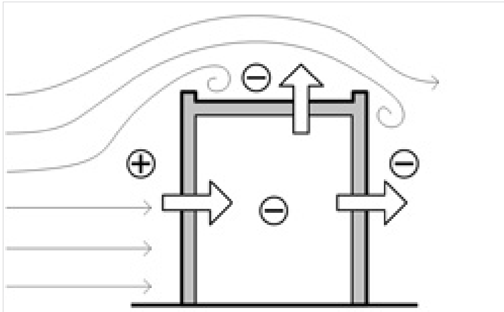
For wind force, both wind pressure as wind suction are important. To overcome these loads, mainly the stiffness of the elements is important. Besides the stiffness, the connections need to be strong enough to overcome possible tensile or pressure forces.

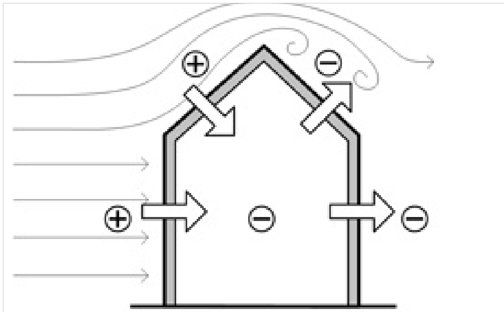
To avoid water or snow from accumulating, horizontal or moderately sloping surfaces should be avoided. Besides the load, long time remaining water can also harm biobased composite surfaces, as well as other materials like steel.

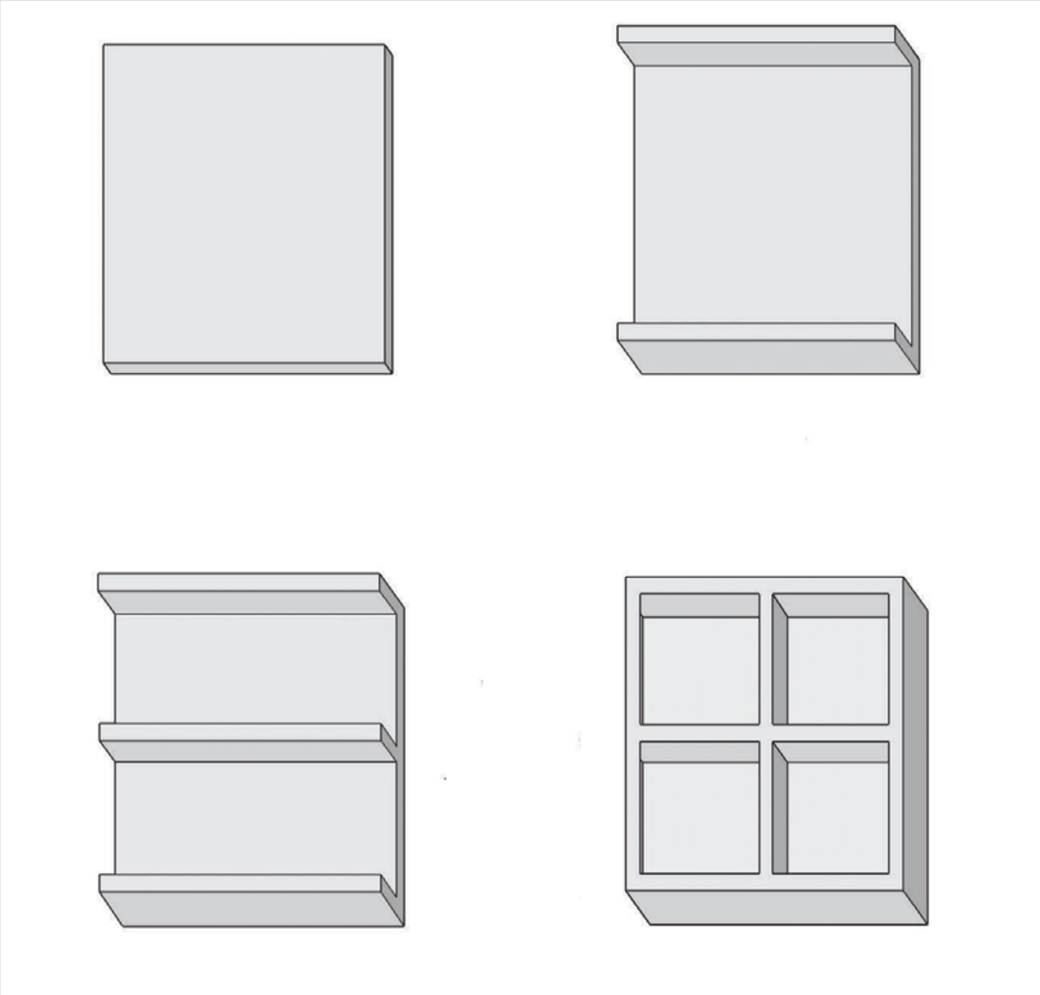
To determine the wind load, two situations are taken into account:
1. Area 1 (highest wind load area in the Netherlands) and a 3 story high building (10m)
For this building, a thrust of 1.02kN/m2 should be taken into account for a vacant area. At the coast, the wind load is even higher and can reach 1.85kN/m2. For a built-up area this is 0.81kN/m2.

2. Area 1 and a high rise building (95m) on the coast the thrust value can be 2.36kN/m2. In vacant areas this is 1.93kN/m2 and in built-in areas 1.74kN/m2.

These are the highest possible wind loads for these type of buildings in the Netherlands (Table NB.4 NEN-EN 1991-1-4).







6.2.3 | Geometry

Regarding the low youngs modulus and the ability to shape composite freely, there are some options to increase the flexural rigidity of biobased composite. This will mean that the thickness can be decreased, which will decrease the weight of the element and the amount of used material.

6.2.3.1 | Ribs

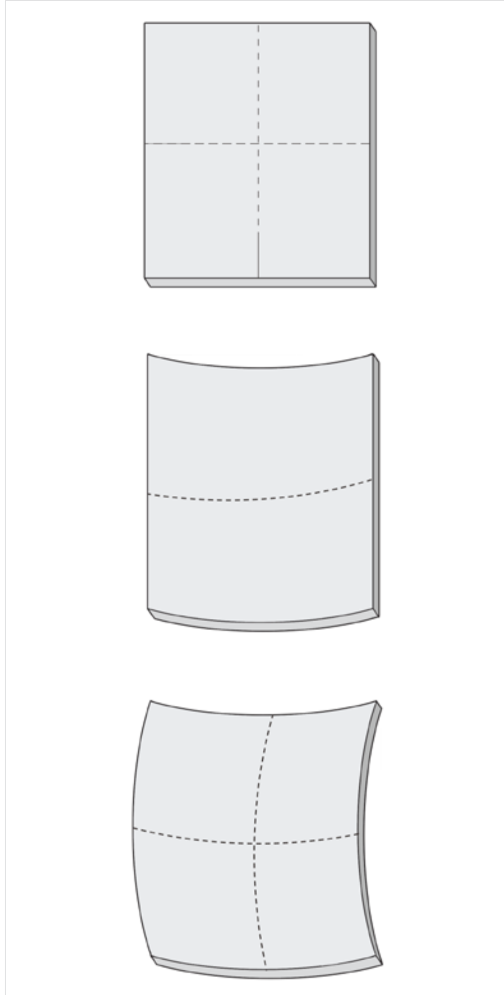
One way to do this is by adding ribs. Ribs decrease the span width and therefore increase the flexural rigidity.

The increase in bending stiffness was calculated for a panel of one square meter, see chapter 7.

The increase in bending stiffness and the therefore optimized decrease in thickeness was first calculated using formulas and hand calculations, however this turned out to be far too complicated.
Then the program Solidworks with the “finite element method”. However it turned out to be very complicated to find a “rule of thumb” for the possible decrease in thickness. Therefore eventually a schematic calculation of the bending stiffness was used.

6.2.3.2 | Curvature

Another method to improve the bending stiffness of a panel is to curve it. The curvature increases the flexible rigidity and therefore less material is needed to obtain the desired bending stiffness.
Besides curvature in one direction, like the middle picture on the right shows, curvature can be added in two directions. This is called double curving and is shown in the lowest picture on the right. Double curvature adds flexible rigidity in two directions.
Because the increase of flexible rigidity is very difficult to estimate and can only be manufactured using specific production techniques, this is not taken further into research.

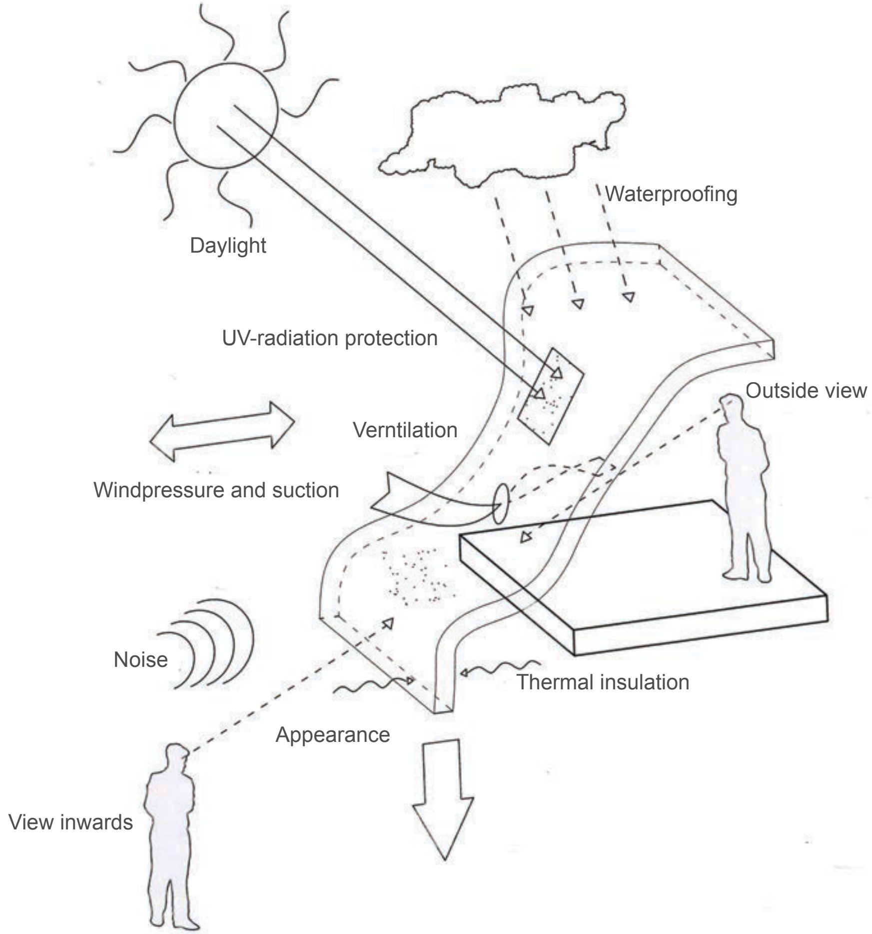


6.2.3.3 | Sandwich element

The third option is to produce an sandwich element as explained in paragraph 4.4.

The youngs modulus of biobased composite is much lower than that of steel and aluminum. Therefore the material deforms more under the same load. For the calculations the thickness of biobased composite is multiplied by the difference in youngs moduli.

Options to reduce the necessary material thickness and to increase the bending stiffness are to add ribs, to curve the material or to produce a sandwich element.



6.3.1 | Facade design aspects

A facade divides the interior from the exterior. It protect the inner space of a building from influences from outside and helps stabilizing the inner climate.
In countries like the Netherlands, were temperatures are more often too low to be comfortable than too high, the insulation of a facade is very important.

The facade also provides the appearance of a building to a large extend.

On the picture on the right all aspects regarding a facade are shown. A facade should protect agaist noise while also being resistant to UV-radiation, wind pressure- and sucking, water and moisture.
The outside view is important while the ability to look inwards also contributes to the appearance of a building.
A facade also determines how much daylight enters the building.

Important aspects for a facade design are therefore:

- Waterproofing (incl. moisture)
- UV-radiation resistance
- Thermal insulation
- Noise damping/ acoustical insulation
- Wind pressure and suction
- In- and outside view
- Appearance of the facade
- Distribute daylight

- Ventilation is optional, this can also be controlled mechanically

Two more aspects of a facade that are very important are
- Fire safety
- Air tightness

6.3.2 | Quality demands

Following from the interviews with specialists in chapter two, a set of quality demands is defined. It turns out to be very difficult to establish very specific quality demands, since for most requirements tests must be carried out. Therefore the requirements as stated now can be seen as the absolute minimum, and where no requirements could be determined, the aspects are important factors that need attention during the design.

According to the results of the interview, requirements for the acoustical insulation, fire-safety and water tightness are defined, as far as specific requirements can be determined. For these aspects the design concepts which will be analyzed. Off course there are much more aspects of importance when designing a facade, however these are the main aspects defined by DGMR consultants.

The interview on sustainability with Jean Frantzen is not directly translated into facade quality demands, however the complete chapter on circularity and the research into the environmental impact of certain materials focusses on this aspect.

6.9 | Schuco parametric system
6.10 | Facade design aspects
6.11 | Delaminarion of composite deck boards
6.12 | (interior) insulation material
6.13 | Faculty of Architecture Delft after fire in 2008
6.14 | Waterdrops at waterproof surface

6.3.3 | Acoustical insulation

The interview with Frank Lambregts of DGMR, see paragraph 2.7, the most important aspects of sound insulation for a facade were summed up.

Mass
Since the mass of a facade influences the amount of noise entering a building, a high mass would be preferable regarding sound insulation.

Sandwich construction
Since biobased composite offers good opportunity to be used in lightweight constructions, a sandwich construction is possible too. For a sandwich element the most important parameters are the thickness of the construction and the type of core material. This thickness defines which sounds enter a building, since the width allows certain sound waves to continue while others are blocked.
The type of insulation foam in a sandwich element is important. The material should be resilient and sound absorbing.

Supports
In general, single point supports between inner and outer parts of a facade should be avoided because they can cause noise “leakage”.

Conclusion:
• Mass/Sandwich construction
• No single point supports

6.3.4 | Fire-safety

The interview with Johan Koudijs of DGMR about fire safety (paragraph 2.7) showed that there are three important aspect of fire-safety.

Fire penetration
Fire penetration through the facade can only be avoided when the material is not consumed by fire, for which openings in the facade appear. This can be provided by any layer in the facade construction: For example a fire-proof retention wall can be placed.

Flash-over
Fire spread from one floor to the floor above through the facade can also be avoided by one continuous layer of fire-proof material in the facade. This doesn`t necessarily need to be the cladding material. Another option is a fire-proof parapet of sufficient dimensions.
• Fire retardant retention wall/ other facade layer

Fire propagation
Most important and most problematic for this research is fire propagation along the facade. This means that a material ignites too quickly, for which the fire quickly spread upwards. Especially for high-rise buildings this causes a high risk since evacuation times are higher.
Since the propagation time of the material is not known, different indicative solutions are:
• Apply a fire-retardant coating
• Use a fire retardant resin
• Apply the material only to low-rise buildings

6.3.5 | Water tightness

Kevin Lenting of DGMR expressed in the interview on facade technology (paragraph 2.7) his concern about the water tightness.

The assumption was made (since a water penetration test was not possible to carry out) that the material needs to be coated for outside applications, but for interior use it can be applied without a coating. This was also decided regarding the UV-radiation blocking properties of most coatings, as recommended by NPSP. When a different colour than brown is desired, a colour coating should be applied, however the composition of this coating can possibly be different which could decreases the environmental impact. For delamination, it is expected that when the material is produced in high quality and an appropriate coating is applied, delamination won`t take place.

Conclusion:
• Coating when applied outside

Three facade quality aspects, derived from the interviews with DGMR specialists, are taken into account for the concept designs. These are the acoustical insulation, the fire-safety and the water tightness of a facade.
The sustainable aspect is already covered by the chapter on circularity and the shadowcosts-comparison.

The specific important aspects are showed with the bullets in the text.

6.4.1 | Dutch office buildings

To establish the commonly used dimensions in office buildings, DGMR provided four different office plans, specifically showing the partition walls and interior layout.
All four office buildings turned out to be based on specific grids based on 300mm. Common found measures are 1200, 1500, 2400, 3000, 3600, 4800, 5400, 6000, 7200 and 9600mm. The picture on the right shows a composition of the grids of these studied buildings.

6.4.1.1 | Element width

The width of an element is usually a multitude of 300 mm, except in the Anglo Saxon countries. A common used size is 1200mm or another multitude of 300mm.

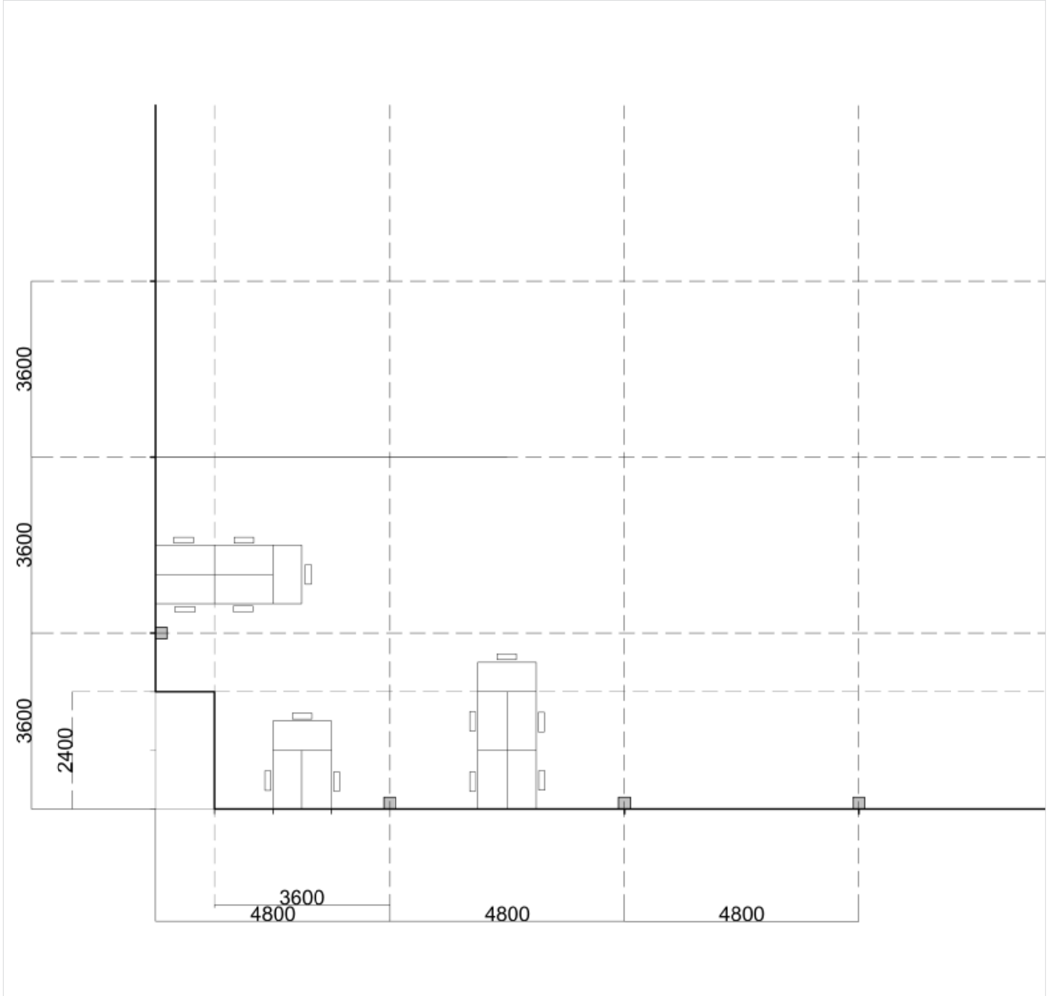
6.4.1.2 | Floor height

In the Netherlands, Dutch office building have been built during the years taking the Dutch standards “Het Bouwbesluit” into account. This standard poses minimum demands to buildings for safety and health.

The standards changed over the years. Floor heights differ approximately from 2,10m to 2,50m free space between the floor and the ceiling. Floor thicknesses are different too. The thickness of the floor construction depends on the floor span and the type of floor. Besides this, suspended ceilings can increase the floor thickness significantly.

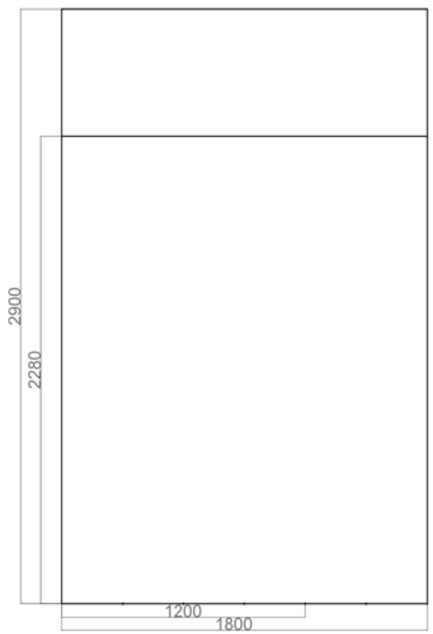
Below a table is shown, giving the numbers of possible floor hights and thickness combinations in the Netherlands.

On the right page, a scheme represents the possible dimensions of a facade element fitting most of the existing office buildings in the Netherlands. The floor height of new built buildings is usually 2,5m.



	Floor thickness									
Floor height	**180**	**200**	**230**	**250**	**280**	**300**	**330**	**350**	**380**	**400**
2500	2680	2700	2730	2750	2780	2800	2830	2850	2880	2900
2300	2480	2500	2530	2550	2580	2600	2630	2650	2680	2700
2100	2280	2300	2330	2350	2380	2400	2430	2450	2480	2500

Table 6.3 | Floor thickness
6.15 | Common dimensions in office building floor plans



6.4.1.3 Daylight openings

The Dutch building standards (Het Bouwbesluit) also includes standards for daylight openings in a facade.
For new buildings, there are demands both for the percentage of the facade which should consist out of daylight openings, and the minimum area of daylight openings any facade should contain.

For existing buildings, there is only a demand for the minimum area of daylight openings in a facade and for renovation there are no demands.

In the table below the values are shown.

New	**Daylight surface**	
Function	% of facade	Minimum area (m2)
Living	10	0,5
Office	2,5	0,5
Education	5	0,5

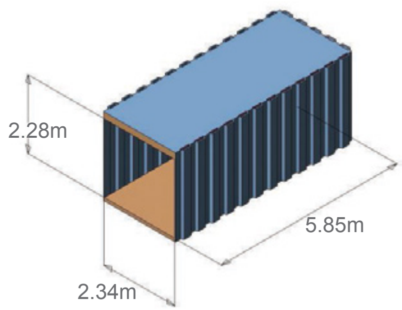
Existing	**Daylight surface**	
Function	% of facade	Minimum area (m2)
Living	x	0,5
Office	x	0,5
Education	x	0,5

Renovation	**Daylight surface**	
Function	% of facade	Minimum area (m2)
Living	x	x
Office	x	x
Education	x	x

6.4.2 | Transportation

To transport the elements, road transport is necessary. A normal truck or semitrailer is 2,55m width and 2,55-2,70m high with a length of 13,4m.
A special trailer has a height of 4,25 and a maximum length of 27,5m.
Low loaders (see picture below) can carry loads of maximum 3,6m and a lengt of 8,7-15m.

If elements need to be shipped, containers are available in two sizes. Normal containers are 2,34m wide and 2,28m high with a length of 5,85m. Extra large containers are 2,70 high and 12,0m long.



6.4.3 | Design dimensions

To design a facade suitable for most office buildings (existing and new), the height of the elements should be adaptable to the heights in the table on the left page.
The width should be a multiply of 300mm. If a framework is used, 300mm is very narrow for a framework.
An option is to apply a 600mm grid with the option to adjust just one element at the side at a distance of 300mm .

The element should contain at least 2,5% daylight openings, or make sure that a composition of different elements meets this demand.
To make the elements adjustable for living and office buildings, it should be possible to raise the percentage of daylight openings. In this case also different standards on acoustical insulation and thermal insulation need to be taken into account.

Elements should have the maximum dimensions of 13.4*2.55*2.70 m to fit in a normal truck, and 15.0*2.55*3.6m to fit on a low loader. For containers this is 5,85*2,34*2,28m or 12,0*2,34*2,70m.

6.16 | Floor hights (from table 6.3)
Table 6.4 | Daylight surfaces
6.17 | Road transport
6.18 | Dimensions of a standard shipping container

There are demands in the Netherlands for minimum daylight opening, which should for an office building be at least 2,5% of the facade.

There are many different floor heights in existing buildings. The width of elements is usually a multiply of 300mm.

For road transport and shipping maximum sizes should be taken into account.

6.5 | SHADOWCOSTS

Since the aim of the research is to design a facade out of biobased composite, however it is likely that other materials will be used too. To be able to establish the environmental impact of several different materials, the shadowcosts were studied.

6.5.1 | Shadowcosts

"Shadowcosts are the cost for the preventive measures which must be taken to reduce the emissions to a sustainable level" (Dudok van Heel, Maas, De Gijt, & Said, 2011, p. 165).

At first the Nibe database, the National Milieu Database and the DGBC material tool were compared.
The NMD did not show information about products they do not own. Therefore the information on materials relevant to this design was very limited.

The DGBC material tool shows schadowcosts of products only. When comparing wood and steel, the only option is to compare a wooden facade cladding with one of steel. This analysis involves the whole facade cladding and thus includes the secondary construction and connection materials. The same applies for steel profiles which are only available in curtain-wall facades.
In the database, the calculations behind the final numbers are not visible, therefore nothing can be stated about the specific material itself.

Using a test-license of DGMR, the environmental profiles of materials per kg can be analyzed. In this environment all values are shown per material, so no other additions are taken into account in the calculation.
When searching the openly accessible Nibe database, only products can be analyzed. These calculations include for example transportation distances, wrapping material and production drop-out rates. For cladding material, they also include secondary structures and connection materials. However the difficulty is that biobased composite is not available yet in this (or any) database. Therefore the products cannot be compared to biobased composite products. For this reason the choice was made to compare all separate materials using the test tool.
The comparison of these materials resulted in the table on the right.

Using the Nibe test-tool (Nibe, n.d.), different types of wood and metal were compared, since these materials are commonly used in facades.

The shadowcosts values in the table on the right are all derived from the Nibe EPD test tool, except the values from biobased composite and it`s coating and PLA foam. The shadowcosts of these three materials are derived from the thesis *The Application of Bio-Based Composites in Load-Bearing Structures* by Van der Linden, D. (2017), p. 107-109.
The biobased composite regards flax fibres (42%) and 48% Super-Sap biobased epoxy.

6.5.1.1 | Shadowcosts calculation

The two tables on the right of this page show how the shadowcosts of materials are calculated.

First for each material the contribution values for the different LCA aspects, such as depletion of abiotic resources or global warming, are being defined.
Then these results are converted to the shadowcosts using the table below on the right.

Table 6.5 | Shadowcosts of different materials
Table 6.6 | Example LCA aspects steel
Table 6.7 | Convertion table LCA to shadowcosts
Table 6.8 | Example of coated flat sheets and profiles

Material	**S-c (€)**	**per**
Steel		
Cladding	€ 0,17	kg
Light construction steel	€ 0,17	kg
Stainless steel	€ 2,12	kg
Coatings		
Powdercoating	*€ 1,54*	*kg*
Wetpainting	*€ 0,97*	*kg*
Galvanising (zinc)	*€ 1,09*	*kg*
Aluminum		
Aluminum (47% secondary)	€ 2,65	kg
Coatings		
Anodising	*€ 0,58*	*m2*
powder coating	*€ 1,52*	*m2*
Wood		
Hard, sustainably managed	€ 0,02	kg
Hard, not-sustainably managed	€ 0,02	kg
Soft, sustainable managed	€ 0,04	kg
Soft, not-sustainably managed	€ 0,07	kg
Soft, laminated	€ 0,07	kg
Plywood, outdoor use	€ 0,16	kg
Coatings		
Paint, nature based/ water based	*€ 0,15*	*kg*
Paint, acrylate	*€ 0,34*	*kg*
Paint, alkyd	*€ 0,57*	*kg*
Paint, stony ground	*€ 0,57*	*kg*
Composite		
Glass fibre reinforced polyester	€ 0,76	kg
Biobased composite	€ 0,23	kg
Coatings		
Spray paint	€ 1,20	kg
Insulation		
Rockwool	€ 0,10	kg
PUR foam	€ 0,38	kg
PLA	€ 0,80	kg
Flax fibre	€ 0,23	kg
Additional		
Gypsum board	€ 0,03	kg
Granite	€ 0,01	kg

		Steel
Depletion of abiotic resources-elements	Kg Sb	2,31E-06
Depletion of abiotic resources-fossil fuels	Kg Sb	1,35E-02
Global warming	Kg CO2 Equiv.	2,50E+00
Ozone layer depletion	Kg CFC-11 Equiv.	1,96E-08
Photochemical oxidants creation	Kg Ethene Equiv.	1,17E-03
Acidification of soil and water	Kg SO2 Equiv.	6,63E-03
Eutrophication	Kg PO43- Equiv.	6,11E-04
Human toxicity	kg 1.4 DB	5,24E-02
Ecotoxicity. fresh water	kg 1.4 DB	4,53E-03
Ecotoxicity. marine water (MAETP)	kg 1.4 DB	1,06E+01
Ecotoxicity. terrestric	kg 1.4 DB	9,95E-04
renewable primary energy ex. raw materials	MJ	1,40E-01
renewable primary energy used as raw materials	MJ	0,00E+00
renewable primary energy total	MJ	1,40E-01
non-renewable primary energy ex. raw materials	MJ	3,04E+01
non-renewable primary energy used as raw materials	MJ	0,00E+00
non-renewable primary energy total	MJ	3,04E+01
use of secondary material	Kg	0,00E+00
use of renewable secondary fuels	MJ	0,00E+00
use of non-renewable secondary fuels	MJ	0,00E+00
use of net fresh water	M3	3,75E-01
hazardous waste disposed	Kg	0,00E+00
non hazardous waste disposed	Kg	0,00E+00
radioactive waste disposed	Kg	0,00E+00
Total LCA value		**7,46E+01**
Schadowcosts		1,70E-01

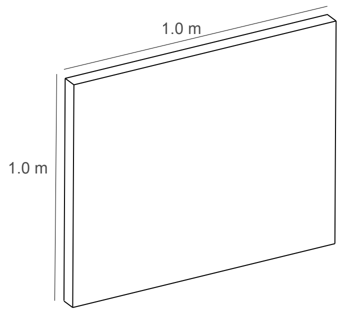
LCA impact catergory	**Unit**	**Shadowcosts**
Depletion of abiotic resources	Ab eq.	€ 0,16
Global warming	CO2 eq.	€ 0,05
Ozone layer depletion	CFC-11 eq.	€ 30,00
Photochemical oxidants creation	C2H2 eq.	€ 2,00
Acidification of soil and water	SO2 eq.	€ 4,00
Eutrophication	PO4 eq.	€ 9,00
Human toxicity	1.4-DCB eq.	€ 0,09
Ecotoxicity, fresh water	1.4-DCB eq.	€ 0,03
Ecotoxicity,marine water	1.4-DCB eq.	€ 0,00
Ecotoxicity,terrestric	1.4-DCB eq.	€ 0,06

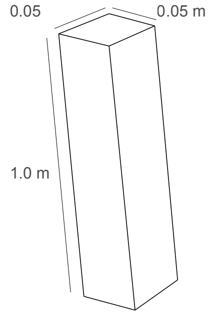
6.5.2 | Possible combinations

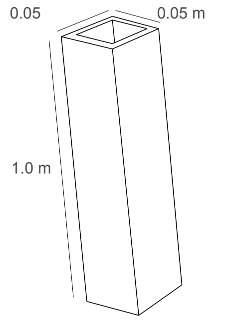
The table on the left shows a great deal of materials and their shadowcosts per kg. For some coatings the shadowcosts are given per m2.
The table is difficult to interprete, since the density of a material defines whether the shadowcosts of an element are high or low. During the calculations in further chapters, the actual influence of these shadowcosts become clear.
Another important influence on the shadowcosts is the fact if materials are coated. The coatings have quite high shadowcosts. Off course, most coatings are applied in very thin layers, such as 7 micrometer. However, some steel parts are galvanized and coated on all sides, and it depends on the surface ratio how much this increases the total shadowcosts.

On the right an example of wood, steel and biobased composite is shown for a flat sheet and a profile. Because steel profiles are usually not massive but hollow, a hollow profile was calculated for steel. For biobased composite, the same was done with a thicker profile.
For both options the shadowcosts of the wooden parts are the lowest. For a flat sheet the biobased composite part has far higher shadowcosts due to the fact that the material is applied much thicker because it`s youngs modulus is much lower than that of steel, see paragraph 6.2. The density of wood is more than half of that of biobased composite and its shadowcosts are more than ten times lower, therefore the material has far lower shadowcosts.

The shadowcosts of a material show the cost for the preventive measures which must be taken to reduce the emissions to a sustainable level.
For a flat sheet and a profile, combinations of steel, wood and biobased composite were made. Matching coatings are added and the total shadowcosts are shown. For a flat sheet biobased composite has far higher shadowcosts due to it`s high thickness. For a hollow profile the shadowcosts are still 1,5 times higher than those of steel and far higher than those of wood.







Cladding	**Wet-painted steel**		**Waterb. painted larch wood**		**Flax-biobased composite**	
	Length:	1.0 m	Length:	1.0 m	Length:	1.0 m
	Width:	1.0 m	Width:	1.0 m	Width:	1.0 m
	Thickness:	0.007 m	Thickness:	0.15 m	Thickness:	0,13 m
	Volume:	0.007 m3	Volume:	0.15 m3	Volume:	0.13 m3
	Density steel:	7870 kg/m3	Density wood:	530 kg/m3	Density b-c:	
	Kg steel:	55.09 kg	Kg wood:	79.5	Kg b-c:	144.95
	Schadowcosts:	0.17/kg	Schadowcosts:	0.02 euro/kg	Schadowcosts:	0.23 euro/kg
	Costs	9.36 euro	Costs:	1.59	Costs:	33.33
	Painted area:	2.028 m2	Painted area:	2.064m2	Painted area:	2.04m2
	Kg paint:	0.2028 kg	Kg paint:	0.206 kg	Kg paint:	0.204 kg
	Schadowcosts:	0.79/kg	Schadowcosts:	0.15/kg	Schadowcosts:	1,20/kg
	Costs:	0.16 euro	Costs:	0.30 euro	Costs:	0.24 euro
	Total	**9.52 euro**	**Total: 1.89 euro**		**Total: 33.58 euro**	
Profiles	**Wet-painted steel**		**Waterbased painted larch wood**		**Flax-biobased composite**	
	Length:	1.0 m	Length:	1.0 m	Length:	1.0 m
	Width:	0.05 m	Width:	0.05 m	Width:	0.05 m
	Thickness:	0.002 m	Thickness:	0.05 m	Thickness:	0,015 m
	Volume:	0.0004 m3	Volume:	0.0025 m3	Volume:	0,00023 m3
	Density steel:	7870 kg/m3	Density wood:	530 kg/m3	Density b-c:	1115 kg/m3
	Kg steel:	3.15 kg	Kg wood:	1.33	Kg b-c:	2,54 kg
	Schadowcosts:	0.17/kg	Schadowcosts:	0.02 euro/kg	Schadowcosts:	0.23 euro/kg
	Costs	0.54 euro	Costs:	0.027 euro	Costs:	0.58 euro
	Painted area:	0.38 m2	Painted area:	2.02m2	Painted area:	0,26 m2
	Kg paint:	0.038kg	Kg paint:	0.202 kg	Kg paint:	0.026 kg
	Schadowcosts:	0.79/kg	Schadowcosts:	0.15/kg	Schadowcosts:	1,20/kg
	Costs:	0.03 euro	Costs:	0.03 euro	Costs:	0.31 euro
	Total:	**0.56 euro**	**Total:**	**0.056 euro**	**Total:**	**0,89 euro**

7 DESIGN CONCEPTS

7.1 | DESIGN CONCEPTS

At the start of this research, the research questions were defined and the aim for a final "best performing" design in biobased composite arose. The question: "What is the best biobased circular modular façade design regarding the quality demands?" would be the main question of the research, and the research parameters were defined to answer this one question.

However, when looking at different common used facades for office buildings in the Netherlands, the answer to this one question became more and more vague.
It became clear that the "best" solution both in terms of biobased composite application as in circular means was subject to the specific properties of the situation. It seemed to be a weighing of all the aspects, in which should be decided if circularity is most important, or for example the weight or production technique.
Therefore a new approach was chosen.

To get a grip on office buildings in the Netherlands, four common office buildings were studied. The characteristics of these buildings are shown in the next paragraphs.

To show what is possible with biobased composite, the first step was to gain a feeling for the application of biobased composite. Which now used facade elements can be replaced by biobased composite, and what is the effect on the weight and schadowcosts of these new elements?

The next step was to use the gained information to define the best way to apply biobased composite to these common used building systems both regarding the environmental friendliness as the technical rationality.

In the formulated research questions, the last four questions were:
"How can the façade be adapted to meet the facade quality demands while keeping the circular aspects and material properties into account?"

"What are the effects of these adjustment for the design?"

"How can the facade be produced and installed?"

"How does the façade relate to other facades in terms of lifetime, costs, production time,
waste, CO2 emission and energy?"

Regarding the previous explained problems concerning the different demands of building projects, these questions cannot be answered directly.
Therefore the approach changed to a more conceptual method.

The following chapter answered the new research questions:

1. What are common used facade elements?
2. How can biobased composite be used in these elements?
3. What is the effect of the change in material use to the weight, shadowcosts and circularity of the element?

Regarding the environmental friendliness of the research, the common elements are, when applicable, provided with a more natural insulation material.

Following this, the four common used facades for office buildings in the Netherlands are showed. The aim is to find the best fitting concept design for each of these facades. The results from the product comparison form the basis of these concept designs.

These original facades are being compared to their biobased composite concept designs in terms of weight, insulation value, schadowcosts and circular scenario.

Comparing these aspects for both the original element and the proposed concept, conclusions can be drawn on the (circular) possibilities of biobased composite for office buildings in the Netherlands. Therefore the new research questions are:

Which variant does suit each of the case study facades best?

How can this variant be applied on the facade?

What does this mean in terms of weight, insulation value, schadowcosts and circularity compared to the original facade?

7.1.1 | Design concepts

In the next paragraphs, first the original facade element is shown. A box at the bottom of the page shows the properties of the original product. This box shows the weight of one square meter of this facade (cladding). If it concerns a cladding or sheet, no connection material or secondary structure are taken into account.
Also the Rc-value is shown, however for ventilated facades (as is the case with some cladding products) this does not add to the Rc-value of the complete wall structure and is simply shown as material property.

The schadowcosts of one sqare meter of the product are calculated and shown. They include a coating (when applied on the outside).

At first the Nibe database was used to gain the schadowcosts of the existing products. However, since the calculation for products was not possible to make for the biobased composite concepts, the comparison was not fully reliable. When products are calculated, for example the transportation distance and maintenance energy is calculated. This calculation does include everything involved in the life-cycle of the product such as wrapping material.

Unfortunately, biobased composite is not yet available in the Nibe database, therefore these calculations could not be made for the new concepts, although there was a test license available through DGMR.
To make a reliable comparison, only the separate materials and their schadowcosts were used to determine the weight and shadowcosts of both the existing products as the biobased composite concepts.

7.1.2 | Circular scenarios

In the info box at every product or concept, the circular scenario is shown at the bottom. This scenario shows the possibility to re-use, adapt or recycle the product or concept.

7.1.2.1 | Re-use

Re-use focusses mainly on the possibility to demount the elements and the estimated quality the part has after being used, which is connected with its lifespan. According to the results of the accelerated weathering tests in chapter 5, the material is estimated to have a sufficient long lifetime to be reused efficiently. At this moment this only applies for outside application when the elements have been coated.
Re-use is ranked as best option regarding circularity because no additional energy (except transport) and no additional material is necessary.

7.1.2.2 | Adapt

Adaptability concerns whether the part can be changed or upgraded, or parts can be replaced. It can also mean that the secondary structure allows for easy re-use with a different cladding material, which reflects the in paragraph 3.2 called "exchangeability of infill elements".
Adaptation is ranked as second best, because little energy and little extra material is needed, and the element remains in the cycle with good quality.

7.1.2.3 | Recycle

The method for recycleability or the possibility in general depends on the material, and this research does not concern the recycleability of other materials than biobased composite.
For some materials, the recycling potential has been included in the calculation.

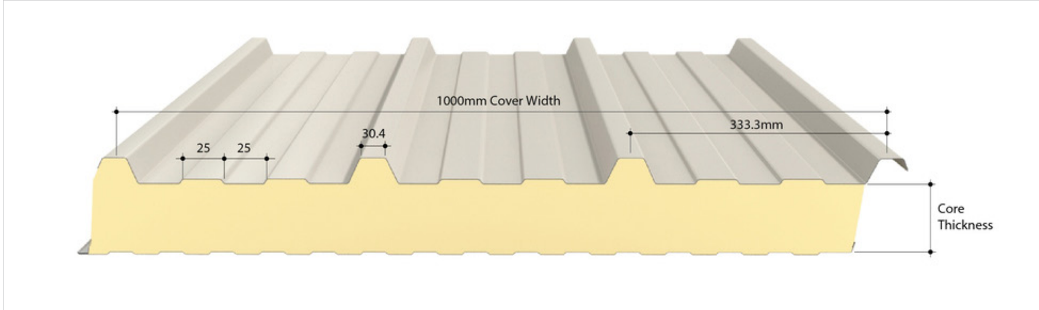
To be able to measure the recycling possibilities, a division is made regarding the ability to separate the used materials. For example glued connections are less recycleable, and coated material also has a lower recycling potential than untreated material.
Because recycling is seen as the last possibility, because it usually needs quite some energy to regain a useful product again, this option has the lowest rating.
Composting is also counted as recycling, because there will be no useful product left.

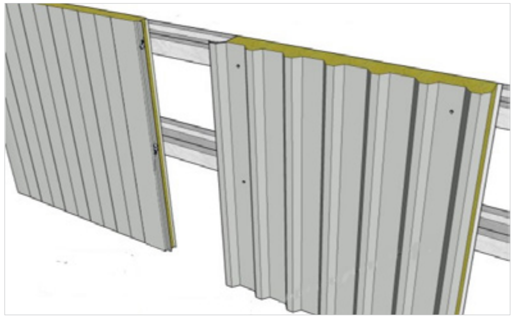
The circular scenario at the bottom of all info boxes shows to what extend the circular options can be met. Red indicates that is it not possible. Orange means it is not optimal, and green that is can be done very good.

		(green)	(orange)	(red)
		2	1	0
Re-use	3	6	3	0
Adapt	2	4	2	0
Recycle	1	2	1	0

Because re-use is rated higher than adaptation or recycling and adaptation is second best, a rating system is used to estimate the circular possibilities.
In the picture above is shown how the color codes are translated into comparable numbers. In this calculation green means 3 points, orange 2 and red 1. In this example, the total score is 9. All following circular scenarios are calculated in the same way.

7.1| Example of the properties box
7.2 | Examples of the circular scenario color codes





7.2.1 | Original steel-PIR sandwich panel

Kingspan KS1000 DR Trapezoidal insulated wall panel has been designed for vertical applications. It has a secret fix jointing system to aid fast building on site. It provides a simple and economic solution when compared to traditional, multi-component built-up systems (SpecifiedBy, n.d.).

The system is available at a 1.000 mm and 2.000 mm width, and has a Rc-value between 2.0 and 7.52 m².K/W depending on the thickness of the insulation. Thermal bridges are limited to a minimum.
Because the panels can be overlapping on the left or right, they can be optimal oriented for the prevailing wind direction.
The panels are tested by Efectis Netherlands and declared fire-safe.

The KS1000 RW is available up to the maximum length of 29.300 mm.

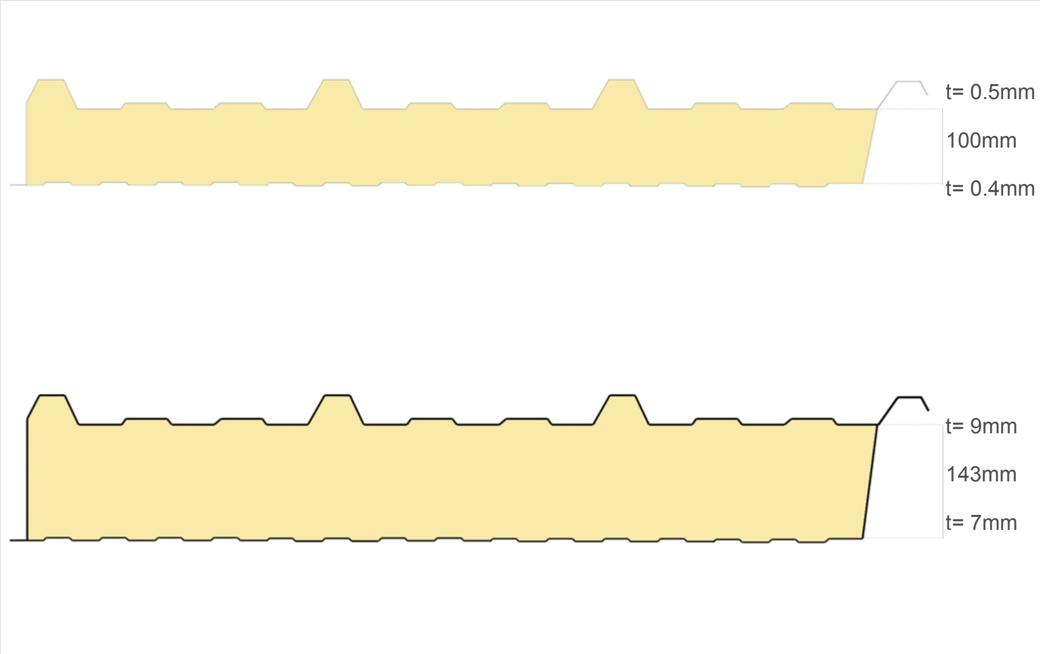
The panels consist out of a PIR insulation panel with a steel layer. Together this forms a sandwich panel.

There are different plate thicknesses available, in this example a plate with Rc of 4.53 m²*K/W is used. The thickness of the steel is 0.5 mm on the outside and 0.4 mm on the inside. The core thickness is 100 mm and the total thickness is 135 mm. The total weight of one square meter of these panels is 12.15 kg/m².

The steel is galvanized and (colour) coated, which increases the environmental impact significantly, see paragraph 4.4.

The Schadowcosts are derived from the Nibe test tool and do not include the connection materials and secondary structure. Unfortunately PIR foam is not available in this database, therefore the schadowcosts of PUR foam are used.

Weight	kg/m²	12.15		
Rc-value	m²*K/W	4.53		
Schadowcosts	€/m²	3.52		
Circular scenario	Re-use	Adapt	Recycle	10



Material	Thickness (mm) at Rd 4,5	Weight (kg/m²)	Schadowcosts (€/m²)	Embodied energy (Mj/kg)	Embodied energy
PIR (original)	99	4,45	1,68	115 (PUR)	511.8 Mj (PUR)
PLA	153	7,65	0,55	51.7	395.5 Mj
Greensulate mycofoam	175	21,4	2,22	18.2	389.5 Mj
Expanded cork	162	19,4	5,05	5	97 Mj

Weight	kg/m²	25.24
Rc-value	m²*K/W	4.5
Schadowcosts	€/m²	10.12
Circular scenario	Re-use / Adapt / Recycle	10

7.2.2 | Biobased composite-PLA

To produce such a panel from biobased composite and with a more environmental friendly core requires more material.
Since biobased composite has a 18 times lower bending stiffness than steel, the layer thicknesses are multiplied by 18. This provides a thickness of 9 mm at the top and 7 mm at the bottom of the new panel.

The core thickness will also increase since the table on the left shows that suitable natural insulation materials which are strong enough to serve as a core material require a larger thickness at the same insulation value than the original PIR foam. In this table, for Greensulate mycofoam the schadowcosts are not available, therefore the schadowcosts for wood-fibre panels are used. The adhesive material is different, but mycofoam also consists out of wood fibres or rice hulls.

The best option from the table turned out to be PLA foam. This material also has the lowest shadowcosts and a lower embodied energy compared to PIR (PUR) foam.
The new design will have the dimensions showed in the picture on the left.

The core material was at first designed to have enough thermal insulation to reach an Rc-value of 4,5 m²*K/W. However, the biobased composite adds per 10mm 0.17 m²*K/W. The upper layer adds 0.15 m²*K/W and the bottom layer 0.12 m²*K/W. Therefore the core material only needs to be 143 mm thick.

When building the biobased pedestrian bridge, the material tests showed that PLA is a very useful core material, however has one specific disadvantage. When an epoxy polymer is used as resin, the temperature rises during the curing period due to a chemical reaction within the resin. This can melt the PLA foam, for which the shape distorts. This can be prevented by adding a thin layer of expanded cork between the biobased composite and PLA foam.
Because this layer is thin and only necessary when epoxy resin is applied, the cork is left out of the schadowcosts calculation.

One important additional advantage of using (biobased) composite to produce the elements is that when vacuum infusion is applied, the composite is directly attached to the core.
The resin adheres both the fibres itself, as well as the composite to the core. This makes an additional layer of glue unnecessary.

The weight of the biobased composite-PLA sandwich panel is more than two times higher than that of the original steel-PIR panel. The insulation value is similar since the Rc-value was a design parameter. The schadowcosts of the new panel are about three times higher as those of the original panel. For steel as separate material, recycling is taken into the calculation.

Both the original element as the concept have the same circular scenario.

A steel-PIR sandwich panel can be produced using biobased composite and PLA foam. The weight will be two times higher and the shadowcosts including the coating are almost three times higher.

The shell will be 18 times thicker because the bending stiffness of biobased composite is 18 times lower. To gain the same thermal insulation as the original element has, the core thickness increases almost by 1.5 times. The circular scenario is equal.

Sandwichpanel

Original	*Dimensions (m2)*	*Volume (m3)*	*Density (kg/m3)*	*Weight (kg)*	*Shadowcosts/kg*	*Shadowcosts*
Steel outer layer	(0,0005*1*1)	0,0005	7870	3,935	€ 0,17	€ 0,67
Steel inner layer	(0,0004*1*1)	0,0004	7870	3,148	€ 0,17	€ 0,54
PIR insulation	1*1*0,100	0,1	45	4,5	€ 0,38	€ 1,71
Total				**11,58**		**€ 2,91**
Galvanising	2*(1*1*0,00007)	0,00007	7140	0,4998	€ 1,09	€ 0,54
Wetpainting	2*(1*1*0,000075)	0,000075	950	0,07125	€ 0,97	€ 0,07
Total coating				***0,57***		***€ 0,61***
Total				**12,15**		**€ 3,52**

Biobased composite	*Dimensions (m2)*	*Volume (m3)*	*Density (kg/m3)*	*Weight (kg)*	*Shadowcosts/kg*	*Shadowcosts*
Biobased composite	2*(1*1*0,009)	0,009	1115	10,035	€ 0,23	€ 2,31
Biobased composite	2*(1*1*0,007)	0,007	1115	7,805	€ 0,23	€ 1,80
PLA foam	1*1*0,143	0,143	50	7,15	€ 0,80	€ 5,72
Total				**24,99**		**€ 9,82**
Spraypaint				0,25	€ 1,20	€ 0,30
Total coating				***0,25***		***€ 0,30***
Total				**25,24**		**€ 10,12**

Element	Ix (m4)	E (Gpa)	EI (Nmm2)	Weight (kg)	**EI/w**	Density (kg/m3)	Stiffness (E/ρ)	Shadowcosts (€)	**EI/Shadowcosts**
Sandwich Steel-PIR	9,02E+07	210	1,89E+10	12,15	1,56E+09	7870	1,65E+06	€ 5,10	3,71E+09
Sandwich biobased composite-PLA	2,09E+09	11,4	2,38E+10	25,24	1,06E-09	1115	1,27E+04	€ 9,56	2,49E+09

Table 7.2 | Calculations of original and concept element
Table 7.3 | EI-calculation results
Table 7.4 | E-moduli original element
Table 7.5 | E-moduli concept element
7.10 | Schematic image of element for EI calculaion
7.11 | Thickness core and shell and calculations original
7.12 | Thickness core and shell and calculations concept

7.2.3 | Shadowcosts/weight calculations

The table above shows the shadowcosts calculation of both the original as the concept element. It turns out that for steel, the weight and shadowcosts of the material are lower.
The steel coatings however add much more to the shadowcosts than the spray painted coating of the biobased composite.

7.2.4 | EI-calculation

The calculations on the right page shows the EI calculations of both the original sandwich element as the biobased composite element. The table above shows the results.
It turns out that the bending stiffness of the biobased composite sandwich panel is 1/4 times higher than that of the original panel. This means that to optimize the panel, the thickness of the biobased composite layers can be decreased by 1/4th.

Calculating the shadowcosts of the biobased composite element regarding this reduction, the shadowcosts are 9,10 euro and the total weight is 20.97 kg.

The calculations show that the shadowcosts for the biobased material are much higher than those of the original element. The coatings are much better than the original steel coatings.

The bending stiffness calculation shows that the bending stiffness of the original element is 1/4 higher than that of the original element.
To optimize the element it can be reduced by 1/4 which decreases the shadowcosts to 9.10 euro.

7.2.5 | Bending stiffness calculations

The bending stiffness of both the steel-PIR sandwich panel as the Biobased composite-PLA sandwich panel as shown on the right were calculated using the EI-calculation method.

7.2.5.1 | Original element

For the calculation of the I-value, the moment of inertia of the original steel-PIR sandwich panel, the upper table on the right was made.
The E-modulus of the element is:

E steel	210	Gpa	
E PIR	?		
E PUR	3,30E-04	Gpa	
E Steel	>600 000	E PUR	(Neglected)

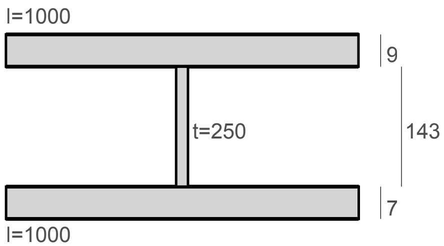
Then the moment of inertia was calculated, resulting in the total bending stiffness, which is Ic(original) * Youngs modulus= 1.89E10 Nmm4.

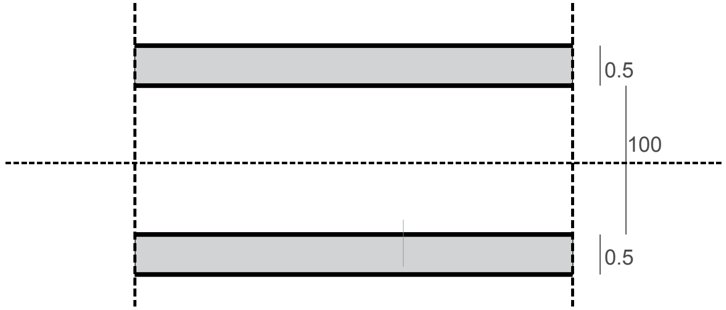
7.2.5.2 | Concept element

For the calculation of the I-value of the biobased composite-PLA sandwich concept element, the lower table on the right was made.
The calculation of the moment of inertia is:

E biobased composite	11,4	Gpa
E PLA	4	Gpa
E biobased composite	2,24*	E PUR

Then the moment of inertia was calculated, resulting in the total bending stiffness, which is Ic(concept) * Youngs modulus= 2.38E10 Nmm4.



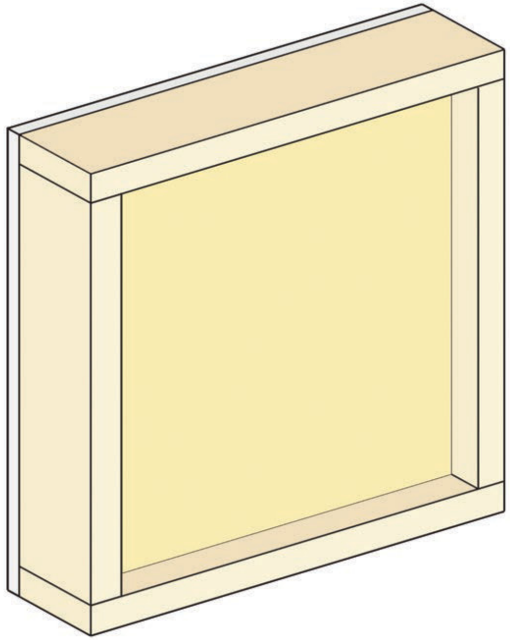


Ix1	=	1/12*b*h^3	=	1/12*1*(5e-4)^3	=	1,04E-11
Ix2	=	1/12*b*h^3	=	1/12*1*(4e-4)^3	=	5,33E-12
A1d^2	=	5,00E-04 *		1,00E-01	=	5,01E-05
A2d^2	=	4,00E-04 *		1,00E-01	=	4,01E-05

Ic= Ix1+A1d^2+Ix2+A2d^2 = 1,04E-11+5,33E-12+5,01E-5+4,01E-5 = 9,02E-05 m4
9,02E+07 mm4

Ix1	1/12*b*h^3	=	1/12*1*0,209^3	=	3,08E-08
Ix2	1/12*b*h^3	=	1/12*0,250*1^3	=	2,08E-02
Ix3	1/12*b*h^3		1/12*1*0,007^3		2,85E-08
A1d^2	(0,009*1,0)	*	0,10045^2	=	9,05E-05
A2d^2	(0,205*1,0)	*	0,00E+00	=	0,00E+00
A3d^2	(0,007*1,0)	*	0,10035^2	=	7,05E-05

Ic= Ix1+A1d^2+Ix2+A2d^2+Ix3+A3d^2 = 3,08E-8+9,05E-5+2,08E-2+0+2,85E-8+7,05E-5 = 2,09E-02
2,09E+10



7.3.1 | Prefabricated timber frame

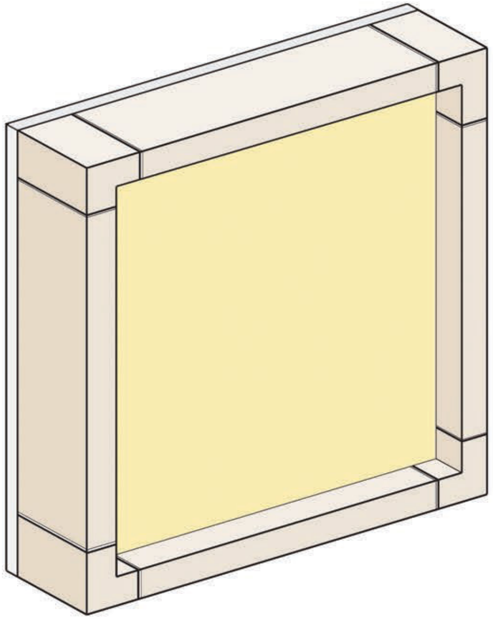
The prefabricated wooden element used for the comparison is simplified shown in the picture on the right above. The element consist out of a wooden frame made out of beams of 38*120 mm.
On the interior side the element is finished with a gypsum board insulation panel. The insulation consist out of 112 mm Rockwool which leaves an air cavity of 8 mm.

The elements usually contain a windows and an outside finish material such as wood, a cladding system or a brickwork wall with a cavity.

In the shown element, the wood provides the structural strength, but also the highest amount of the total weight. The structure can be layered in this way because the thermal transmittance of wood is quite low, otherwise the wood would form a thermal bridge.

The elements can be reused, especially when the dimensions are designed project independent. If reuse is not possible, the elements can be adapted or recycled. Because the construction is built up out of different materials which are screwed of bolted together, the elements can be easily adapted. For example the insulation material can be improved. Recycling per material is possible because the materials are good separable.

Weight	kg/m²	36.63		
Rc-value	m²*K/W	3.5		
Schadowcosts	€/kg	2.38		
Circular scenario	Re-use	Adapt	Recycle	12



7.3.2 | Biobased composite concepts

For the biobased composite concept of the timber frame structure, two options are proposed. The first one is a frame constructed out of timber frame elements and the second one is an element-sized structural part in the form of a trapezoidal panel.

7.3.2.1 | Hollow profile

The first option is an element is which the wooden structure is replaced by a biobased composite profile structure. For this structure the profiles can be extruded and connected in the corners with special connection tubes. The hollow profiles fit in these tubes and can be attached through bolting.
The thickness of the profiles and connecting tubes is estimated at 10 mm. This means that a square construction of 1 m² has a volume of 0.011 m³ biobased composite and weights 12.27 kg. Because the biobased composite is used at the inside of the construction it can be applied without a coating.

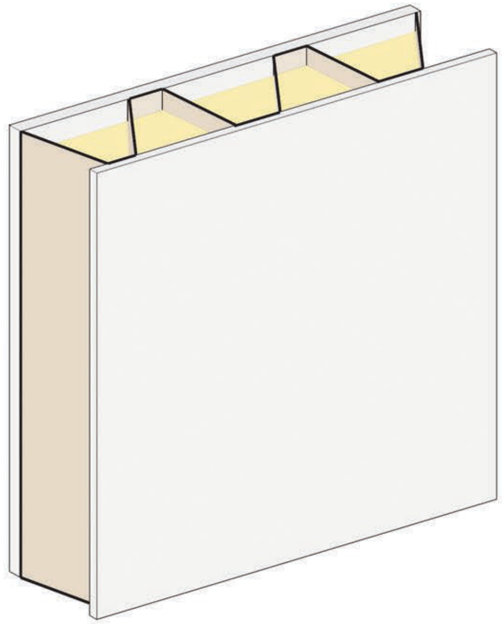
The gypsum board and insulation material are added to this weight. The gypsum board (0,95 cm) weights 7.62 kg. The insulation will be changed to flax rolls. To reach an Rd value of 3.5 the insulation layer should be 133 mm thick. This means the construction need to be thicker than the 120 mm is was in wood-Rockwool.

7.13 | Prefab timber frame structure element
7.14 | Schematic picture of original construction
6.15 | Overview properties original
6.16 | Schematic picture of option one
6.17 | Overview properties concept
7.18 | Steel example of corner profile and hollow profiles

For a standardized wood timber frame there are two options for construction in biobased composite showed.

The first option regards a hollow profile framework and the second one regards a trapezoidal plane as structural element.
Option one is much lighter than the original construction, but the shadowcosts are two times higher than those of the original construction.

Weight	kg/m²	23.21		
Rc-value	m²*K/W	3.5		
Schadowcosts	€/kg	5.34		
Circular scenario	Re-use	Adapt	Recycle	12



TFS						
Original	*Dimensions (m2)*	*Volume (m3)*	*Density (kg/m3)*	*Weight (kg)*	*Shadowcosts/kg*	*Shadowcosts*
Wood	0,048*0,120*4	0,02304	530	12,21	€ 0,01	€ 0,12
Rockwool	1*1*0,112	0,112	150	16,8	€ 0,03	€ 0,50
Gypsum board	1*1*0,0095	0,0095	802,11	7,62	€ 0,23	€ 1,75
Total				**36,63**		**€ 2,38**
Option one	*Dimensions (m2)*	*Volume (m3)*	*Density (kg/m3)*	*Weight (kg)*	*Shadowcosts/kg*	*Shadowcosts*
Biobased composite	0,038*0,113* (t=0,01)	0,011	1115	12,27	€ 0,23	€ 2,82
Flax panel insulation	1*1*0,133	0,133	25	3,325	€ 0,23	€ 0,76
Gypsum board	1*1*0,0095	0,0095	802,11	7,62	€ 0,23	€ 1,75
Total				**23,21**		**€ 5,34**
Option two	*Dimensions (m2)*	*Volume (m3)*	*Density (kg/m3)*	*Weight (kg)*	*Shadowcosts/kg*	*Shadowcosts*
Biobased composite	0,01*2,26*1	0,0226	1115	25,199	€ 0,23	€ 5,80
Flax panel insulation	1*1*0,133	0,133	25	3,325	€ 0,23	€ 0,76
Gypsum board	2*(1*1*0,0095)	0,019	802,11	15,24	€ 0,23	€ 3,51
Total				**43,76**		**€ 10,07**

7.3.2.2 | Trapezoidal structural panel

Option two is to produce an equivalent element by using a trapezoidal plate. This element provides the structural rigidity toghether with the attached finishing plates. Because the biobased composite is used at the inside of the construction it can be applied without a coating.

In between of the biobased composite trapezoidal plate and the finishing plates the insulation is provided. This is a flax roll insulation material with a thickneenss of 133 mm.
The volume of biobased composite is in this option much higher than in option one, with 25,2 kg.
Such an element can only be constructed in this way because of the very low thermal transmittance of biobased composite. When produced with a steel trapezoidal sheet, the steel would form a huge cold-bridge. Biobased composite has a thermal transmittance of only 0.056 W/m^2 K. Wood has an average lambda value of 0.18 W/m^2 which means that wood functions even more as a thermal bridge than biobased composite. For steel this is even 50 W/m^2 K.

Both options can be re-used, especially since there is no biobased composite used on the outside which will presumably enlarge the lifetime of the element. Option one can easily be adapted, where option two is more difficult to demount and transform. Both options can be split into the different materials for which recycling is good possible.

7.3.3 | Shadowcosts/weight calculations

In all options, the outer cladding layer is neglected. Because all building materials are therefore situated on the inside of the construction, no coatings are applied.

The hollow profiles in the same dimensions as the original wooden profiles have almost the same weight. This would mean that wood and biobased composite can be used for the same purposes if the biobased composite is produced in hollow profiles.

6.19 | Schematic picture of option two
6.20 | Overview properties concept two

Weight	kg/m²	43.76		
Rc-value	m²*K/W	3.5		
Schadowcosts	€/m²	10.07		
Circular scenario	Re-use	Adapt	Recycle	10

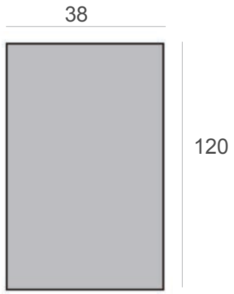
Element	Ix (m4)	E (Gpa)	EI (Nmm2)	Weight (kg)	**EI/w**	Density (kg/m3)	Stiffness (E/ρ)	Shadowcosts (€)	**EI/Shadowcosts**
Wooden beam timber frame	5,47E+06	13	7,11E+07	12,21	5,82E+06	530	6,89E+03	€ 0,37	1,92E+08
B-c hollow same dimensions	3,97E+06	11,4	4,53E+07	12,27	3,69E+06	1115	1,27E+04	€ 6,54	6,92E+06

7.3.4 | Bending stiffness calculations

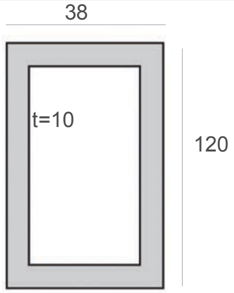
The calculation on the right show the bending stiffness of the biobased composite hollow profile and the original wooden profile. The results from these calculations are shown in the table above.

The results show that the bending stiffness of the hollow biobased composite profiles is almost half of the bending stiffness of the original wooden beams. This means that the profiles are in these dimensions not strong enough. The thickness and/or dimensions of the biobased composite hollow profiles should increase to obtain more bending stiffness. This will increase the weight and shadowcosts even more.

The thicker profiles having exactly the same bending stiffness as the original wooden beams would be 1.4 times thicker. Therefore the weight would increase to 28.1kg which makes the shadowctosts to 6.46 euro.



Ix	=	1/12*b*h^3		
Ix	=	1/12*0,038*0,120^3	= 5,47E-06	m4
			= 5,47E+06	mm4

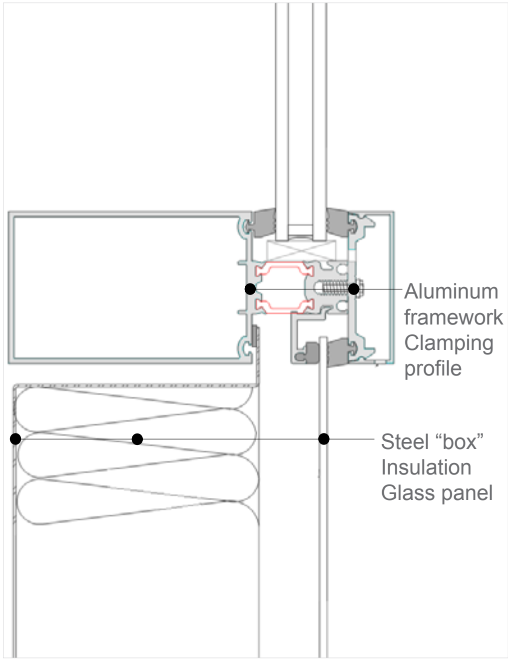


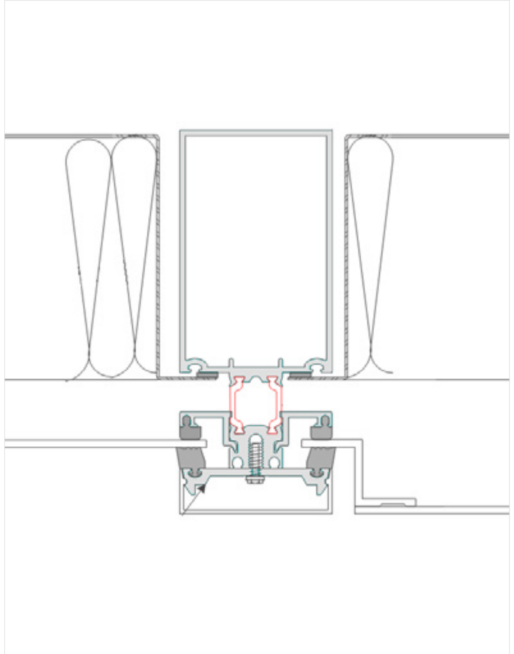
Ix1	=	1/12*0,038*0,120^3	= 5,47E-06	m4
Ix2	=	1/12*0,018*0,100^3	= 1,50E-06	m4
Ixt	=	Ix1-Ix2	= 3,97E-06	m4
			= 3,97E-06	mm4

Table 7.6 | Calculation of original and concept element
Table 7.7 | EI-calculations
7.21 | Schematic section wooden beam and calculation
7.22 | Schematic section hollow biobased profile and calculation

The second option is much heavier than the original construction and the schadowcosts are almost four times higher.

The calculated bending stiffness of the original wooden beam and the hollow profile show that the biobased composite profiles do not have enough bending strength in these dimensions. Therefore the dimensions and/ or the thickness should be increased which increases the weight and shadowcosts.





7.4.1 | Glazed spandrel

The curtain wall used for this comparison is an aluminum frame filled with glass panels. This framework has been developped extensive through the years to improve the insulation values, appearance, fire-safety and flexibility. Therefore the question to replace this framework by biobased composite requires a depth research which includes a mechanical simulation or calculations as well as thermal calculations showing whether for example condensation will occur.

However, besides the framework, curtain walls often contain glazed spandrels. These “boxes” distinguish themselves from shadowboxes by being one element. A shadowbox regards a glass panel with a finish panel more backwards in between the battens and an air cavity with insulation in between.

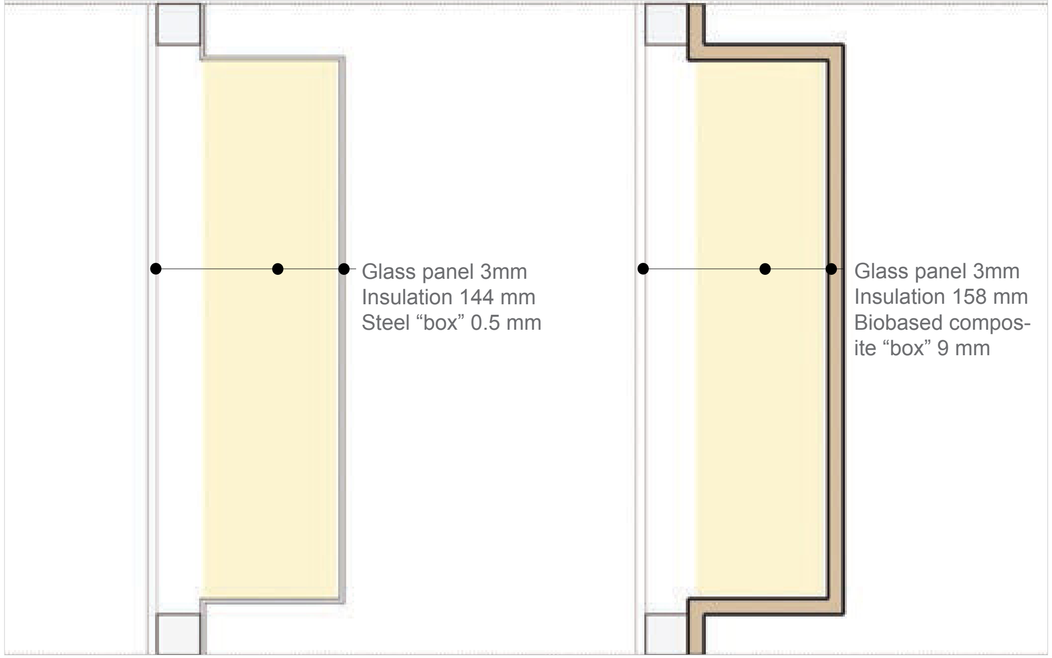
Glazed spandrels are in fact a sandwich panel which is clamped on four sides into the profiles of the curtain wall in the same way the glass panels are normally. A glazed spandrel can be applied before the floors, or at other locations where clear glass is not convenient.
The spandrel consists normally out of a steel box open on the side of the glass, filled with insulation material.
Normally there is no air cavity between the insulation material and the outside glass.

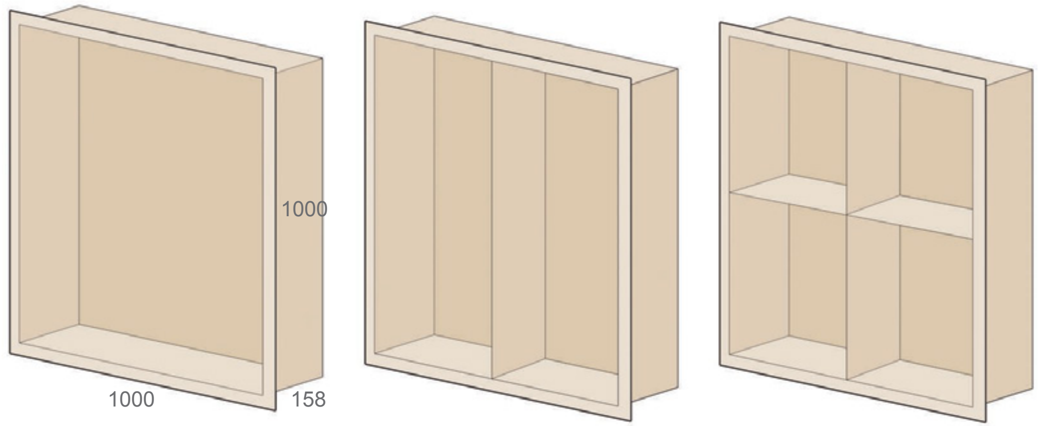
On the picture on the right above details of such a spandrel are shown. The example is constructed out of a frosted glass plane of 4 mm thickness followed by an insulation layer of 144 mm Rockwool. The inside consists out of a steel “box” of 0,5 mm thick which is not galvanised because it is placed at the inside of the water barrier. To avoid corrosion resulting from leakage the steel box is wet-painted.
The schadowcosts of glass are not available, therefore they are not taken into account both for the original spandrel as for the biobased composite variant.

7.23 | Curtain wall with glazed spandrels
7.24 | Vertical section curtain wall with glazed spandrel
7.25 | Horizontall section curtain wall with glazed spandrel
7.26 | Overview properties original
7.27 | Thicknesses
7.28 | Thicknesses with and without ribs
7.29 | Overview properties concept

Weight	kg/m²	22.22
Rc-value	m²*K/W	4.52
Schadowcosts	€/kg	0.75

Circular scenario	Re-use	Adapt	Recycle	12





Ribs: 0
Area: 1.632 m^2
Thickness: 9 mm
Volume material: 0.015 m^3
Kg material: 16.72

Ribs: 1
Thickness ribs: 6 mm
Thickness shell: 6 mm
Area: 1.83 m^2
Volume material: 0.011 m^3
Kg material: 12.17

Ribs: 2
Thickness ribs: 3 mm
Thickness shell: 3 mm
Area: 1.95 m^2
Volume material: 0.0059 m^3
Kg material: 6.58

Weight	kg/m²	10.53		
Rc-value	m²*K/W	4.55		
Schadowcosts	€/kg	2.42		
Circular scenario	Re-use	Adapt	Recycle	12

7.4.2 | Biobased composite-flax-glass

The proposed biobased composite glazed spandrel consists out of the same frosted glass panel on the outside, followed by an insulation layer of 158 mm flax-fibre insulation roll. The steel box is replaced by a biobased composite box. The box is 9 mm thick, because the original steel box was 0,5 mm thick.

This box can be made using a compression molding process, or the box can be shaped by folding a sheet, for example using a heated prepreg. In this last case seams will be visible.

As shown on the next page, the bending stiffness (EI) increases significantly when ribs are added to the element. Adding one rib of the same thickness as the rest of the "box" increases the moment of inertia by 1/3. Therefore the thickness of the complete box is decreased by 1/3 when a rib is placed. In this example of one square meter, the picture on the right above shows whether this is interesting regarding the amount of material. The figure above proves that the addition of ribs is a valuable method to decrease the material thickness.

The proposed biobased composite glazed spandrel consists out of a two-ribbed box from biobased composite, produced using a molding or compression method. The total weight of this element is 10.53 kg, which is half of the weight of the original spandrel.
The biobased composite does not need to be coated, because the glass panel seals the material from weather influences. The shadowcosts are much higher however. This is mainly caused by the fact that the steel box is very thin, which keeps the shadowcosts caused by the steel very low.

Both the original element as the biobased composite concept are very good reusable since the glass takes on the most ageing while it is on the outside, and glass is a rather durable material. Because they can be demounted while only removing the clamping bars on the inside, the elements can be adapted. For example broken glass can be replaced without wasting the other materials, or the insulation can be improved. The materials are not attached to each other, therefore they can be recycled quite easily.

Since the question if a curtain wall can be constructed out of biobased composite need extensive research, the comparison is done between a steel glazed spandrel and a biobased composite one.
Additional ribs in a structure decrease the necessary material thickness by 1/3 per rib.
The biobased composite spandrel is half the weight of the original facade, however the schadowcosts are significantly higher. Their circular scenarios are equal.

Glazed spandrels

Original	*Dimensions (m2)*	*Volume (m3)*	*Density (kg/m3)*	*Weight (kg)*	*Shadowcosts/kg*	*Shadowcosts*
Steel	1*0,158*0,0005	0,000079	7870	0,62173	€ 0,17	€ 0,11
Rockwool	1*1*0,144	0,144	150	21,6	€ 0,03	€ 0,65
Total				**22,22**		**€ 0,75**

Biobased composite	*Dimensions (m2)*	*Volume (m3)*	*Density (kg/m3)*	*Weight (kg)*	*Shadowcosts/kg*	*Shadowcosts*
Biobased composite	1,95	0,0059	1115	6,5785	€ 0,23	€ 1,51
Flax panels	1*1*0,158	0,158	25	3,95	€ 0,23	€ 0,91
Total				**10,53**		**€ 2,42**

Table 7.8 | Calculation of original and concept element

7.4.3 | Shadowcosts/weight calculations

In all options, the outer cladding layer is neglected. Because all building materials are therefore situated on the inside of the construction, no coatings are applied.

7.4.4 | Bending stiffness calculations

The bending stiffness of both sections as shown on the right were calculated, using the EI-calculation method.

7.4.1.1 | Without rib

For the calculation of the I-value, the moment of inertia of the plate without a rib, the upper table was made.
The calculation of the moment of inertia is:

$$\bar{y} = \frac{A^*\bar{y}tot}{Atot} = \frac{8{,}69E\text{-}05}{0{,}0118} = 7{,}4E\text{-}3 \text{ m} \quad (7{,}4 \text{ mm})$$

$$Ix=\sum Ix` + \sum Ad^2 = 7.04E\text{-}06+2.08E\text{-}05=2.79E\text{-}5m^4$$
$$(=2.79E7mm^4)$$

7.4.1.2 | With rib

For the calculation of the I-value, the moment of inertia of the plate with a rib in the middle, the lower table was made.
The calculation of the moment of inertia is:

$$\bar{y} = \frac{A^*\bar{y}tot}{Atot} = \frac{4{,}49E\text{-}04}{0{,}0221} = 20{,}3E\text{-}3 \text{ m} \quad (20{,}3 \text{ mm})$$

$$Ix=\sum Ix` + \sum Ad^2 = 1.06E\text{-}05+3.14E\text{-}05=4.19E\text{-}5m^4$$
$$(=4.19E7mm^4)$$

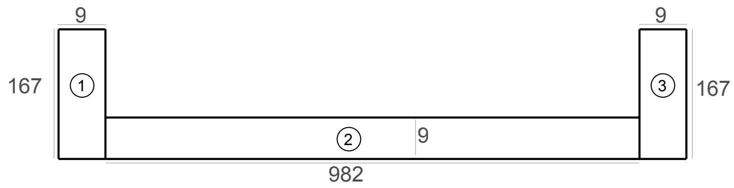
7.4.1.3 | Conclusion

The calculation shows that the moment of inertia of the plate without a rib is 1,5 times lower than of the plate with a rib in the middle (4,19E7/2,79E7).
Multiplied with the youngs modulus (E) of biobased composite, the results are:

- 2.79E-5 m^4*11.4 Gpa= 3,18E-4 Nmm^2
- 4.19E-5 m^4*11.4 Gpa= 4.77-4 Nmm^2

4.77E-4/ 3.18E-4 =1.5 times higher.

Therefore the it can be concluded that the bending stiffness increases by 1.5 times while adding one rib.



	A (m)	ȳ (dx)	ȳA	Ix`	dy²A
1	0,0015	0,083	1,25E-04	3,49E-06	1,09E-05
2	0,0088	0,0045	3,69E-05	5,96E-08	1,78E-07
3	0,0015	0,083	1,25E-04	3,49E-06	1,03E-05
∑	0,0118	0,1705	8,69E-05	7,04E-06	2,08E-05

7.4.5 | Calculation of the shape

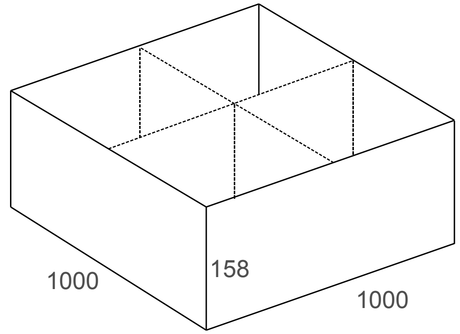
A= 1*1+((0.158*1)*4)=1.632 m^2

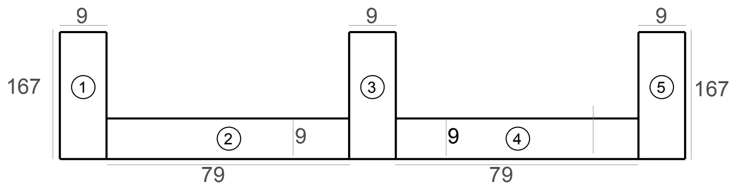
t=9mm: 1.632*0.009= 0.015m^3

t=6mm: 1.632*0.006 + (one rib: 0.0158*1*0.006)=0.011m^3

t=3mm: 1.632*0.003 + (two ribs: 2*(0.158*1*0.003))= 0.0059m^3

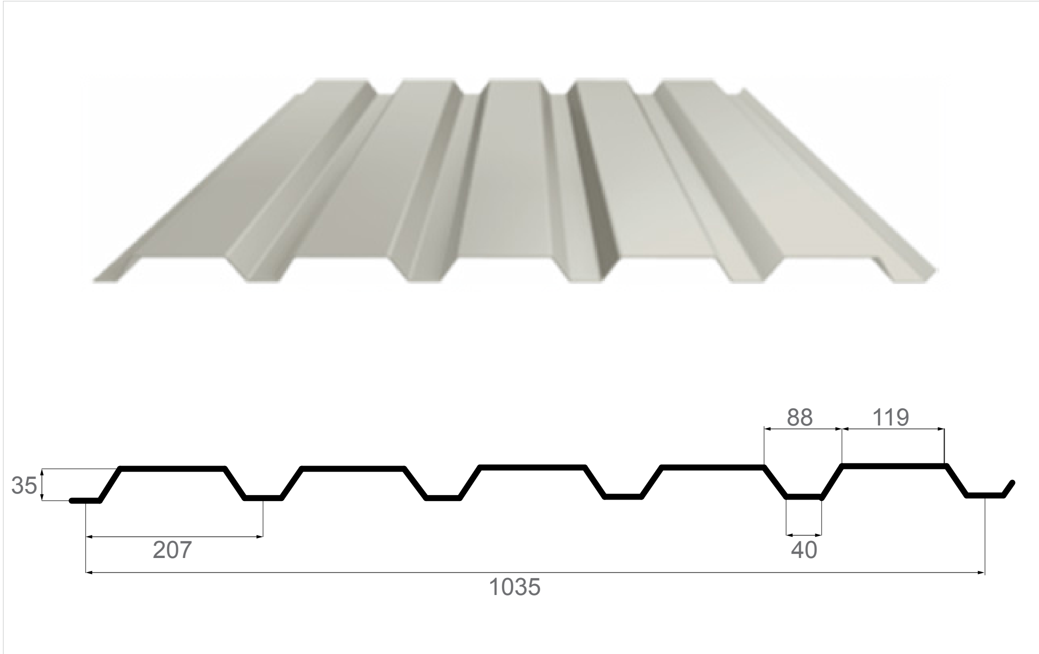
EI without rib: 2.79E-5m^4
EI with one rib: 4.19E-5m^4
Decreases by 1.5 times.





	A (m)	ȳ (dx)	ȳA	Ix`	dy²A
1	0,0015	0,083	1,25E-04	3,49E-06	1,03E-05
2	0,0088	0,0045	3,69E-05	5,96E-08	1,78E-07
3	0,0015	0,083	1,25E-04	3,49E-06	1,03E-05
4	0,0088	0,0045	3,69E-04	5,96E-08	1,78E-07
5	0,0015	0,083	1,25E-04	3,49E-06	1,03E-05
∑	0,0221	0,258	4,49E-04	1,06E-05	3,13E-05

7.30 | Schematic section box without rib and calculation
7.31 | Schematic section box with rib and calculation
7.32 | Schematic image box with two ribs



7.5.1 | Trapezoidal steel sheet

A common used facade element is a corrugated steel plate. Usually these sheets are galvanized and coated with a color-coat.

There are many different shapes, for example corrugated sheet, trapezoidal plates and point profiles.
For the comparison a trapezoidal plate is used because the sharp corners and flat edges allow for easy attachment of finishing materials or secondary structures.

For this comparison, a SAB 35/1035 profile is used because this is the most widely sold profile. The shape and dimensions are shown in the picture on the right above (SAB Profiel, 2017).

The steel for these types of plates can be very thin because they are attached to a secondary structure and the ribs provide bending stiffness in the other direction.

Trapezoidal panel

Original	*Dimensions (m2)*	*Volume (m3)*	*Density (kg/m3)*	*Weight (kg)*	*Shadowcosts/kg*	*Shadowcosts*
Steel	1*1,37*0,00063	0,00086	7870	6,7682	€ 0,17	€ 1,15
Total				**6,77**		**€ 1,15**
Galvanised	2*(1*1,73*0,00007)	0,0002422	7140	1,729308	€ 1,09	€ 1,88
Powdercoated	2*(1*1,37*0,000075)	0,0002055	950	0,195225	€ 0,97	€ 0,19
Total coating				**1,92**		**€ 2,07**
Total				**8,69**		**€ 3,22**

Biobased composite	*Dimensions (m2)*	*Volume (m3)*	*Density (kg/m3)*	*Weight (kg)*	*Shadowcosts/kg*	*Shadowcosts*
Biobased composite	1*1,37*0,0113	0,015	1115	16,725	€ 0,23	€ 3,85
Total				**16,73**		**€ 3,85**
Spraypaint				0,17	€ 1,20	€ 0,20
Total coating				**0,17**		**€ 0,20**
Total				**16,9**		**€ 4,05**

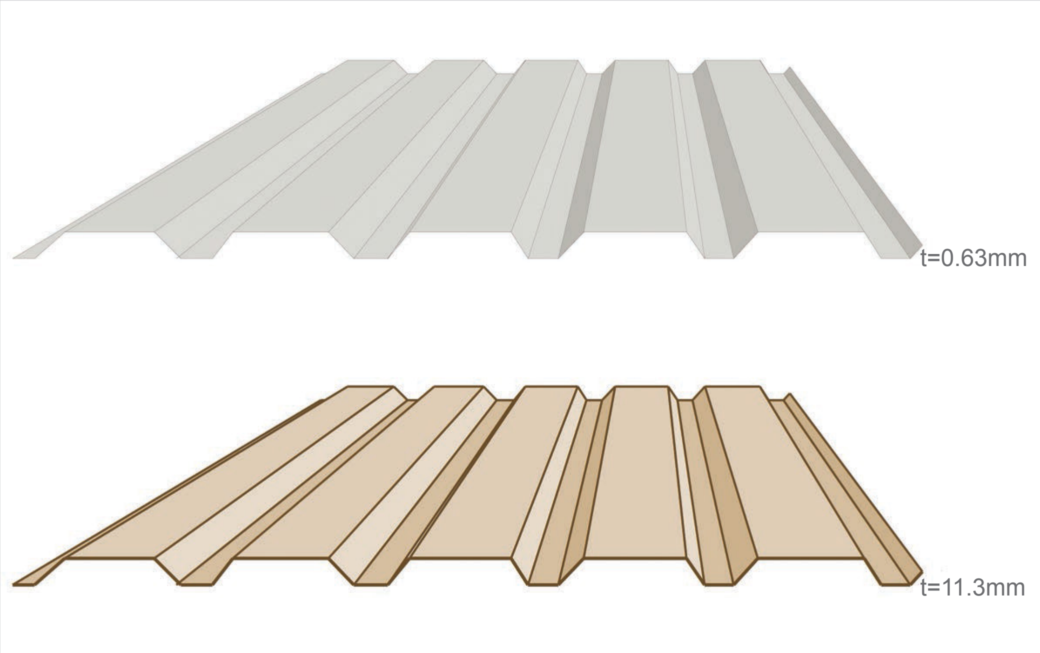
Table 7.9 | Calculation of original and concept element

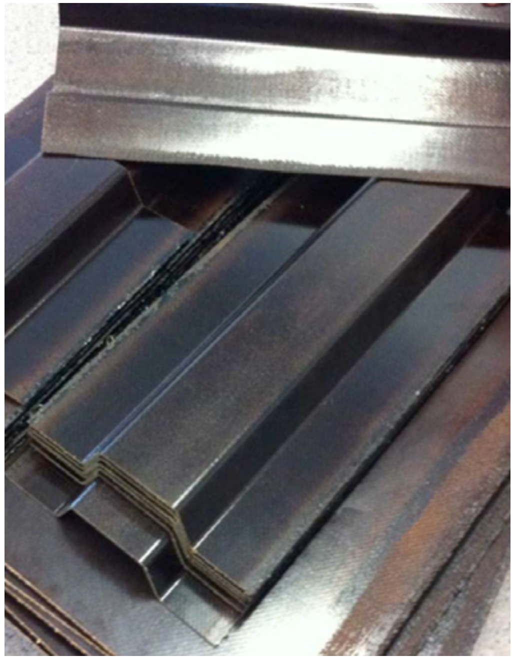
Plate thicknesses vary for this profile between 0.63 mm and 9.48 mm. For this calculation a plate thickness of 0.63 mm is used.
The amount of material per square meter is 8.6E-4 m^3. The weight of this square meter plate is 6.77 kg. The sheets are galvanized on both sides and powder coated on one side. The schadowcosts per square meter are 3.22 euro.
This calculation does not include the secondary structure and connection materials.

Because steel is a durable material the sheets can be reused. They are not really adaptable, other than that the sheets can be cut in smaller dimensions. The recycleability of steel is quite good, however demands much energy. More important is that these sheets are galvanized and coated, and that these coatings will pollute the recycled steel.

Weight	kg/m²	8.69
Rc-value	m²*K/W	0.014
Schadowcosts	€/kg	3.22

Circular scenario | Re-use | Adapt | Recycle | 10





Weight	kg/m²	16.90		
Rc-value	m²*K/W	0.2		
Schadowcosts	€/kg	4.05		
Circular scenario	Re-use	Adapt	Recycle	10

7.5.2 | Trapezoidal biobased composite panel

In biobased composite this plate should be 18 times thicker because of the 18 times lower youngs modulus of biobased composite. For a SAB 35/1035 trapezoidal sheet this means a thickness of 11.3 mm.

Because the sheet is not flat, one square meter contains more than 1 m² material. The amount of material for one m² is 1,37 m width and 1,0 m height and 0.0113 m thickness. This gives a material volume of 0.015 m³. The weight of one square meter of biobased composite trapezoidal sheet is almost twice the amount of that of a comparable steel sheet.

The schadowcosts of biobased composite panels are significantly higher than of coated steel. This is mainly caused by the weight ratio of the steel and biobased composite. Because steel has a far higher youngs modulus it can be applied much thinner. The weight is also almost twice as high as the weight of the steel sheet.

Because the lifetime of biobased composite is estimated to be long enough to be reused, the circular scenario is equal to that of the original element.

Because the shape of the panels is the same as the steel sheets, the adaptability only includes cutting them in smaller dimensions. Biobased composite can be recycled but this process is still being developed, see paragraph 3.3

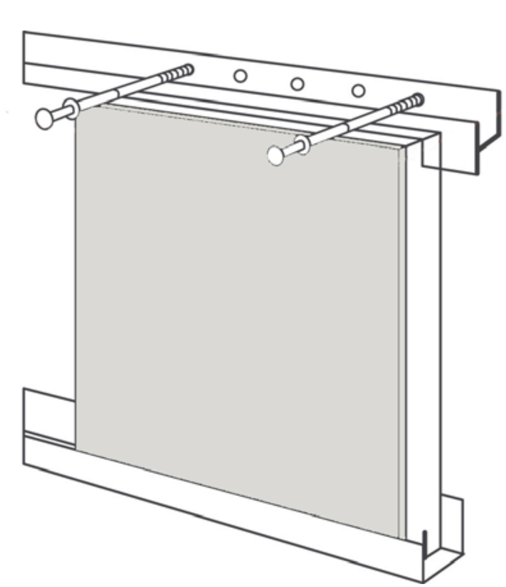
For these panels, biobased composite can be shaped using semi-continuous compression molding techniques like the Arup case study has researched for the external cladding kit, see paragraph 1.4.

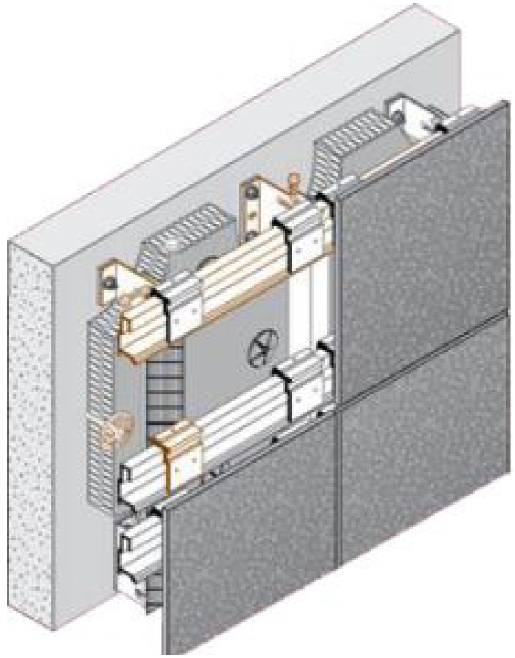
Another possibility is to use pre-preg sheets and fold them using thermoforming and a sheet metal brake or compression molding machine with rolls.

7.33 | Facade out of trapezoidal plates
7.34 | SAB 35/1035
7.35 | Dimensions SAB 35/1035
7.36| Overview properties original
7.37 | Thicknesses
7.38 | Overview properties concept
7.39 | Compressionmolded profiles by the BioBased case studies
7.40 | Process of semi-continuous compression molding

A trapezoidal steel sheet can be produced out of biobased composite, however the thickness is 18 times higher. This means that the weight is almost doubled. Because the lifetime of biobased composite is estimated to be long enough to be reused, the circular scenario is equal to that of the original element.

The insulation value of biobased composite however is much higher than of a steel sheet.





7.6.1 | Panels

The flat plate is commonly applied in for example natural stone facade claddings. There are many different connection methods and connection materials available, on the top right two different options are shown.

To estimate the plate thickness of biobased composite plates different plate materials are compared in the table on the right. This table also shows the weight of different plate materials with the same dimensions.
For the comparison a 30 mm thick granite panel is used.

The comparison concerns only the panels itself and not the connection materials or secondary structure. The Rc-value is calculated, however this layer is ventilated for which the insulation value is not important. The value is just shown to compare the materials with each other.

The weight of the granite plates is quite high, however the panels are made of natural material with a long lifespan and which can be reused and recycled.
The facade can be adapted by means of removing the panels and reuse the secondary structure with other cladding material. Also the panels can be cut to smaller dimensions.

Material	Youngs modulus (Gpa)	Strength (Mpa)	Thickness (mm)	Weight (kg/m3)	Weight panel (m2)
Natural stone (granite)	55	3	30	2700	81
Glass	69	32,2	12	2500	30
Wood	12	70	16	350	5,6
Biobased composite	11,4	273	7	1115	7,805

Weight	kg/m²	81.0
Rc-value	m²*K/W	0.01
Schadowcosts	€/m²	0.81

Circular scenario: Re-use | Adapt | Recycle | 10

Flat sheet						
Natural stone	*Dimensions (m2)*	*Volume (m3)*	*Density (kg/m3)*	*Weight (kg)*	*Shadowcost*	*Shadowcosts*
Granite panels	1*1*0,03	0,03	2700	81	€ 0,01	€ 0,81
Total				**81,00**		**€ 0,81**
Biobased composite	*Dimensions (m2)*	*Volume (m3)*	*Density (kg/m3)*	*Weight (kg)*	*Shadowcost*	*Shadowcosts*
Biobased composite	1*1*0,007	0,007	1115	7,805	€ 0,23	€ 1,80
Total				**7,81**		**€ 1,80**

Table 7.8 | Calculation of original and concept element

Weight	kg/m²	7.81			
Rc-value	m²*K/W	0.125			
Schadowcosts	€/m²	1.80			
Circular scenario	Re-use	Adapt	Recycle	10

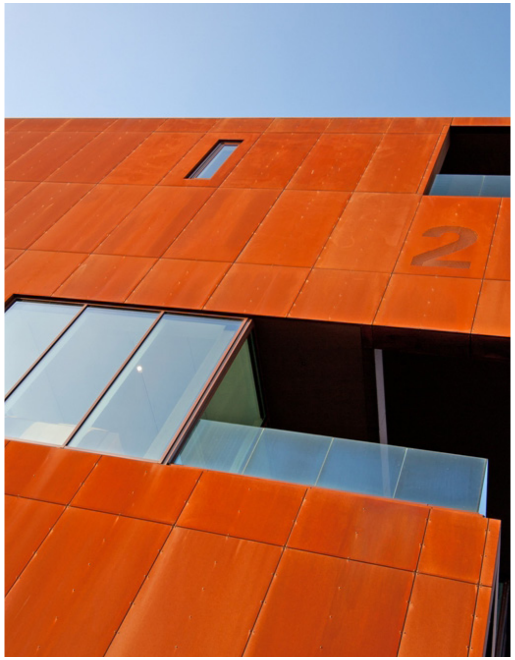
The biobased panels are estimated 7 mm thick. The density of biobased composite is much lower than of granite which reduces the weight significantly. This also means that the secondary structure can be lighter however this is not taken into the calculation.

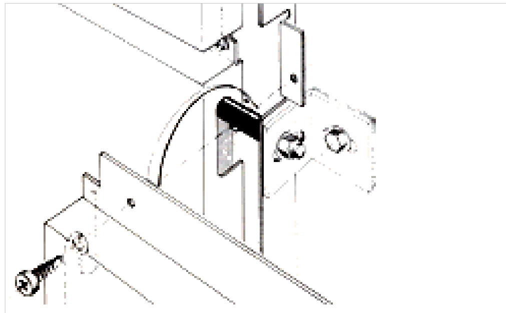
The Rc-value is much higher. As explained before this does not increase the total Rc-value of the construction but is shown as a material property.
The schadowcosts however are much higher, because granite has a quite low environmental impact.

For adaptation, the same applies as for granite panels, the secondary structure can be reused. Also these panels can be cut to smaller dimensions.
Reuse is possible when the element is coated, since the lifetime is estimated long enough.
The panels can be easily detached and are not mixed with other materials, therefore they can be good recycled.
This makes the circular scenario equal for both options.

Granite cladding is very heavy, however the schadowcosts of the material is quite low. The secondary structure needs to be much stronger than in the case of a lightweight biobased composite facade.
Granite has a long lifespan and can be reused. Biobased composite is, coated, estimated t be efficiently reusable also. The secondary structure can be reused for other cladding material. Both materials can be recycled because they are not mixed with other material.

7.7 | CASSETTES





The third cladding variation concerns a cassette facade. The folded cassettes usually consist out of 0,5 mm thick aluminum folded plates which are connected using the method showed on the right.

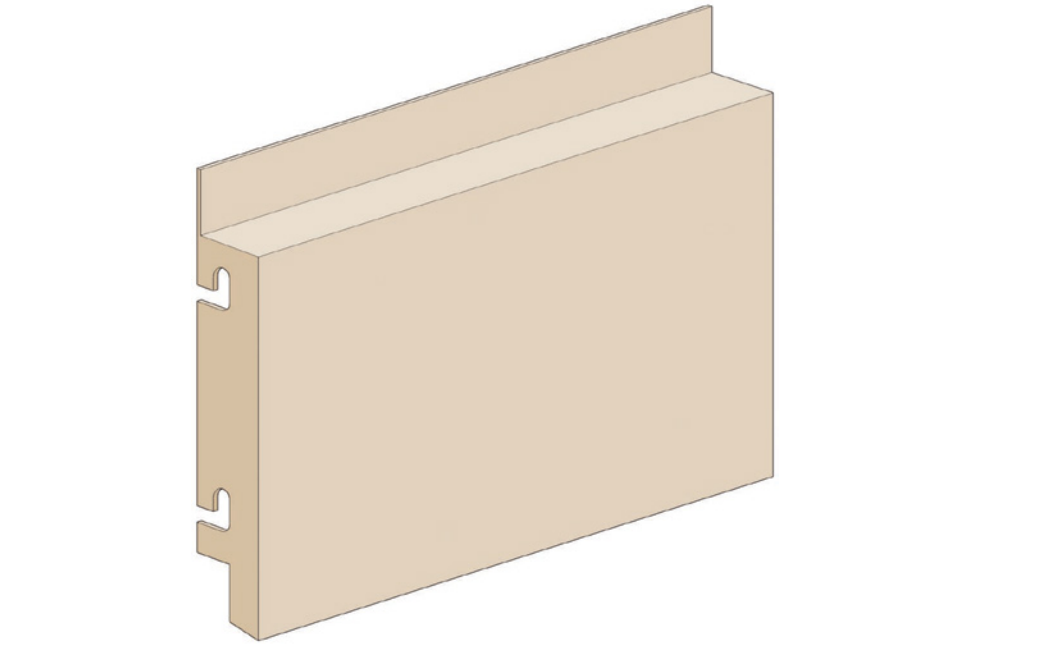
The schadowcosts of the aluminum coated cassettes is calculated using the Nibe test tool and based on the weight of 1m² of these panels. The aluminum is powder-coated on the outside.

The cassettes are in biobased composite six times thicker because of the drop in youngs modulus. Therefore they are more than twice as heavy. Their Rc-value is much higher than that of steel cassettes, however the facade is ventilated and therefore this insulation value does not add to the thermal insualtion of the facade.

In this example the biobased composite is calculated with a coating on both sides since both sides are influenced by the weather.

Aluminum is good recycleable, however this process requires a lot of energy. The secondary structure is in both cases easy reusable with other cladding material but this material has to fit on this specific mounting system. Therefore the adaptability is not an optimal solution.

Weight	kg/m²	1.66		
Rc-value	m²*K/W	0.0000035		
Schadowcosts	€/m²	4.25		
Circular scenario	Re-use	Adapt	Recycle	10



Cassettes						
Aluminum	*Dimensions (m2)*	*Volume (m3)*	*Density (kg/m3)*	*Weight (kg)*	*Shadowcosts/kg*	*Shadowcosts*
One casette						
Aluminum	0,416*0,350*0,0005	0,0000728	2700	0,19656	€ 2,65	€ 0,52
Total				**0,20**		**€ 0,52**
Powdercoated	*0,416*0,350*0,000075*	*0,00001092*	*950*	*0,010374*	*€ 0,97*	*€ 0,01*
Total coating				**0,01**		**€ 0,01**
1 M2 of cassettes (8)				1,66		€ 4,25
Total				**1,66**		**€ 4,25**
Biobased composite	*Dimensions (m2)*	*Volume (m3)*	*Density (kg/m3)*	*Weight (kg)*	*Shadowcosts/kg*	*Shadowcosts*
One casette						
Biobased composite	0,416*0,350*0,003	0,000437	1115	0,487255	€ 0,23	€ 0,11
Total				**0,49**		**€ 0,11**
Spraypaint	2*(0,416*0,350)			0,036	€ 1,20	€ 0,04
Total coating				**0,04**		**€ 0,04**
1 M2 of cassettes (8)				4,19		€ 1,24
Total				**4,19**		**€ 1,24**

Table 7.11 | Calculation of original and concept element

Weight	kg/m²	4.19
Rc-value	m²*K/W	0.75
Schadowcosts	€/m²	1.24
Circular scenario	Re-use, Adapt, Recycle	10

The thickness of the biobased composite cassettes is six times higher than that of the aluminum cassettes. Therefore the tickness is 3,0 mm. The schadowcosts of the biobased composite cassettes are more than ten times lower. However the weight is about 2,5 times higher than that of the aluminum cladding.

The panels can be folded out of heated prepregs using thermoforming.
This makes different dimensioning much easier than in case molds need to be used. Another option is to apply ribs in the cassette, such as in the case of the glazed spandrel, however this cannot be produced using thermoforming and prepregs or SMC but need a compression method. All molding techniques are more expensive and have a lower production rate than techniques using a prepreg. Therefore in this element extra ribs are left out of the design to make an efficient production process possible.

Another aspect in the design needing extra attention is the design of horizontal surfaces. It is better to prevent water from staying on a surface too long considering the possible degradation of the material. Therefore the surfaces should either be placed at an angle or drainage holes should be provided.

Because the cladding in biobased composite is 2.5 times more heavy, the secondary structure presumably needs to be stronger which usually means it contains more material. The shadowcosts are almost 3,5 times lower than those of the aluminum cassettes.

The biobased composite cassettes can be reused when they are coated.
Adaptation of the cladding is possible while reusing the secondary structure with a new material. The cassettes themselves are not adaptable. Both cassettes can be recycled since the materials is not mixed with other materials or glued to other materials.

7.48 | Aluminum casette facade
7.49 | Corten steel cassettes
7.50 | Close-up aluminum casette construction
7.51 | Connection method aluminum casette
7.52 | Concept picture biobased composite cassette
7.53 | Overview of properties original
7.54 | Overview of properties concept

Cassettes can be produced from biobased composite. The weight is much higher, however the schadowcosts decrease more than 3,5 times. Presumably the secondary structure needs to be stronger which means that it requires more material.

The panels can be folded using prepregs and thermoforming.

7.8.1 | The conceptual possibilities of biobased composite

Regarding the researched building products, some statements can be made about the use of biobased composite.

1. Curving
Flat panels need more thickness to accomplish the same structural integrity, therefore the material is not pre-eminently useful to produce flat elements. The great advantage of biobased composite, such as of all composites, is it`s form freedom. The material becomes stronger when (double) curved.

2. Ribbed elements
If flat elements are made, it is efficient to provide a 3-dimensional element with ribs, as shown in the picture below. This does decrease the necessary thickness significantly, see paragraph 6.3.
When biobased composite is applied with a high thickness, the material does not compete with other materials in terms of weight and schadowcosts.

3. Reduced dimensions
When flat sheets are produced, another method to get around high thicknesses and high weight is to reduce the dimensions. However, usually this means that the secondary structure is more heavy.

4. Hollow framework
The study with the timber frame structure showed that the material can be used as a framework. This does only apply if the designed connections allow a good load transfer.
An element-sized structural part turns out to be too heavy. Corrugated sheets are both as a cladding or a structural panel too heavy to enhance an improvement regarding the current products.

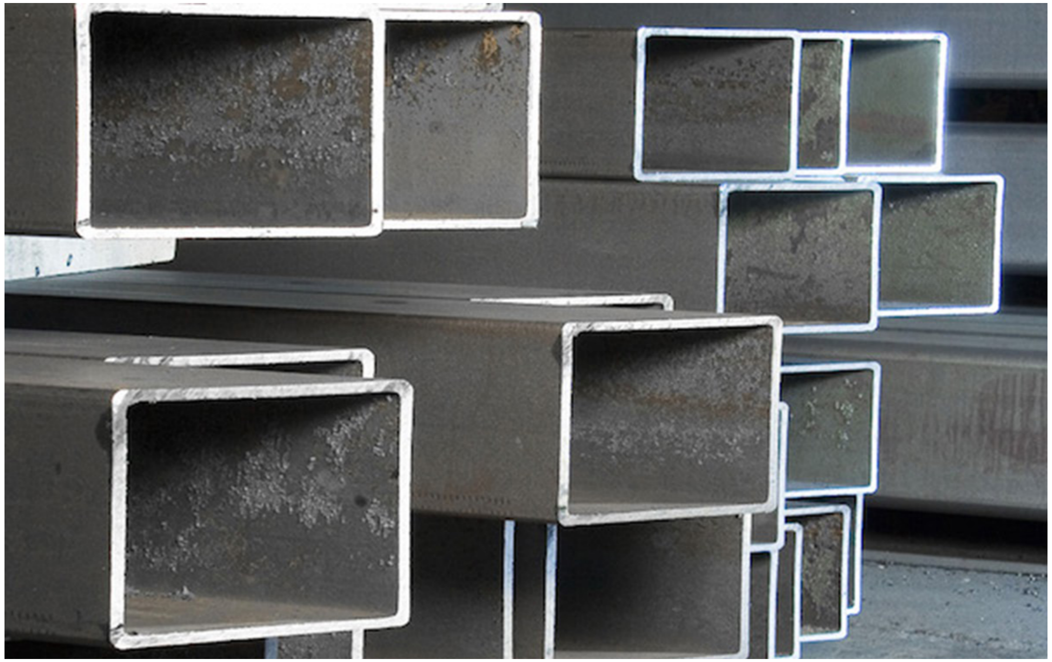
5. Dismountable
For circularity, the aspect recycling regards mainly the ability to separate the materials. The circular scenario increases significantly when the product is dismountable, because both the adaptability as the recycleability increase in most situations.
For materials which are glued together or otherwise inseparable this aspect has a negative (red) score. Biobased composite can be vacuum injected easily, but when this is done with another material as a core materia (such as in the case of the sandwich element) the construction cannot easily be separated. When circularity is an important aspect, sandwich panels are not the best option.

7.8.1.1 | Restrictions

1. Weight
The weight of biobased composite, caused by the low youngs modulus and the therefore high thickness restricts the application of biobased composite to smaller objects or smart shaped elements.

2. Shadowcosts
Together with the high weight of biobased elements, the shadowcost cause biobased composite it`s negative impressions. The shadowcosts can however be improved when the material is further developed.

3. Weathering influences
Biobased composite requires for external use a coating to prevent from degradation due to weather influences. This does increase the shadowcosts.



Product	Original					Biobased composite concept					
	Weight (kg/m2)	*Rc value (m2*K/W)*	*Schadowcosts (€/m2)*	*Weight/Rc value*	*Circular scenario*		*Weight (kg/m2)*	*Rc value (m2*K/W)*	*Schadowcosts (€/m2)*	*Weight/Rc value*	*Circular scenario*
Sandwich element	12,15	4,53	€ 3,52	2,68	10		25,24	4,5	€ 10,12	5,61	10
Timber frame construction	36,63	3,5	€ 2,38	10,47	12	*option one*	23,21	3,5	€ 5,34	6,63	12
						option two	43,76	3,5	€ 10,07	12,50	10
Glazed spandrel	22,22	4,52	€ 0,75	4,92	12		10,53	4,55	€ 2,42	2,31	12
Trapezoidal steel sheet	8,69	0,014	€ 3,22	620,71	10		16,9	0,2	€ 4,05	84,50	10
Flat plate	81,00	0,01	€ 0,81	8100,00	10		7,81	0,125	€ 1,80	62,48	10
Casette	1,66	0,0000035	€ 4,25	474285,71	10		4,19	0,75	€ 1,24	5,59	10

Product	Weight (* original)	Shadowcosts (* original)
Sandwich element	+2	+2,8
Timber frame structure	**-1,6**	+2,25
Glazed spandrel	**-2,1**	+3,2
Trapezoidal panel	+1,94	+1,25
Flat plate	**-10,37**	+2,22
Cassette	+2,52	**-3,43**

The first table above sums up the calculated properties of both the original products and the biobased composite concepts.
The circular scenarios are added, showing the calculated values of the circular scenarios (see paragraph 6.1). The higher the number, the better the circular scenario.

Besides the previous calculated values, the products and concepts are also weighted for their Rc-value-weight scenario. For this result, the weight of one square meter of this facade is divided by its Rc-value. The higher this number is, the more lightweight and insulating an element is.

7.55 | Hollow frame elements (in this case of steel)
7.56 | Reinforcement through ribs
Table 7.12 | Summarized results of the product comparison
Table 7.13 | Increase and decrease in weight and shadowcosts of the original products and the biobased composite concepts

7.8.2 | Facade systems

The upper part of the table shows the results for facade systems. The glazed spandrels are not a system itself but an infill element in a curtain wall construction. Therefore they are placed between the facade systems and the claddings.

Looking at the table, option one of the timber frame structure has the lowest schadowcosts and the best circular scenario. The weight is also the lowest of the three concepts, but the weight-Rc-value ratio is a little higher of that of the sandwich element. For a very fast producible construction with a high insulation-weight ratio for which circularity is not the most important aspect, the sandwhich element would be a better option.

The glazed spandrel is a concept for a curtain wall system which contains glazed spandrels or shadowboxes anyway. The amount of improvement the concept accomplishes depends on the amount of spandrels in the construction.

7.8.3 | Facade claddings

For the claddings, the cassettes have the lowest shadowcosts, and also the lowest weight-insulation value ratio. However, since these constructions are usually ventilated the Rc-value does not add to the insulation value of the wall.

Presumably, using cassettes the secondary structure can be lighter, since the elements can be larger while retaining the same flexural strength due to their folded sides. For flat panels, considering their bending stiffness and corresponding thickness and weight, the plate dimensions are limited. To provide a secondary structure for plates with a smaller span width, there is more material needed than when the mutual distance in the framework is larger. Considering the higher weight of the panels the secondary structure also needs to be stronger and thus more material is needed.

The increase in weight is due to the fact that biobased composite has a quite low youngs modulus and therefore needs to be applied much thicker than steel or aluminum, while the density is not that much lower.

The shadowcosts are only reduced for the cassettes. This is specifically due to the fact that the shadowcosts for aluminum are so much higher that the much more beneficial weight-bending stiffness ratio of aluminum cannot overcome these high shadowcosts.

In general, the table shows that the biobased composite concepts have the same circular scenario as the original elements.

7.8.4 | Conclusion

It is difficult to establish which system or cladding is the "best" because this depends on the specific demands of the situation, and often on the requirements of the customer.

At this point, it can be concluded that the transformations reduce the weight in three cases, namely for the timber frame structure, the glazed spandrel and the flat plates.

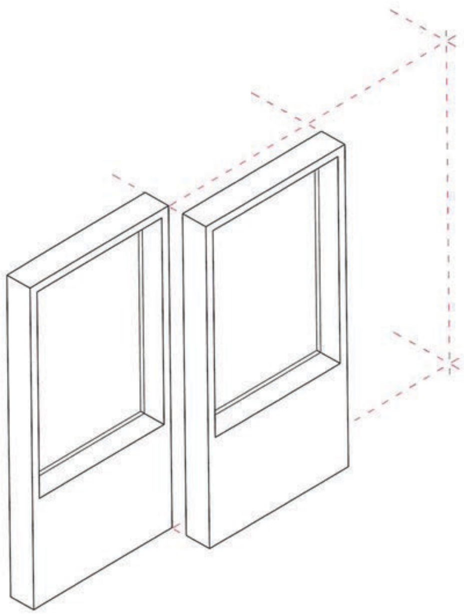
Only for three products the weight of the concept is lower than that of the original product. The shadowcosts are only in one case lower.

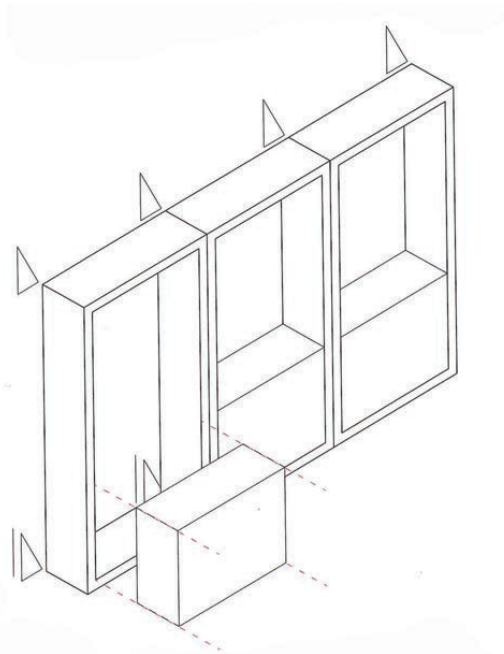
The high weight and shadowcosts are mainly due to the high density and low youngs modulus of biobased composite.

In general, the table shows that the biobased composite concepts have the same circular scenario as the original elements.

In this paragraph the different facade typologies will be discussed accompanied by schematic pictures. The information as well as the pictures in this part are obtained from “Gevels” (Knaack, Klein, Bilow & Auer, 2011).

In the next chapter, the different facade typologies are further explored as case study and linked to a fitting solution in biobased composite. The case study typologies are based on four common used facades for office buildings in the Netherlands. The projects are provided by DGMR, therefore details of the projects could be studied. In these case studies, the framework facade is interpreted as a timber frame structure and a fourth common used facade is added, the parapet facade.





7.9.1 | Element facade

Other than built in situ or framework facade construction, element facades can be prefabricated in one piece and assembled on site with little manpower.

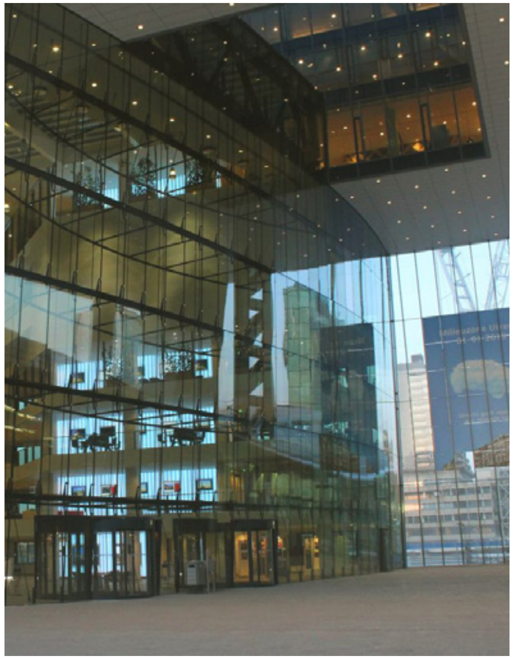
Depending on the type of structure a facade can be prefabricated in different parts and then be combined together on site, or the entire system wall can be prefabricated elsewhere, and be installed at location as one whole element.

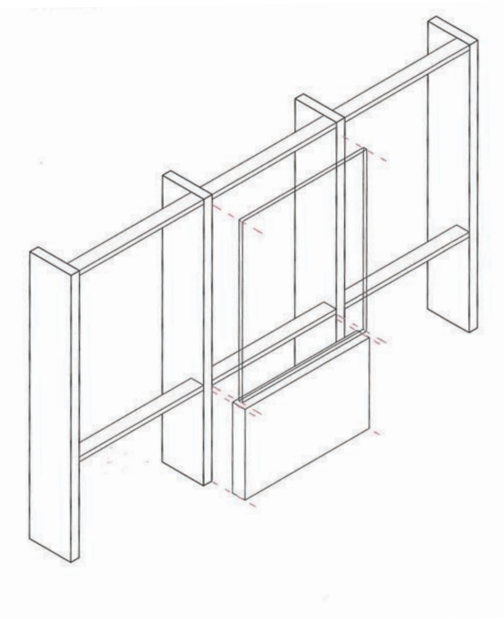
Despite advantages such as guaranteed production quality, short assembly time and low labour investment on the construction site, this approach is still limited to special applications such as high-rise buildings, on behalf of the major logistical investment required.

7.9.2 | Curtain wall

Because the construction is nearly independent of the supporting structure of the building itself, the facade can be divided almost at random, and cladding and glazing can be applied under varying aesthetic or functional requirements.

The vertical and horizontal loads are usually transferred level by level to the ground, but special load-bearing elements can be added in order to make larger spans possible.



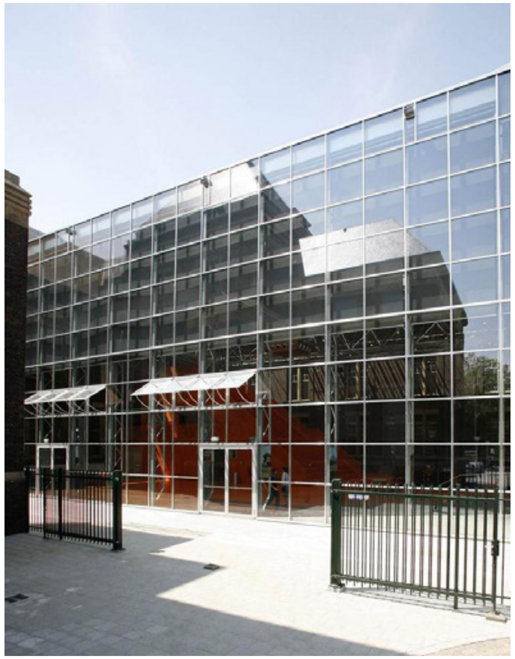


7.9.3 | Framework facade

The design of framework facades comprises floor to ceiling trusses connected with horizontal battens.

The spaces between successive trusses and battens can perform different functions, such as giving entry to natural light, providing views or ventilation, or they can be closed with solid panels.

In these standing framework facades the trusses do not only serve to transfer the wind force and the weight of the structure to the ground, but also as a carrier of the cladding and other functions.



7.9.4 | Parapet facade

The structure of a parapet facade consists out of parapets at floor height, in between which windows are placed.

A parapet facade functions as a structural element, namely as a very thick "beam" at floor height. Since this is a part of the load bearing structure of the facade, this parapet cannot be removed.

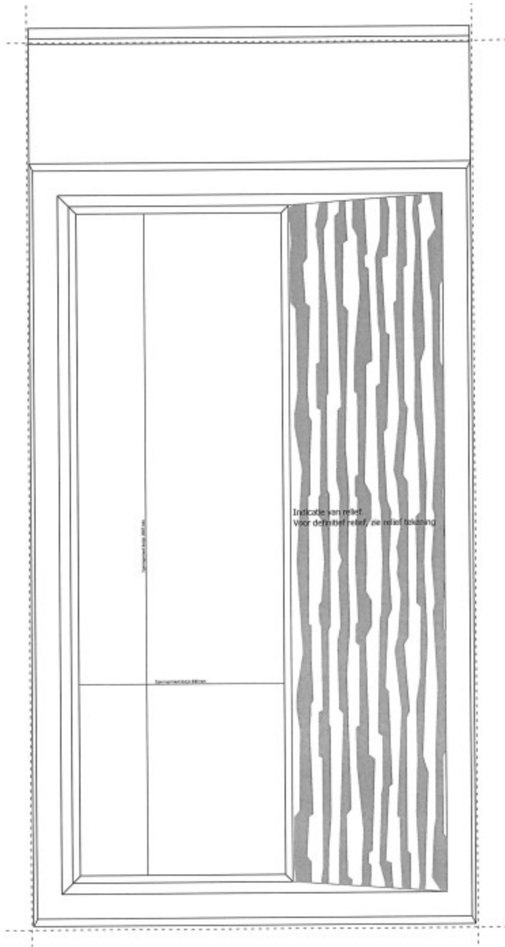
In the next paragraphs, common applied facades for office buildings in the Netherlands are showed. The four typologies explored are an element facade, a curtain wall facade, a prefabricated framework facade and a parapet facade.

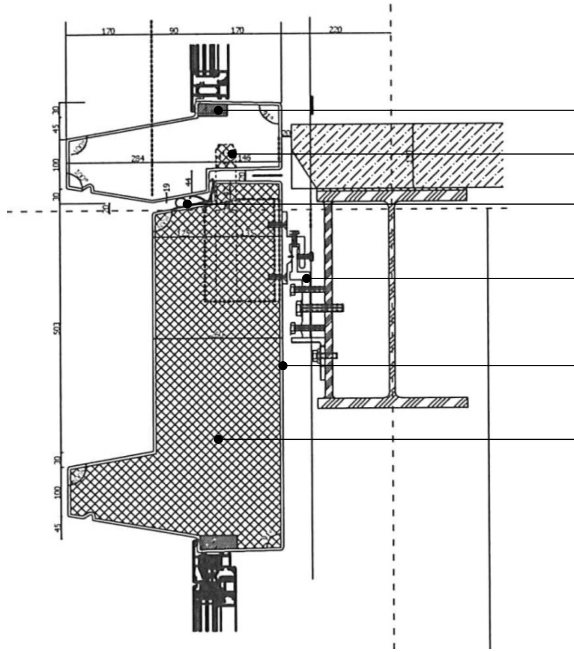
In the case studies the framework is a prefabricated timber frame facade. The framework facade itself is not researched further since this research is more dealing with the structural aspects of biobased composite than the facade technology aspects.
The parapet facade regards a structural parapet facade, because a non-structural parapet facade can be replaced by the slightly adjusted solution for the element facade and the timber frame facade.

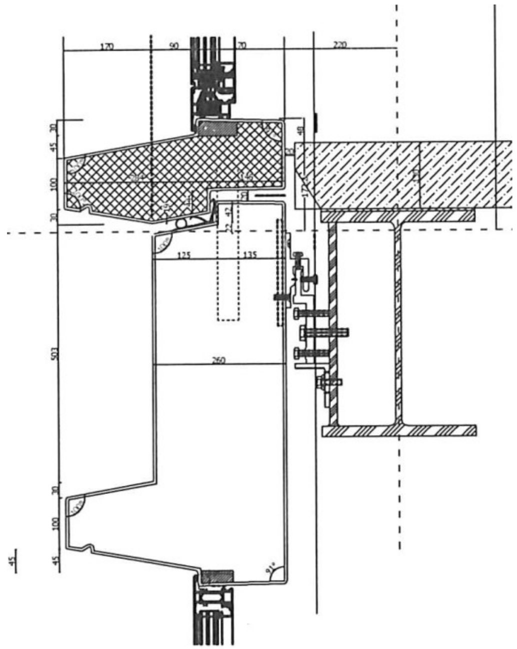
7.57 | Element facade
7.58 | Element facade of "SoZaWe"
7.59 | Curtain wall
7.60 | TU Delft Auditory
7.61 | Municipal office Utrecht
7.63 | Framework facade
7.63 | Faculty of Architecture, TU Delft
7.64 | Parapet facade

Four different facade typologies are showed briefly and further explored in the next chapters.
The typologies are an element facade, a curtain wall and a framework facade. A parapet facade is added since this is a common applied facade in Dutch office buildings.

The further researched facade typologies do not include a framework facade since this research requires a more structural approach. The parapet facade is a structural parapet.







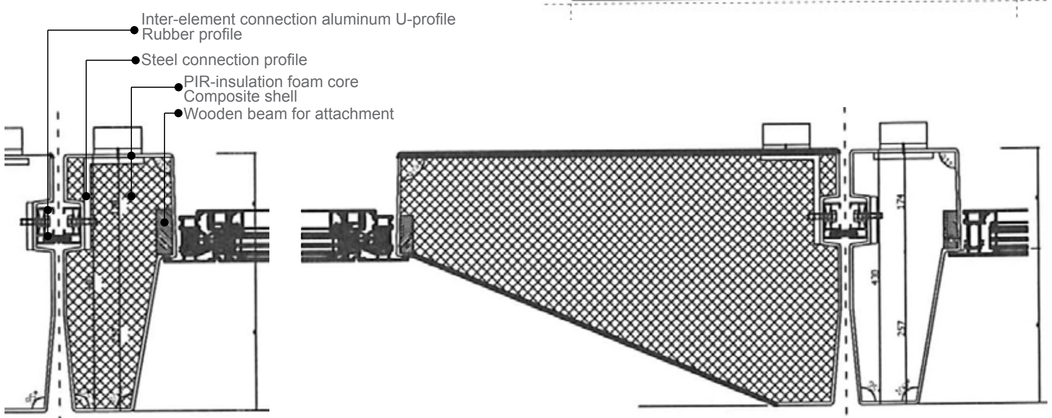
7.10.1 | Element facade

The studied element facade is the facade of SoZaWe, the social insurance bank in Groningen designed by MVSA (Meyer van Schooten Architects). The buildings is completed in 2013.

The facade consists out of composite elements which are prefabricated to be mounted easily at location. The elements have a prefabricated "profile" to mount a window frame on.

The interconnections are made through u-shaped profiles mounted in the elements, which are connected by a rubber profile. The elements are connected to the same construction that carries the floor. This construction is therefore not visible at floor level because a suspended ceiling covers this construction. The bottom part of an element contains an metal strip which slides into the element underneath. In this way they are connected and air and waterproof.

The inside of an element is also made of composite and does not need a finish layer.



Wooden beam for attachment

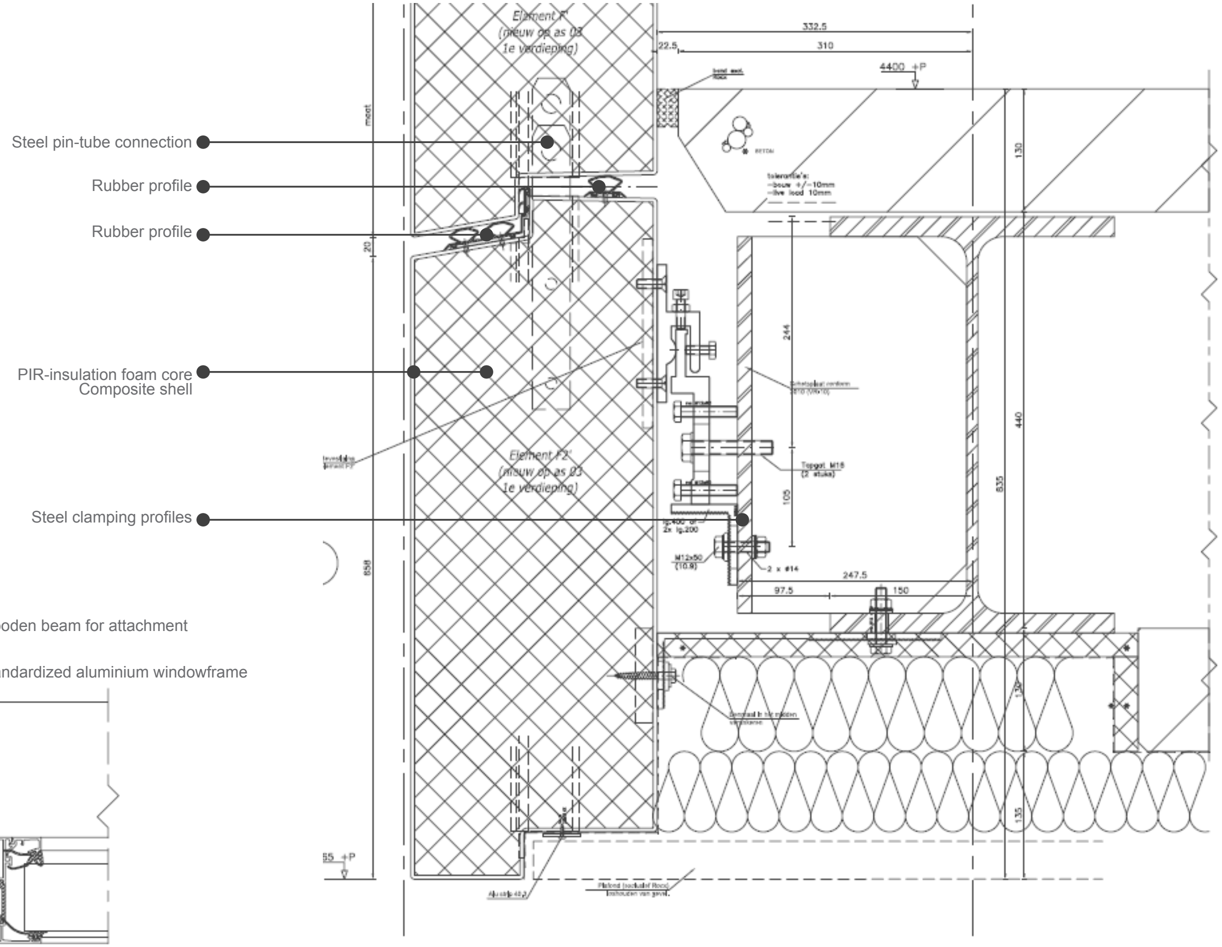
Steel pin-tube connection

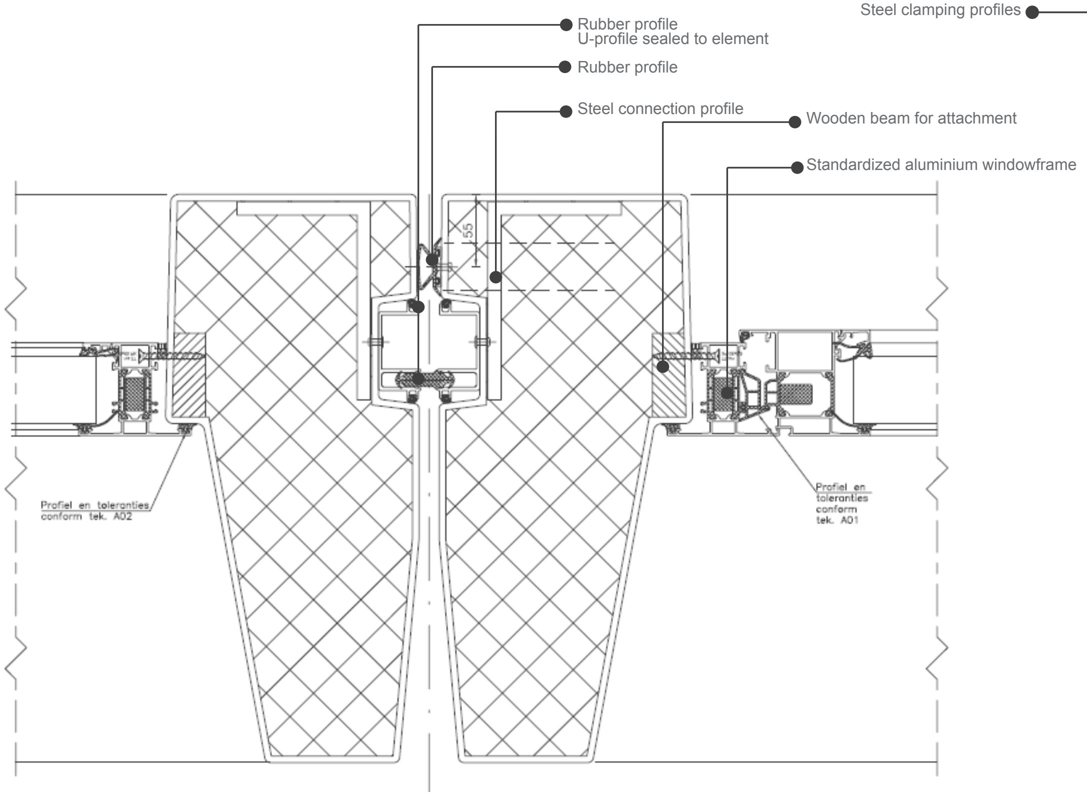
Rubber profile

Steel clamping profiles

Composite shell

PIR-insulation foam core





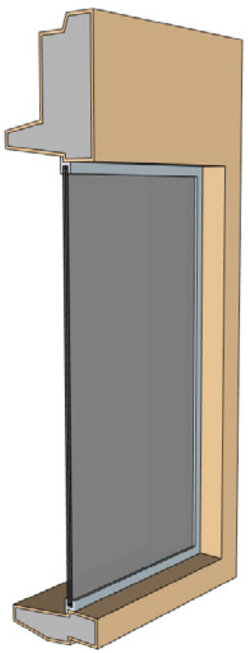
7.65 | SoZaWe building, element facade
7.66 | Front view element
7.67| Horizontal section element
7.68 | Vertical section element
7.69 | Detail vertical connections
7.70 | Detail horizontal connections elements

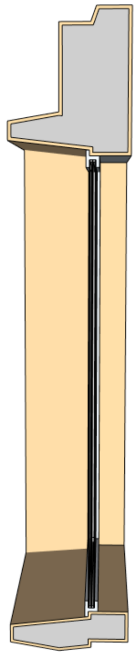
7.10 | ELEMENT FACADE

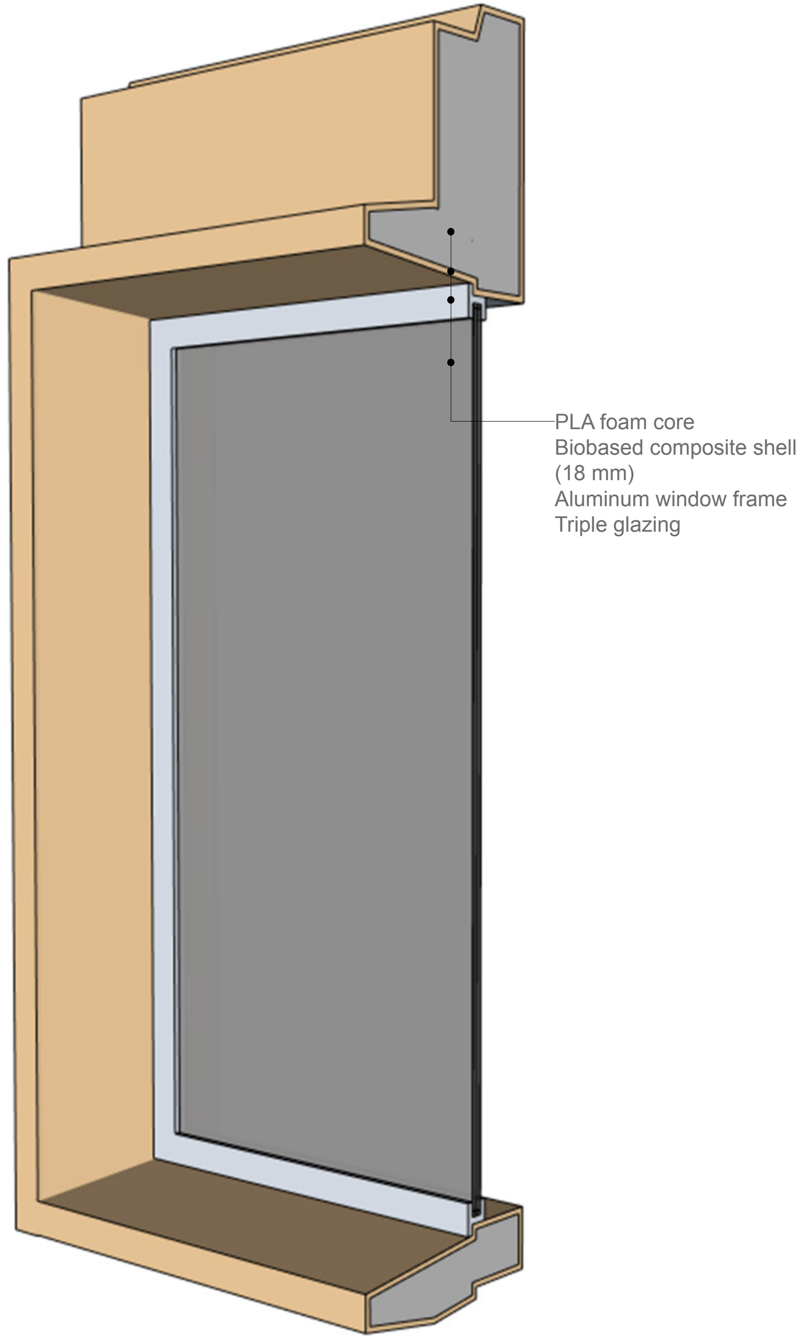
7.10.2 | Possible concept

An element facade can be produced as a sandwich element, as shown in the case study. Another option, which makes the circular scenario much better, is to design it as a timber frame structure. However, since this is shown in paragraph 6.12. This paragraph will focus on the possible design as a sandwich panel.

Table 7.14 | Shadowcosts calculations for the original facade and the conceptual design per sqare meter facade
7.71 | Section of the element, interior side
7.72 | Vertical section
7.73 | Section of the element, interior side
Table 7.15 | Conclusion weight and shadowcosts concept relative to original







Original						Concept					
Material	**Volume (m3)**	**Density (kg/m3)**	**Weight (kg)**	**Shadowcosts (€/kg)**	**Shadowcosts (€)**	**Material**	**Volume (m3)**	**Density (kg/m3)**	**Weight (kg)**	**Shadowcosts (€/kg)**	**Shadowcosts (€)**
PIR foam (as PUR foam)	1,76	50	83.5	€ 0,73	€ 31.73	PLA foam	2,64	50	132	€ 0,80	€ 105,60
Composite (glass fibre reinforced polyaminde)	0,038	2000	76.0	€ 0,76	€ 57.76	Biobased composite	0,23	1115	256.45	€ 0,23	€ 58.98
Total			**159.5**		**€ 89.49**	**Total**			**388.45**		**€ 143.61**
Total per m2			**46.63**		**€ 26.17**	**Total per m2**			**113.58**		**€ 41.99**

7.10.3 | Calculation method

Glass reinforced composite has about the same properties as aluminum (Composites NL, 2017). Therefore the tensile strength and youngs modulus are estimated to be the same as for aluminum. This means that the thickness of the biobased composite layer should be 6 times higher than the original composite layer. The biobased composite is therefore 18 mm thick.

PLA needs to be 1,5 times thicker to reach the same insulation value. Therefore the amount of insulation material in the concept calculation is multiplied by 1,5. This does increase the amount of shell material too, since a larger object needs to be covered.

The windows, wooden frame around the windows and the connection materials are left out of the calculation because they are the same in both options.

The Nibe database only contains the shadowcosts of glass fibre reinforced polyamide, while the usual resins for composites are polyesters. Therefore the shadowcosts of the original composite might differ slightly from the calculated values.

In the same way as in the case of the steel-PIR sandwich panels in paragraph 6.2, a thin layer of cork should be added to prevent the PLA from melting due to the heat produced by the curing reaction of the (epoxy) resin. Unfortunately the shadowcosts of expanded cork are not available, and because the layer is very thin it is neglected.

The coating is left out of the calculation, because, until there are better biobased coatings available for biobased composite, they are similar.

7.10.4 | Results

Weight kg/m²	46.63	113.58	65.37
Schadowcosts €/m²	26.17	41.99	35.83

The table shows that because the materials for a biobased sandwich panel needs to be applied in a higher volume, the shadowcosts are 1.6 times higher and the weight of the element is 2.4 times higher.

Important to know is that the biobased composite variant does not improve the circular scenarios. The element is not better adaptable or recycleable since it has been constructed in the same way as the original facade, which is presumably vacuum infusion around the PIR-foam, or another not-separable mold technique. This means that the composite is very difficult separable from the core.
Because the lifetime of biobased composite is estimated to be shorter than that of polyester composite, the reusability of these elements is poorly or impossible. Therefore the circular scenario of the biobased composite element is lower than that of the original, not-biobased element.

As shown in the drawings of the picture, biobased composite has a brown color. It is therefore very likely that a pigment will be applied in the resin or the coating. This will increase the environmental impact of the element.
The EI value for both sandwich panels were calculated. The result showed on the next page demonstrate that the bending stiffness of the biobased composite element is 2,8 times higher than that of the original element.

This means that the concept element can be produced with a thinner composite shell, which will decrease the weight and shadowcosts. For these calculations see the next page.

If the biobased composite shell is 2.8 times thinner, the weight of the biobased composite reduces by 2.8 times. Therefore the total weight becomes 65.37 kg and the shadowcosts become 35.83 euro. This means that in the actual needed thicknesses, the biobased composite element does show a large improvement over the original element.

7.10.5 | Bending stiffness calculations

The bending stiffness of both the steel-PIR sandwich panel as the Biobased composite-PLA sandwich panel as shown on the right were calculated using the EI-calculation method.

7.10.5.1 | Original element

For the calculation of the I-value, the moment of inertia of the original steel-PIR sandwich panel, the upper table on the right was made.
The E-modulus of the element is:

E GRP	26	Gpa	
E PIR	?		
E PUR	3,30E-04	Gpa	
E Steel	>70 000	E PUR	(Neglected)

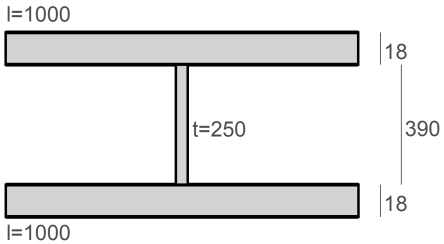
Then the moment of inertia was calculated, resulting in the total bending stiffness, which is Ic(original) * Youngs modulus= 1.89E10 Nmm4.

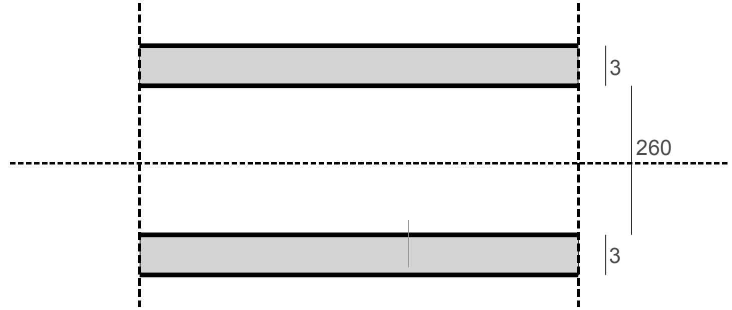
7.10.5.2 | Concept element

For the calculation of the I-value, the moment of inertia of the biobased composite-PLA sandwich concept element, the lower table on the right was made.
The calculation of the moment of inertia is:

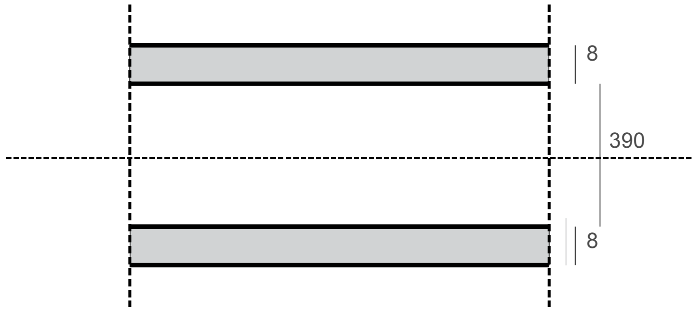
E BC	11,4	Gpa
E PLA	4	Gpa
E BC	>1/4	E PLA

Then the moment of inertia was calculated, resulting in the total bending stiffness, which is Ic(concept) * Youngs modulus= 2.38E10 Nmm4.





Ix1	=	1/12*b*h^3	=	1/12*1*(0,003)^3	=	2,25E-09
A1d^2	=	3,00E-03	*	(0,2615)^2	=	2,05E-04
A2d^2	=					
Ixt	=	2(2,25E-9)	+	2(2,05E-4)	=	4,10E-04 m4
					=	4,10E+08 mm4



Ix1	= 1/12*b*h^3	=	1/12*1*(0,018)^3	=	4,86E-07
Ix2	= 3,00E-03	*	1/12*0,250*(0,390)^3	=	1,20E-03
Ix3	= Ix1				
A1d^2	= 0,018	*	0,399^2	=	0,0029
A2d^2	= 0,097	*	0	=	0,00E+00
A3d^2	= A1d^2				

Ic= Ix1+A1d^2+Ix2+A2d^2+ Ix3+A2d^2 = 4,86E-7+0,0029+1,20E-3+0+4,86E-7+0,0029 = 7,00E-03
7,00E+09

7.10.6 | Conclusion

The shadowcosts of biobased composite are already 1.1 times higher than glass-fibre reinforced polyester composite, however due to increase in amount of material while adapting the original element to be more natural based element, the weight is 1.4 times higher than that of the original element, and the shadowcosts are 1.3 times higher.

The circular scenario is equal to that of the original element, however this scenario is not that good, since adaptation and recycleability are very difficult.

7.10.7 | Facade quality

7.10.7.1 | Acoustics

The sandwich panel could offer very good sound insulation, but the exact width of the PLA core and thickness of the shell should be calculated.

7.10.7.2 | Fire-safety

The fire-safety of the element depends mainly on the fire spread along the facade, both on the in and outside. This should be tested and when necessary additional fire-proofing powder should be added to the resin and/or a intumesent coating can be added, when this is visually acceptable.

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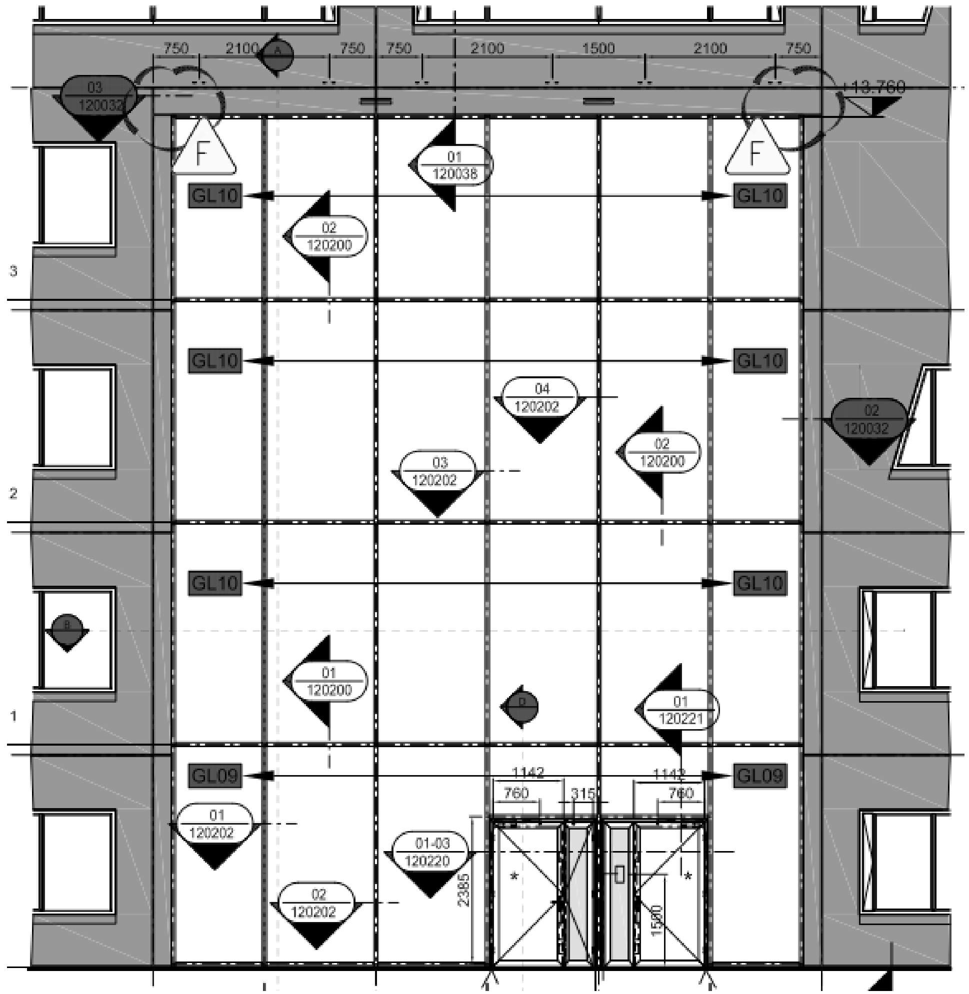
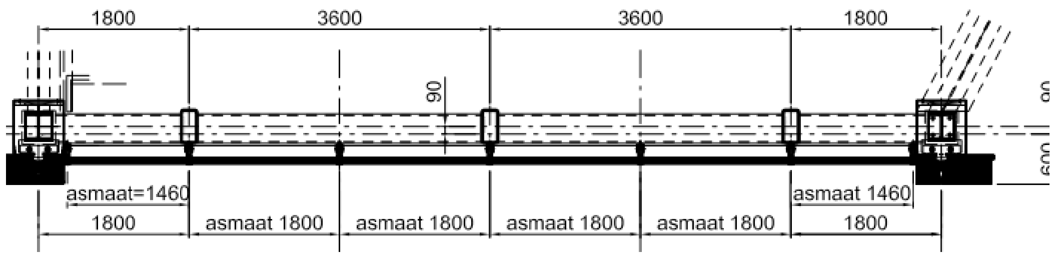
7.10.7.3 | Water tightness

The elements should be coated on the outside with a waterproofing and UV-blocking coating. If needed structural maintenance should be carried out on the coating.

Table 7.16 | E-moduli original element
Table 7.17 | E-moduli concept element
7.74 | Schematic image thickness shell original element and core original element and calculations
7.75 | Schematic image thickness shell and core conceptual element and calculations

A sandwich panel can be made from biobased composite and with a natural based core material. The weight is 2.4 times higher and the shadowcosts are 1.6 times higher. However when the actual bending stiffness is taken into account the is reduced to 1.4 times higher weight and 1.4 times higher shadowcosts.
The circular scenario is equal to that of the original element, however this scenario is not that good, since adaptation and recycleability are very difficult.



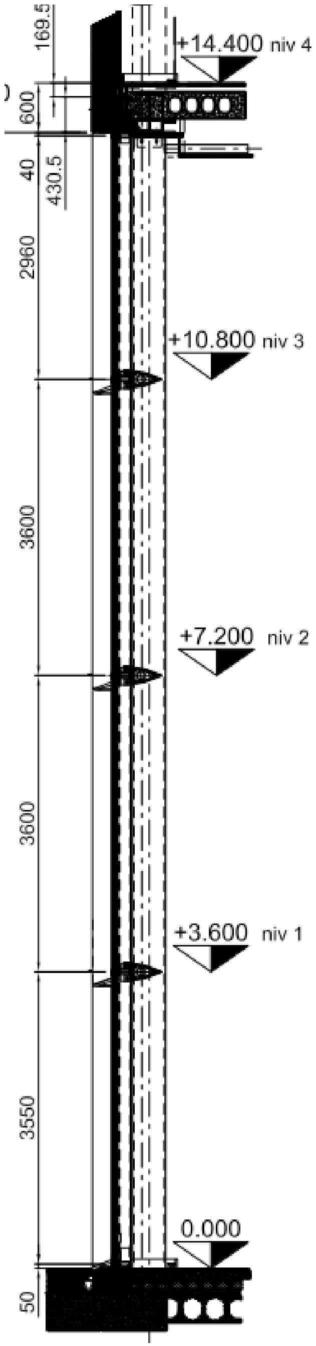


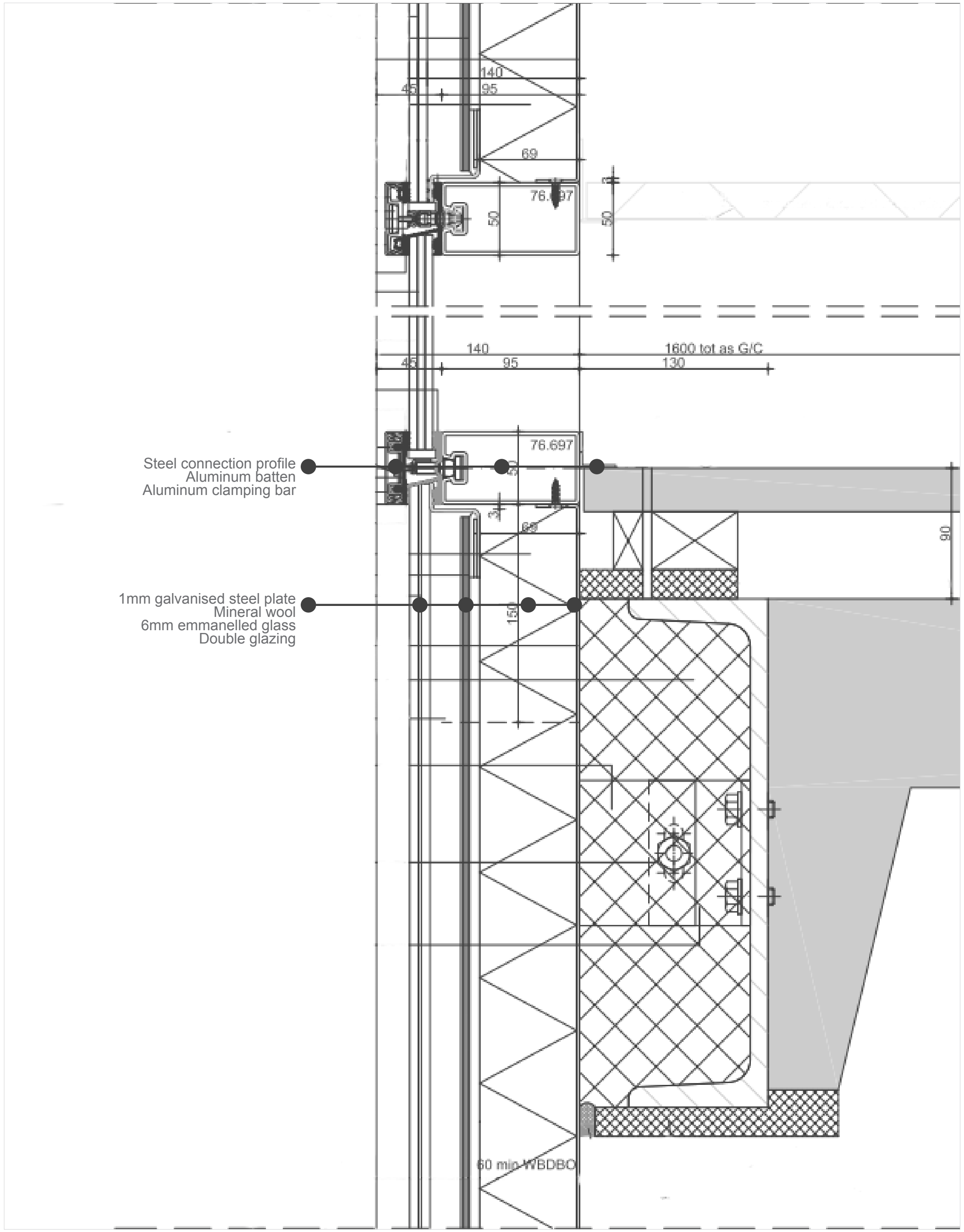
7.11.1 | Curtain wall

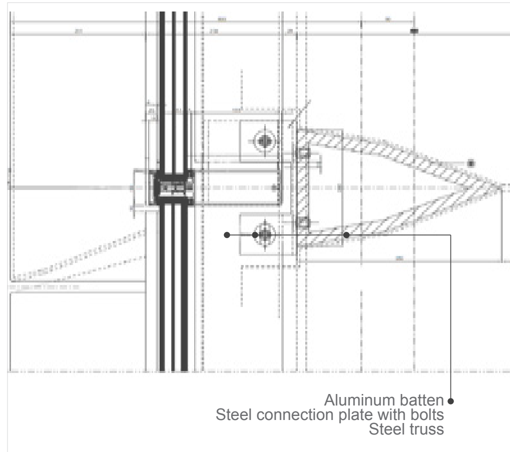
The details of this curtain wall are of the City hall of Utrecht, designed by Kraaijevanger architects.

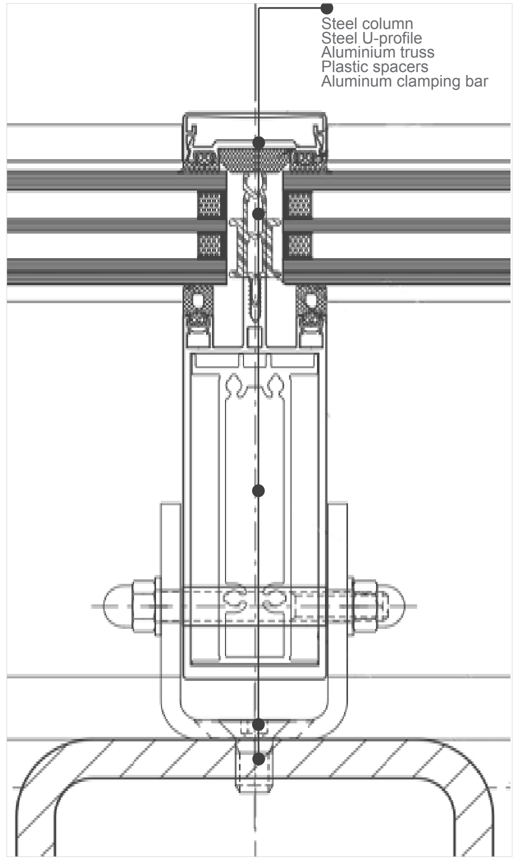
In between of the composite element facade, some areas of full-glass are added to create transparency in the building. These glass-surfaces are created using a curtain wall-system of which the details are shown on the right.

7.76 | Municipal office Utrecht
7.77 | Facade view
7.78 | Horizontal section
7.79 | Vertical section
7.80 | Detail connection to floor, vertical
7.81 | Detail secondary structure
7.82 | Detail horizontal connection to secondary structure

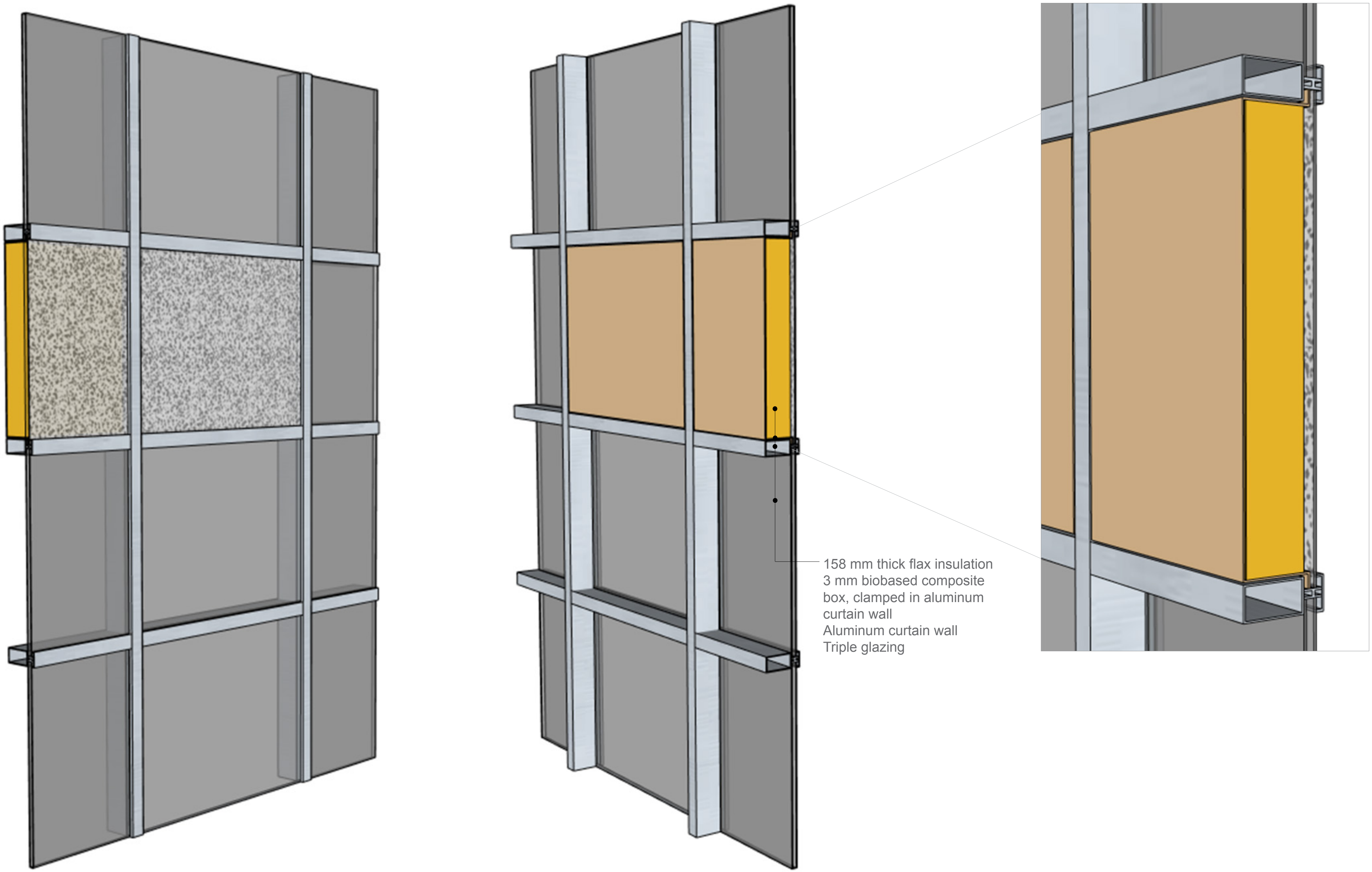

+14.400 niv 4
+10.800 niv 3
+7.200 niv 2
+3.600 niv 1
0.000
169.5
600
40
430.5
2960
3600
3600
3550
50


Steel connection profile
Aluminum batten
Aluminum clamping bar
1mm galvanised steel plate
Mineral wool
6mm emmanelled glass
Double glazing
140
45
95
69
76.697
50
1600 tot as G/C
130
90
150
60 min WBDBO


Aluminum batten
Steel connection plate with bolts
Steel truss


Steel column
Steel U-profile
Aluminium truss
Plastic spacers
Aluminum clamping bar

7.10 | CURTAIN WALL



Original					
Material	**Volume (m3)**	**Density (kg/m3)**	**Weight (kg)**	**Shadowcosts (€/kg)**	**Shadowcosts (€)**
Curtain wall (Al 97% secondary)	1 m2		4,5		€ 3,55
Total			**4,50**		**€ 3,55**
Glazed spandrel					
Steel sheet (2x)	0,002	7870	15,74	€ 0,17	€ 2,68
Rockwool	0,089	150	13,35	€ 0,10	€ 1,34
Total			**29,09**		**€ 4,01**
Galvanising (zinc)	0,00000028	7140	0,0019992	€ 1,09	€ 0,00
Total coating			**0,00**		**€ 0,00**
Total			**29,09**		**€ 4,01**

Concept					
Material	**Volume (m3)**	**Density (kg/m3)**	**Weight (kg)**	**Shadowcosts (€/kg)**	**Shadowcosts (€)**
Curtain wall (Al 97% secondary)	1 m2		4,5		€ 3,55
Total per m2			**4,50**		**€ 3,55**
Glazed spandrel					
Biobase composite box	0,0059	1115	6,5785	€ 0,23	€ 1,51
Flax insulation	0,158	30	4,74	€ 0,23	€ 1,09
Total per m2			**11,32**		**€ 2,60**
Total			**11,32**		**€ 2,60**

7.11.2 | Calculation method

In the table above first the shadowcosts of one square meter curtain wall are showed. These are the same for both options.

The glazed spandrels differ on the material used for the box and the insulation material. Therefore only these two aspects are compared. The glass, being the third element of the glazed spandrel, is equal in weight and shadowcosts for both options.

7.11.3 | Results

Weight kg/m²	29.09	11.32
Schadowcosts €/m²	4.01	2.60

The table above shows that the weight of a biobased composite glazed spandrel with two ribs, as calculated in appendix B, is more than 2,5 times lighter than the original steel design. The shadowcost are in this case more than 1,5 times lower.

7.11.4 | Conclusion

In a facade where either shadowboxes or glazed spandrels are applied, improvements can be made replacing them with this biobased composite concept. The weight will decrease significantly, which increases the ease of mounting and allow the curtain wall to be less mechanically resistant and therefore less heavy.

Since opaque glass prevents from looking in, the appearance of the facade doesn`t change.

7.11.5 | Facade quality

7.11.5.1 | Acoustics

The acoustical properties are mainly provided by the curtain wall itself, while the glazed spandrels are only a small part of the complete facade. The glass panel provides the first sound barrier but since this is very thin, additional sound insulation in the glazed spandrels might be necessary. However since they are usually placed before floors or other non-accommodated spaces the impact might be minimal.

7.11.5.2 | Fire-safety

The material itself cannot be easy flammable or cause much smoke. Since the elements are usually placed in horizontal lines, fire spread can theoretically not take place vertically, however in horizontal direction it is possible. Therefore the fire-spread and inflammability should be tested and precautions in the form of a coating or powder might be necessary.

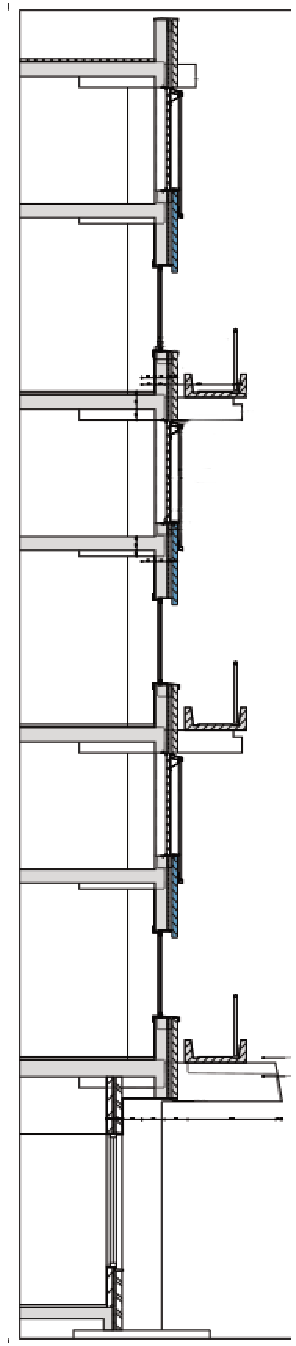
7.11.5.3 | Water tightness

The elements are placed on the inside and are shielded from water and direct sun radiation by the frosted glass panel. Therefore a coating does not need to be applied.

Since the aluminum curtain walls know a long development and both the thermal as safety aspects are optimized, many components cannot just be replaced by another material with different properties.

A shadowbox or glazed spandrel can be replaced by a biobased composite element. This decreases the shadowcosts by 1,5 times and sequential the weight significantly.
.

Table 7.18 | Shadowcosts calculations for the original facade and the conceptual design per sqare meter
7.83 | Section of the element, exterior side
7.84 | Section of the element, interior side
7.85 | Detail of the “box”
Table 7.19 | Conclusion weight and shadowcosts concept, relative to original



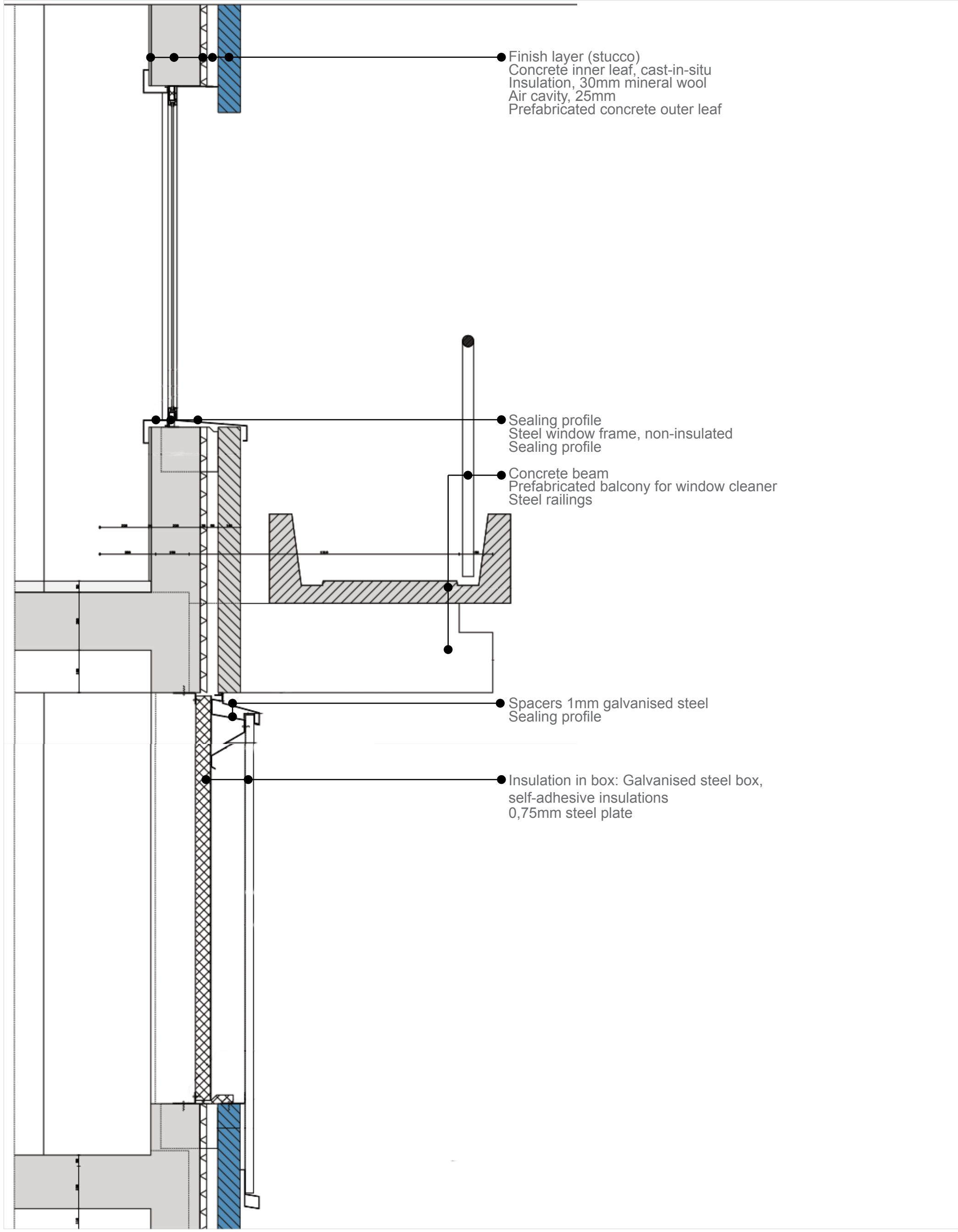
7.12.1 | Case study

The AMC (Amsterdam Medical Centre) used to be the Netherlands larges and most modern hospital at it`s opening in 1983. The building was designed by Dick van Mourik, Marius Duintjer, Istha and Kramer & Van Willegen.

The building consists out of three separate buildings connected by covered streets.

This facade concerns a so called "parapet facade" which means that instead of an element spanning floor to floor, an element is placed at floor level which spans a specific lengths under and above the floor.
In between the gaps windows are placed.

7.86 | AMC Amsterdam
7.87 | Facade view
7.88 | Parapet facade principle
7.88 | Vertical section
7.90 | Details vertical section
Table 7.20 | Possible cladding concepts



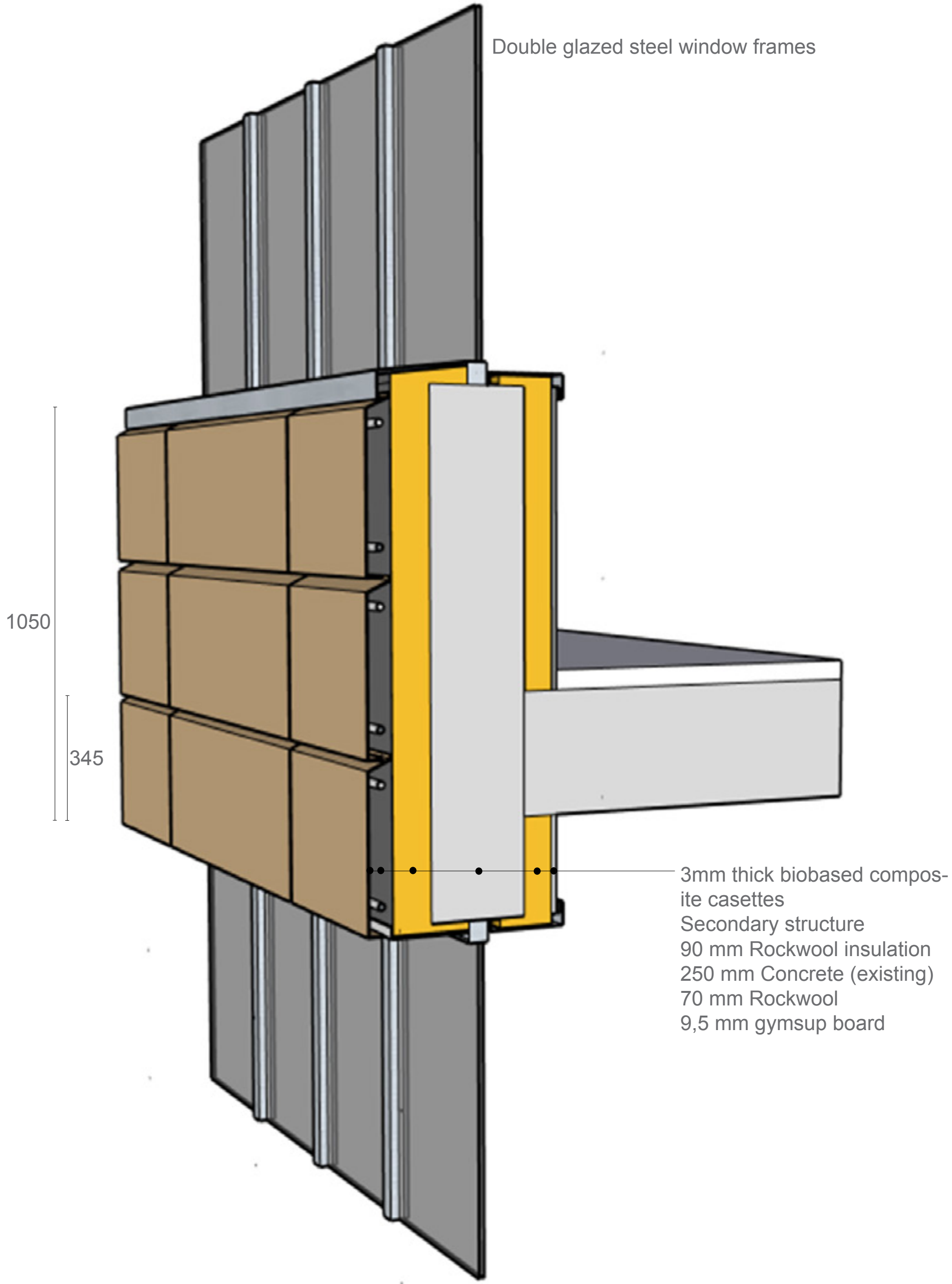
	Weight (kg/m2)	Rc value (m2*K/W)	Schadowcosts (€/m2)	Weight/Rc value	Circular scenario
Trapezoidal panel	16.9	0,2	3.47	84.50	7
Flat plate	7,81	0,125	1,51	62,48	7
Casette	4,19	0,75	0.42	5.59	7

7.12.2 | Possible concept

All possible cladding materials have a combined number for circularity of seven. Regarding this aspect therefore no classification can be made. The schadowcosts and weight however differ significantly.

Because the cladding is attached to a secondary structure, it is best if the cladding is as light as possible since this allows the secondary structure to be lighter. This saves the amount of necessary material for the secondary structure.

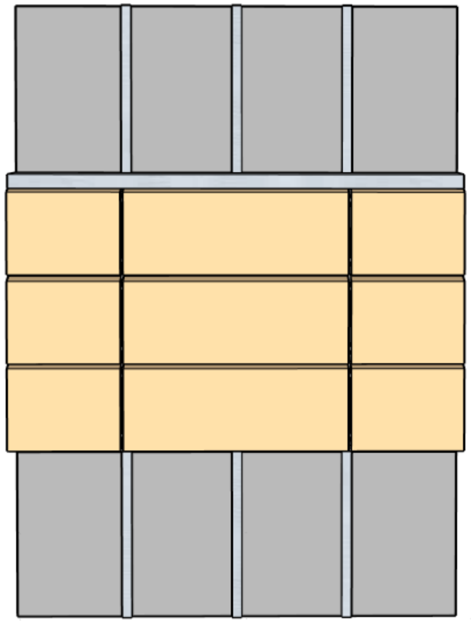
The biobased composite trapezoidal panel is the heaviest and has the highest shadowcosts. The flat panels are half of the weight and shadowcosts of the trapezoidal panels. Both the weight as the shadowcosts of the cassettes are the lowest. Therefore the facade will be designed with cassettes. For the design see the next page.

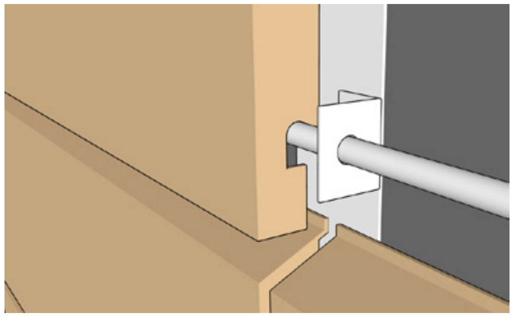


The insulation value of the facade is enlarged to have an Rc-value of at least 4,5 m*K/W. To make the facade more biobased, the insulation material is changed to flax panels with a thickness of 68 and 90 mm, in total 158 mm.

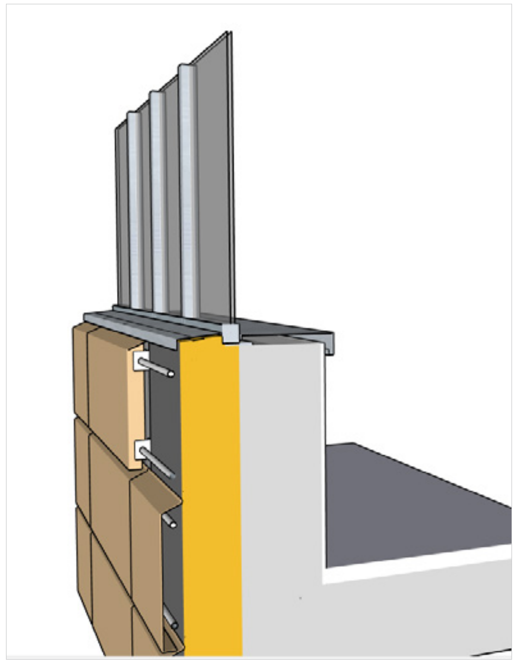
The cassettes are mounted at a glavanzed steel secondary structure. The system is based on an existing mounting system for aluminum cassettes.

To improve the insulation value enough, insulation is placed on the inside and outside and around the window frames. The window frames are replaced with double glazed windows, but this is not taken into the calculation since there are no reliable calculation values available.





The facade as shown on the left would regard a renovation for which the windows do not need to be replaced. However, the thermal insulation in this concept is not optimal, since the facade forms a cold bridge around the window.
The concept on the right requires a more extensive renovation in which the windows are moved to be in line with the insulation.



Material	Volume (m3)	Density (kg/m3)	Weight (kg)	Shadowcosts (€/kg)	shadowcosts (€)	Material	Volume (m3)	Density (kg/m3)	Weight (kg)	Shadowcosts (€/kg)	shadowcosts (€)
Rockwool insulation	0,03	150	4,5	€ 0,10	€ 0,45	Flax panel insulation (in and outside)	0,158	30	4,74	€ 0,23	€ 1,09
Concrete cladding	0,1	2000	200	€ 0,01	€ 2,00	Biobased composite cassettes (+coating)			4,19		€ 1,24
Connection materials						Connection materials				€ 0,17	€ 0,00
Steel	1,39E-04	7870	1,1	€ 0,17	€ 0,19	*Steel*	2,66E-04	7870	2,1	€ 0,17	€ 0,36
Glavanising (Zinc)	5,59E-07	7135	0,0039	€ 1,09	€ 0,00	*Glavanising (Zinc)*	1,07E-06	7135	7,63E-03	€ 1,09	€ 0,01
Gympsum board			7,62	€ 0,03	€ 0,23	Gympsum board			7,62	€ 0,03	€ 0,03
Total			**213,22**		**€ 2,87**	**Total**			**18.65**		**€ 2,73**

Table 6.21 | Shadowcosts calculations for the original facade and the conceptual design per sqare meter facade

7.12.3 | Calculation method

For the comparison, there are some materials left out of the calculation. At first the concrete is left out, since the amount of concrete is exactly the same in both variations and the concrete is an existing element.

The steel window frames (single and double glazed) are left out because there is no reliable data on frames with single or with double glazing and the shadowcosts of glass on itself is not available. Besides this, window frames are calculated per square meter, which would mean that the upper calculations are per two square meter. As third, the facade construction only serves as a basis to mount the windows on, and is therefore quite separate from these windows. The type of windows can easily be changed afterwards without adapting the rest of the construction too much.

At last, the waterproof layer is in both construction left out of the calculation since it is the same amount and the same material.

For the cassettes, more connection material and secondary structure is needed because the mounting system is more complex. However, the concrete slabs are far heavier, therefore the same amount of mounting material is calculated as for the cassettes.

To simplify the comparison, the original facade is used without the balcony and corresponding railing.

The shadowcosts and weight of one square meter of biobased composite cassettes is based on the results of paragraph 7.6.

7.12.4 | Results

Weight kg/m²	213.22	18.65
Schadowcosts €/m²	2.87	2.73

The total amount of weight of the original construction is more than ten times as high as of the new concept. This is simply because of the weight of the concrete outer leaf.
The shadowcosts of the original construction are slightly higher, even when the amount of insulation material and connection materials are much lower than of the concept facade.

The calculations shows that the concept design in biobased composite has a slightly better environmental impact than the original construction, however does include much more insulation. Besides this, the weight of the facade is much lower which could improve the mounting methods (a lighter crane) and the possibility to mount the system on a different wall construction.

Besides the direct environmental impact caused by materials and their production and transport, the long-term environmental impact is estimated to be just a little better. The new design is not very good adaptable other than to reuse the secondary structure however this also applies for the original facade. Reuse of the cassettes is possible when they are coated, and recycling is very well possible, and compared to the concrete elements, smaller elements can be replaced when necessary.

7.12.5 | Conclusion

Regarding the weight of the concrete outer leaf of the original construction, improvements are made easily.

Although the thick outer leaf is replaced by thinner cassettes, the total wall thickness will be similar due to the increased insulation value. While improving the facade, the shadowcosts are still lower than of the original facade. The weight is more than then times lower.

The benefit of this concept is that separately damaged elements can be easily replaced.

7.91 | Section and view
7.92 | Front view
7.93 | Mounting detail
7.94 | Optimal insulated element
Table 7.22 | Conclusion weight and shadowcosts concept relative to original

7.12.6 | Facade quality

7.11.6.1 | Acoustics

If needed sound insulation can easily be provided behind the cassettes, either directly using the thermal insulation or additional insulation in the back of the cassettes.

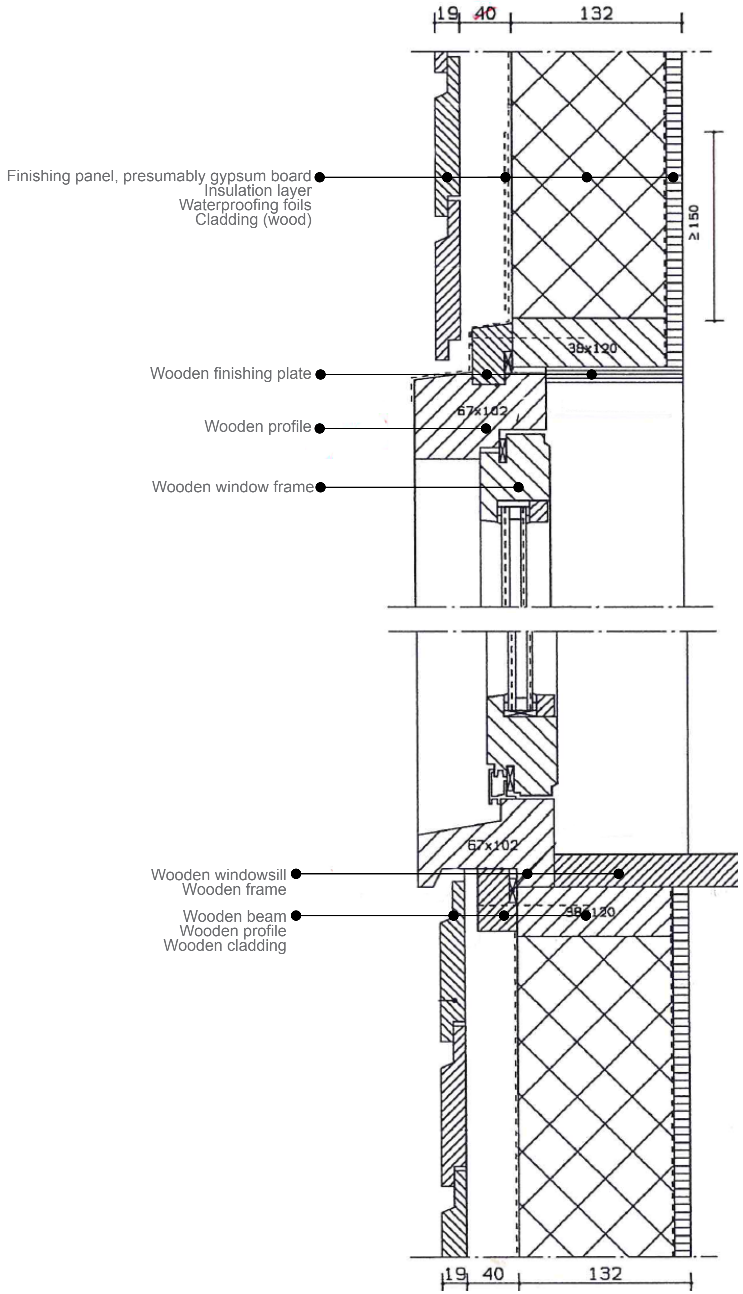
7.12.6.2 | Fire-safety

Recommendations for this facade focus mainly on the fire-safety. Fire spread through the facade cladding is something which should be avoided. Therefore both fire-retardant coatings or powders can be applied. If the cassettes are applied in vertical zones with significantly small dimensions and fir example windows placed between the parapets, precautions might be unnecessary.

7.12.6.3 | Water tightness

The elements should be coated on the outside with a waterproofing and UV-radiation blocking coating.

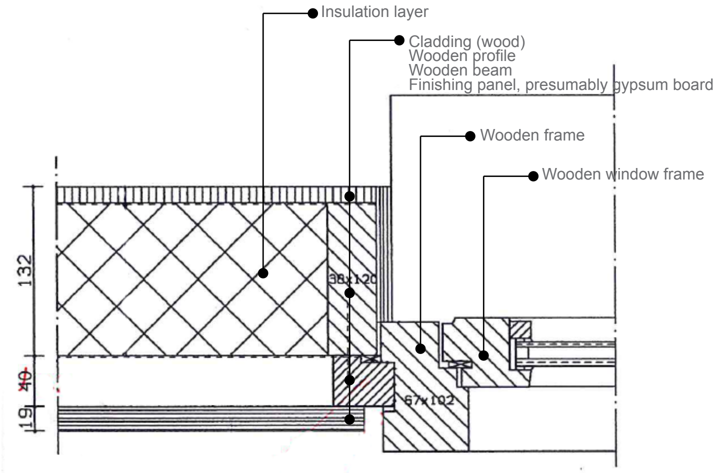
The best option to design a facade for a load-bearing parapet facade is using a biobased composite cassette system. The system is mounted on a common used mounting system for aluminum cassettes.
To make the facade more environmental friendly the insulation material is upgraded to a natural based material.
The weight of the concept facade is more than ten times less than the original facade and the shadowcosts are slightly lower.



7.13.1 | Case study

Timber frame constructions are in this case pre-fabricated wooden frames with cladding on both sides and insulation on the inside. The elements are in the Netherlands mainly applied on housing and low-rise buildings.

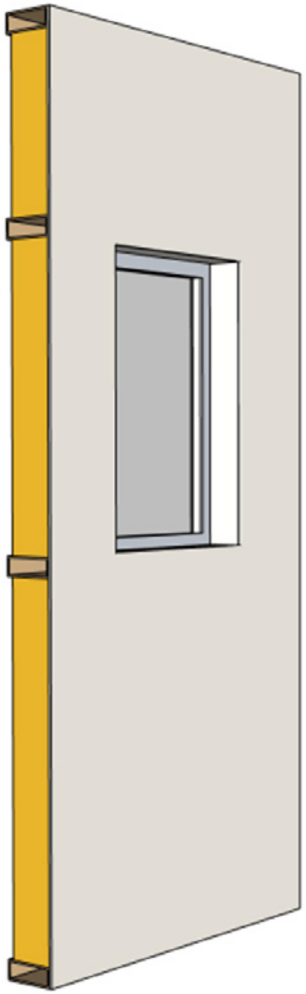
Because there was no example project available, the general details for these elements are used for this comparison. They are obtained from the SBR details.

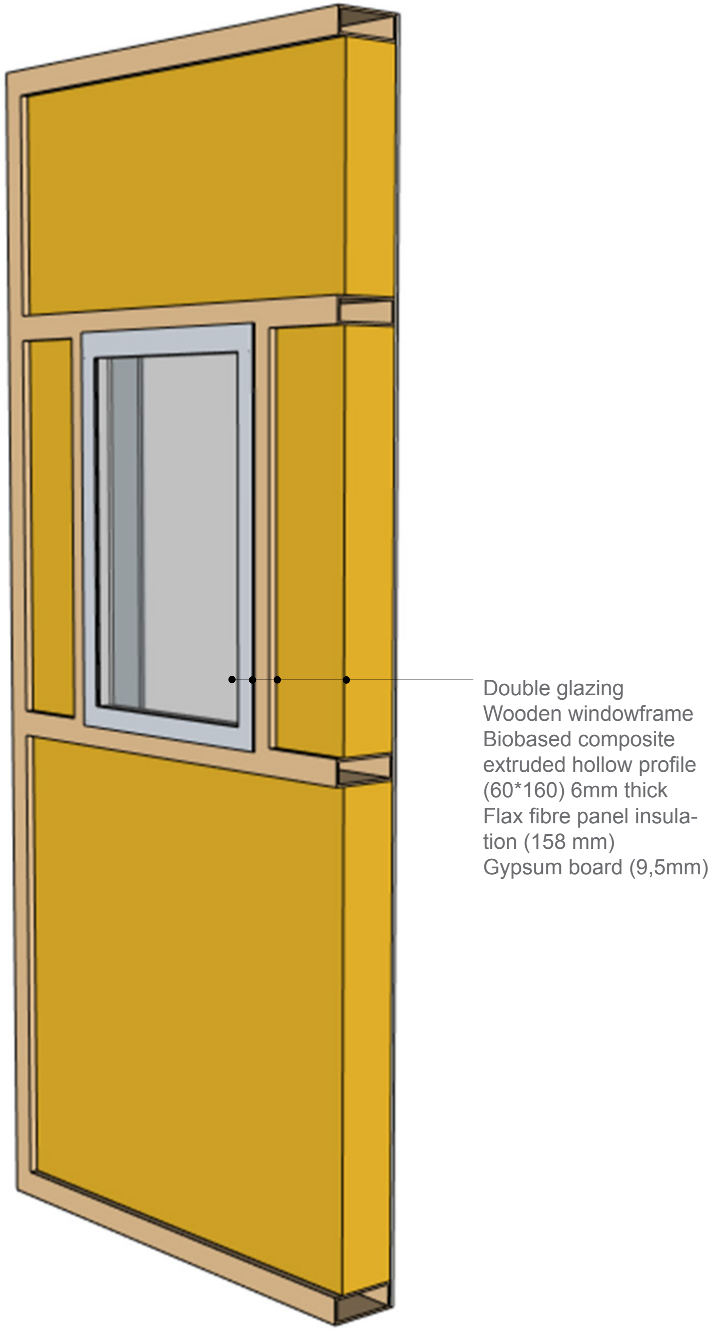


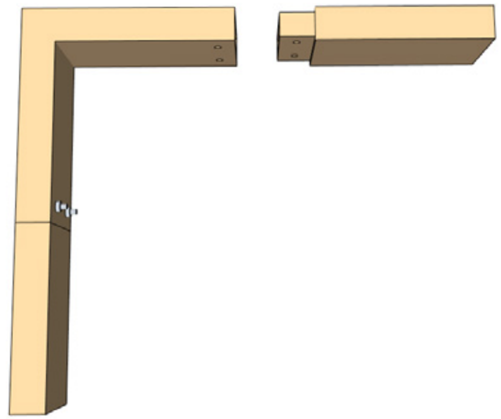
7.95 | Example timber frame structure facade
7.96 | Horizontal section
7.97 | Vertical section
7.98 | Inside view of the facade concept
7.99 | View of the concept (without cladding)
7.100 | Corner connection
7.101 | Truss-beam connection

7.13.2 | Possible concept

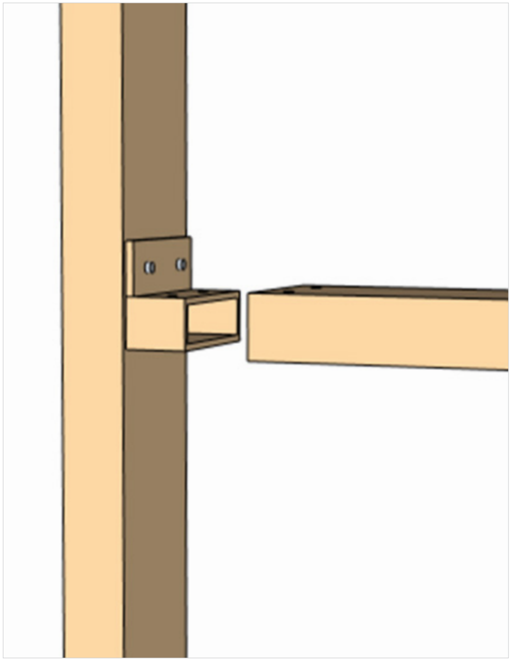
As shown in the product comparison, the timber frame structure can best be replaced by a hollow biobased composite structure filled with insulation material. An element sized structural part turned out to be too heavy, and therefore the shadowcosts increased too much, see paragraph 6.5.







The elements require special connections to allow good load transfer and dismountability.



Original

Material	Volume (m3)	Density (kg/m3)	Weight (kg)	Shadowcosts (€/kg)	Shadowcosts (€)
Rockwool insulation	0,27	150	40,5	€ 0,10	€ 4,05
Wooden beams	0,07	530	37,1	€ 0,01	€ 0,37
Gympsum board			17,15	€ 0,03	€ 0,51
Total			**94,75**		**€ 4,94**
Total per m2			**42,11**		**€ 2,20**

Concept

Material	Volume (m3)	Density (kg/m3)	Weight (kg)	Shadowcosts (€/kg)	Shadowcosts (€)
Flax panel insulation (in and outside)	0,36	30	10,8	€ 0,23	€ 2,48
Biobased composite profiles	0,03	1115	33,45	€ 0,23	€ 7.69
Gympsum board			17,15	€ 0,03	€ 0,51
Total			**61,40**		**€ 10.68**
Total per m2			**27.41**		**€ 4.75**

Concept small

Material	Volume (m3)	Density (kg/m3)	Weight (kg)	Shadowcosts (€/kg)	Shadowcosts (€)
Rockwool insulation	0,27	150	40.5	€ 0,10	€ 4.05
Biobased composite profiles	0,021	1115	23,415	€ 0,23	€ 5.39
Gympsum board			17,15	€ 0,03	€ 0,51
Total			**81.07**		**€ 9.94**
Total per m2			**36.03**		**€ 4.42**

Table 6.23 | Shadowcosts calculations for the original facade and the conceptual design per sqare meter

7.13.3 | Calculation method

At first the weight and shadowcosts for the complete facade were calculated. The facade was drawn 2700mm high and 1200mm wide. After concluding the amounts of weight and shadowcosts, the weight and costs per square meter are shown, see the lowest line of the table.

The calculation does not include a facade cladding although a cladding is shown in the details of the original facade. However the type of cladding is free to choose, and can for both options be the same.

The windowframe is left out of the calculations because this frame adds the same weight and shadowcosts to both the calculations.

The connection materials are left out of the calculation to simplify it, and because they are estimated to be similar. The biobased composite beams however contain some extra material at the places where they overlap, but compared with the overall length this is neglected.

7.13.4 | Results

Weight kg/m²	42.11	27.41	20.72
Schadowcosts €/m²	2.20	4.75	3.16

The weight of the original timber frame construction is lower than that of the concept facade, however this new proposed construction contains larger beams and more insulation material.

The concept facade has larger beams, however they are hollow. The larger beams allow for an improved insulation material and a higher insulation value. The 120mm insulation is increased to 158 mm of flax fibre insulation.

Because the beams are hollow (they are 6mm thick) the weight of one meter beam in biobased composite weights 2.78 kg while a wooden beam of 38*120mm weights 3.05 kg.

The shadowcosts of the original construction are half of those of the concept. This is simply because the shadowcosts for untreated wood are very low.

The proposed concept facade shows that the shadowcosts of the improved concept are higher than of the original facade.

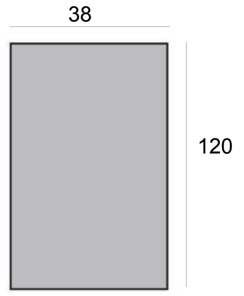
The table "Concept small" shows the values for a concept facade with beams of the same sizes of the original facade. In this case the insulation material in Rockwool, just as in the original facade since this provides the necessary Rc-value at this low thickness. Using flax insulation, the insulation value of the element will decrease.
The beams are in this case 48*120mm and 6mm thick and the insulation material is 120mm thick. The weight of the facade is in this case slightly lower of that of the original facade, however the shadowcosts are doubled.

The bending stiffness calculations on the right page show that the bending stiffness of the small sized beam are not sufficient, while the bending stiffness of the improved beam are almost two times higher. Therefore the thickness of the larger beam can be reduced which decreases the shadowcosts and weight.
If the thickness of the large hollow beam is reduced 1.2 times, the weight of the biobased composite structure is 6.76 kg and the shadowcosts of this structure are 6.09 euro. The total weight of one sqare meter will become 20.72 kg and the shadowcosts 3.16 euro.
This means that the shadowcosts will be slightly higher but the weight will be decreased 2 times.

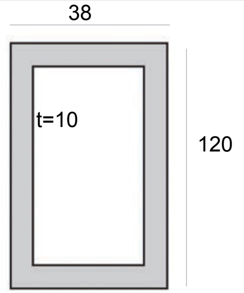
Element	Ix (m4)	E (Gpa)	EI (Nmm2)	Weight (kg)	EI/w	Density (kg/m3)	Stiffness (E/ρ)	Shadowcosts (€)	EI/Shadowcosts
Wooden beam timber frame	5,47E+06	13	7,11E+07	12,21	5,82E+06	530	6,89E+03	€ 0,37	1,92E+08
B-c hollow same dimensions	3,97E+06	11,4	4,53E+07	12,27	3,69E+06	1115	1,27E+04	€ 6,54	6,92E+06
B-c hollow larger dimensions	7,51E+06	11,4	8,56E+07	25,2	3,40E+06	1115	1,27E+04	€ 4,57	1,87E+07

7.13.5 | Bending stiffness calculation

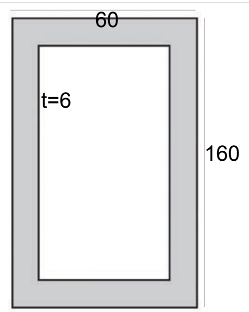
The calculation underneath show the former calculated moment of inertia of wood and biobased composite plus the concept beam of larger dimensions. The bending stiffness (moment of inertia times youngs modulus) of the larger concept beam turns out to be 1,2 times higher than the bending stiffness of the original wooden beam. This decreases the weight and shadowcosts to 20.72 kg and 3.16 euro.



Ix	=	1/12*b*h^3		
Ix	=	1/12*0,038*0,120^3	= 5,47E-06	m4
			= 5,47E+06	mm4



Ix1	=	1/12*0,038*0,120^3	= 5,47E-06	m4
Ix2	=	1/12*0,018*0,100^3	= 1,50E-06	m4
Ixt	=	Ix1-Ix2	= 3,97E-06	m4
			= 3,97E-06	mm4



Ix1	=	1/12*0,060*0,160^3	= 2,05E-05	m4
Ix2	=	1/12*0,048*0,148^3	= 1,29E-05	m4
Ixt	=	Ix1-Ix2	= 7,51E-06	m4
			= 7,51E+06	mm4

7.13.6 | Conclusion

The improved facade, containing natural based insulation and therefore thicker profiles, has higher shadowcosts than the original design. The weight is decreased a lot due to the much lower density of the natural insulation material. When the profiles are calculated in the same size as the original design and the original insulation material is kept, the shadowcosts are two times higher than the original facade, but the weight is slightly lower.

For the improved facade with larger beams, the bending stiffness is almost twice as high as the weight of the original wooden beams. Therefore the construction was calculated with a lower thickness. This decreases the weight and shadowcosts to 20.72 kg and 3.16 euro.

When circularity plays an important role, these timber frame structures offer good opportunities. The structures can be reused, since the biobased composite is applied on the inside of the element and has therefore an estimated much longer lifetime than when applied for external purposes.
Besides reuse, the facade is adaptable and can be completely dismounted which increases the ability to recycle the different materials.

The frames allow easy demounting, therefore separate parts can easily be replaced.

7.13.7 | Facade quality

7.13.7.1 | Acoustics

The acoustical properties are partly determined by the cladding, which is, in this concept, not specified. The insulation layer and insulated profiles can provide sound insulation but the difficulty is the direct connection between the inner and outer layer though the profiles. Here either a damping material such as felt can be added or the cladding can be attached resilient.

7.13.7.2 | Fire-safety

The fire-safety precautions for this concept focus mainly on the fire propagation and smoke development of the profiles itself. They are designed uncoated, but a fire-retardant coating or additional powder might be needed. Since the profiles are not visible, the aesthetic properties of the profiles are not important, which makes applying a fire retardant coating more easily.

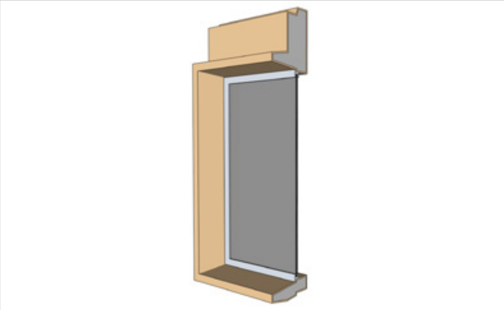
7.13.7.3 | Water tightness

The biobased composite is applied on the inside of the construction, therefore no waterproofing or UV-blocking coating is needed.

Table 7.24 | Conclusion weight and shadowcosts concept relative to original
Table 7.25 | EI-calculations
7.102 | Schematic image original wooden beam and calculations
7.103 | Schematic image biobased composite hollow beam in original dimensions and calculations
7.104 | Schematic image biobased composite hollow beam in larger dimensions and calculations

The weight and shadowcosts of the concept facade are higher than those of the original facade. However, the concept facade has thicker insulation and therefore larger beams. When reducing the thickness of the beams according to the calculated bending stiffness, the weight is two times lower than that of the original facade.

When the concept facade is compared to the original facade in the same dimensions, the weight is slightly lower but the shadowcosts are doubled.



7.14.1 | Sandwich element

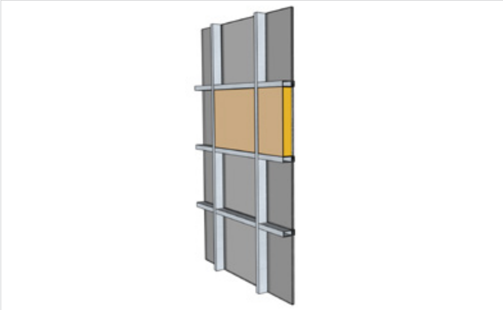
The sandwich element in biobased composite and PLA foam weights 2.4 times more and the shadowcosts are 1.6 times higher. However when the actual bending stiffness is taken into account the weight is 1.4 times higher and the shadowcosts are 1.4 times higher.
Important is that the circular scenario is not better, but got even worse due to the shorter lifetime of biobased composite.
To improve the circularity, the sandwich element should be redesigned to be adaptable and/or demountable.

7.14.1.1 | Application

For easy producible and fast to mount constructions, a biobased composite sandwich element shows potential. Also when difficult to produce shapes are required, a sandwich element can show potential over a framework facade. However only when circularity and environmental impact are not important requirements.

7.14.1.2 | Recommendations

Regarding circularity, a sandwich element requires more research and redesign to produce an adaptable and/or demountable element. When the shadowcosts of biobased composite decrease or the geometry can be even more improved the environmental impact might become lower of that of the original element.



7.14.2 | Curtain wall

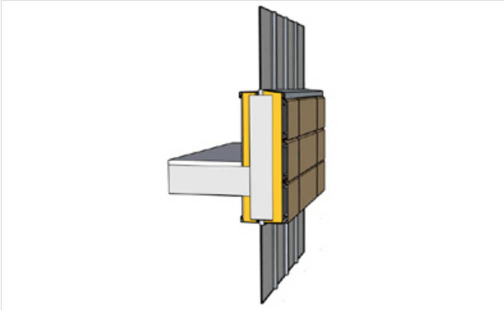
The glazed spandrels in biobased composite offer a lower weight, but have higher shadowcosts than the original steel shadow box. They are designed having two crossing ribs in the middle of the “box” to be able to decrease the material thickness.

7.14.2.1 | Application

The application of glazed spandrels with biobased composite offers improvement over steel glazed spandrels or shadowboxes in a curtain wall facade.

7.14.2.2 | Recommendations

The structural dimensions have only been calculated briefly for an element of one square meter. For other dimensions, new calculations should be made. Also the bending stiffness of a box with smaller but more ribs could be made.



7.14.3 | Parapet facade

The cassettes on the parapet facade are about ten times lighter than the original concrete facade. The shadowcosts, including a large improvement in insulation material and insulation value, are almost similar but slightly lower.

7.14.3.1 | Application

The cladding and insulation have now been added to a concrete parapet facade. Off course this cladding can also be used for other applications. Since the insulation value now has been calculated taking the concrete in mind, the insulation might need to be thicker.

7.14.3.2 | Recommendations

Whether biobased composite in these dimensions is strong enough to be connected using this clamping method should be research further.
Another questionable aspect is possible wear caused by movement over the steel mounting tubes. Composite is in general very wear-resistant but this should be calculated and/or tested.

The horizontal surfaces should be designed very carefully to avoid long term reaction with water.

7.14.4 | Timber frame structure

The weight of the construction when designed in the same dimensions as the original is only 1.16 times lower.
The shadowcosts are two times higher since the shadowcosts of wood are very low.

The improved facade, with larger beams and more insulation is 1.5 times lighter than the original facade however has more than two times higher shadowcosts.
When the actual bending stiffness is taken into account, the weight can be reduced to 0.5 times the original weight, however the shadowcosts are still 1.4 times higher.
The great benefit of the construction is that the circular scenario is very good.

7.14.4.1 | Application

The biobased composite hollow frame construction can be used instead of a timber frame construction, but also as an prefabricated element facade. The frame itself could be used for structural purposes, for example for stage technique.

7.14.4.2 | Recommendations

Since this is a concept design, the bolt strength in hollow biobased composite profiles was not calculated. For an actual design, this should be researched.
Also the degradation in strength of the hollow profiles at the connections after a certain amount of time should be tested, because this defines whether the elements are really reusable.

Element	Ix (m4)	E (Gpa)	EI (Nmm2)	Weight (kg)	**EI/w**	Density (kg/m3)	Stiffness (E/ρ)	Shadowcosts (€)	**EI/Shadowcosts**
Sandwich Steel-PIR	9,02E+07	210	1,89E+10	12,15	1,56E+09	7870	1,65E+06	€ 5,10	3,71E+09
Sandwich biobased composite-PLA	2,09E+09	11,4	2,38E+10	25,24	1,06E-09	1115	1,27E+04	€ 9,56	2,49E+09
Sandwich Sozawe	4,10E+08	69	2,83E+10	46.63	6.06E+08	1578	1,09E+05	€ 26.17	1,08E+09
Concept sandwich	7,00E+09	11,4	7,98E+10	65.37	1.21E+09	1115	1,27E+04	€ 35.83	2,22E+09
Wooden beam timber frame	5,47E+06	13	7,11E+07	12,21	5,82E+06	530	6,89E+03	€ 0,37	1,92E+08
B-c hollow same dimensions	3,97E+06	11,4	4,53E+07	12,27	3,69E+06	1115	1,27E+04	€ 6,54	6,92E+06
B-c hollow larger dimensions	7,51E+06	11,4	8,56E+07	25,2	3,40E+06	1115	1,27E+04	€ 4,57	1,87E+07

7.14.5 | Bending stiffness

The table above shows the values EI/weight and EI/shadowcosts of the elements for which the EI was calculated. For both values applies that, in the case of a facade element rated on bending strength, the higher the value the better. This means that the bending strength is high but the weight of an element is low. Regarding the shadowcosts it means a high bending strength and low environmental impact.

The wooden beam has a higher score for EI/weight than the hollow biobased composite profiles. The steel-PIR element has the highest value of the sandwich elements.

Regarding the EI/shadowcosts, steel-PIR element is also the highest.

7.14.6 | Shadowcosts

While comparing the products and biobased composite concepts, in many cases the biobased concepts turned out to have higher shadowcosts. This has two reasons:

1. Youngs modulus

The thickness of the material for a facade element is mainly dependent on the bending stiffness, and therefore the youngs modulus. Since the youngs modulus of biobased composite is not very high the thickness increases compared to for example steel. The density is much lower, however not in the same ratio as the thickness increases. The thickness though, can be lower than calculated regarding only the youngs modulus, when the bending stiffness of the geometry is taken into account. This is explained in the next part.

2. Shadowcosts

The shadowcosts of one kg biobased composite are at this moment 0,23 euro. For steel they are 0,17 euro and for wood 0,02 euro. Compared to the density the shadowcosts per m_3 are calculated (see the table below).

This table shows that taking the necessary thickness (calculated regarding the youngs modulus) into account, all materials have lower shadowcosts than biobased composite, except aluminum. The shadowcosts of wood are right now 27 times lower. For steel this is 3.5 times and for glass-fibre reinforced polyesther this is 1.01 times. Aluminum has 4.7 times higher shadowcosts per m_2.

When taken the calculated bending stiffness into account, for the steel-PIR sandwich panel the conceptual biobased composite thickness could be reduced 1.25 times, which makes the biobased composite shadowcosts 2.8 times higher.

For the glass-fibre reinforced element facade, the biobased composite shell could be reduced in thickness 2.81 times which makes it 2 times lower than the original.

Eventually the biobased composite hollow beam can have a 1.20 times lower thickness, however this makes the shadowcosts of biobased composite still 22.5 times higher.

Material	**Density (kg/m3)**	**Shadowcosts (€)**	**Youngs modulus**	**Shadowcosts/m2**
Wood	530	€ 0,02	13	0.17
Steel	7870	€ 0,17	210	1.33
Aluminum	2700	€ 2,65	69	21.47
Glassfibre-reinforced composite	2000	€ 0,76	69	4.56
Biobased composite	1115	€ 0,23	11,4	4.61

3. Improvements

To decrease the shadowcosts of biobased composite several improvements can be made:

- Improve (decrease) the shadowcosts
- Decrease the density (resin)
- Increase the youngs modulus (resin and fibre)

The shadowcosts can be decreased by improving the resin. The amount of natural based substance could be approved. When less toxic substances are added, the shadowcosts will drop. Most important are solvents, which are in general very toxic for the environment, but also directly for people while working with the material.

To decrease the density of biobased composite, mainly the resin should be improved. Whether this is possible should be researched by biochemists.

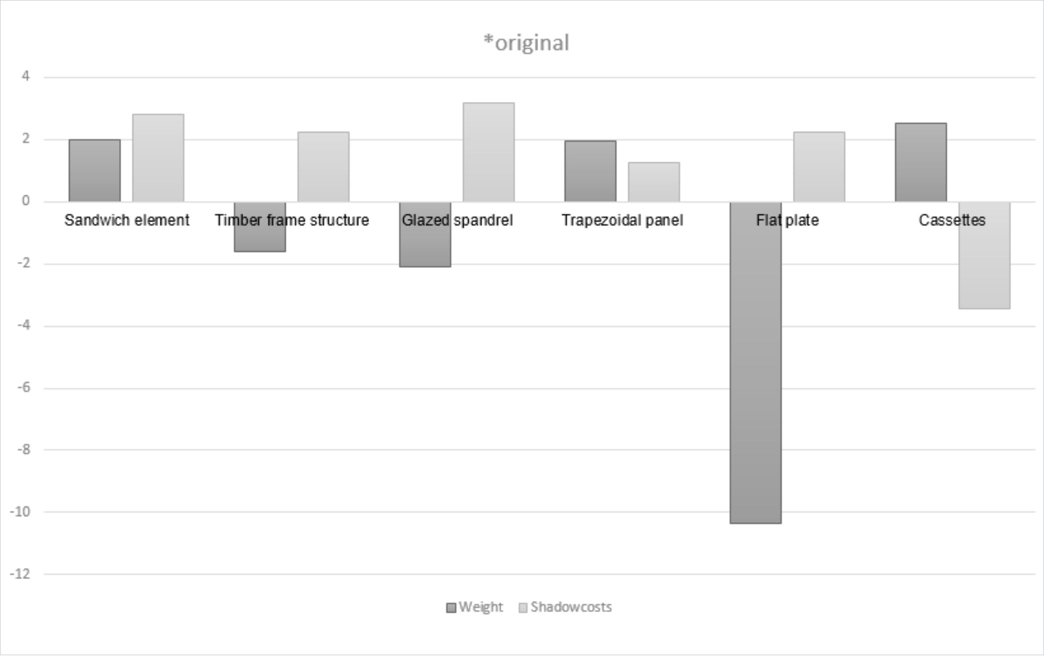
The increase of the youngs modulus can be provided by the fibres and the resin. Whether fibres can be used in a smarter way, or mixtures of different fibres can be applied, should result from further research. The resin also adds to the youngs modulus, for which the connection between the resin and fibres is very important. Whether this can be optimized is a research in itself. The bending stiffness can also be improved regarding the moment of inertia. For this the geometry is very important.

On the left page the end conclusions for all facade typology concepts are shown.
The bending stiffness is also calculated using the “EI” value. These results are shown in table 7.9.

Almost all biobased composite concept thicknesses can be slightly thinner than first estimated, which will decrease the total weight and shadowcosts.
The shadowcosts of biobased composite should decrease to make the material more competitive.

Product	Weight (* original)	Shadowcosts (* original)
Sandwich element	+2	+2,8
Timber frame structure	**-1,6**	+2,25
Glazed spandrel	**-2,1**	+3,2
Trapezoidal panel	+1,94	+1,25
Flat plate	**-10,37**	+2,22
Cassette	+2,52	**-3,43**

Product	Weight (* original)	Shadowcosts (* original)
Sandwich element	+2,44	+1,60
Adjusted sandwich elements	+1,40	+1,37
Curtain wall	-2,56	-1,54
Parapet facade	-11,43	-1,05
Timber frame structure	-1,54	+0,50
Adjusted Timber frame structure	-2,03	-1,44



7.14.7 | Results

Both the tables above and the graphs on the right show the increase or decrease in weight and shadowcosts of all calculated concepts.
First the results of the products are shown, followed by the results of the facade design concepts. The numbers show how many times the weight and/ or shadowcosts decrease or increase.

7.14.7.2 | Design concepts

For the facade design options, the biobased concepts show more improvement.
The weight decreases for 3 of the 4 concepts. The shadowcosts also decrease for all of the concepts, however concerning the timber frame structure they only decrease for the adjusted concept.

7.14.7.1 | Products

For half of the products, the weight of the concept is lower, namely for the timber frame structure, glazed spandrel and flat plate. For the other three products the weight increases.

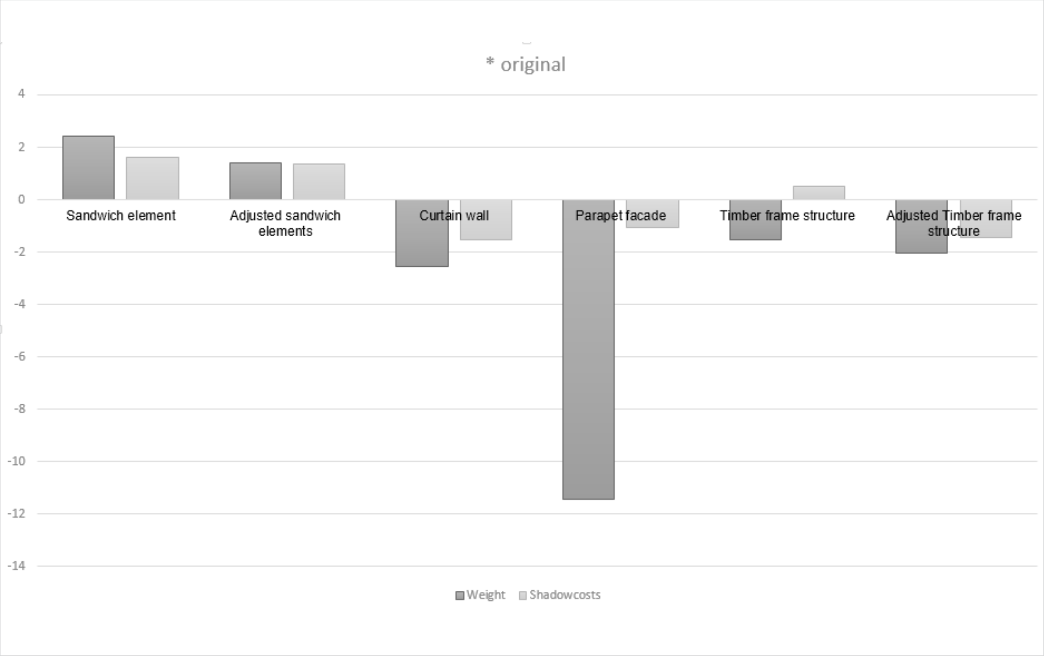
The shadowcosts are higher than the shadowcosts of the original elements for all products except the cassettes.
The main reason why the weight and shadowcosts increase in many cases is the higher thickness which is applied using the ratio of youngs moduli. The (few) bending stiffness calculations show that the thickness can be decreased in most options, therefore the biobased composite could become more competitive.

7.14.7.3 | Conclusion per material

The reason for the difference between the products and facade designs are probably due to the difference in materials used in the original elements.

Steel

Many parts of the products are constructed out of steel. Steel cannot be translated very positively to biobased composite due to the large increase in thickness of the conceptual elements. A valuable improvement for the material thickness turned out to be the use of ribs, which reduced the material thickness and therefore the weight and shadowcosts. By creating a sandwichpanel with a thicker core, the bending stiffness increases for which the thickness of the biobased shell can be reduced again, which reduces the shadowcosts. They are then 2.8 times higher than the original element. This means that biobased composite, not regarding the other materials in the element, should increase 2.8 times to equate the shadowcosts of steel.



Wood

The same environmental impact as wood has is difficult to attain because the shadowcosts and the density are very low, however by increasing the dimensions and using hollow profiles the weight can be reduced. Regarding only the youngs modulus, wood has a 27 times better environmental impact than biobased composite, however when the actual bending stiffness is taken into account, this decreases into 22.5 times. Therefore the shadowcosts of biobased composite need to improve enormously to make the material competitive to wood.

Glass-fibre reinforced composite

The sandwich element in biobased composite and PLA foam weights 2.4 times more and the shadowcosts are 1.6 times higher. Glass fibre reinforced polyester is 1.01 times more environmental friendly, however when the bending stiffness of the increased thicknesses are taken into account, the shell thickness can be reduced 2.81 times. This decreases the shadowcosts to 2.77 times less than the original GRP shell costs.

Aluminum

The shadowcosts of aluminum are very high, 4,5 times higher of those of biobased composite. Replacing aluminum by biobased composite is therefore an environmental friendly move.

Coating

The coating for biobased composite is quite polluting, however the coatings for steel and aluminum are also very harmfull.

Steel: For powder-coated and galvanized steel the shadowcosts are 10 times higher than for the spraypaint used for biobased composite. For wetpainted and galvanised steel this is two times. Anodized and powder-coated aluminum has 4 times lower shadowcosts than the spraypaint. In none of the compared products or elements the coating determined if the biobased composite concept was an improvement or deterioration.

7.14.8 | Conclusion

7.14.8.1 | Application of biobased composite

The results of the comparison between an existing design or product show more improvements for the facade design than for the products.

1. Type of material

Whether applying biobased composite is an improvement depends on the type of material which is replaced. Additionally a coating can influence the decrease or increase in shadowcosts.

2. Shadowcosts

The resulting numbers for shadowcosts of the comparisons between existing facades and building products will change positively when the shadowcosts of biobased composite decrease, see paragraph 7.14.6. The table below shows how many times the shadowcosts of biobased composite are higher or lower (when -) than the showed materials. The first column was calculated regarding the necessary thickness based on the difference in youngs moduli. The second column shows this aspect based on the difference in bending stiffness of the researched concepts.

3. Thickness

The applied thickness is based on the youngs modulus ratio of the original materials, however this turned out to be an over dimensioning in most of the cases.

Regarding the bending stiffness`s, all calculated biobased thicknesses can be reduced slightly, except for the hollow profile in original dimensions. The reduction of thicknesses will decrease the total weight of the elements and therefore the shadowcosts. Reducing these thicknesses according to the calculated bending stiffness`s reduces the shadowcosts of the biobased composite compared to the original element. Still, in half of the cases the environmental impact of the biobased composite is far worse than the original material.

4. Insulation value

The insulation value of the claddings show that for example a trapezoidal panel of biobased composite has a 143 times higher insulation value than the original steel sheet.

The lambda value, or thermal transmittance is more than three times lower than that of wood, which is commonly applied on places where cold bridges can appear, due to the low thermal transmittance of wood. This means that biobased composite can be applied at critical spots were a high thermal insulation is required.

7.14.8.2 | Circularity

1. Products

The circular scenarios of the products are equal to the scenarios of the original elements. None of the circular scenarios have increased compared to the original product.

At this moment the lifetime is, when designed properly, estimated to be sufficiently long to reuse the elements efficiently. Properly designed means coated when necessary and with a sufficiently high bending stiffness, including a safety margin.

2. Facade design concepts

The facade design concepts are based on the products researched in chapter 7, therefore the circular scenarios are similar to those of these products. Concerning the circular scenarios themselves the same applies as explained for the products.

Material	Shadowcosts * original	Shadowcosts * original (bending stiffness)
Steel-Biobased composite	3.5	1.3
Wood-Biobased composite	27	22.5
GRP-Biobased composite	1.01	-2
Aluminum-Biobased composite	-4.7	x

7.14.8.3 | Conclusion

The conclusion of the comparison between existing elements and biobased composite concepts is that improvement in terms of weight and shadowcosts can be made, however this depends on the design and the applied materials in the original element.

To improve the environmental impact of biobased composite the shadowcosts should be improved, which means the shadowcosts per kilogram should decrease.

Regarding circularity, the scenarios of the researched products and designs are equal to the original element. If future tests show that the lifetime is shorter, the scenarios will decline since reuse is than probably not possible or not efficient.

Table 7.28 | Increase and decrease of weight and shadowcost for the original and concept products
Table 7.29 | Increase and decrease of weight and shadowcost for the original and concept facade designs
Graph 7.1 | Increase and decrease of weight and shadowcost for the original and concept products
Graph 7.2 | Increase and decrease of weight and shadowcost for the original and concept facade designs

Improvement in terms of weight and shadowcosts can be made, however whether the designs are improved depends on the shape and applied materials of the original element. To improve the environmental impact the shadowcosts should be decreased.

Regarding circularity, the scenarios of the researched products and designs are equal to those of the original element.

8

CONCLUSIONS & RECOMMENDATIONS

8.1.1 | Biobased composite

“What is possible with biobased composite when used for a circular facade design?”

The main questions, as repeated above, will be answered according to the research questions.

1. What is biobased composite?
Biobased composite consist out of natural grown fibres and a partly natural based resin. A coating can be applied to improve the durability or to add other desired properties.

2. What is biobased composite, for what can it be used, and for what not?
Biobased composite can be applied for a wide range of purposes. Different concepts for facade design are researched in chapter 7. In this chapter, it becomes clear which applications can improve existing elements and which not. It depends mainly on the type of material of which the original element is constructed, if the environmental impact of biobased composite is higher or lower.

3. Why application for façade design?
The choice for biobased composite is based on two properties. The first is that the material grows and is therefore “infinite”, in contrast to some other commonly applied materials like steel. Thereby the expectation was that the material is easy recycleable. However, since it is not compostable and the recycling method is still in its infancy, this expectation was refuted later. Thereby, so far biobased composite was mainly research for bridge building purposes. Therefore the question arose whether the material could be used for this purpose too.

4. Which types of biobased composites are applicable?
There are a wide range of resin-fibre configurations available. Due to it`s high strength flax fibre was chosen to use for the calculations in combination with cardolite resin. To specifically determine which fibre-resin matrices can be used best, more reserach must be done.

5. What are the first restrictions related to the facade quality demands?
The interviews with specialists of DGMR resulted in the following important aspects:
1. Acoustical insulation
• Mass/Sandwich construction
• No single point supports

2. Fire-safety
• Fire retardant retention wall/ other facade layer
• Apply a fire-retardant coating
• Use a fire retardant resin
• Apply the material only to low-rise buildings

3. Watertightness
• Coating when applied outside

For more extensive information see paragraph 6.3.

6. Which production processes are useful to produce a façade?
In paragraph 4.1 all applicable production techniques are showed and explained.

7. What would be the best production technique regarding the environmental impact?
Regarding production processes, three properties are of influence on the environmental impact of the process:
• The required energy, this is mainly decided by the need of an autoclave
• The necessary additional materials like molds, vacuum bags, etc.
• The emissions evaporating during the process.
Closed molds and vacuum processesn perform better on this matter.

8.What does this mean for the façade design?
The use of an autoclave is in most situation not necessary.
Closed molds can be used, but require two molds which are expensive. Vacuum injection around a core material is difficult to disassemble after use. Per facade design should be decided which production processes fits best, also concerning the (costs) efficinecy rules as described in section 4.1.2.

8.1.2 | Circularity

1. How can a biobased composite façade be designed circular?
The aim is to keep materials and products “performing” as long as possible, avoiding discarding them.

2. What does circular mean?
The circular building principles enhances “closed loop thinking”, adaptive design and upgrading. Three important rules are:
1. Reduce resources
2. Reuse resources
3. Apply circular solutions

3. How can biobased composite be used in the most circular way?
A division was made between reuse, adaptation and recycling. Based on these aspects, proposed concepts were analyzed.
Re-use focusses mainly on the possibility to demount the elements and the estimated quality the part has after being used, connected with its lifespan.

Adaptability concerns whether the part can be changed or upgraded, or parts can be replaced.

To be able to measure the recycling possibilities, a division is made regarding the ability to separate the used materials.

4. Which facade typologies are there, and which are most suitable for this design?
Four different facade typologies are further explored in chapter 7.
The typologies are an element facade, a curtain wall, a parapet facade and a framework facade.

5. How does this influence the façade design?
This questions cannot be answered directly since the final result changed from one final design into different concepts, see paragraph 7.1.

8.1.3 | Design orientation

1. What are common used facade elements?
To cover most of the common used building materials, but also to cover most of the different application methods of biobased composite, the products were defined as:

- Sandwichpanel
- Timber frame structure
- Glazed spandrel

Cladding:
- Trapezoidal panel
- Flat sheet
- Cassettes

2. How can biobased composite be used in these elements?
At first, the necessary thickness of biobased composite when applied instead of the original structural material was calculated. Then the insulation material or core material was changed to a more natural based material with the same or improved insualtion value. Then the total element was drawn in sketchup and the aspect weight, insulation value and shadowcosts were compared. Besides this the circular scenario was analyzed.

3. What is the effect of the change in material use to the weight, schadowcosts and circularity of the element?
The results are shown in chapter 7 and on the next page summarized.

8.1.4 | Concept design

1. Which variant does suit each ot the case study facades best?
The analyzed products logically fit to the case studies. Therefore the sandwich element is designed as a biobased composite-PLA element and the timber frame as a hollow framework of biobased composite.
The parapet facade is cladded with the most environmental friendly cladding. In the curtain wall the shadowboxes are replaced by the biobased composite glazed spandrels.

2. How can this variant be applied on the facade?
In general, the structural element is replaced by a biobased composite element in the calculated necessary thickness. For the drawings see chapter 7.

3. What does this mean in terms of weight, insulation value, schadowcosts and circularity compared to the original facade?
For the products, in half of the cases the weight increases, and in almost all cases the shadowcosts increase.
For the facade design concepts, the weigt decreases in three of the four cases and the shadowcosts decrease in half of the four cases. However when the actual bending stiffness is taken into the calculation, the shadowcosts decrease in three of the four cases.
The insulation value remains the same, since this was a design parameter.

The circular scenarios of the products and designes are equal to the scenarios of the original elements. None of the circular scenarios have increased compared to the original product.

At this moment the lifetime is, when designed properly, is estimated to be sufficiently long to reuse the elements efficiently.
Properly designed means with a coating when necessary and with a sufficient bending stiffness, including a safety margin.

This page contains the answers on the research questions.

8.1.5 | Conclusions per subject

Biobased composite
Biobased composites are fibre-reinforced materials that are partly or completely made from renewable raw materials.

Biobased composite consists out of:
☐ **Natural fibre**
Random oriented fibres are economical advantageous, however due to the random orientation the specific structural properties cannot be established. Fibres can be protected by encasing them in a polymer or by coating them with a synthetic material.

☐ **Resin**

☐ **Coating** (optional)
Coatings can be added to provide water tightness, UV-radiation blocking, fire-safety or colour.

Quality requirements

At this moment, with still relative little information on the material available, it is difficult to define requirements for a biobased composite facade. Together with specialists of DGMR, the next "rules" were defined.

Acoustical insulation:
☐ Mass/Sandwich construction
☐ No single point supports

Fire-safety
Since the propagation time of the material is not known, different indicative solutions are:
☐ Apply a fire-retardant coating
☐ Use a fire retardant resin
☐ Apply the material only to low-rise buildings

Facade technology
☐ Coating when applied outside

Material scarcity, waste and landfill loading

• Biobased composite does not directly offer a solution for the waste problem

Because biobased composite is not compostable and not yet recycleable, after use the material leads to downcycling or landfill loading. For future improvements see the section "recycling".

• Biobased composite could offer a solution for the scarcity of raw materials used for building components

Common used materials in the building industry are estimated to run out within a limited time. Since the fibres of biobased composite grow, and the resin is partly produced from agricultural waste, this material could offer a solution for the raw material problem. Wood also is a material which grows "infinitely" however grows quite slow, and there are restrictions to the producing scale when sustainable managed forests are required.

Circularity

The three main rules for a circular design are:
☐ **Reuse** resources
☐ **Reduce** resources
☐ Apply **circular solutions**

Thereby the goal is to keep materials performing as long as possible, without having to discard them. Therefore the quality of a material is very important.
In this research a circular scenario for a facade was interpreted as the possibility to either
• Reuse
• Adapt
• Recycle
the products, whereby reuse would be the best option since little extra material and/or energy is required to keep the product performing, after which adaptation follows. Recycling is rated lowest for this reason.

The circular scenarios of the products are equal to the scenarios of the original elements. None of the circular scenarios have increased compared to the original product.

At this moment the lifetime is, when designed properly, estimated to be sufficiently long to reuse the elements efficiently. Properly designed means coated when necessary and with a sufficiently high bending stiffness, including a safety margin.

Recycling

The recycleability of biobased composite is still at it`s infancy. Biobased composite can be decomposed into fibres and resin, when the resin is dissolved using a solvent and boiling it.
Two problems still need to be solved while doing this:
• The fibres might degrade due to the solvent and the high temperature
• The resin (and coating) are mixed with the solvent and recapturing this solvent requires further research.
Also the bonding`s in the resin could be destroyed.

Which substances are applicable to dissolve epoxy resins and or epoxy coatings requires further research as well.

Manufacturing

Environmental impact
Three properties are of influence on the environmental impact of a production process:
• The required energy, which can be reduced significantly by avoiding the use of an autoclave.
• The necessary additional material like molds, vacuum bags, etc.
• The emissions evaporating during the process. Closed mold and vacuum processes perform better on this matter.

☐ Choose a production process that fits your design
☐ Avoid using an autoclave
☐ Avoid additional material like molds, vacuum bags, etc.
☐ Avoid harmful emissions from evaporating

Connections

Connections between composite parts can both be adhesive bonded as mechanically joined.

Adhesive bonded joints have the benefit that there is no need to drill holes in the composite. Holes interrupt the fibres and produce therefore stress concentrations.

Mechanical joints can be much easier disassembled and inspected. Regarding circularity, mechanical joints offer a great benefit over adhesive connections.

☐ Apply mechanical joints as much as possible

Thermal insulation

☐ Since 2015, for new buildings and large renovations, **the thermal insulation of a construction should at least be 4,5 m2·K/W.**

Both petrochemical based insulation as natural based insulation are available.
Important is the thermal conductivity of a material, as well as the density of the material.

Thermal conductivity biobased composite

The thermal conductivity of biobased composite is 0.056 W/m*K. Compared to wood, with a average thermal insulation value of 0.18 W/m*K this is very low. This means the material has a very high thermal insulation value and can be applied at places where thermal bridges might appear.

Durability

☐ The expectation is that when the material is coated and the bending stiffness is designed including a safety margin, the lifetime would be similar to other common facade materials.

To establish the estimated lifetime of biobased composite two test were performed:
• Warmth-cold cycle test, performing 5 cycles of 24 hours for temperatures are between -20 °C and 70 °C.
• Freeze-thaw test performing 30 cycles of 24 hours. The machine first soaks the samples in water and then freezes them up until -20 °C.
• Thereby a initial group of control group was used, which was not exposed to any accelerated weathering influences.

For each test three coated and three uncoated samples are used.

Durability results

Tensile tests were performed to establish how much the samples degraded under the accelerated weathering tests.
Visually there were almost no differences between the samples before and after the tests. The edges of the uncoated samples tested for the freeze-thaw cycles were a little more rough, some fibres were sticking out.

These tests must be interpreted as an indication.
• The warmth-cold cycles tested group shows a small increase in tensile strength and a small decrease in youngs modulus.
• The freeze-thaw cycles tested samples showed a large increase in tensile strength and a large (13%) decrease in youngs modulus.

Shadowcosts

For steel, one square meter of steel replacing by biobased composite with a thickness calculated regarding only the youngs modulus means that the shadowcosts increase by 3.5 times. When regarding the calculated bending stiffness the shadowcosts decrease 2.8 times. This means that the shadowcosts of biobased compsitie should decrease 2.8 times, and become 0.08 euro to compete with steel in terms of shadowcosts.

Wood is lighter and has far lower shadowcosts. Regarding the youngs modulus the shadowcosts increase by 27 times but regarding the bending stiffness this is 22.5 times, meaning that the shadowcosts of biobased compsoite should decrease to 0.01 euro to compeet with wood. The only benefit biobased composite has over wood at this moment is the fact that the fibres grow much faster and are therefore almost “infinitely available”.

Glass-fibre reinforced polyester hass slightly higher shadowcosts per sqare meter, however when calculating the bending stiffness and following decreasing the thickness, the shadowcosts are almost two times better. This means that at this moment biobased composite offers a better environmental solution than glass-fibre reinforced polyester.

For aluminum, the shadowcosts are much higher, therefore when structurally possible, aluminum replacing by biobased composite would be a good option.

The shadowcosts of biobased composite can be improved by further development of the resins and coatings. These can be made more biobased, removing harmful solvents.
Other options are to decrease the density or to increase the youngs modulus which decreases the necessary thicknesses.

The thickness can be decreases by improving the bending stiffness in a different way, such as increasing the core thickness of a sandwich element or increasing the dimensions of a hollow profile.

The colored table on the right shows how many times the shadowcosts of biobased composite are higher or lower (when -) than the showed materials, regarding the necessary thickness based on the difference in youngs modulus. The second column shows this aspect based on the difference in bending stiffness of the researched concepts. The third column shows what the shadowcosts of biobased composite should become to have the same environmental impact as those materials.

Future methods to improve the shadowcosts are:

- **Explore the recycling methods**
Recycling methods decrease the shadowcosts because the materials performs longer.

- **Decrease the weight**
This mainly applies to the resin which causes most of the weight.

- **Improve the resin**
When toxic solvents are removed from the resin and the biobased content increases, the shadowcosts decrease.

Geometry

The geometry is very important for the weight and shadowcosts of an element in biobased composite.
The thinner biobased composite can be applied, the lower the weight and the lower the shadowcosts.
The bending stiffness depends on the geometry of the element, and can be significantly improved when for example:

- **Ribs** are applied
- The element is double curved (not researched)
- The **dimensions of a hollow profile are increased**
- A **sandwich element** is produced, preferably with a thick core

Material	Youngs modulus	Bending stiffness	"Needed" shadowcosts
Steel	3.5	1.3	0.17
Wood	27	22.5	0.01
GRP	1.01	-2	X
Aluminum	-4.7	X	X

Material	Density (kg/m3)	Shadowcosts (€)	Youngs modulus	Shadowcosts/m2
Wood	530	€ 0,02	13	0.17
Steel	7870	€ 0,17	210	1.33
Aluminum	2700	€ 2,65	69	21.47
Glassfibre-reinforced composite	2000	€ 0,76	69	4.56
Biobased composite	1115	€ 0,23	11,4	4.61

Facade products

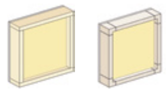
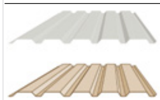
The comparison between the original facade products and their biobased composite concepts show some opportunities and some shortcomings of biobased composite.

The products in which the material is used thin and/or in small dimensions show opportunities in terms of weight reduction or shadowcost reduction.

The element-sized products such as the sandwich panel and the trapezoidal panel show high weight and therefore high shadocosts. These options do not offer benefits over their original product other than a biobased product which prevents depletion of finit resources.

External application of biobased composite requires a coating to prevent quick degradation. This coating is at this moment environmentally harmful and therefore increases the environmental impact.

Which products can be applied best depends on the specific situation and the requirements of the customer. For example a timber frame structure has better circular options, but requires more manual work during construction which increases the production time. A sandwich panel is easier to produce, however has a higher environmental impact and a worse circular scenario.

Product	Weight (kg)			Shadowcosts (€)			Circular scenario	
	12.15	25.24	20.97	3.52	10.12	9.10	10	10
	36.63	23.21	28.1	2.38	5.34	6.46	12	12
	22.22	10.53		0.75	2.42		12	12
	8.69	16.9		3.22	4.05		10	10
	81.00	7.81		0.81	1.81		10	10
	1.66	4.19		4.25	1.24		10	10

Facade concepts

The results from the calculations of the case study facades and their biobased composite concepts show which concepts show improvements and therefore which concepts show potential.

When constructing a biobased composite sandwich element, the weight is, taking the actual bending stiffness into account, 1.4 times higher. Besides this the shadowcosts are also 1,4 times higher.

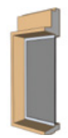
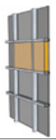
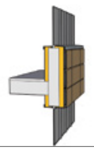
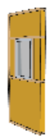
Biobased composite shadowboxes or glazed spandrels in a curtain wall weight less than a third of the original element and have a significantly lower environmental impact.

A load-bearing concrete parapet facade can be cladded with biobased composite cassettes. The constructions weight decreases more than 11 times, including highly optimized insulation, while having about the same environmental impact.

A timber frame structure can be produced with hollow profiles of biobased composite. The weight decreases 2 times regarding the bending stiffness but the shadowcosts increase 1,4 times. However the circular scenario is very good.

The circular scenario of the sandwich panel is quite bad since it cannot be adapted or recycled. The glazed spandrel and timber frame structure both have a long lifespan and can be reused, adapted and recycled. The parapet facade can also be reused, adapted and recycled.

Smaller parts of the curtain wall, parapet facade and timber frame elements can be replaced while damaged, which increases the life time of the overall facade. For a sandwich element only complete elements can be replaced.

Concept	Weight (kg)	Shadowcosts (€)	Circular scenario
	46.63 113.58 65.37	26.17 41.99 35.83	
	29.09 11.32	4.01 2.60	
	213.22 18.65	2.87 2.73	
	42.11 27.41 20.72	2.20 4.75 3.16	

Best concept

It is very difficult to establish the best concept in general. The choice for the best application depends on the specific situation and the requirements of the costumer. For example a timber frame structure offers a good circular scenario`s, while for an easy to produce element (when circularity or environmental friendliness is not very important) a sandwich element might be more desirable.

"What is possible with biobased composite when used for a circular facade design?"

When designing with biobased composite, the concepts in this report can be used as guideline for a high performance facade.

"Is biobased composite an environmental friendly material?"

At this moment, the shadowcosts of biobased composite are a tiny bit higher than those of glass-fibre polyester composite. This means that the environmental impact of biobased composite is still quite high. Right now the biggest advantage of biobased composite is that it is produced from fast growing fibres and party agricultural-waste-based resin, and therefore spares scarce raw materials.

"Can biobased composite offer designers the same options current materials offer?

The comparisons between the common used facades and the concept facades showed that in theory is it possible to exchance common used materials for biobased composite. While calculating the bending stiffness, for some materials the weight and shadowcosts decrease, however compared to other materials they increase. Besides this, there still is much work to do to get from designing with biobased composite to actually building with it. More testing, designing and producing needs to be done before high quality facade elements can be made, especially ones which meet the safety regulations. However, regarding the information in this research, it seems very well possible.

Table 8.1 | Necessary increase in shadowcosts to compeet with material
Table 8.2 | Shadowcosts per sqare meter material regarding youngs modulus
Table 8.3 | Summarized product results
Table 8.4 | Summarized facade concept results

Different design aspects influence the environmental impact of a biobased composite element. The shadowcosts of biobased composite do not compete with most materials at this moment. The shadowcosts should be improved.

Biobased composite offers mainly an improvement regarding the scarcity of raw materials, however requires more research and development before the material can actually be applied safely.

8.2.1 | Material

1. Shared information
While starting up this research, it became clear pretty quick that little information on the material itself was available. Most information was vague, in terms of "has a high strength-weight ratio" and some testresults, such as of fire-safety tests was confidential and therefore not available. For the development of the material, researcher would benefit very much from shared information.

8.2.1.1 | Material development

1. Increase biobased quantity of resin
The material needs further development in terms of biobased quantity. The resins need to be improved to compeed with wood in terms of environemental impact.

2. Environmental friendly coatings
Coatings are at this moment not biobased avaiable. Instead of natural and vegetable, they are very toxic and harmfull for man and the environment. The picture ob the right was taken when coating the samples using DD-laquer.
A natural based non-toxic coating could improve both the environmental impact as the workability of the material, because right now the coating causes a danger for the applicants.

8.2.1.2 | Testing

1. Fire-safety tests
Fire safety is an important aspect that highly defines wheter a facade is safe to use, needs far more testing and research. Unfortunately reliable fire-testing requires a full sized element of the specific facade desing, which is only possible when the design is completely elaborated.

2. Accelerated weathering over a long period
The weathering test performed so far don`t cover the accelerated weathering for a long period including UV-radiation. Many defects appear after 1,5 years, and a simulation for roughly this time including UV-radiation has not been carried out yet.

8.2.2 | Recycling

1. Recycling coated element
Recycling of biobased composite has only been tested for one non-coated element, while the effect of coated elements are just as important since external applications require a coating.

2. Degradation of fibres
So far the experiments on recycling biobased composite did not include inspecting the degradation of the fibres. Allthough this is not the most urgent part to recycle, since fibres grow, it will be nice to know the effects of temperature and an alkaline environment on natural fibres.

3. Separation of resin and catalyst
It has been proven that biobased composite can be taken apart. However the next step, which is decisive for the application of a recycling cyclus on large scale, has not been tested yet.

The resin and catalyst need to be separated, before the resin can be inspected. This process needs evaluation and testing by an biochemicus. Even when this is proven possible, there might be too many bondings in the epoxy broken, for which a re-esthering process should be applied. However this should be tested too. To learn if all steps are possible and if the endproduct is worth performing this cycle, an extensive research is needed which should preferably be started before the material will be used in large quantities.

8.2.3 | Durability

1. Tests
The preformed tests were indicative tests. More exact tests should be performed to establish more reliable data. The exact estimated lifetime of biobased composite requires extensive testing and practical results from an actual building situation. This requires more time and investing.

2. More samples
To accurately test the compared aspects, more samples should be tested. At least five samples are required by most test-standards. Since there was a limited amount of material available, these tests were performed with less samples.

3. Different machines
To get around deviations caused by the test machines, different machines should be used, for which the results should be compared.

4. Longer testperiod
The results of the warmth-cold cycles test are not very different from the control group. For this test, an existing test standards was followed, but when the warmth-cold cycles are performed longer, the results might be more interesting.

5. Test with UV-radiation
Finally, all tests were performed without UV-radiation. Since this is a very important aspect for accelerated weathering (according to one of the specialists of SKG-Ikob an indispensable aspect) this should be tested more extensively too. At this moment, the best solution is to apply a UV-radiation blocking coating, but if this is really necessary is not clear. If the exact influence over time is proven, for some applications a coating could be unnecessary, which could decrease the environmental impact.

8.2.4 | Design and calculations

1. Further calculations
The design options have now been approached in a conceptual way. Therefore for example no structural calculations have been performed other than the calculation of the bending stiffness. To establish whether mounting anchors or bolt connections will be strong enough far more calculation are needed.

2. Broader scope
The research has focussed preliminary on office buildings in the Netherlands. To show if these results are applicable on European or worldwide scale requires more research. One thing is that different countries handle different standards. Besides that weather influences can differ a lot. In the Netherlands wind and water are usually the main problems, however in some countries sun or earthquakes are far more important.

3. Further detailling
The concepts serve as a design direction, but need more elaboration and detailing before more specific numbers of weight insulation value can be provided.
One example is that for cladding concepts the secondary structures are not taken into account, while they can be of great influence on the total amount of material and therefore the environmental impact.

4. Further design
Besides that, for example the sandwich element has very poor circular scenarios. This element can be further designed to improve the circualr scenario.

8.1 | Necessities to safely apply the coating
8.2 | Samples sawn and coated for the accelerated weathering tests

8.2.5 | Additional recommendations

1. Specific building parts
The question wheter windows or curtian walls can be constructed out of biobased composite might be interested to answer. This research concerns a more structural approach together with a termal-bridge simulation.

2. Structural tests on different matrices
For a designer, it would be very helpful when different material combinations, meaning fibres and resins, are being tested for their structural performance.

In software which calculated the strength of different fibre configurations, natural fibres are not available. Therefore the difference between fewer different fibre configurations is difficult to estimate, while this is for a detailed design very important.

3. Shadowcosts
Even while being very lucky to have entrance to the Nibe EPD database, some shadowcosts of materials are not available. The solution in this research was to find the most similar material and use that for the shadowcost calculation, however this decreases the accuracy of the research. To increase the ability to accurately calculate shadowcosts, the database needs further completion.

8.2.6 | Further research

Since some very common used building materials will run out very quickly, and also petrochemical based products are estimated to be finish soon, new building materials are needed. The building industry is tend to increase, therefore research into possibly new building materials should already be started.

The materials lead, zinc and copper are estimated to run out in the next 40 years, but when petroleum runs out, also petroleum based materials are no longer available.

The material researched with a quite large stock, aluminum, turns out to have a high environmental impact. Wood has a very low environmental impact, when managed sustainable, however grows quite slow.

Regarding the difficulties faced when setting up the indicative materials tests, the fact that no reliable test standards for new materials exists and the expected future demand for new building materials, initializing the development of new building materials seems a necessity.

Regarding the conclusions drawn on biobased composite, and especially the results of the accelerated weathering tests, biobased composite seems to offer good opportunities for further development. The environmental impact can be decreased by further improvement of resins and coatings. The great benefit of biobased composite is that the fibre simply grows. As long as it doesn`t compete with the food chain, those fibres can be grown endlessly. When the resin is made 100% natural based, the same applies.

Biobased composite could offer a solution to:
• the scarce raw material problem,
• possibly to the landfill loading problem
• definitely to the use of raw materials by the building industry
However to actually give the material al fair chance, some extra research should be performed, as explained beneath.

(Bio)chemical:
• Extensively research into the possibility of recycling biobased composite on large scale. To do this different catalysts should be tested and the focus should be on the separation and reusability of the resin.

• Research on resin improvement, if a higher natural based content can be reached, the shadowcosts can drop significantly.

• Research to improve the coatings, if a higher natural based content can be reached, or the amount of toxic solvent can be reduced, the environmental friendliness of the coatings for biobased composite can improve a lot.

Facade technical:
1. Structural calculation:
• What can be done with biobased composite in terms of structural profiles?
• How is the wear resistance of biobased composite?
• How is the strength of bolted connections?

2. Thermal simulations:
• How is the thermal transmittance? Can for example curtain wall systems or window frames be made from biobased composite?

3. Circular building:
• How can the circular scenarios of the concept facades be improved?

9

REFLECTION

9.1.1 | First design approach

When starting the design, a very conceptual approach was chosen. In study projects a specific situation and statement of requirements were mandatory. Therefore the design was from the beginning restricted to certain requirements which created design guidelines.

In this design for common used office buildings in the Netherlands, there were no restrictions other than the standard requirements for facades and common used dimensions.

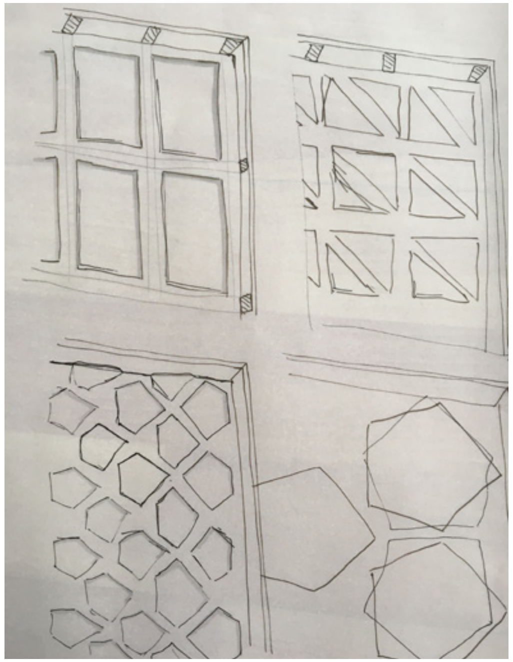
9.1.2 | Second design approach

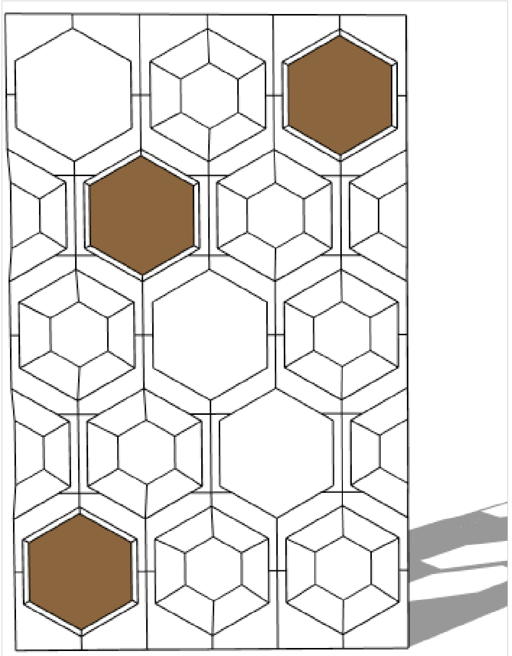
After the conceptual approach, which turned out to be far too “open” to lead to a technical well thought through design, a more technical approach was chosen. Common used dimensions in office buildings formed the lead in an element facade built up using trapezoidal panels.

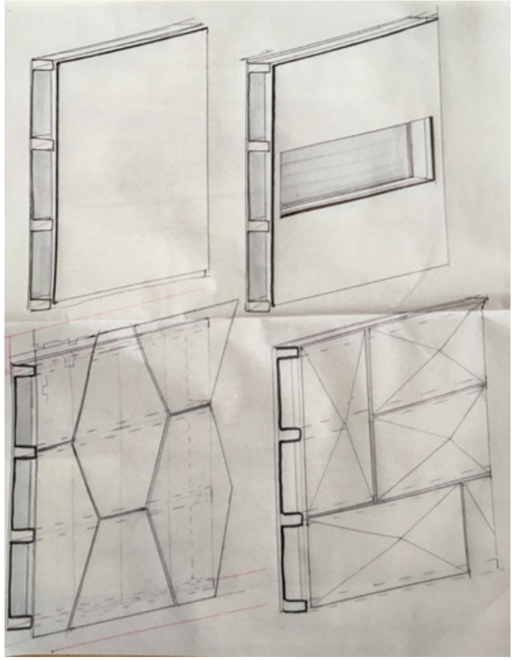
Insulation was applied on the inside, and while the structural integrity was provided by the trapezoidal panels, any cladding could be applied on the outside.

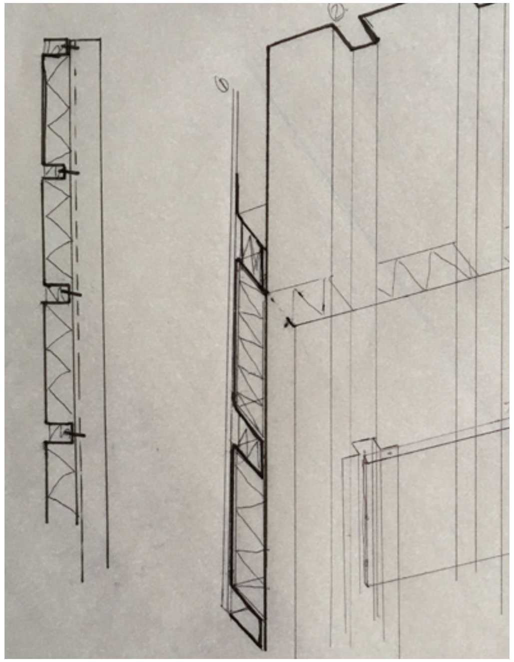
This approach soon ran into its shortcomings, since many different standardized details were being assembled to maintain qualities like water tightness and thermal insulation.

Besides that, the question arose whether this was the most optimal design using biobased composite, regarding the material properties.









9.1.3 | Product concept approach

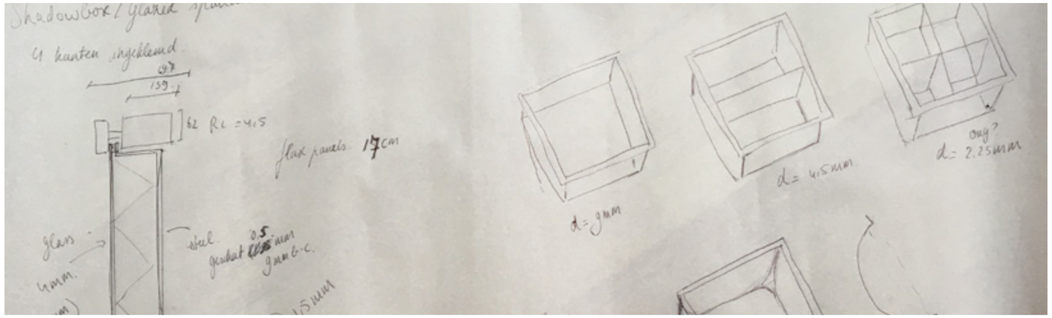
To get a grip on the possibilities of biobased composite, five frequently used building products were transformed into a natural based product with biobased composite as structural material.
The necessary new dimensions were calculated and an impression of the new product was made.

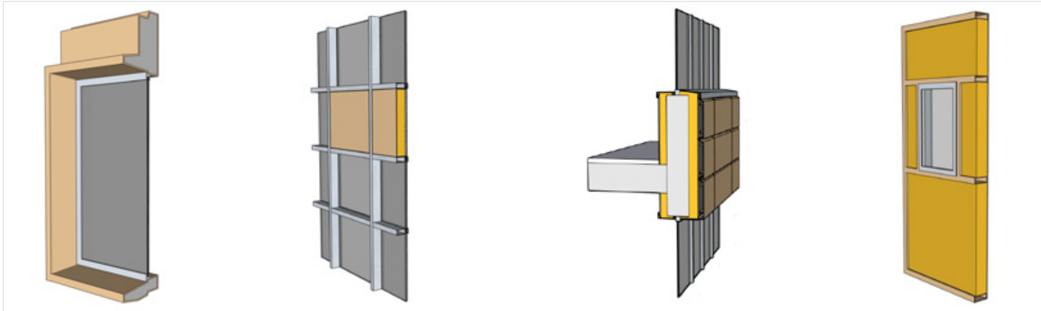
To analyse the impact on weight, shadowcost, insulation value and circular scenario, these aspects were for each element evaluated.

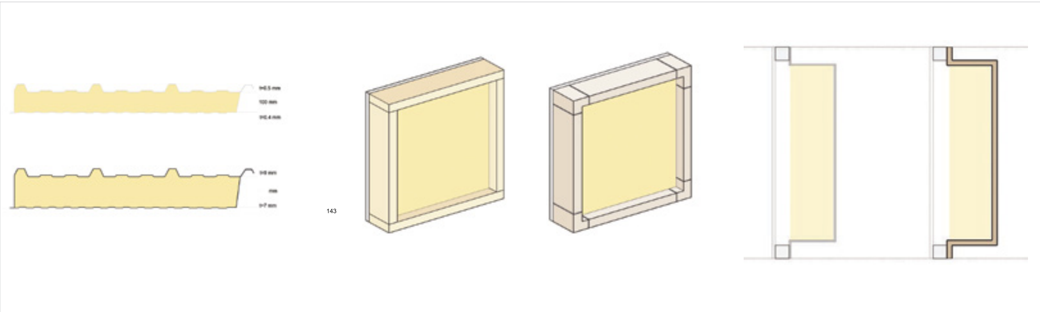
9.1.4 | Final concept designs

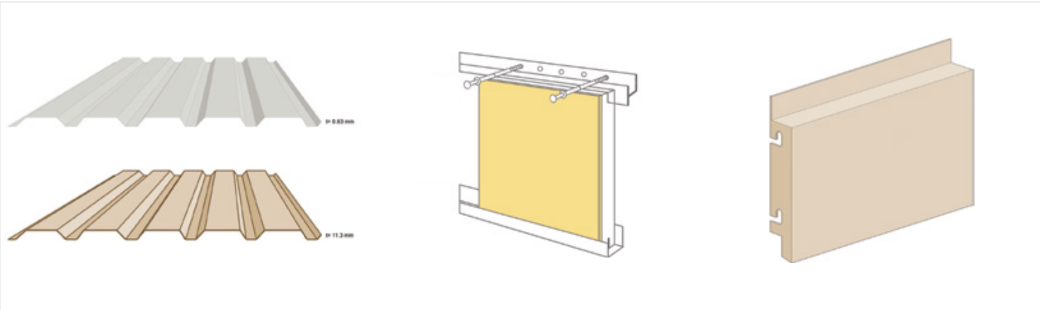
The results from the product survey led to a solution for all four case studies of common used office buildings in the Netherlands.

These concepts and original facades were again evaluated in terms of weight, shadowcosts and circular scenario to conclude whether a biobased composite facade design offers improvements over its original design.





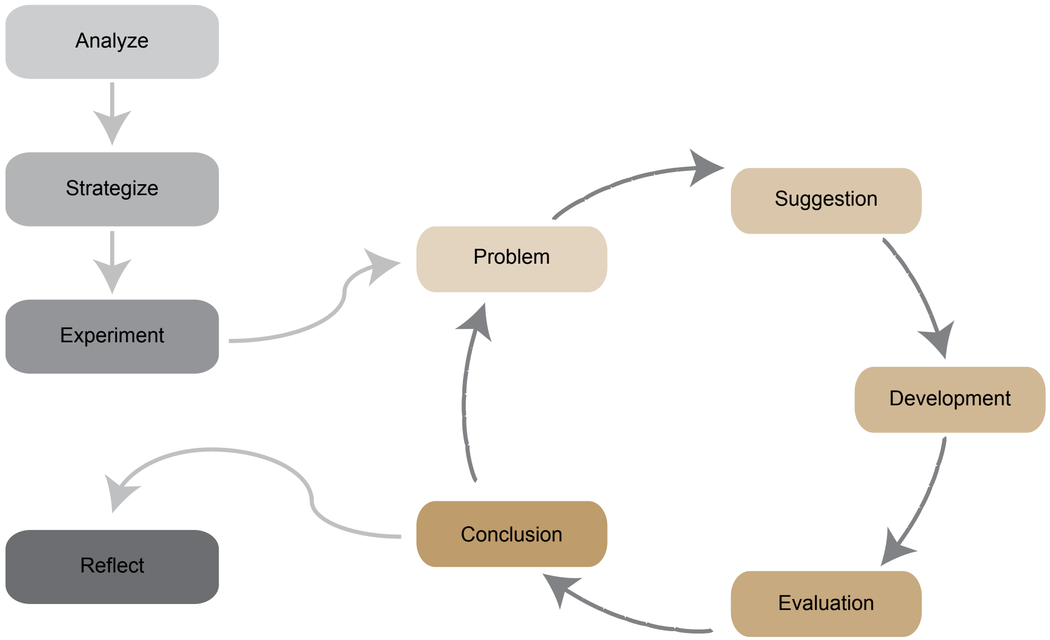




9.1 | Conceptual sketches
9.2 | FIrst design approach in sketchup
9.3 | Second sketch attempt
9.4 | Element made out of trapezoidal panels
9.5 | Calculations and design of natural based products
9.6 | Facade products
9.7 | Facade caldding products
9.8 | Final concept designs
9.9 | Pile of sketches

Four design phases can be defined.
At first a very conceptual approach was chosen but this design was too “free”. Then a more technical approach was combined with strict dimensions. The question arose whether this led to the best option using biobased composite, therefore first common used building products were transformed into natural based products with biobased composite structural elements and evaluated. The outcome of this survey led to four designs for case studies.

9.2 | REFLECTION



3. Pre design

Pre-design:
How can the façade be adapted to meet the facade quality demands while keeping the circular aspects and material properties into account?

What are the effects of these adjustment for the design?

4. Design

What is the best biobased circular modular façade design regarding the quality demands?

How can de facade be produced and installed?

How does the façade relate to other facades in terms of lifetime, costs, production time, waste, CO2 emission and energy.?

9.10 | Abstract view of the proposed research method

9.2.1 | Research outline

From the beginning the aim of the research was to gather information to support a final design. Biobased composite is a developing material which hasn`t been tested or used much yet, therefore information on the subject was very limited. This made de research as much difficult as challenging.

The other part of the research question, to design a circular facade, made the research and especially the design part far more complicated. The few example projects that have been designed with biobased composite are not circular because this was not a requirement.

The method showed above was proposed during the P2 evaluation. The idea behind it was that in the experiment phase, the part were the design should take place, a continuous cycle of problem solving and development took place which should result in the “best” design option for both biobased composite as circularity, combined in a facade design.

Why was this approach applied? Information was gathered from various directions and the results would be used as a foundation for a final design. These two steps would form the analyse and strategize after which the experiment should start. This experiment consists out of a series of developing, evaluation and adapting the design until the “best” design was found.

9.2.1.1 | Problem

During the research it turned out that is was very difficult to draw conclusions which would lead into one direction and which could be used as design guidelines. All information was, until then, gathered with the idea that one final design would respond to all this information.

When starting the design, due to a lack of restrictions it was very difficult to define any design guidelines.
For this reason a more technical approach was chosen which first looked into the optimal application of biobased composite in consultation with circularity and then to which options fitted four relevant case studies best.

9.2.1.2 | Research questions

This change in approach directly changed the second part of the research questions. The research questions regarding the design could no longer be answered. These questions were therefore changed in chapter 6, which introduction substantiates this shift.

3. Product concepts

What are common used facade elements?

How can biobased composite be used in these elements?

What is the effect of the change in material use to the weight, schadowcosts and circularity of the element?

4. Final concept design/Case study.

Which variant does suit each ot the case study facades best?

How can this variant be applied on the facade?

What does this mean in terms of weight, insulation value, schadowcosts and circularity compared to the original facade?

9.2.2 | Adapted method

As shown above in the text, the new method focused first on common applied products to establish the possibilities of biobased composite and their effect on the products properties.
These results were used to establish which concept designs could be defined for four case studies. These facade typologies were defined to represent common office buildings in the Netherlands.

The research results shifted thereby from being the foundation for one final design to input for several facade concepts.

9.2.3 | The process

While starting up the process, there were several parts of the research which needed direct action to be able to gather the information in time. Two main parts were collecting (scientific) information and preparing material tests.

9.2.3.1 | Gathering information

To gather information on specific material properties from the few companies who had carried out tests, many institutions have been contacted. However, by emailing or calling authorities with a question concerning a graduation research the main answer is “the information is confidential”, or no answer at all appears.

An approach that worked far better is approach people in person at a fair or conference.
Much information was later on handed by employees of DGMR who had visited conferences providing very useful information.

Although a strict planning was set up at the start of the graduation, unforeseen aspects such as new useful information turned up at later stages.

9.2.3.2 | Material tests

This part was divided into recycling tests and ageing tests. The material tests took rather longer than expected.
At first a research plan for recycling test was set up, but unfortunately the authority who would help suddenly backed out. After discussing the plan with another scientist, it turned out to be too complicated to generate any useful results. The recycling tests were neglected.

The planned accelerated ageing tests were also delayed since no institution in the Netherlands had the required QUV machine available. Eventually another test machine was found, which would provide different but useful results. The material tests were performed at the last possible moment since the duration of one of the tests was a full month. Even though, it is very nice to finally have the chance to perform the tests and add a part to the overall knowledge of biobased composite.

9.2.3.3 | Planning

At the start of the graduation an overall planning was made including week tasks and week goals. This planning would make it easy to keep eye on the progress but also to grant all action with an appropriate amount of time.

This planning was off course several times changed. It was also affected by the change in final product, for which the actions changed.
The problems finding information and finding the facilities to perform material tests also influenced the planning.

Overall, the planning was very useful and helped the project both by starting up quickly as by structuring it. It has changed several times during the process due to different factors but the broad lines remained the same.

The original research focused on one final design. During the research it turned out that the results could be better translated into different concepts than into one design. The design approach was changed and a more technical and conceptual approach was used. This did influence the research questions.
The overall planning as set up at the beginning of the project has changed several times due to different influences, however the broad lines could be maintained.

9.2.4 | Theme of the graduation studio

The theme of the graduation lab "Sustainable design graduation studio" implies that the research should add something to the knowledge about sustainability in any form.

Since the increasing landfill and pollution are actually a real concern of mine, also outside the graduation studio, a possible (sub)solution to this problem interests me. After researching a former composite facade project of DGMR during my internship there, the possibilities of composite arose my interest. The complex production process and the fact that the possibilities can still be further explored make room for technical innovation.
Combining these aspects has placed me on the path of biobased composite, a composite which is reinforced with natural, growing fibres. Combined with circularity, which regards the whole life cycle of an element, most aspects of a facade that can be connected to sustainability are covered.

9.2.5 | Wider social context

One quote forms the basis of the problem definition. "The Dutch building industry produces annually twice as much waste as all Dutch households together, which increases the burst of landfill loading" (SUEZ, 2016).

Waste and landfill loading are problems that eventually will concern everyone. When the building industry is able to improve its material-management and decrease the amount of waste, this will decrease the problem significantly.
Large steps are necessary to improve the end-of-life scenarios significantly, and waste separation is also not commonly applied. When products are at least designed to be reusable, demountable or otherwise recycleable or compostable, it makes it far more easy to actually do so, which is a good first step.
Therefore I wanted to make a first step designing the facade in the most circular way possible.

Another problem concerning everyone, is the end of finite resources. Some resources are already scarce and some commonly used materials will run out. When this happens it is very comforting if replacing possibilities have been researched already. Therefore biobased composite would serve a good example of an "infinite'' material, because it simply grows.

To continue the above mentioned statement, another problem was found during the research. A personal difficulty when defining the test environment turned out to be a worldwide problem: The certification of new materials.

Long-term applied materials such as concrete and brickwork all have certain quality certificates, and their laboratory test methods have been developed linked to the results of long-term degradation in real life situations.
Contractors or investors have, very understandable, a great preference for these materials which have proved themselves over the past hundreds of years. The problem is, how can new, possibly very sustainable materials, acquire their position on the market when no one is interested in taking the first step and test their qualities?

The laboratory tests for accelerated weathering are not defined for other materials than the widely accepted ones. Since the test results are linked to practical results it is very important to take a first step and apply these new materials, but also to share the results of these first practices. Only when information is shared and extensive practical and laboratory tests are carried out these materials will stand a change on the building market. Regarding the depletion of resources of a great deal of common building materials and the immense amount of waste produced by the building scene, innovation seems just the necessary thing.

9.2.6 | Research and Design

From the beginning of the graduation, and even before that, I had the idea that the final result of my graduation should be one final design, elaborated into details.
One reason for this was that detailing facades is the part that I like most during my Masters. Besides this, the graduation has taken place in cooperation with DGMR, who are specialized in facade technology and have a lot of experience supervising building detailing.

To be able to design a facade using a new material I knew little about, I started with an extensive research. Since few information is publicly available, this included calling and emailing institutions up until Italy. Quite some information is researched concerning bridges, however the safety requirements of a facade focus on very different aspects. For example fire-safety and thermal and acoustical insulation are main elements for a facade. Information about these aspects was very limited, and in many cases not publicly available. Some information I have only found through asking the entire office of DGMR, after which employees provided me with very useful databases and conference papers.

Some information however does not exist yet.
The fire-safety of an facade element can only be tested when the whole element in its actual size is built and tested using a huge oven. This was not possible during this research because I firstly lack the resources to build such an element and besides that the time and resources are far too limited. On aspects like this nothing else than substantiated guesses can be made.

My plan was to gather all the information, and weigh all possibilities of the aspects such as production methods and connection methods, to find a set of optimized design parameters which would lead into a facade design. However, there were still many different options after doing this.

The approach of building-up knowledge to form a basis for the design decisions worked to a certain level, but then a lack of knowledge on the specific possibilities of biobased composite application appeared.

A different approach was defined using examples of building products to get a grip on the possibilities of biobased composite. For this, more research was done in order to make a design. Also for the final design the case studies were defined and analyzed to serve a concept.

The main method for this graduation research was research through design. The information found was all collected to serve as background information on material properties or possible concepts, and to explore the possibilities of the material. Off course while designing, minor problems occurred which needed to be answered, and therefore research through design has also taken place.

9.2.7 | Expectations

When starting a scientific research, an objective attitude must be adopted. However, when starting to research a subject you are enthusiastic about, it is almost insurmountable not to wish the research results are positive.

9.2.7.1 | Result

The result I had in mind was a final design which responded to the shortcomings of the material and therefore made it possible to be used for a high performance facade design.
However the result itself had changed. The new concepts could still show that biobased composite was a very good option, but because the approach was different and one to one compared to existing designs, the shortcomings of the material became very clear as well.

9.2.7.2 | Reflection on result

These results were the objective results from the research, however they showed that biobased composite is not by far in all applications desirable.

These findings are off course very valuable, however they were not as positive as hoped for when starting the research.

My personal impression is that the material can still be very valuable, but need extensive research to be optimized and generally accepted in the building environment. The last aspects probably needs time too.
It is important to use biobased composite for the right purposes, but when the shadowcosts can be reduced I believe it will offer new possibilities.

9.11 | Cotton
9.12 | Dried flax

The research connects to the theme of the graduation studio by adding knowledge on renewable materials which can lead to sustainable solutions. The wider social context is mainly addressed by the fact that a solution to the increasing pile of landfill was approached.

The research method was mainly research through design.
The research results were not as positive as hoped for when starting the research.

10

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Chapter 3
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7.97 | SBR detail

Chapter 8
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Chapter 9
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Chapter 10
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Chapter 11
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10.1.3 | Graphs

Graph 2.1 | Tjeerdsma, 2014. p.12

Graph 4.2 | Own graph, based on based on Gkaidatzis, R. (2014). *Bio-based FRP structures: A pedestrian bridge in Schiphol Logistics Park* (master thesis). *Retrieved from uuid:81cf-de58-90dc-4bd0-9506-01ec1d85839b*

Graph 7.1 | Own graph

Graph 7.2 | Own graph

10.1.4 | Tables

Table 2.1 | Results of tensile test Van der Linden (Van der Linden, D. (2017). *The Application of Bio-Based Composites in Load-Bearing Structures* (Master thesis). *Retrieved rom uuid:-e6a03c90-de45-44e7-b2f6-74cf7b7d79d5*)

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Table 4.1 | Own table, based on results found using CES EduPack 2016

Table 4.2 | Own table, based on results found using CES EduPack 2016

Table 4.3 | Own table, based on results found using CES EduPack 2016

Table 4.4 | Based on the following webpages:
www.bouw-energie.be/nl/bereken/r-waarde-isolatie
www.kingspaninsulation.nl/producten/kingspan-therma.aspx
www.ekbouwadvies.nl/tabellen/lambda.asp
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www.ekbouwadvies.nl/tabellen/lambdamaterialen.asp
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www.bre.co.uk/filelibrary/pdf/projects/low_impact_materials/IP15_11.pdf
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www.sheepwoolinsulation.ie/products/premium_insulation_technical.asp
naturalhomes.org/img/ricehullhouse.pdf
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www.ausurethane.com/pir.html

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www.rfcafe.com/references/general/density-building-materials.htm
www.psyclops.com/tools/technotes/materials/density.html
www.engineeringtoolbox.com/thermal-conductivity-d_429.html

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Table 6.1 | Based on Van der Linden, D. (2017). *The Application of Bio-Based Composites in Load-Bearing Structures* (Master thesis). *Retrieved from uuid:e6a03c90-de45-44e7-b2f6-74cf7b7d79d5*

Table 6.2 | Own table, based on results found using CES EduPack 2016

Table 6.4 | Own table, based on based on Bouwbesluit:

Table 6.5 | Based on Nibe. (n.d.). Nibe EPD application. Retrieved from https://www.epdnibe.com/app/

Table 6.6 | Based on Nibe. (n.d.). Nibe EPD application. Retrieved from https://www.epdnibe.com/app/

Table 6.7 | Based on Van der Linden, D. (2017). *The Application of Bio-Based Composites in Load-Bearing Structures* (Master thesis). *Retrieved from uuid:e6a03c90-de45-44e7-b2f6-74cf7b7d79d5*

Table 7.1 | Based on table 6.2 and Nibe. (2017). Milieuclassificaties. Retrieved from http://www.nibe.info/nl/members

Table 7.10 | Own table, based on results found using CES EduPack 2016Table 7.3 | Own table