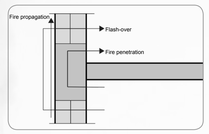
HOW TO DESIGN AND MANUFACTURE A CIRCULAR BIOBASED COMPOSITE FACADE

FIRE-SAFETY



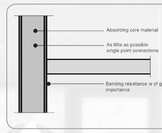
There are three types of fire loads:
- **Fire penetration**
- **Flash-over**
- **Fire propagation**

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.
☐ **Fire proof retention wall**

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.
☐ **Continuous fire-proof layer**
☐ **Fire-proof parapet**

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**

SOUND INSULATION



Requirements
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 40 dB(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.

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".

☐ **Mass**
☐ **Sandwich construction**
☐ **No single point connections**

THERMAL INSULATION

Insulation materials
In the table below 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.

Because 4,5 m2·K/W is the required minimum, an office building could be insulated better, which decreases the energy consumption of the building. Therefore the necessary thicknesses are also shown for 6,0 m2·K/W.
Both petrochemical based insulation as biobased or more environmental friendly insulation materials are showed in the table.

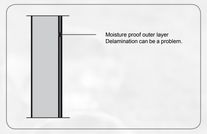
Important is the thermal conductivity of a material, as well as the density of the material. The table shows the necessary thicknesses of insulation materials to obtain a thermal insulation of 4,5 and 6,0 m2·K/W. Besides this, the table shows the consequent weight per m_2.

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.

Table thermal insulation values petrochemical and natural based insulation

Insulation	λ (W/m*K)	Rd	d (mm)	Density (kg/m3)	Weight(kg)	Rd	d (mm)	Weight (kg/m2)
Rockwool	0,032	4,5	144	100	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
Cellulose	0,038	4,5	171	56	9,58	6	228	12,77
Schwepwool	0,035	4,5	158	22	3,47	6	210	4,62
Rice hulls	0,3	4,5	1350	110	247,50	6	3000	330,00
Straw	0,26	4,5	1170	115	135,70	6	3000	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
Greenculate 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	3,19	6	126	4,23

WEATHER TIGHTNESS & APPEARANCE



Coating
Regarding the coating, the focus should be on water tightness, Therefore the most interesting test (by its test results) would be a water penetration test.
Also delamination could be a problem.

To be able to test the water tightness accurately, a water penetration test should be carried out. Since this was not possible, the assumption was made 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. NPSP advises to always coat an element for exterior application, both for water tightness and UV-radiation.
☐ **Coat elements when applied outside**

Color
Off course, when a different color than brown is desired, a color coating should be applied anyway. However the composition of this coating can possibly be different from coatings for water tightness and UV-blocking purposes which might decrease the environmental impact.

Delamination
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.

Coatings can provide:
- **Water tightness**
- **UV-radiation blocking**
- **Fire-safety**
- **Aesthetic properties such as color**

WEIGHT

Bending stiffness
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:
☐ **add ribs**
☐ **curve the material**
☐ **produce a sandwich element.**

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

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

Roughly can be assumed that the necessary thickness of biobased composite is 6 times the higher than that 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.

Weight
The graph underneath shows the weight according to the needed thickness to achieve the same strength as one millimeter steel, according to the ratio of youngs moduli.
How the bending stiffness can be improved, other than by increasing the thickness is explained in the section about "shape".

Weight per square meter

	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
Weight/m2	kgm2	7,9	9,1	20,07

SHADOWCOSTS

Table shadowcosts

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
Weatherring	€ 0,87	kg
Galvanizing (zinc)	€ 1,09	kg
Aluminum		
Aluminum (47% secondary)	€ 2,65	kg
Coatings		
Anodizing	€ 0,58	m2
powder coating	€ 1,50	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	€ 0,16	kg
Paint, acrylate	€ 0,34	kg
Paint, alkyd	€ 0,57	kg
Paint, strong groundf	€ 0,87	kg
Composite		
Glass fibre reinfroced plastic	€ 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	€ 0,85	kg
Flax fibre	€ 0,23	kg
Additional		
Gypsum board	€ 0,03	kg
Granite	€ 0,01	kg

Table shadowcosts per sqare meter material based on youngs modulus

Material	Density (kg/m3)	Shadowcosts (€)	Youngs modulus	Shadowcosts/m2
Wood	500	€ 0,02	13	0,17
Steel	7870	€ 0,17	210	1,33
Aluminum	2700	€ 2,65	69	21,47
Glassfibre reinfroced composite	2000	€ 0,76	69	4,56
Biobased composite	1115	€ 0,23	11,4	4,61

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.

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

This table shows how many times the shadowcosts should increse/decrese to compete with the materials, regarding the youngs modulus or bending stiffness.
Shadowcosts are calculated per kg weight. 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.

CIRCULARITY

Circular building principle
The circular building principles enhances "closed loop thinking", adaptive design and upgrading.
The aim is 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".

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)

New stepped strategy
The NSS (new stepped strategy) introduced 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 the research, a division was made between three aspect of the circular scenario of an element:

☐ **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.

☐ **Adaptability** concerns whether the part can be changed or upgraded, or parts can be replaced.

☐ **Recyclearbility.** This research does not concern the recyclearbility of other materials than biobased composite. To be able to measure the recycling possibilities, a division is made regarding the ability to separate the used materials.

Reuse was rated highest since this strategy requires the least additional energy and/ or material, then Adaptability and last recyclearbility.

MODULARITY & EFFICIENCY

Efficiency
For (cost) efficiency there are 9 design rules:
1. Minimize part counts
2. Eliminate threaded fasteners
3. Minimize variation
4. Easy serviceability and Maintainability
5. Minimize assembly directions
6. Consider ease of handling
7. Design for multifunctionality
8. Design for ease of production
9. Prefer modular design
Not all design rules are applicable to a circular composite design, therefore compromises might need to be made. The most important aspects are explained more detailed, for the explanation of the other rules see paragraph 4.1.

☐ **Minimize part counts**
Composite materials offer a good potential for part integration, which minimizes the need for assembly.

☐ **Easy serviceability and Maintainability**
Products should be designed in such a way that parts are easy accessible for assembly, disassembly- and inspection.

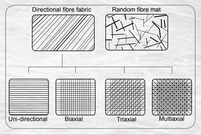
☐ **Minimize assembly directions**
While designing a product, it is important to think about the operations needed to attach different parts.

☐ **Consider ease of handling**
For smooth assembly and ease of handling, parts should not be heavy and not have too many curves.

☐ **Design for ease of production**
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 modulus, each module can independently be designed and improved without affecting the others. Besides this, replacement and assembly will be easy.

FIBRE



Fibre properties

Fibre	Density (kg/m3)	Tensile strength (Mpa)	E-modulus (Gpa)	Moisture absorption (%)
Flax	1400	1100	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

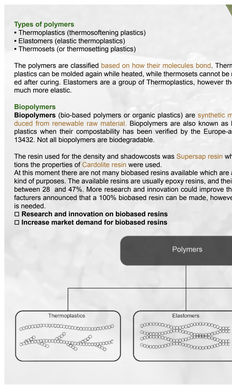
Types of fibres
- Inorganic fibres (glass and carbon),
- Polymer fibres (synthetic),
- Metal fibres and
- Natural fibres

In this research the focus was on natural fibres such as Flax, Hemp, Sisal, Jute, Ramie, Cotton and Coir.

Fabrics
Besides random oriented fibres, fabrics can be applied. 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. Oriented fabrics can provide strength in a particular direction, therefore adding different fabrics together can provide strength in different directions.

Both due to the good properties of flax as the fact that most information on biobased composite was about flax these fibres were used in all calculations. Thereby the provided test samples, see the section on durability, were made with flax fibres. Other fibres could prove to be just as good, however they require more research before this can be established.
☐ **Research on different natural fibres and combinations**

RESIN

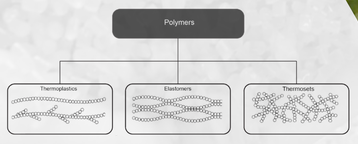


Types of polymers
- Thermoplastics (thermosoftening plastics)
- Elastomers (elastic thermoplastics)
- Thermosets (or thermosetting plastics)

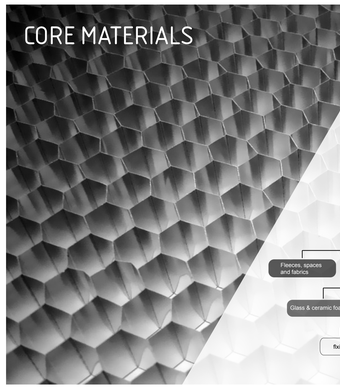
The polymers are classified based on how their molecules bond. Thermoplastics can be molded again while heated, while thermosets cannot be melted after curing. Elastomers are a group of Thermoplastics, however they are much more elastic.

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. Not all biopolymers are biodegradable.

The resin used for the density and shadowcosts was Supersap resin while for other calculations the properties of Cardolite resin were used.
At this moment there are not many biobased resins available which are actually useful for these kind of purposes. The available resins are usually epoxy resins, and their biobased content varies between 28 and 47%. More research and innovation could improve the resins quite a lot. Manufacturers announced that a 100% biobased resin can be made, however first more market demand is needed.
☐ **Research and innovation on biobased resins**
☐ **Increase market demand for biobased resins**

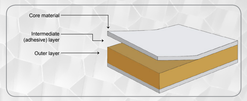


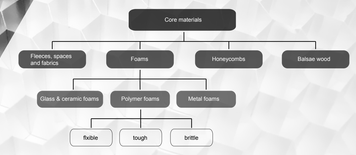
CORE MATERIALS



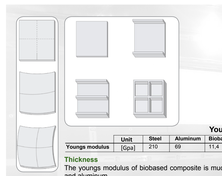
Sandwich constructions
Sandwich constructions are materials consisting out of two outer layers and one inner core material. These three layers are usually glued together.

Core materials
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.





SHAPE



Youngs moduli

	Unit	Steel	Aluminum	Biobased composite
Youngs modulus	[Gpa]	210	69	11,4

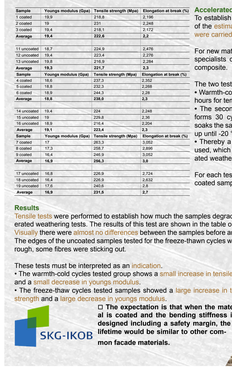
Thickness
The youngs modulus of biobased composite is much lower than that of steel and aluminum.
For the calculations the thickness of biobased composite is multiplied by the difference in youngs moduli.

Increase bending stiffness
Options to reduce the necessary material thickness and to increase the bending stiffness are to:
☐ **add ribs**
☐ **curve the material**
☐ **produce a sandwich element**
☐ **Increase the dimensions of a hollow profile**

The table below shows the calculated bending stiffnesses of the concept facades. This table shows that the thicknesses based on the youngs moduli are (highly) over dimensioned. For the specific calculations see chapter 7 of the thesis.

Element	ls (mm)	E (Gpa)	EI (Nmm2)	Weight (kg)	**Elite**	Density (kg/m3)	Stiffness (Gpa)	Shadowcosts (€)	**E/Shadowcosts**
Sandwich Steel PIR	9,03E+07	210	1,89E+10	12,15	1,56E+09	2870	1,65E+08	€ 6,10	2,71E+09
Sandwich biobased composite PLA	2,08E+09	11,4	2,28E+10	25,24	1,56E+09	1115	1,27E+04	€ 9,56	2,49E+09
Sandwich Sicowe	4,10E+08	69	3,83E+10	46,63	6,06E+08	1578	1,09E+05	€ 28,17	1,08E+09
Concept sandwich	7,00E+09	11,4	7,98E+10	85,37	1,21E+09	1115	1,27E+04	€ 35,63	2,23E+09
Wooden beam timber frame	5,47E+06	13	7,11E+07	12,21	5,62E+06	530	8,98E+03	€ 6,37	1,92E+08
8x x hollow same dimensions	1,97E+08	11,4	4,52E+07	12,27	5,68E+06	1115	1,27E+04	€ 6,34	6,92E+08
8x x hollow larger dimensions	7,51E+08	11,4	8,58E+07	25,2	3,40E+06	1115	1,27E+04	€ 4,57	1,87E+07

PRODUCTION TECHNIQUES

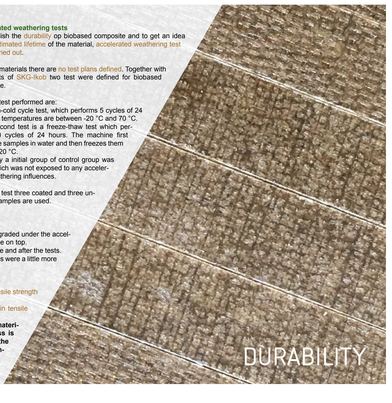


Process	Ex. batch size	Production rate (/hr)	Process	Spread	Costs	Strength	Size
Filament winding	> 10.000	0-10 /2	Filament winding	slow-fast	low-high	high	small-large
Hand lay-up	< 5000	0.1-0.5	Pultrusions	fast	low-medium	high (longitudinal)	small-medium CS
Automated lay-up	< 5000	0.1-0.5	Hand lay-up	slow	high	high	small-large
Spray up	< 5000	0.1-5	Automated lay-up	slow	medium	medium-high	medium-large
RTM	500-5000	1-5	Spray-up	medium-fast	low	low	small-medium
SMC molding	5000-10.000	10-80	RTM	medium	low-medium	medium	small-medium
			SMC molding	fast	medium	medium	small-medium
			Injection molding	fast	low-medium	low-medium	small

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. and 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**

DURABILITY



Sample	Youngs modulus (Gpa)	Tensile strength (Mpa)	Elongation at break (%)
1 coated	18,6	218,8	2,196
2 coated	19	231	2,248
3 coated	19,4	218,1	2,172
Average:	**19,4**	**222,6**	**2,2**
11 uncoated	18,7	224,5	2,476
12 uncoated	19,4	223,4	2,275
13 uncoated	19,5	216,8	2,284
Average:	**19,2**	**221,6**	**2,3**
Sample	**Youngs modulus (Gpa)**	**Tensile strength (Mpa)**	**Elongation at break (%)**
4 coated	18,6	237,1	2,302
5 coated	18,8	232,3	2,289
6 coated	18,9	244,3	2,29
Average:	**18,8**	**238,2**	**2,3**
14 uncoated	19,4	224	2,249
15 uncoated	19	229,4	2,35
16 uncoated	19,3	226,1	2,319
Average:	**19,1**	**233,4**	**2,3**
Sample	**Youngs modulus (Gpa)**	**Tensile strength (Mpa)**	**Elongation at break (%)**
7 coated	17	283,3	3,083
8 coated	17,3	258,7	2,898
9 coated	16,4	246,9	3,002
Average:	**16,9**	**296,3**	**3,0**
17 uncoated	16,8	226,9	2,724
18 uncoated	17,1	240,3	2,8
19 uncoated	17,4	245,8	2,8
Average:	**16,9**	**231,0**	**2,7**

Accelerated weathering tests
To establish the durability op biobased composite and to get an idea of the estimated lifetime of the material, accelerated weathering test were carried out.

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

The two test performed are:
- Warmth-cold cycle test, which performs 5 cycles of 24 hours for temperatures are between -20 °C and 70 °C.
- The second test is a freeze-thaw test which performs 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.

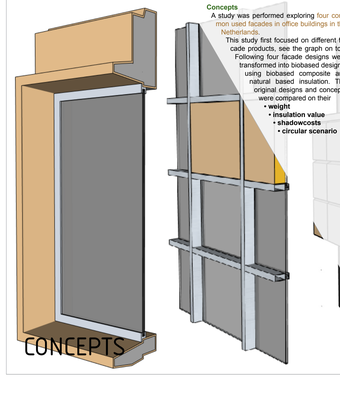
Results
Tensile tests were performed to establish how much the samples degraded under the accelerated weathering tests. The results of this test are shown in the table on top.
Visually there were almost no differences between the samples before and after the tests. The edges of the uncoated samples tested for the freeze-thawn 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 decrease in youngs modulus.

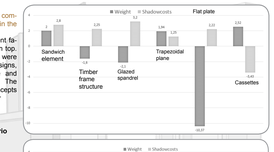
SKG-IKOB

☐ **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.**

CONCEPTS



Concepts
A study was performed exploring four common used facades in office buildings in the Netherlands.
This study first focused on different facade products, see the graph on top. Following four facade designs were transformed into biobased designs, using biobased composite and natural based insulation. The original designs and concepts were compared on their
- **weight**
- **insulation value**
- **shadowcosts**
- **circular scenario**



Conclusion
The graphs above show how many times the weight and shadowcosts increase or decrease compared to the original element. It shows that improvement in terms of weight and shadowcosts can be made replacing common used building materials by biobased composite, however not for all designs and materials. To improve the environmental impact the shadowcosts themselves should be improved too.
The cirpular scenarios turned out to be equal to those of the original elements.

A CIRCULAR BIOBASED COMPOSITE FACADE

Research project
This poster was made based on the content of the graduation research "A circular biobased composite facade: research on a high performance and circular application of biobased composite on a facade" as part of my graduation for the track Building Technology at the Technical University of Delft. The research is performed in cooperation with DGMR.

"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"

"Most construction waste goes into landfills, increasing the burden of landfill loading and operation"

Both quotes together define the problem definition.
The aim was 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 possibilities of a facade design mainly constructed out of biobased composite have been explored.

Marijn Flore Verlinde

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

TU Delft

DGMR Facade Technology
DGMR The Hague
Casuarieستraat 5
2511 VB Den Haag
dGmR

For more information and the references, see the thesis

"A circular biobased composite facade"
Verlinde, M. F. (2017).