



UNITIZED MEMBRANE ENVELOPE

FOR HIGH-RISE BUILDINGS IN
TROPICAL CLIMATES

MITCHELL EVERTS
4415531

UNITIZED MEMBRANE ENVELOPE

FOR HIGH-RISE BUILDINGS IN TROPICAL CLIMATES

MASTER THESIS, P5 REPORT

STUDENT: MITCHELL EVERTS
STUDENT NUMBER: 4415531

MEMBERS OF THE GRADUATION COMMITTEE:
FIRST MENTOR: PROF. DR. ING. ULRICH KNAACK
SECOND MENTOR: DR. REGINA BOKEL
DELEGATE EXAMINER: DR. IR. KLASKE HAVIK

DELFT UNIVERSITY OF TECHNOLOGY
FACULTY OF ARCHITECTURE AND THE BUILT ENVIRONMENT
MSC ARCHITECTURE, URBANISM AND BUILDING SCIENCES
MASTER TRACK OF BUILDING TECHNOLOGY

DATE: 02-07-17

ACKNOWLEDGMENT

The past months have been a roller coaster. With many ups and definitely some downs. This graduation was great to do, but it will probably also signify the last work I will ever do at the university in Delft. That's too bad, because I loved the assignments, the studying and all the people involved. However, my true career as an engineer will start.

I thought I would be better prepared after already completing a graduation project at a university of applied sciences, but that was another story entirely. The pressure to perform was even higher and the expectations as well, but I wouldn't have it any other way, because only this way a person learns and grows the most.

I would like to thank everybody that helped me reach this far, because without them the end result would have been vastly different. Starting with my main mentor Prof. Dr. Ing. Ulrich Knaack. At the start he said he would try to push me further and make my life so much about school that I will almost hate him for it. In the end, he did push me farther and his advice was always exactly what I needed, but I remember it fondly. I would also like to thank my second mentor Dr. Regina bokel. It was unfortunate that the project took a

turn away from her speciality in thermal building physics, but her advice and expertise on building physics and researching in general was very helpful nonetheless. Her support and willingness to help was also very much appreciated.

During the development of the design and consequent practical testing some extra expertise was needed and I would like to thank Dr. Ir. Martin Tenpierik for his time and effort in teaching me more about acoustics and arranging the lab and test equipment with which the acoustic tests could be held. Also a great thank you to Dr. Ing. Marcel Billow for giving us advice on building the mock-up, because without him the final mock-up would have probably collapsed as well.

Of course, I wouldn't dare to forget to mention all my fellow students and friends who gave me a helping hand or a kick under the butt when I needed. I want thank Antigoni Lampadiari Matsa especially. It was a pleasure to work with you. Even though it was only during the tests.

Last but not least, I would like to thank my parents and Yorick who supported me any way they could, intellectually, mentally and financially.

ABSTRACT

Membrane envelopes have been used at an increasing rate in recent decades and are still developing. However, they have not been used in unitized façade systems as a main building material. Even though their qualities have a high potential of improvement in this sector. They are far lighter, which means less powerful equipment can be used or larger panels can be build. This can further decrease build time, which is one of the main advantages of unitized facades. Membranes can also be more easily recycled, if used properly, and are therefore more appropriate for relatively short term use. A membrane envelope can provide great flexibility and mobility with less materials in less time. A façade that is according to sustainable design principles.

The objective of this graduation research is to design an adaptive unitized façade system, that utilizes membrane materials as a main building material, to be applied on residential high-rise buildings in a tropical environment. This to provide a more sustainable and/or more appropriate alternative compared to currently available systems, while still maintaining interior comfort and quality.

The proposed design was developed along a number of iterations. Each draft design used the advantages of membranes differently. However,

building physical requirements were difficult to meet until calculations showed that a membrane façade with a vacuum cavity could provide high acoustical insulation values, which is a property that most membrane façades lack.

Vacuum is difficult to achieve, especially with membranes. Therefore, a lot of effort has been placed in structural, thermal and acoustical performance of the membrane and the spacers that keep the membranes separated.

During development the final design has acquired a lot of negative properties in order to achieve the vacuum. The spacers and many membrane layers lower the visual comfort and the façade isn't more sustainable compared to common glass curtain walls. However, the qualities the façade does have, can make it useful in indoor applications or low buildings, with less wind force. It just isn't the most optimal solution for a high-rise building in Singapore.

Further research is absolutely necessary, because the acoustical qualities haven't been properly tested. Membrane materials and a vacuum cavity have never been combined for this purpose and can therefore act unexpectedly and have vastly different properties.

Table of contents

1 - INTRODUCTION	11
1.1 - Introduction	12
1.2 - Research questions	13
LITERATURE STUDY	15
2 - CONTEXT AND REQUIREMENTS	15
2.1 - Qualities of a facade	16
2.2 - Case location selection	18
2.3 - Adopted building	20
2.4 - Building requirements	24
2.4 - Indoor comfort	26
2.5 - Facade requirements	28
3 - MEMBRANE MATERIALS	31
3.1 - Fibre material types	32
3.2 - Membrane properties	34
3.4 - Size availability	38
3.5 - Membrane connections	38
3.6 - Coatings	39
3.7 - Membrane materials	41
3.8 - Numerical comparison	47
4 - MEMBRANE STRUCTURES	51
4.1 - Types of structures	52
4.2 - Points of attention	55
4.3 - Reference projects	55
5 - UNITIZED CURTAIN WALLS	67
5.1 - Curtain wall types	68
5.2 - Unitized systems	69
5.3 - Detailing	70
5.4 - Installation	71
5.5 - Reference projects	71
THE DESIGN	77
6 - SKETCH DESIGNS	77
6.1 - Solution pathways	78
6.2 - Draft designs	79
6.3 - Summary	85
6.4 - Further development	86
7 - PRELIMINARY DESIGNS	89
7.1 - Fold-out facade	90
7.2 - Mechanical cushion	94
7.3 - Unitized vacuum	98

8 - NUMERICAL EVALUATIONS	103
8.1 - Calculation assumptions	104
8.2 - Thermal insulation	106
8.3 - Therm simulation	108
8.4 - Acoustic insulation	110
8.5 - Forces	112
8.6 - Gas permeability	114
8.7 - Conclusion	115
9 - PHYSICAL VALIDATION	117
9.1 - Vacuum spacer mock-ups	118
9.2 - Vacuum acoustics tests	134
10 - FINAL DESIGN	141
10.1 - The design	142
10.2 - Membranes	144
10.3 - Spacers	146
10.4 - Sunshading	148
10.5 - Panel	150
10.6 - Frame	151
10.7 - Additional design aspects	152
10.8 - Build order	154
10.9 - The south-east facade	158
10.10 - Construction details	160
10.11 - Visual comfort	174
11 - SUSTAINABILITY REVIEW	179
11.1 - Introduction	180
11.2 - Embodied energy	181
11.3 - Conclusion	184
12 - CONCLUSIONS AND REFLECTION	187
12.1 - Conclusion	188
12.2 - Further research	189
12.3 - Reflection	190
13 - BIBLIOGRAPHY	193
13.1 - Bibliography	194
13.2 - Table of figures	197
14 - APPENDICES	201

1

INTRODUCTION

1.1 - Introduction

Membrane envelopes have been used at an increasing rate in recent decades and are still developing. However, they have not been used in unitized façade systems as a main building material. Even though their qualities have a high potential of improvement in this sector. To properly apply membranes in a unitized façade system on high-rise buildings they have to be able to reach current standards and requirements. Any deficiencies they have in building physical properties have to be developed. Especially where membrane envelopes commonly underperform like; thermal insulation, thermal radiation protection and acoustical insulation (Knippers, 2011).

Because the Sail at Marina bay has a centralized climate control systems, this doesn't have to be arranged in the facade. The main focus will be thermal comfort through insulation and radiation ,and Auditory comfort through outside noise insulation. These are the three properties where membrane facades commonly underperform (Knippers, 2011). therefore this research will limit itself by going into detail in these subjects only. Visual comfort, olfactory comfort and hygienic comfort will only be superficially considered.

Membranes are one of the earliest materials used in the construction of shelters and buildings. They are flexible, light and have other properties that make especially ideal for lightweight, mobile structures (Llorens, 2015). In the thousands of years that they have been used their application was almost exclusively for mobile or temporary structures. In the past century new developments in the durability and longevity of membranes have led to them being used in permanent buildings as well. Now there are membranes that have enormous strength and coatings that can repel dirt. They are used in many second skin, shading or façade systems. Developments will even keep accelerating in the future (Knippers, 2011).

Unitized curtain walls are, when compared to membrane structures, very modern. They have been developed in the past 120 years to be quick, cheap and have a high quality standard.

Because of these qualities they have been primarily used on large office buildings or high-rises (Murray, 2009). A high rise is a building that is high enough to require an elevator for accessibility. In the Netherlands this is demanded for a building with 4 stories or more. Or if the highest functional floor is higher than 12.5m (www.bouwbesluitonline.nl). Very tall buildings are sometimes called skyscrapers and these are taller than 40 storeys. The main material used for these systems is often glass. It is transparent, durable, could be structural and developments have improved their insulating qualities. Design gets a bit monotonous, however, therefore some professionals desire more variety and a material that can provide a more appropriate solution in certain situations (Barf, 2010).

Membranes could provide a solution for these kinds of systems. They are far lighter, which means less powerful equipment can be used or larger panels can be build. This can further decrease build time, which is one of the main advantages of the systems. Membranes can also be more easily recycled, if used properly, and are therefore more appropriate for relatively short term use. A membrane envelope can provide great flexibility and mobility with less materials in less time. A façade that is according to sustainable design principles (Llorens, 2015).

It could therefore have a far lower ecological impact compared to most systems used in the current building environment. This can result in more sustainable high-rise designs with less building materials used or other applications. Developing this system may also provide possible solutions for higher membrane insulation values.

Singapore is a good location to develop this for. It is a very demanding location, for which many solutions need to be found. If these are found they can help in implementing the system in other locations as well. Singapore also has many high rise buildings and they are going to need to build many more, especially for residential use, because they have a land shortage. Hence, the market and demand is big.

1.2 - Research questions

The objective of this graduation research is to design an adaptive unitized façade system, that utilizes membrane materials as a main building material, to be applied on residential high-rise buildings in a tropical environment. This to provide a more sustainable and/or more appropriate alternative compared to currently available systems, while still maintaining interior comfort and quality. This leads to the following research question that will be answered in this graduation thesis and a design task as outlined in figure 1.

Main research question

How can an adaptive unitized façade be designed by utilizing the advantages of membrane envelopes for residential high rise buildings in Singapore?

Sub-questions

- o What are the properties required of a façade for residential high rise buildings in Singapore?
- o Which types of membranes or membrane systems have the desired properties, as defined in the first sub-question?
- o What types of membrane envelopes have been built and how are they materialized, detailed and constructed?
- o What types of unitized façades are used on high rise buildings and how are they materialized, detailed and constructed?
- o What are the advantages of membrane envelopes compared to commonly used unitized façade systems?

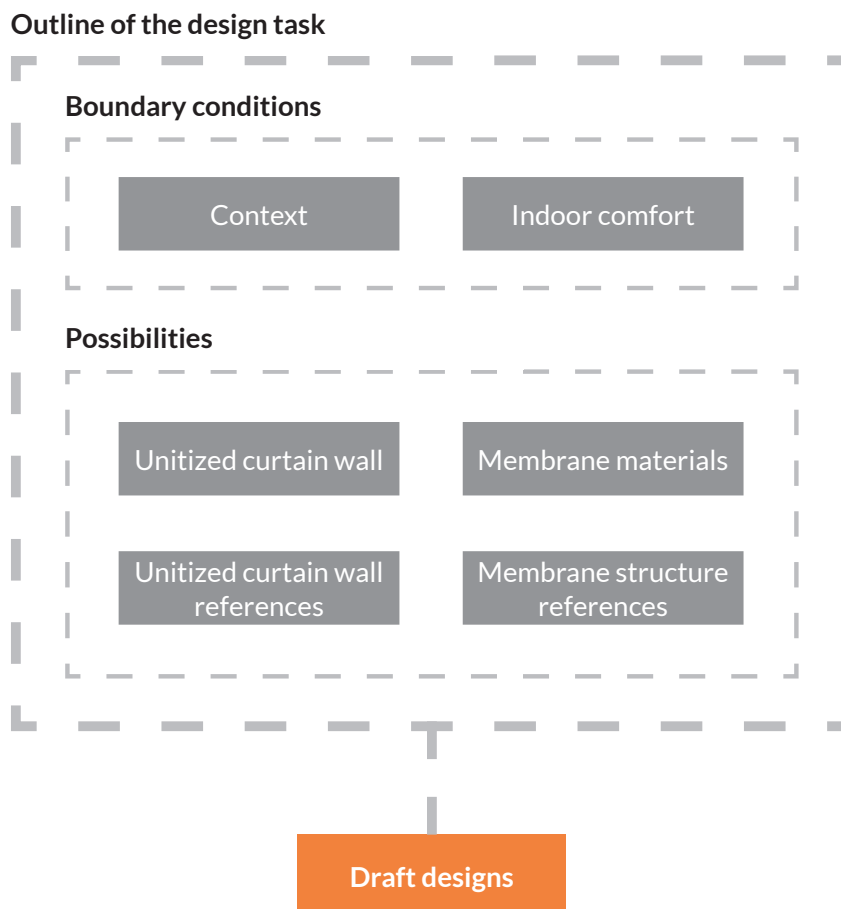


Fig. 1 Outline of design task

2

CONTEXT AND REQUIREMENTS

2.1 - Qualities of a facade

A structure can have many purposes, but most often their main purpose is to be a shelter for the occupants. They provide a suitably comfortable space for the users of the structure to work or life undisturbed. This space needs to be protected from outside influences like: wind, rain and snow. Or from less obvious elements like: sound, heat and cold. The outer barrier or envelope of the building, is the part that provides the protection (Knaack, 2011). The façade performs more functions however, which can be seen in figure 3. Some facades excel at certain points more than others, but all need to deal with the points mentioned one way or another. The upper part of the scheme is directly related to climate and comfort. Current demands on sustainability have increased the value of these aspects and will need to be considered thoroughly.

The exterior climate is therefore important in designing comfortable and sustainable buildings. Two topical locations for this research have been defined and will be elaborated on in chapter 2.2. One will be chosen for the final design.

Not only the climate is different, but the people that use the buildings are different too. Cultures, habits, preferences and personal accessories vary all over the world and the people are used to different climate conditions, as well as different living standards. All this makes each individual have their own preferences for their own comfort. Not every aspect will be directly dependant on the exterior façade, however. The most critical aspects will be considered in this research.

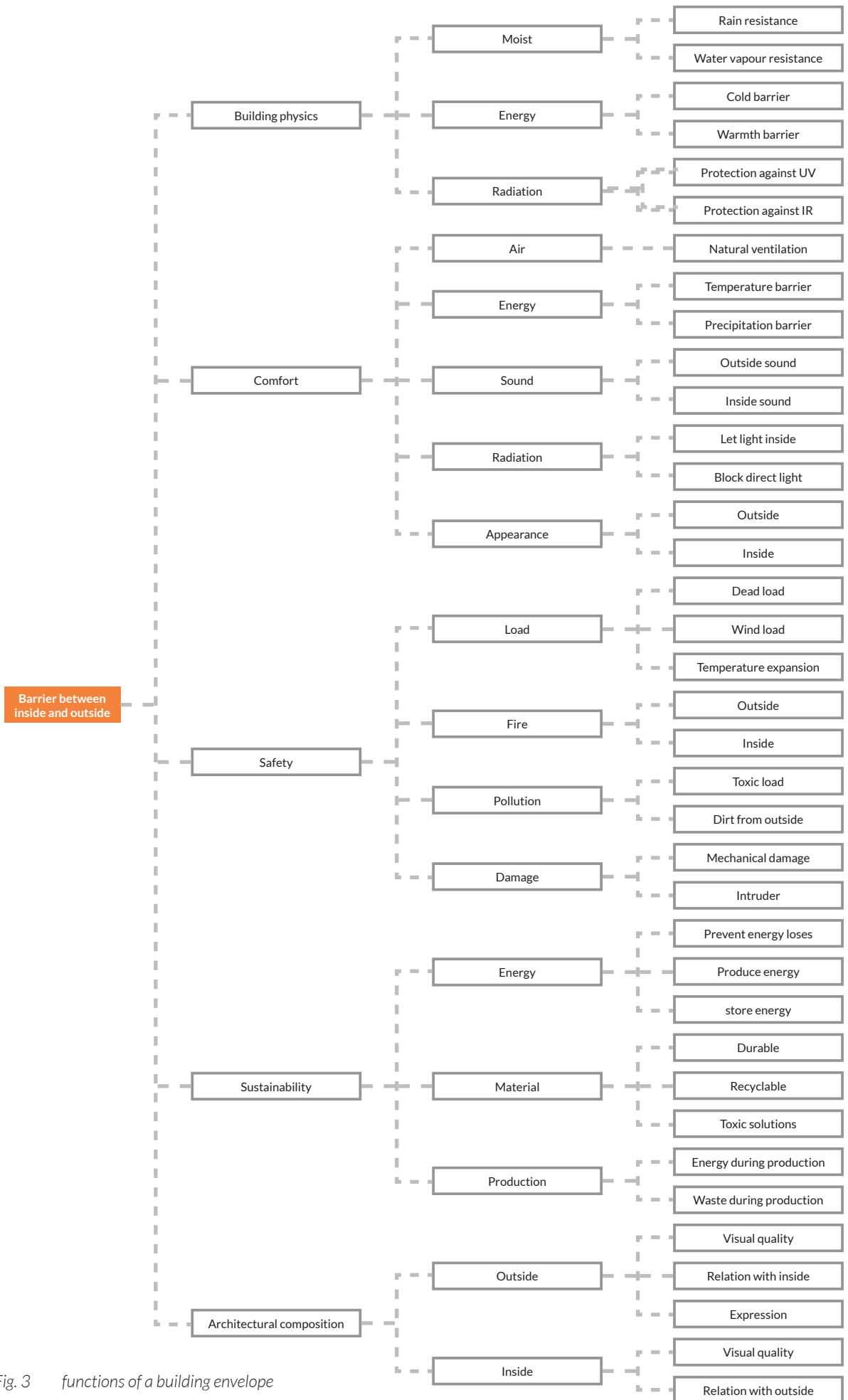


Fig. 3 functions of a building envelope

Santiago, Chile

33° 27' ZB, 70° 40' WL

Santiago is the capital of Chile in South America. It is positioned on low planes between the coast and the Andes mountain range. The city and its surrounding area, called 'Región metropolitana', houses around 40% of the population of Chile. The city centre is dotted by classical architecture and areas with high-rise buildings.

According to the Köppen-Geiger climate classification, which can be seen in figure 8, Santiago has a temperate climate with dry and hot summers (Csb). This means that Santiago has summers with a lot of solar irradiation, high temperatures and low humidity. Winters in Santiago have, however, high humidity and temperatures around 15°C (Peel, 2007). Important to mention is that Santiago has a problem with smog in the winter. An effect called thermal inversion traps polluted air against the Andes mountains. The normative values of climate consultant can be seen in figure 9. They are more specific to Santiago and more exact. The full data list can be found in the Appendix.

A membrane envelope in this situation should consider both the high and low temperatures. The most important problem is the high solar irradiation in the summer. The system should focus most attention in good solar. Beside that the air should not enter the building unfiltered and pollutants should be able to be cleaned easily.

Advantages of the area are the cold at night, which can be used in conditioning the interior climate, low humidity and the low wind speeds, because of the cover the mountains provide.

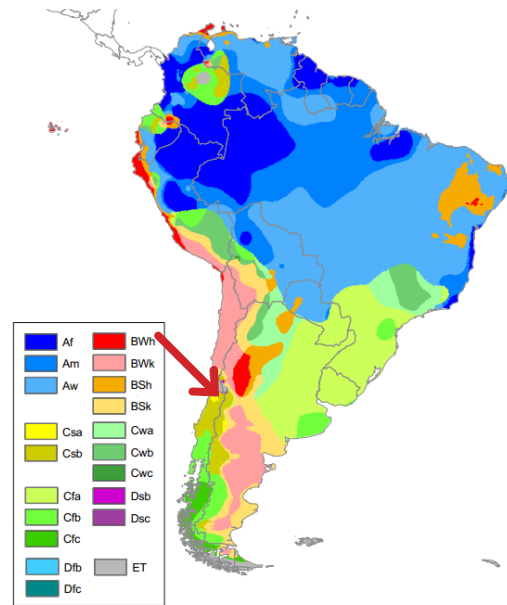


Fig. 8 Köppen-Geiger climate classification South-america

Santiago	Monthly mean (lowest-highest)	
Direct normal radiation (avg hourly)	168-567	Wh/sq.m
Diffuse radiation (avg hourly)	108-177	Wh/sq.m
Dry bulb temperature (avg monthly)	7-21	°C
Relative humidity (avg monthly)	55-85	%
Wind speed (avg monthly)	1-2	m/s

Tab. 2 climate table Santiago



Fig. 10 skyline Santiago

Case location

In terms of developing a membrane envelope, both Singapore and Santiago have their own advantages and disadvantages. Considerations have been on a few key points.

- o Santiago has higher direct normal solar radiation on average each day. Indirect solar radiation is higher in Singapore, however. This is caused by the high degree of cloud cover in Singapore.
- o Both areas do not experience truly low temperatures. Singapore is always warm. Santiago could get cold in the winter, but with the high solar irradiation present it isn't a problem. Heating won't be necessary. Santiago has more variations in temperature. This means it becomes both colder and warmer, at times. This requires more adaptivity.
- o Santiago has less aggressive weather, however. In a year there is less precipitation and less wind.

After review of both climates, Singapore will be the case location for the adaptive membrane envelope. It seems to have more challenges to solve. The challenges are also very different from other membrane structures that have been built. Membrane envelopes have already been extensively applied in situations where much solar control was necessary.



Fig. 11a Sail west facade

2.3 - Adopted building

A building was adopted to provide a basis for the unitized membrane envelope. This smoothens the design process, by providing a platform with the necessary design information besides the façade. If the façade can be theoretically applied on the building with success, it could count as proof of concept.

Singapore has a lot of high-rise buildings. In fact, Singapore has the second most people living in high-rise buildings in the world. So there is a lot of choice, like:

- DUO, Buro Ole Scheeren, 2017
- One raffles place, Kenzo Tange Associates, 1986
- Tanjong pagar centre, Skidmore, Owings & Merrill LLP, 2017
- Sail at marina bay, Peter Pran and Team Design, 2008

DUO, Buro Ole Scheeren, 2017

This is the newest known residential high-rise project in Singapore. It will house not only residences, but also offices and shops. The building will be 190m tall. A downside is that the residences have balconies all the way around, which won't be added to the design of the unitized membrane envelope, so makes this choice impractical.



Fig. 11b DUO tower

One raffles place, Kenzo Tange Associates, 1986
 With a height of 280m, One raffles place is the highest tower in Singapore for a couple of decades now, but it will soon be surpassed. The building only houses offices.

Tanjong pagar centre, Skidmore, Owings & Merrill LLP, 2017

The Tanjong pagar centre will be the highest tower in Singapore with a height of 290m. The building was mostly finished in 2016, but the spire which will make the building reach its final height will be installed later in 2017. The tower will have residences and offices, but clear drawings could not be found.

Sail at marina bay, Peter Pran and Team Design, 2008

The right tower is the Sail at Marina Bay and is currently the highest residential tower in Singapore with a height of 245m over 70 storeys. The building provides luxury apartments and suites specifically designed for use by expats. The name reflects its sail like shape and it would be more than apt if the material would reflect the same reference as well. That and the availability of some plan data made this building an ideal site for the unitized membrane envelope.

Because of the reasons mentioned the Sail at marina bay will be the building for which the membrane envelope will be developed.



Fig. 11c One raffles place



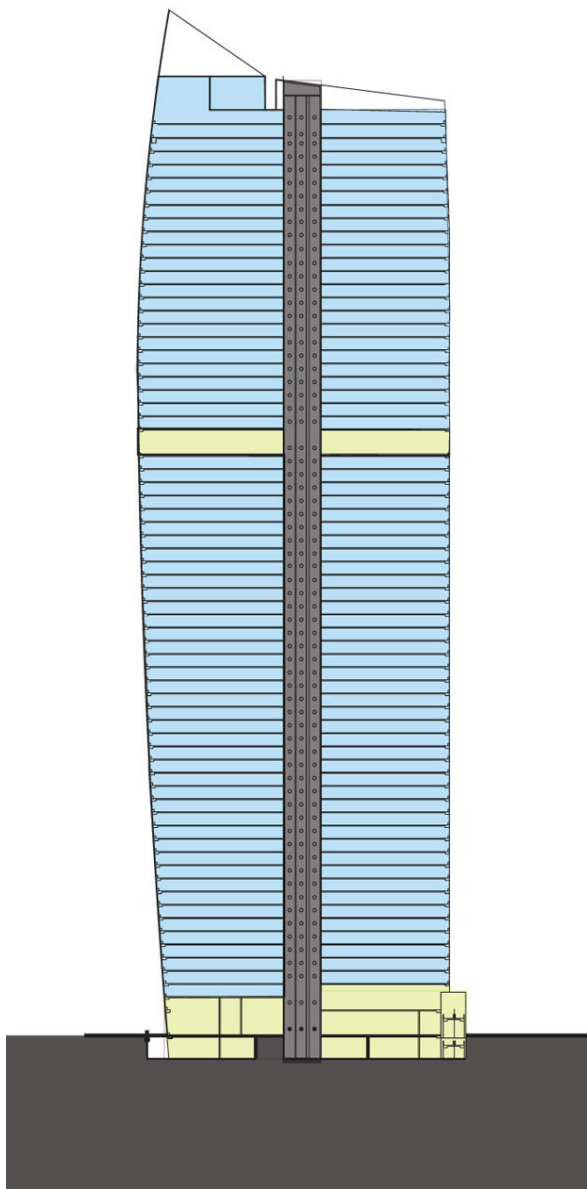
Fig. 11d Tanjong pagar centre



Fig. 11e Sail view across the marina bay

This choice has many consequences, because the Sail isn't a straightforward angular building. The west facade is the most prominent and will be the main focus of the design. This facade is indicated with the orange line. It receives a lot of sunshine, which means sunshading is a must have. The facade also has added functionality in the shape of a window. This will also be copied in the new design. All of this needs to happen in a slightly curved facade.

These pictures will be the only ones used to form the basis of the design. Precise application is not sought for, but a proof of concept.



TOWER 1

Fig. 11f Sail section

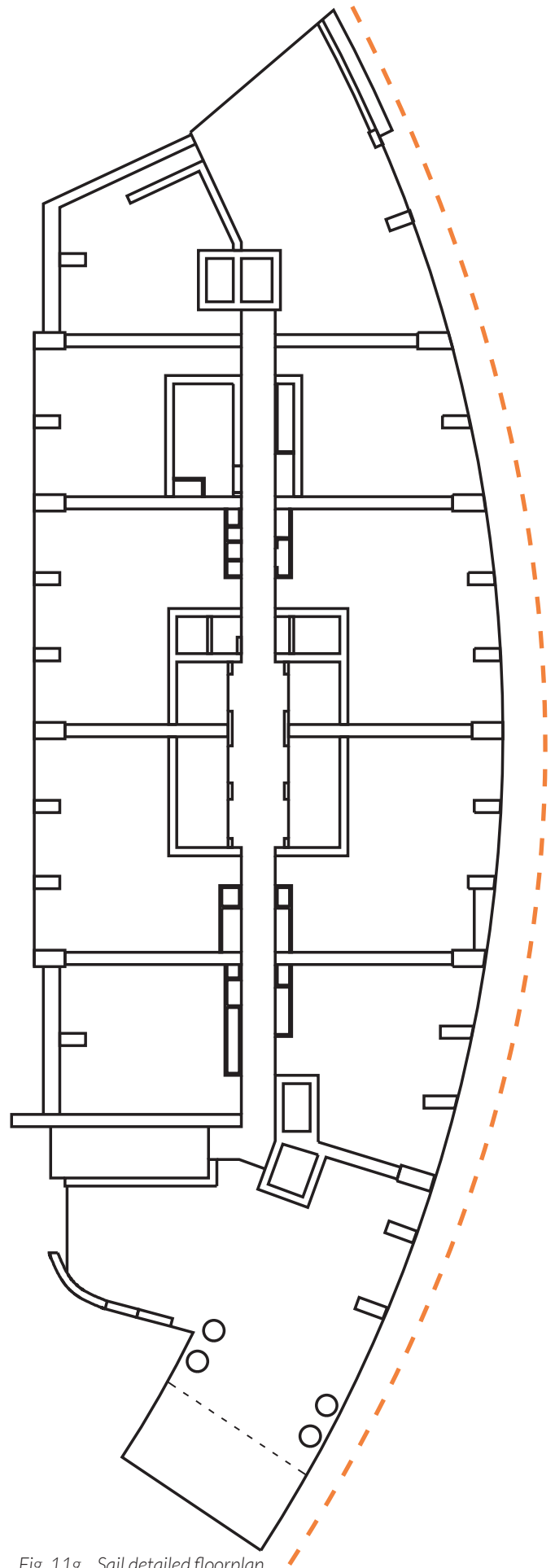


Fig. 11g Sail detailed floorplan

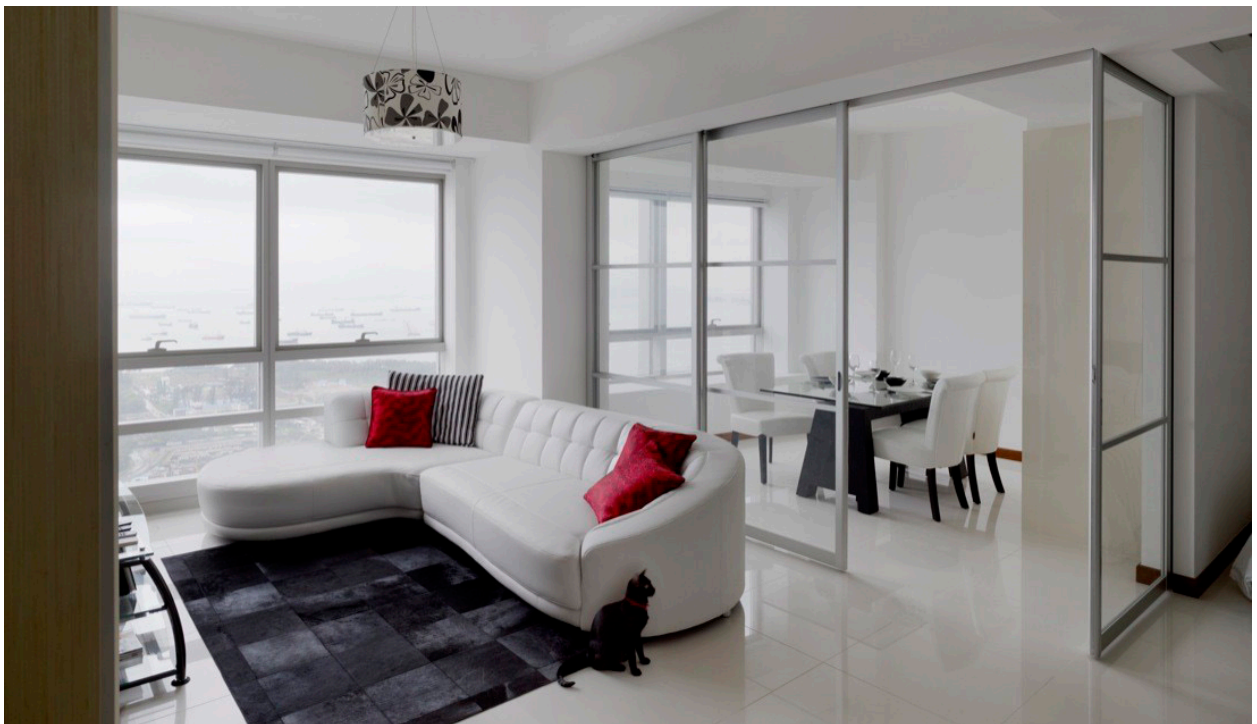
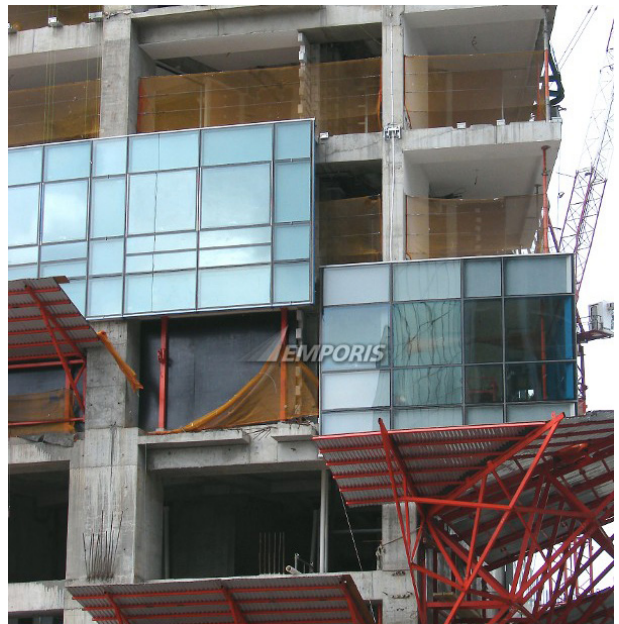


Fig. 11h Collage of the Sail at marina bay

2.4 - Building requirements

Singapore maximum build height

The Singapore government has a height map, which states the maximum height to which can be build. On the east of the island the maximum build height is exactly the height of the current structures. This is because this area requires an official application for any high rise build (www.ur.gov.sg).

The reason behind this is the airport. The airport obstruction map highlights in green where a regulated build height is enforced, which can be seen in figure 14. Everything, including cranes or other temporary structures, in the green zone needs special permit when above 150m. Permits have been provided to each specific building site, resulting in various different maximum build heights for each site. Therefore, please refer to the government height map found online for specific heights.

Buildings at the marina have been given permission for building up to 280m some times. So this is not really a problem anymore, when applying for a new permit.

Façade design

Globally there are more high rise buildings than ever before and they are getting higher and higher as well. Building this high and getting a comfortable indoor climate does get more difficult, however. The effect of ambient air temperature

and pressure increases over the height of the building. Because of this extra care should be taken to prevent leakage, pressure resistance and thermal insulation. Solar transmission also becomes an heightend issue, because there are no surroundings anymore.

Also, besides the specific conditions found in the separate areas, there are a few that are not specific to the locations, but present almost everywhere. In designing a façade for high rise buildings they are especially worth considering. These are conditions like noise.

Transparency

The area doesn't help to shade so shading should be effective to stop at least 85-90% of solar radiation (Simmonds, 2015). However, visual comfort is still required. A facade should preferably have as much transparent surface area as possible. Modern curtain walls often have a transparent surface area of at least 90%.

Wind and ventilation

The average wind speed is already shown in climate consultant data, however they are higher and therefore more important at higher altitudes. Singapore has no mountains and is next to the sea. Fast winds can deliver high pressures, especially damaging to pressure systems like inflatables and deflatables. Figure 12 shows that wind speed increases a lot in the first meters of height

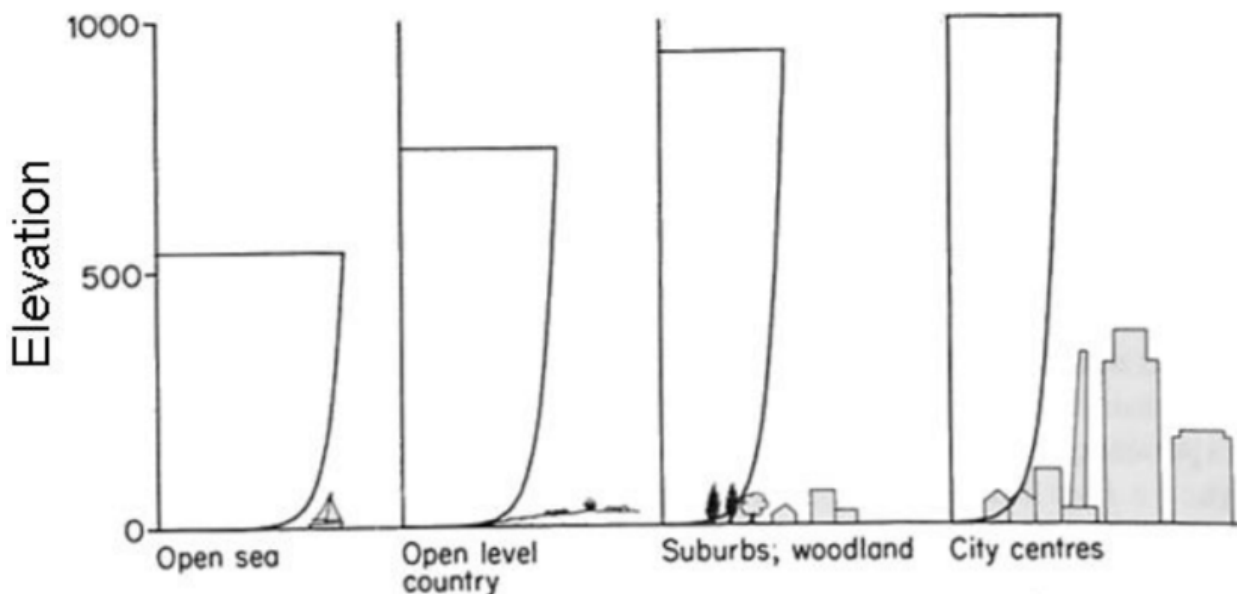


Fig. 12 wind strength at altitude

difference. When the wind isn't hindered by surrounding buildings the force will fall directly on the high-rise facades (Mendis, 2007). In the case of Singapore the wind is coming from open sea, which is even more violent.

This high wind pressure hampers the use of natural ventilation. The ventilation openings can't be directly open, because the wind will push through with too much force. Some kind of buffer is needed for comfortable ventilation speeds (Simmonds, 2015).

Noise

Activities in and around the city create a lot of noise. Regulations limit the sound levels to around 65 decibels, during the day (www.ashrae.org.sg). This won't be the case every day or all day, but it should be taken into account as a worst case scenario. The sound levels will exceed the comfortable level, which is explained in the chapter interior comfort.

Maintenance

An important aspect of design that typically only comes to light after realisation is maintenance. On high altitudes this becomes increasingly difficult, so extra care should be taken to make it possible in a safe and secure way, without damaging the building.



Fig. 13 maximum allowed sound levels in Singapore



Fig. 14 build height regulation zones Singapore

2.5 - Indoor comfort

Comfort is when an individual is satisfied in their well-being and surrounding climate (Boerstra, 2015). The comfort can be divided in different categories ((Bluyssen, 2009), which will be explained later in this chapter. These categories are:

- o Thermal comfort
- o Auditory comfort
- o Visual comfort
- o Olfactory comfort
- o Hygienic comfort

To aid in designing structures capable in being comfortable, guidelines have been created. Comfort guidelines like ISO, which is an international guideline or ASHRAE, which is the guideline created by the united states of America. Singapore has their own guideline, which is heavily based on the ASHRAE guideline. It is specifically made for the people in that climate and their preferences (www.ashrae.org.sg).

Achieving comfort in each category and for every person is inherently hard to achieve though. The main reason for this is because we are all individuals with our own cultural background, upbringing, standards, expectations, preferences and more. Therefore the guidelines work with

the percentage of dissatisfaction (PPD). A PPD lower than 10% is considered a comfortable area (Boerstra, 2015).

Thermal comfort

The thermal comfort of an individual is in principle when their bodies heat gain and loss is in equilibrium, so that they can maintain their constant core temperature (Boerstra, 2015). This is determined by a couple of variables (www.designingbuildings.co.uk). These variables are:

Air temperature

This is the temperature of the air surrounding the person. Heat is transferred through convection and on contact through conduction. Air temperature is measured by the dry bulb temperature.

Radiant temperature

Is a collection of the temperatures surrounding a person. This includes every surface and radiation sources. Radiant temperature is measured by the mean radiant temperature.

The sun has a very large effect on the radiant temperature. Adaptive sun control, through for

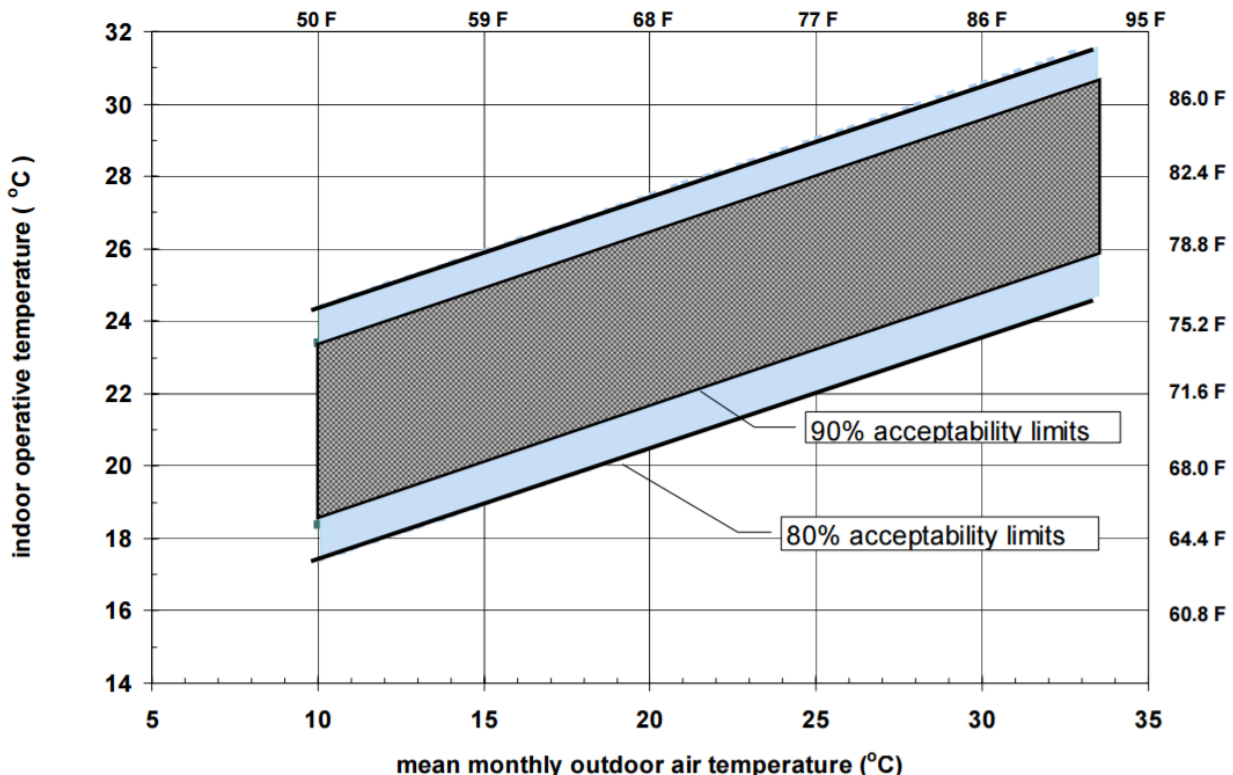


Fig. 15 thermal comfort range

instance sunshading, can also control a large part of the thermal comfort.

Operative temperature

This is not a measurable temperature, but a calculated average of both air and radiant temperature variables. The operative temperature is calculated by:

t_o = Operative temperature
 t_a = Air temperature
 t_{mr} = Mean radiant temperature

$$t_o = \frac{t_a + t_{mr}}{2}$$

This combined temperature is used in figure to define the desired inside temperature in relation to the outside temperature, as dictated by ASHREA guidelines (www.ashrae.org.sg). In Singapore, with an outside temperature of 30°C, a comfortable temperature for 90% of the occupants would be between 26°C-29°C

Air velocity

Is the speed at which air passes by the person. Faster air movement results in a quicker heat exchange through convection. Air velocity is measured in meters per second. A lower value than 0.2 m/s is considered comfortable (www.ashrae.org.sg).

Relative humidity

The correlation between the maximum amount of water that air could hold at a certain temperature and the amount of water that is actually evaporated in the air. A lower relative humidity would make evaporative cooling easier. Relative humidity is measured in percentages. Differences in relative humidity is hard for humans to feel between 25-60% therefore this is the minimum and maximum RH dictated in the guideline. Any value exceeding the limits will have effect on the comfort of an individual

Clothing and metabolic rate

Both aren't values measured, but do have effect on ones feeling of comfort. Clothing acts as an insulator towards all the effects mentioned before. Metabolic rate is the amount of heat produced in the human body. More heat produced, means

more heat needs to be lost to keep an equilibrium and vice versa.

Auditory comfort

Is related to what people can hear. Human hearing is between the frequency of 20 and 20000 hertz. These frequencies are created through waves of compression of air that we pick up with our ears. The loudness of the sound is determined by the sound pressure level. Described by decibel(dB). Humans can hear sounds as low as 0 dB and even higher than 130 dB, but that will cause permanent damage. However, 0 dB will not be achieved in day to day life. A silent area is often still 15 dB (Bluyssen, 2009).

Auditory comfort is achieved when sound levels are low enough to concentrate and people can communicate properly with others without other auditory disturbances. This is determined by a couple of variables (Bluyssen, 2009). These variables are as follows:

Noise

Is the sound pressure level of ambient noises, audible by the person. This can come from outside, the room next door, the same room or often from equipment. Multiple sound sources can lead to

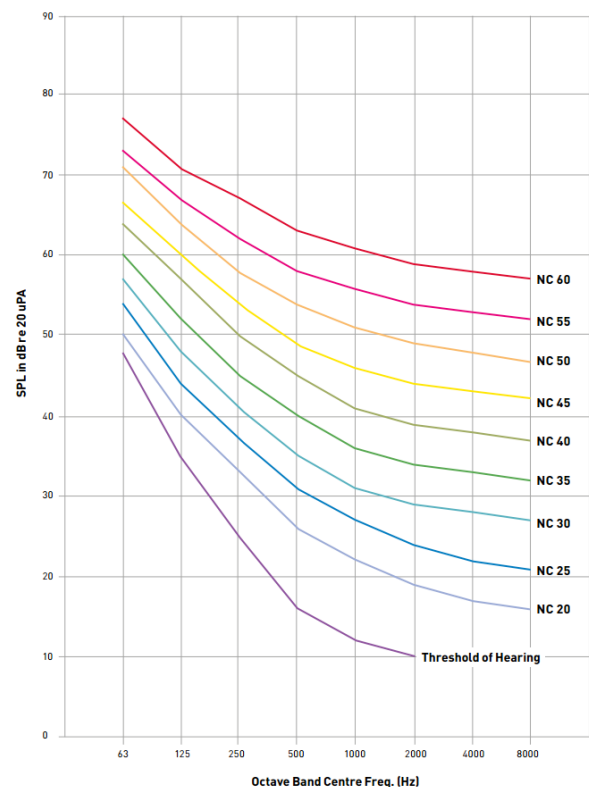


Fig. 16 noise criteria

a higher combined noise level. The amount of noise is measured in decibel. Guidelines from Singapore dictate a noise criteria for indoor functions. Offices need to comply to NC 35 or 40. Residential areas need to comply to NC 30-40. The sound pressure level at different frequencies for the noise criteria can be found in the figure below.

Reverberation time

This is the amount of time a sound takes to decrease 60 dB. It is measured in seconds per octave band frequency. It has an audible effect most people call echo when the reverberation time is very long. Echo can lead to a disturbing increase in ambient noise. Too short of a reverberation time can feel 'dead' and decreases audibility of a speaker. Different types of mediums require different reverberation times. Ranging from 0.5 to 6 seconds. Reverberation time is dictated by the volume of the room and the amount of acoustical absorption material that is inside. Absorption materials have specific qualities depending on the frequency of the sound.

Visual comfort

Is the comfort experienced by things we see or what we don't see. This pertains to the amount of light in a room, the colour rendering qualities of the light, glare and view.

Hygienic comfort

Both types of comfort relate to the air quality in a space. Olfactory comfort is hindered when unsettling smells linger in the air. Hygienic comfort is achieved by a fresh air supply. Too much carbon dioxide or a clogged air filter can lead to dissatisfaction.

2.6 - Facade requirements

Following the literature study of the outdoor climate and the desired indoor climate, facade requirements can be set to which the design of the unitized membrane envelope should be held. They will be explained in three parts. comfort, material and practical requirements.

Comfort

The Sail at Marina Bay in Singapore is a residential building, therefore comfort demands are high. The façade should be able to have the required properties to provide a sufficient comfort level.

The required properties is determined to be at least that of a modern curtain wall, with the same added functionality as the current facade of the building.

Thermal insulation

High performance double glazing currently used in many unitized façade systems have a U-value of 1.2-1.7 W/m²K. Facade systems with triple glazing can even achieve a U-value of 0.6 W/m²K.

The goal of the unitized membrane envelope is to have at least an U-value of 1.7 and strive for 0.6.

Viewing area

To be comparable with the façade currently on the the Sail at Marina Bay, the unitized membrane envelope should have a transparent area of at least 90% at eye height.

Light transmittance value

The unitized membrane envelope should have a Lt value of at least 0.7. (70%)

Solar radiation transmittance value

Solar radiation should be let through the facade adaptively. The solar heat should be able to be let in for heating or reflected to prevent overheating.

To achieve this the unitized membrane envelope should be able to have a solar transmittance value of at least 0.7 (70%). Sun shading should be able to lower this to at least 0.15 (15%).

Acoustical insulation

Sound pressure levels should be able to be reduced from 65 dB, which is the maximum allowed sound pressure level during daytime in

Singapore, to a minimum of 35 dB, which is the preferred sound pressure level in residential functions. This requires an insulation value of 30 dB.

Weather protection

The unitized membrane envelope should be air and water tight. Even in severe storms with winds of 25 m/s.

Adaptivity

Additional adaptivity could increase comfort and functionality further. Therefore this should be explored in the design phase.

The most important and absolutely necessary variable for this is:

- Solar radiation transmittance (shading)

Other functional variables could be:

- Air tightness (ventilation)
- Thermal insulation

Building physical variables that shouldn't be adaptive are:

- Acoustics
- Water tightness
- Hygienic comfort
- Durability
- Etc.

Secondary variable functions could add unique selling points or make the system extra attractive, but aren't necessary to its function. These could be for instance:

- Appearance
- Colour
- Shape
- Texture
- Functionality (seat, sticky wall, whiteboard, dartboard)

Material

The main material used in the design must be a membrane. E.g. fabric, foil, sheet, etc.

Lifetime of used materials should be at least 25 years or very easily replaceable.

The resulting designs should be more sustainable than common curtain wall systems. Either through lightweight, ease of use/application, energy efficiency, more protection of inside from outside. This will be checked by an evaluation of the final design.

Practical

Safety

The facade should be safe, considering falling protection, fire transfer and falling of components.

Maintenance

The unitized membrane envelope should be able to be maintained regularly.

Unitized curtain wall

The design must be a unitized curtain wall and function appropriately. The exact definition of a unitized curtain wall will be explained in detail in chapter 5.

<p>Thermal insulation <1.7 W/m²K</p>	<p>Visual transparency >70 %</p>	<p>Acoustical insulation >30 dB</p>
<p>Solar transmittance value 15-80 %</p>	<p>Light transmission >70 %</p>	<p>More Safe, air/water tight, functional, etc.</p>

Tab. 3 Facade requirements

3

MEMBRANE MATERIALS

Membrane is a word that can trace its origins to Latin, where it means skin or parchment (Kaltenbach, 2004). This is an ideal example because they share the same properties of being thin surfaces. The definition as dictated by the textile institute is (Tubbs, 1991):

“A material that has substantial area in relation to its thickness and sufficient inherent cohesion to give the assembly mechanical strength.”

Materials that apply to this definition can be divided in membranes and fabrics. Membranes are isotropic volumes, which means that they have the same properties in every direction, of a single material. Whereas fabrics are an assembly of fibres. This creates a an-isotropic surface, which means that they have different properties in different directions (Huntington, 2013).

3.1 - Fibre material types

Membranes can be constructed out of a large range of materials. Homogeneous membranes are made from isotropic materials, that have the same properties in every direction, like metals or certain plastics. And will be discussed in the next chapter (Huntington, 2013).

In contrast to membranes, fibres aren't made from one homogenous material, but are consist of many fibres, filaments, monofilaments or yarns. For clarification and understanding of the key definitions in this research the definition of each is listed below.

Fibre

Textile raw material, characterized by flexibility, fineness and high ratio of length to thickness (Tubbs, 1991).

Filament

A man-made fibre of indefinite length. Related to monofilament, which is a filament consisting of one single thread (Tubbs, 1991).

Yarn

A product of substantial length and relatively small cross section consisting of fibres and/or filaments, with or without twist (Tubbs, 1991).

Twine

Twisted cordage consisting of yarns, with or without twist (Tubbs, 1991).

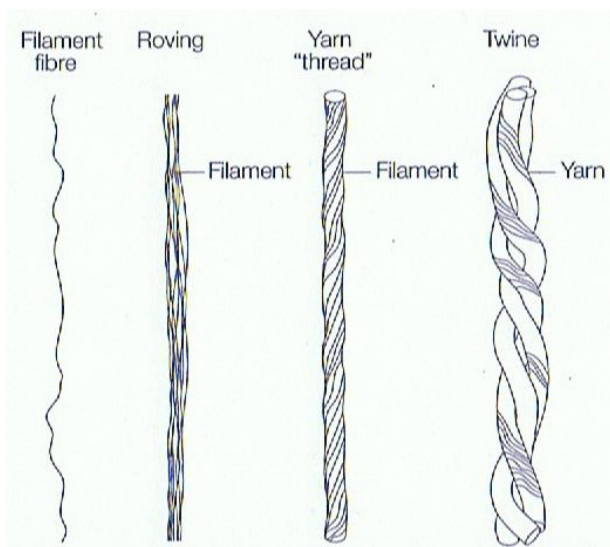


Fig. 18 fibre structures

Fibres are made from many materials. Natural or man-made. Figure 20 shows the main types of fibres used to make fabrics.

Natural fibres

Have not been used much in the construction industry because of lack of control during growth. The fibres have a variation in diameter, tensile strength and other mechanical properties. They are also sensitive to moisture. Vegetable fibres are the only ones relevant for construction and are increasingly popular due to their environmental friendliness (Knippers, 2011).

Polymer fibres

Is the most commonly used fibre type in the building industry. Many properties are available, but they do experience a lot of creep and are compostible. The fibres do have higher mechanical properties than their solid polymer forms. Comparatively, the polymer fibres are, in general, tougher and lighter than inorganic fibres, but the tensile strength is lower (Knippers, 2011).

Inorganic fibres

Are fibres that aren't carbon based, except for carbon fibre, which is still in the inorganic set. Inorganic fibres have very different properties compared to the other groups, because they have a high heat resistance, are stiffer and do not experience creep, which means they do not have extra elongation under long term loading (Knippers, 2011).

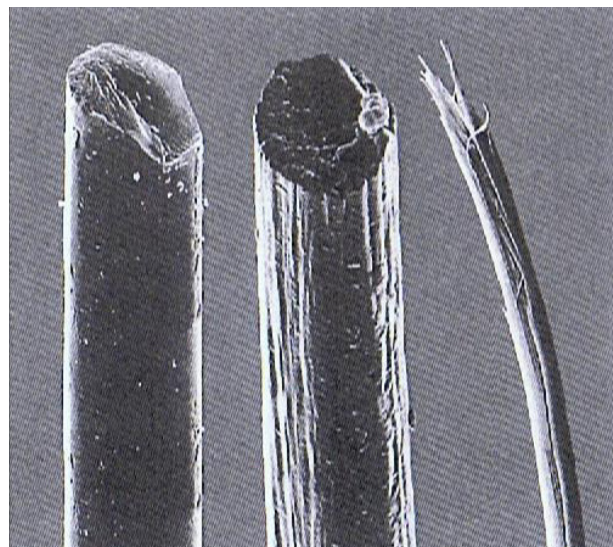


Fig. 19 fibre materials under microscope

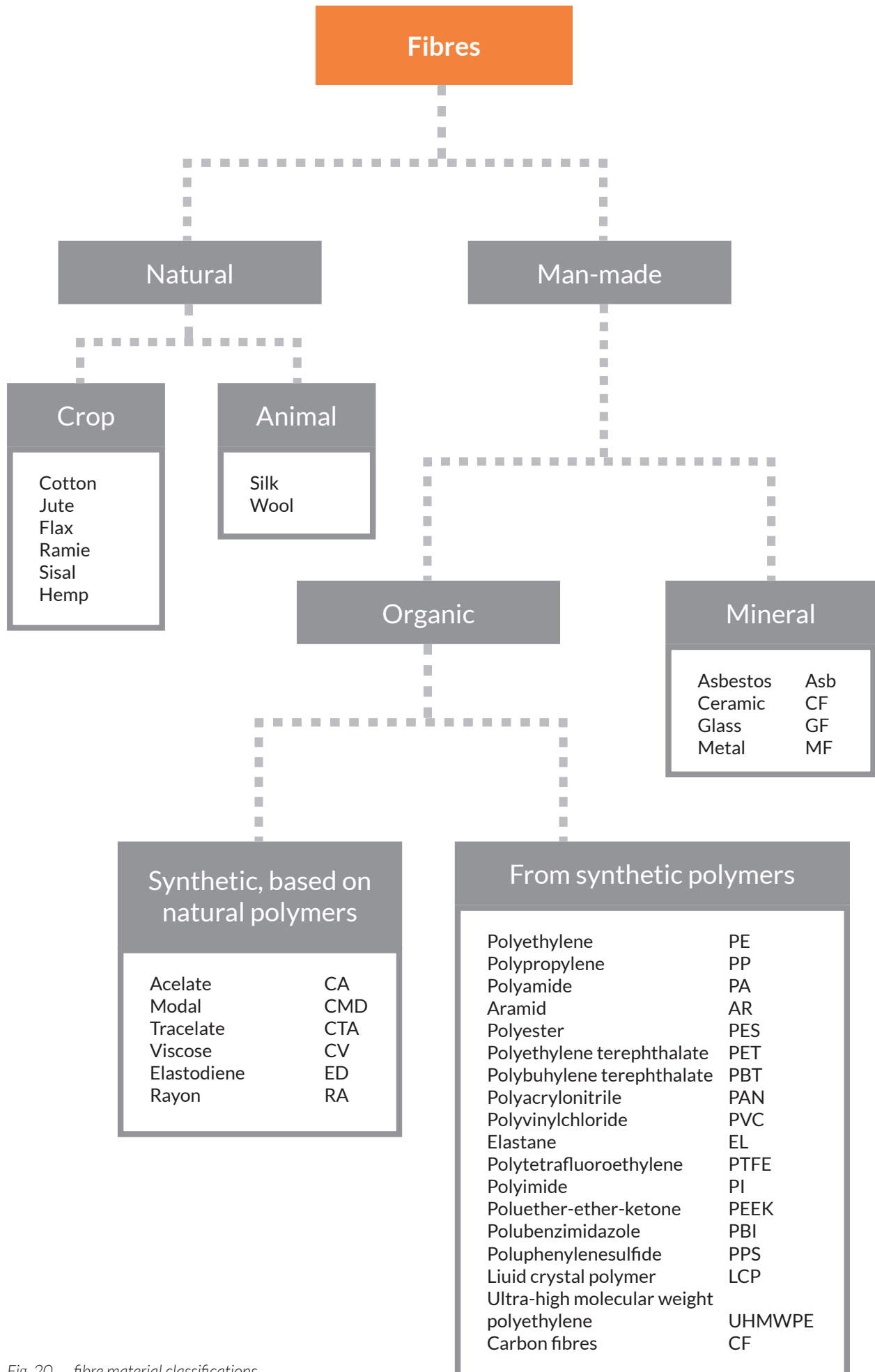


Fig. 20 fibre material classifications

3.2 - Membrane properties

Membrane materials behave differently compared to the mostly rigid materials common in the build environment. Therefore membrane materials have a set of their very own values and tests to quantify these values to identify their strengths and weaknesses.

When dealing with fabrics the following definitions are most often used to give value to properties, ranging from strength to fire resistance.

Tensile Strength

The maximum tensional stress the material will sustain before fracture (Tubbs, 1991).

Yield strength

The stress corresponding to a specified permanent plastic deformation (Tubbs, 1991).

Tearing strength

The stress required to further propagate and existing tear (Tubbs, 1991).

Elongation

The increase in the gauge length, measured after fracture of the specimen (Tubbs, 1991).

Strain

The change of shape, relative to the original shape, caused by stress in the material (Tubbs, 1991).

Tex

Tex is a unit of density used for fibres or filaments. It is defined as the weight in grams per thousand meters length of the fibre or filament (Tubbs, 1991).

Denier

The Denier is very similar to a Tex. It is also a unit of density used for fibres or filaments. It is defined as the weight in grams per nine thousand meters length of the fibre or filament (Tubbs, 1991).

N/tex

Is a measure of strength per density. Used in the textile industry to define the strength of fibres or filaments. The unit is Newton/grams in a thousand meters (Tubbs, 1991).

Tenacity

The tenacity is the unit of strength of a fibre or filament. Also called the textile strength. It is defined as the weight(grams) x Force (N) / Denier (Tubbs, 1991).

LOI (limiting oxygen index)

Is the minimum fraction of oxygen in nitrogen necessary to sustain burning (Llorens, 2015).

Free tearing length

This is a relation between tensional strength and weight and it is valued by the maximum length a fibre or filament could be before failing under its own weight (Tubbs, 1991).

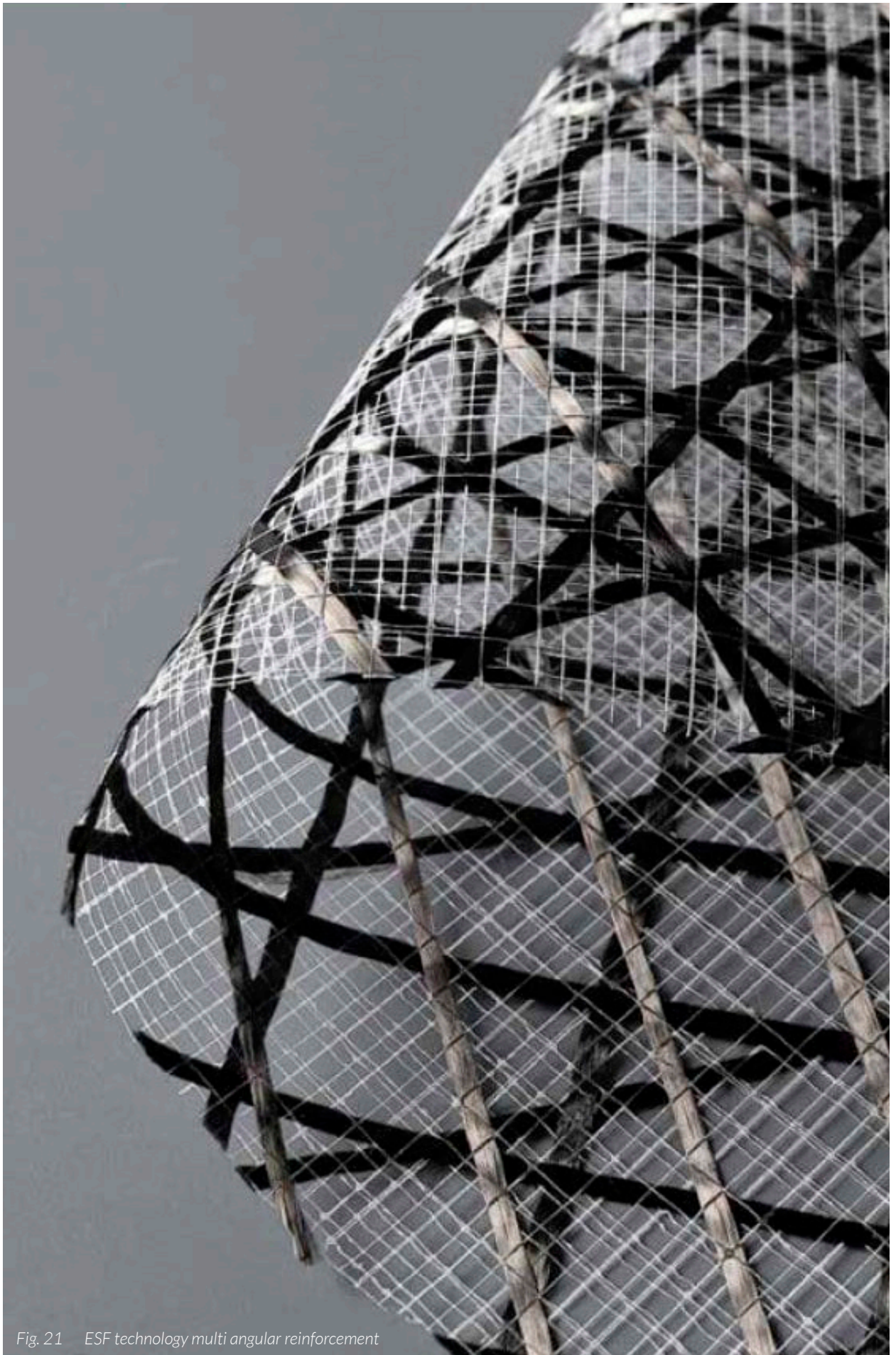


Fig. 21 ESF technology multi angular reinforcement

3.3- Fabrics and isotropic membranes

After creation of the fibres they need to enter the next phase of processing to create a surface and give it the membrane properties. This can be done by a number of techniques. These techniques result in the following types of fabrics:

Woven fabrics

Are fabrics in which threads cross at right angles. The thread that runs in the direction in which the fabric is manufacture is called the warp. The threads in the right angle direction are called the weft and are placed there by hand or shot with a shuttle system. There are many kinds of weaves, which all provide different properties. Different types can have effects on the water tightness, transparency and more. Figure 18 shows the plain weave, which is the most homogenous and therefore the strongest to use for building applications. A satin weave has warp threads skip more wires before weaving under, which creates longer thread surface, which is more appropriate for clothing, because it has more stretch and feels softer. Compared to knitted fabrics, woven fabrics have a low degree of elongation in either direction (Kaltenbach, 2004).

Narrow textiles

These fabrics are produced similar to the woven fabrics, but are later reinforced with high density woven strips that are stitched on. These reinforced belts can significantly increase strength and span of a fabric (Pohl, 2010).

Knitted fabrics

Knitted fabrics are made by looping and stitching threads together. Machines are capable of making the fabrics with high precision, which was traditionally done by hand. However, the open mesh structure of the fabrics make them useful for indoor applications only. Compared to woven fabrics they have more flexibility and shape retention, due to their mesh structure (Pohl, 2010).

Nonwovens

Are a random collection of fibres that stay together by friction force only. Processing technologies

have increased the use of nonwoven fabrics in other fields, like air filters. Mechanical building applications are not possible, but breathable, water tight films can be created (Pohl, 2010).

Spacer fabrics

Are created weaving two fabric layers together by a stiff medium, which keeps them apart. 3D knitting techniques can also produce spacer fabrics. The thickness gained increases both thermal and acoustical insulation dramatically, but this comes at the cost of flexibility (Pohl, 2010).

Meshes

Are comparative to knitted fabrics, but the intersections of the fabric are joined together. This is done through heat bonding of the plastic or coating of the mesh. Meshes can also be created by perforating a polymer sheet and then stretching it out of proportion. Grids only have a structural quality for itself or as reinforcement of a layered system (O'Mahony, 2011).

Laminates

Laminated fabrics are a collection of fabrics stacked on top one another. The layers are glued by adhesives or heat bonded to each other to make a single whole. Each layer can be a different kind of fabric with different properties. The ideal fabric and property can be chosen for each layer making an effective composite. The result is a fabric that is used in high performance applications, like ship sails, arctic tents or zeppelins (Verheul, 2009).

Isotropic membranes

In case of membranes the raw materials can be directly processed to a membrane. This is done through calendaring of extrusion. Calendaring is used on metals and certain polymers like PVC. During this process the material is heated to malleable temperatures and passed between a series of increasingly tighter rollers. The resulting thickness is thicker than by extrusion however. In that process the material is pressed through a shaped die and can even be pultruded by pulling it further (Knippers, 2011).

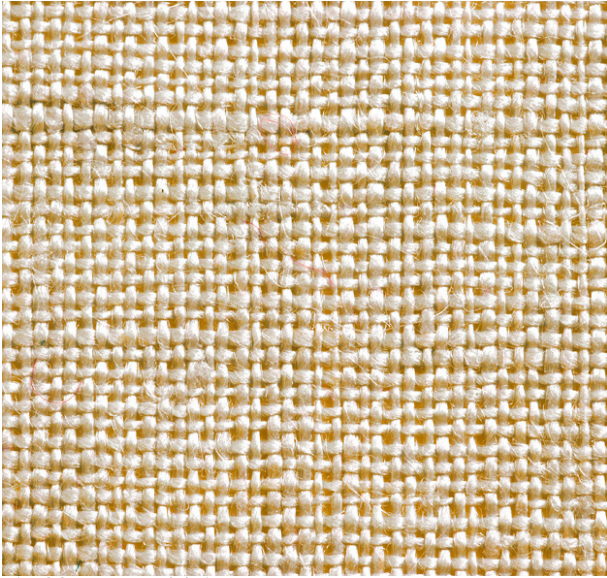


Fig. 22 woven fabric



Fig. 25 knitted fabric

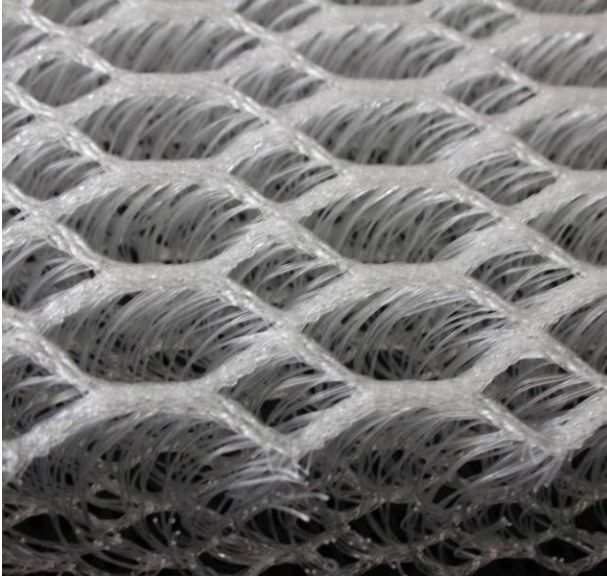


Fig. 23 spacer fabric



Fig. 26 nonwoven fabric

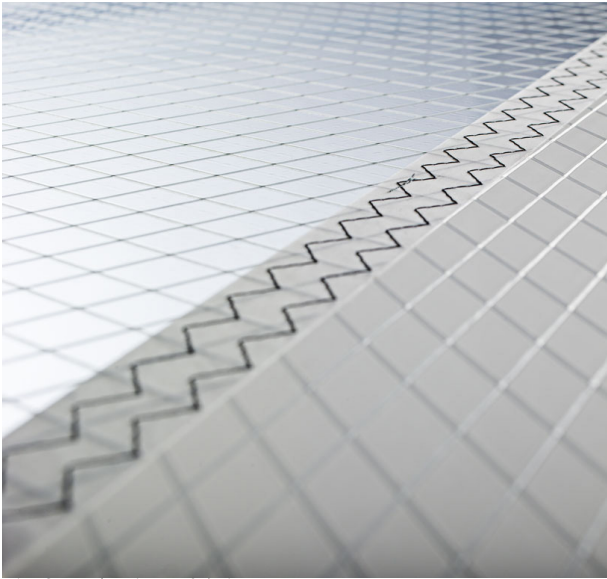


Fig. 24 laminate fabric



Fig. 27 membrane

3.4 - Size availability

Because of the fabrication methods of the membrane materials or the methods with which the coatings are applied the membranes have a maximum size at which a single, unassembled sheet is available. Larger could be and even are used, but they are made from many smaller pieces that are combined with one of the techniques mentioned in the next sub-chapter.

The length of the fabrics are produced in an indefinite stream, if desired, but are often cut of at a distances of around 100m. The width of the bolt, which is the industry name for a roll of fabric, is the deciding factor. Size greatly depends on the exact product and finish.

Below a couple of normative fabrics and their generally available widths are given.

Foils

Most foils like mylar or ETFE are available between: 150-220 cm

Technical fabrics

Technical fabrics like Nomex or Kevlar are available between: 102-152 cm

Common fabrics

Common fabrics like cotton or polyester are so well established that the production factories have specialized large machinery capable of producing bolts of: 2.74 cm

Metal foils

Metal foils have highly varying production sizes.

Aluminium	125 cm
Stainless steel ultra-thin (25um)	60 cm

Mineral sheets

Similar to metal foils, mineral sheets vary highly, because they are specialty products.

Nippon glass	80 cm
Scotch ultra-thin glass	50x50 cm

Fibres and filaments

Filaments are produced at very great lengths. Far beyond the scope of this project. An simple way of checking if a fibre can be structurally applied on a span is the free-tearing length.

Steel 25km, cotton 48km, carbon fibre 153km, aramid 190km.

3.5 - Membrane connections

In the building environment a single membrane will never be used on its own. It will always be in combination with other materials. A rigid structure to hold the membrane in the required shape or other membranes connected by a seam to make larger surfaces possible.

The area where these materials meet is the connection between the two. This connection can be realised in a number of ways. Each with their advantages and disadvantages. More information can be found in (Knippers, 2011).

However, each material and coating combination has different properties, which make them more suitable for certain methods of connection. Figure 28 will show some proven connection details and techniques used for fixing or connecting seams of foils and fabrics for membrane structure applications (Knippers, 2011).

			Polyester- PVC	PTFE/ glass	Glass- silicone	Coated PTFE	PTFE
Seam	Permanent	Stitched	+	--	--	+	++
		Welded	++	++	--	+	--
		Glued	-	--	++	--	--
Linear support	Detachable	Laced	+	-	-	+	+
		Clamping bar	++	-	-	+	+
		Keder rail	+	++	++	+	+
	Flexible	Webbing belt	+	--	--	+	+
		Wire rope	+	+	--	+	+
Edge	Rigid		+	+	--	+	+
	Flexible	Webbing belt	+	--	--	+	++
		Rope in pocket	++	-	+	+	+
		Seperate edge cable	+	+	+	+	-
	Rigid	Laced	+	-	-	+	+
		Clamping bar	++	+	+	+	+
		Keder rail	+	++	++	+	+
Corner	Open		++	+	+	+	+
	Closed	Ring/eye	+	--	--	+	++
		Plate	+	++	+	+	+
High/low point	Flexible	Cable loop	+	+	+	+	+
		Scalloped	+	-	-	+	++
	Rigid	Ring	++	++	+	+	+
		Hump	+	+	+	+	+

Tab. 4 membrane connection methods and their viability

++ typical + possible - rare -- not possible

3.6 - Coatings

Coatings are often applied to the fabrics and membranes to increase durability through protection against UV radiation, moisture, fire and fungus. Thereby their lifetime is extended. An especially important aspect when making materials for use on buildings. Coatings can also provide aesthetical variation through the use of printing, pigmentation or other finishes. Coatings can be applied to a single side, but are practically always coated on both sides for extra protection (Knippers, 2011).

Almost every fabric is coated for waterproofing and for bonding the fabrics together. The fabrics themselves are difficult to join through adhesives and can't be heat welded or joined through high frequency welding. The coatings act as a medium for these connection methods. Therefore the strength of any seam is dictated by the coating and joining method (Llorens, 2015). The only exception to this are fluoropolymer fabrics (Kaltenbach, 2004).

The most used coatings in the building environment are PVC, PTFE and Silicon coatings. They have a high resistance against temperature variations, cracking through aging and UV radiation. The coating with one of the highest protection values is PVF, but it is expensive and it prevents welding or any adhesives. Seams need to be shielded during coating and treated after welding, which makes the process even more expensive (Kaltenbach, 2004). Specialized coatings like FEP, PFA. Titanium dioxide coatings are used as a final top coat for dirt resistance. Titanium dioxide can even transform carbon dioxide into oxygen and thereby purify the air (Garbe, 2008).

For solar control low-e coatings can be applied as well. This means that the coating material has a low radiation emission coefficient. These are similar as to the coatings applied to glass, but aren't transparent. This does make them exponentially more effective however (Knippers, 2011).



Fig. 29 PVC coated polyester

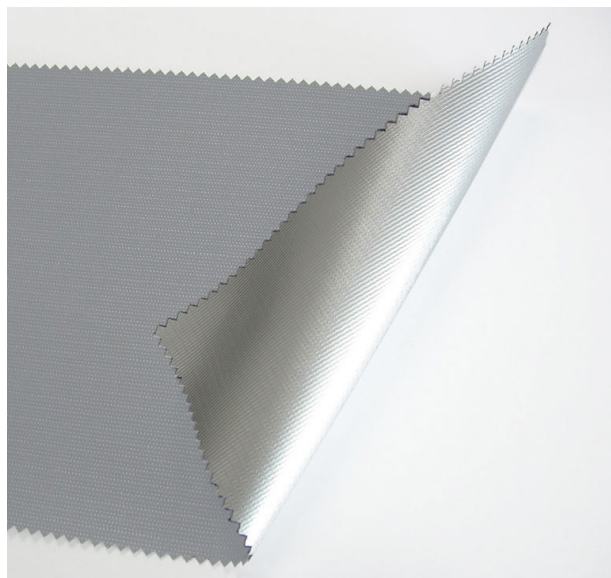


Fig. 30 Low-e metalized coating

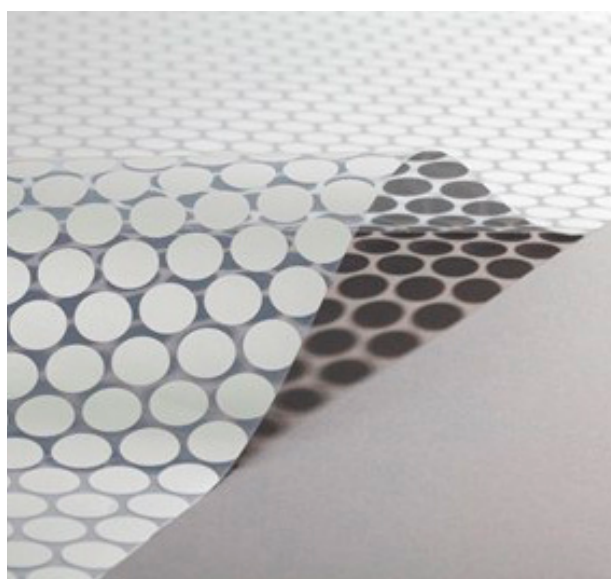










Fig. 31 printed etfe

3.7 - Membrane materials

The different materials, production types and coatings result in a large amount of membrane materials. All with different properties and therefore different strengths and weaknesses. For an application like a building envelope there is however not one definitive membrane that can fix everything. A layered or composite structure of different types will always be needed.

For orientation into the available materials, the most suitable for architectural applications have been listed, in different categories according to their strengths. The categories mentioned are all important properties in design of building envelopes. They are indicated with icons for easy reference. The properties along which classifications are made are:

Tensile strength	
Fire resistance	
Thermal insulation	
Transparency	
UV protection	
Acoustical insulation	
Ventilation	
Other	

Tensile strength

Ultra-high molecular weight polyethylene (UHMWPE)

UHMWPE are currently the strongest fibres known. They were developed in the Netherlands by DSM., through a process that fully unfolds the polymer strands in the material, which makes them extra strong. Their tensile moduli are greater than 70 GNm⁻². This is around two times as high as para-aramids like Kevlar and fifteen times as high as steel. UHMWPE materials also have low densities, are chemically inert and abrasion resistant. However, their melting point is at 150 °C. (Horrocks, 2000). Dyneema and Spectra are common brands for fabrics made from these kinds of material.

Para-aramids

Para-aramids are a form of aramids. These are aromatic polyamides, produced by spinning fibers from a liquid crystal polymer solution. Para-aramids were developed after UHMWPE materials in search of high strength polymers with a higher temperature tolerance. The materials carbonize and lose properties at around 425 °C. It is also possible for water to attach itself to the para-aramid, which makes it able to adhere by for example epoxy. The advantages do come at the cost of lower strength, however. Protection against UV radiation is also needed, because they photo degenerate. Other properties are very similar to UHMWPE materials. Kevlar, Twaron or Vectran are common brands for fabrics made from these kinds of material. In comparison, Vectran can be dyed more easily (Horrocks, 2000).

Carbon fibres

Carbon fibres are made from filaments of pure carbon atoms, which are aligned in crystal formation. This alignment gives the material high strength, high stiffness and low weight properties. Carbon fibre cloths also have high conductivity and won't degrade at extreme temperatures. The material is however quite brittle and is therefore best applied in composite panels in combination with resins. Carbolon or Thornel are common brands for fabrics made from these kinds of material (Horrocks, 2000).

Fire resistance

Meta aramids

Meta aramids belong within the same material group as the para aramids and are developed in the same way. However, the meta aramids are made with less symmetry and order in the material structure, which results in different properties. The materials have lower tensile strengths, but greatly increased resistance against extreme temperatures. Nomex and Newtex are common brands for fabrics made from these kinds of material. Nomex has the added property of expanding when under heat load, which increases its insulating properties (Horrocks, 2000).

Novoloid fibres

Are fibres also created by melt spinning material, but this is made by applying resins to the process. The resulting fibres are weak, but do not melt and have a heat resistance twice as high as para aramids. The burning cloth slowly carbonizes at 250 °C, but because the carbonization protects further damage, it can take flames of 2500 °C over 12 seconds long. Smoke emission and toxicity are virtually non-existent. Kynol is a common brand for fabrics made from these kinds of material (www.kynol.de).

Polyethylene Terephthalate (PET)

PET is a polyester, which can be processed into a fabric or a membrane. The material is used often in industrial and electronic applications, because of its high dimensional stability and durability against chemicals and extreme temperatures. Mylar is a common brand for fabrics made from these kinds of material (O'Mahony, 2011).

Thermal insulation

Ceramic fibres

A material developed by NASA for their space shuttles. The material provides a high range of properties. It is lightweight, fire resistant, high strength, chemically resistant and has a high insulation value. Currently often used in high grade clothing or furnace lining. Nextel is a common brand for fabrics made from these kinds of material (www.3m.com).



Fig. 32 UHMWPE



Fig. 35 Nomex

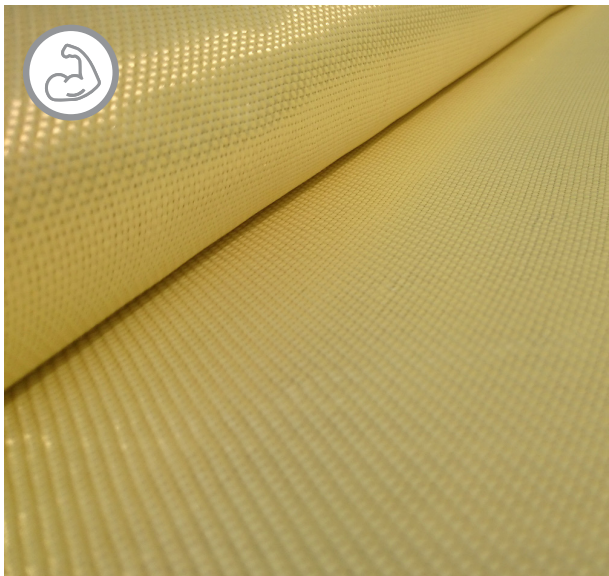


Fig. 33 Kevlar



Fig. 36 Mylar foil



Fig. 34 carbon fibre cloth

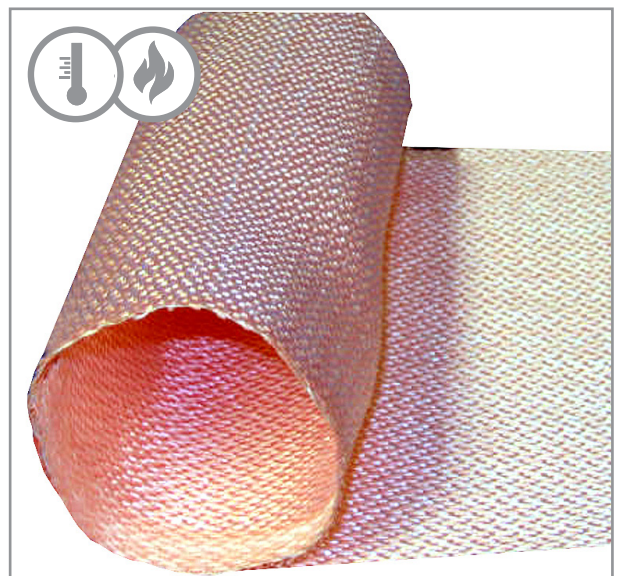


Fig. 37 Nextel

Aerogel

Aerogel is the lightest solid material known. It is made from more 95% air, has excellent insulation properties and is extremely lightweight. The normally solid material can be processed to spun fibres and formed into sheets. Some of its properties are lost this way, but it gains flexibility and strength. Spaceloft and Tensotherm are common brands for fabrics made from these kinds of material. The Tensotherm variant is applied in a layered sandwich structure with two layers of PTFE. A laminate of 24mm can have U-values of 0.56 w/m²K (Augustyniak, 2016).

High density Polyether (HDPE)

This material can be made into sheets by thermally fixating fibres in a paper like membrane. The membrane won't tear and is waterproof, while still open to vapours. It is often used as water barrier films, but new developments have created a 3.8cm thick variant capable of reaching insulation values of R5.0. This material is developed by Tyvek (www.construction.tyvek.com).

Transparency

Fluoropolymers (PTFE, ETFE, TFA, PFA, TFE, HFP, VDF, THV, FEP, PVDF)

This group of materials are applied in various transparent membranes. They have strong polymer bonds which give them high chemical, biological, UV and weather resistance. Coating may be necessary for water tightness on some types. Coatings or dyes can be applied as well for sun shading or aesthetical reasons. Current architectural structures often use these kinds of materials because their transparency is greater than 90%, which is higher than some insulated glazing types. ETFE is best applied as an envelope, because its higher properties (Kaltenbach, 2004).

THV

THV membranes are as resilient and transparent as ETFE membranes. Transparency is 95% and many types of coatings can be applied. Tearing strength is lower, however, which makes it unsuitable for large spans (Kaltenbach, 2004).

UV protection

Low-E coating

Every fabric can have high UV protection with high grade PVC or silicon coatings. These won't become brittle after long-term exposure and are dirt repulsive. The coatings can also be metalized to give them a 80% reflection of incoming radiation. These coatings are the same as is used in insulated glazing, but because these aren't transparent, they are far more effective. Sunworker is a brand for fabrics made from these kinds of material (O'Mahony, 2011).

Scotchlite

Fabrics from Scotchlite have a specialized surface treatment of inset glass beads or a screen print of glass beads. The beads reflect incoming light. Scotchlite is however designed for highly visible emergency jackets, not for UV protection (www.3m.com).

Acoustical insulation

PTFE acoustic liner

PTFE is a fiberglass membrane coated with Teflon. It has a high durability and weather resistance. The thick and rough woven types have a high acoustical absorption of 0.7 sabins/m², which is very high compared to other types of membranes. Fabrasorb is a brand for fabrics made from these kinds of material (www.sheerfill.com).

Ventilation

Eco storm

Eco storm is a fully recyclable polyester fabric that is both waterproof and breathable. The material is made from two different types of weaves bonded together. The inner weave is a thicker water repellent layer, which is woven out of thicker strands. The outer layer has a tight, fine weave, which increases strength and dirt resistance. Ecostorm is a product developed by Tejin (www.teijin.com).



Fig. 38 Spaceloft

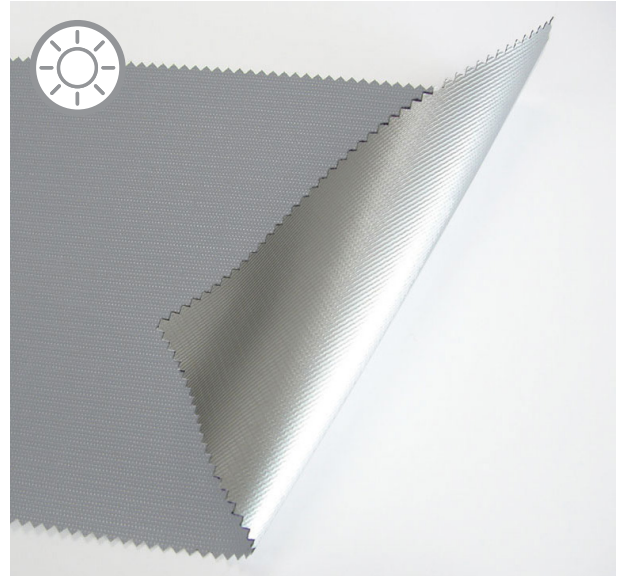


Fig. 41 Sunworker metalized

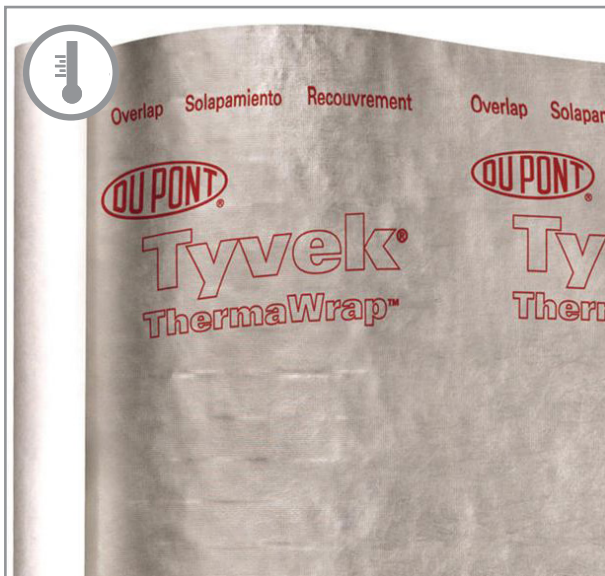


Fig. 39 Tyvek thermawrap

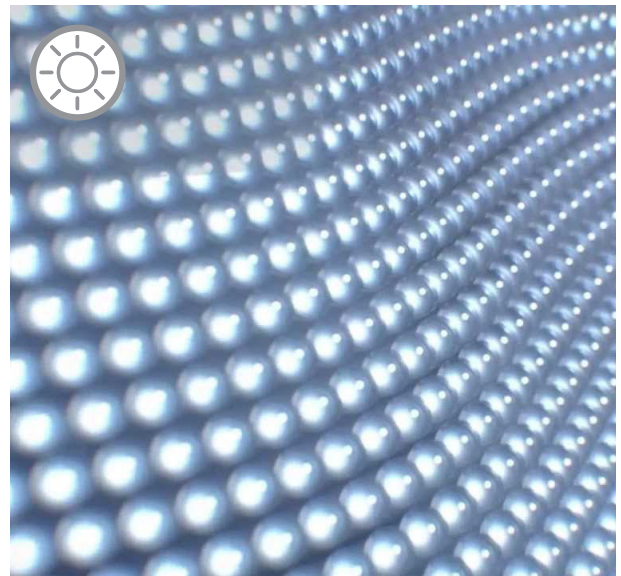


Fig. 42 Scotchlite

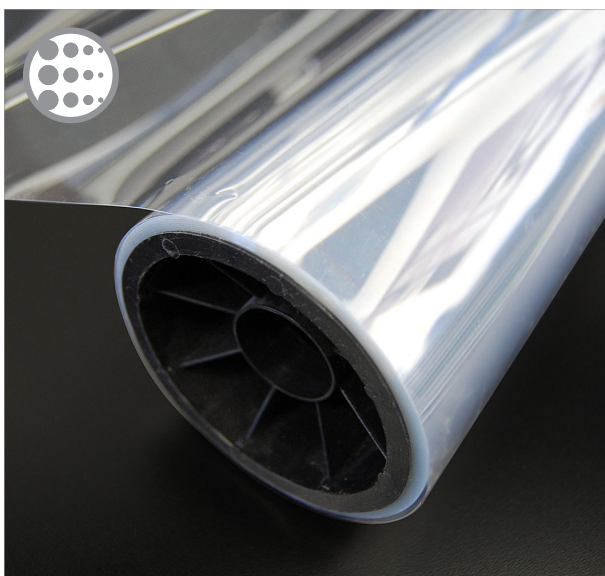


Fig. 40 ETFE membrane



Fig. 43 Fabrasorb

PTFE membrane

A foamed product of PTFE is essentially a porous product, but the pores are too small for water. This makes the membrane waterproof, but breathable. Gore-tex uses this material between a sandwich of polyurethane for structural integrity. The laminated sandwich membrane is used in many types of clothing (www.gore-tex.nl).

Other

Flexible PV panels

Photovoltaic cells have been developed greatly in recent years. Special plasma processes can deposit amorphous silicon between two ETFE foils to create a flexible PV panel, capable of generating electricity. The foils protect it on either side. Maximum size is currently 300mm by 3000mm, but this can be done created right next to each other. A reference project in Stuttgart, Germany deliver 45-50 Wp m². Solarnext has developed this project (www.solarnext.de).

PVC coated polyester fabrics

These fabrics are currently the most used fabrics on the building market. They have reasonable properties at a low cost. Their high elasticity, tearing strength and tensile strength makes them usable for large span structures. Also, the fabric is also receptacle for a large range of treatments, like coatings, dyes or printing (Kaltenbach, 2004).

Metal membranes

Metals are commonly used in the build environment as 3D shapes or sheets, but aren't common as standalone membranes. Metals often have very high reflection coefficients and are vapour tight, which makes them excellent façade applications, but they have very low tear resistance. Space blankets for instance have a metalized layer on Mylar film to provide high reflection with toughness.

Glass membranes

Advanced technology makes it possible for glass to be produced with a thickness of 25 micrometres, this thinness gives it relatively higher strength and flexibility. Currently used in technology like displays, cameras and sensors. The favourable properties could be used in many more applications, but at high financial costs



Fig. 44 Gore-tex

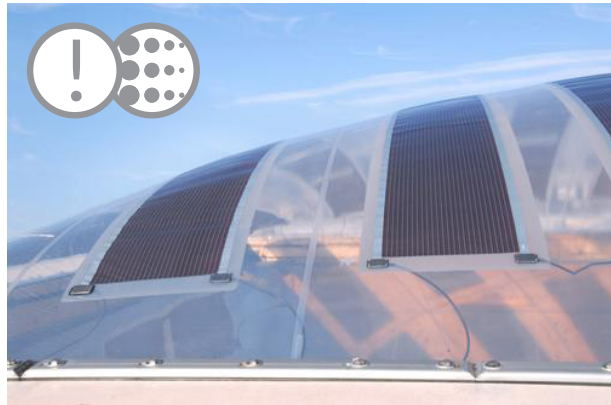


Fig. 45 Flexible PV



Fig. 46 PVC coated polyester fabrics



Fig. 47 aluminium foil

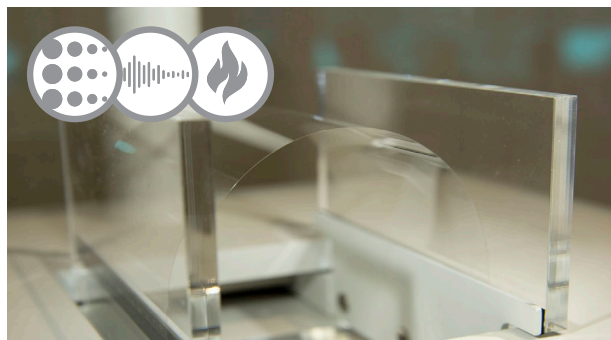


Fig. 48 ultra thin glass

3.8 - Numerical comparison

The following tables contain the key data about the fibres, filaments and foils that are discussed in the previous pages. The numerical values given can vary slightly per supplier.

Strong materials

	Density (g/cm ³)	Tensile strength (N/mm ²)	Tensile strain (%)	Elasticity (N/mm ²)
Cotton	1,5	350-700	6,0-15,0	4500-9000
Polyamide (nylon)	1,14	<1000	15,0-20,0	5000-6000
Polyester fibre	1,4	1000-1300	10,0-18,0	10000-15000
Fibreglass	2,55	<3500	2,0-3,5	70000-90000
Para-Aramid fibre	1,45	<2700	2,0-4,0	130000- 150000
Carbon fibre	1,7-2,0	2000-3000	<1,0	200000- 500000
UHMWPE	0,97	3300-3900	3,0-4,0	109000- 132000

Heat resistant materials

	LOI (%)	Heat resistance (°C)	Thermal conductivity (x10 ⁻⁴ W/m.K)
Meta-aramids	29	275	9,5
Novoloid fibres	30-34	150-250	1,3-2,5
PET		254	3,7
Ceramic fibres		1800	0,000012

Heat insulating materials

	Thermal conductivity (W/m.K)
Ceramic fibres	0,12
Aerogel	0,02
HDPE	0,52

Heat insulating materials

	Transparancy (%)
ETFE	90-95
THV	87-93
Mylar	21-60

Acoustic insulating materials

	Acoustical absorbtion (sabins/m ²)
PTFE acoustic liner	0,7

Air permeable / water resistant materials

	hydrostatic resistance (mm)
Ecostorm	20000

Tab. 5 numerical comprison tables

3.9 - Unitized envelope membrane

There are many membrane materials that each have their own advantages and disadvantages. What becomes obvious when these materials are ordered as is done in figure 51, is that the technical fabrics and foils each have a specific property for which they are designed to function very well. All the other properties are too low to mention. This means that for a membrane envelope that wants to have each property will always need a combination or composite of materials.

In the creation of a unitized membrane envelope transparency is very important. There are not many materials that have this quality. The ones that do are Fluoropolymers or THV. Aerogel and PET are only translucent. All others are completely opaque. Because of this reason Fluoropolymers, specifically ETFE, are used far more often in building applications. Something which will be shown in the next chapter. For high-strength and high-durability applications PET could also be a very suitable material.

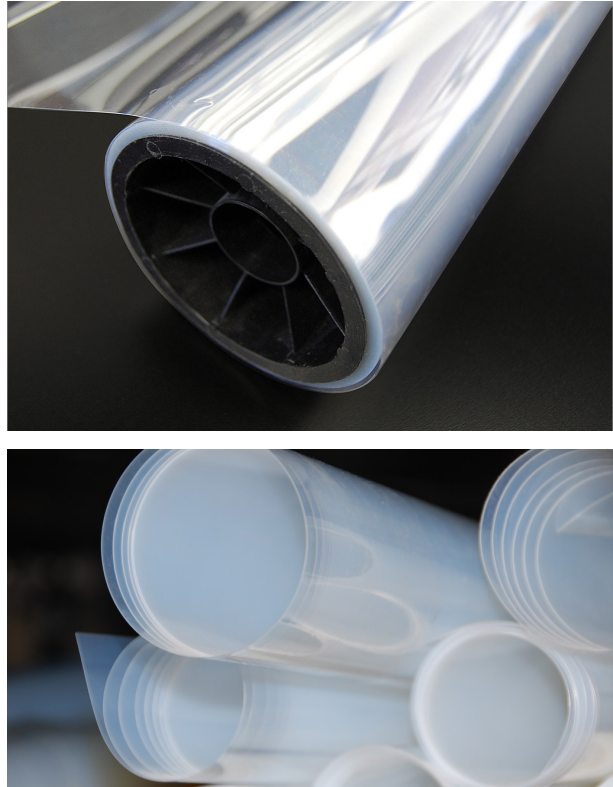










Fig. 50 ETFE membrane and mylar foil

								
Ultra-high molecular weight polyethylene (UHMWPE)	●	○	○	○	○	○	○	○
Para-aramids	●	○	○	○	○	○	○	○
Carbon fibres	●	○	○	○	○	○	○	○
Meta aramids	●	●	○	○	○	○	○	○
Novoloid fibres	○	●	○	○	○	○	○	○
Polyethylene Terephthalate (PET)	●	●	○	●	○	○	○	○
Ceramic fibres	○	●	●	○	○	○	○	○
Aerogel	○	○	●	●	○	○	○	○
High density Polyether (HDPE)	○	○	●	○	○	○	○	○
Fluoropolymers (PTFE, ETFE, TFA, PFA, TFE, HFP, VDF, THV, FEP, PVDF)	●	○	○	●	○	○	○	○
THV	○	○	○	●	○	○	○	○
Low-E coating	○	○	○	○	●	○	○	○
Scotchlite	○	○	○	○	●	○	○	○
PTFE acoustic liner	○	○	○	○	○	●	○	○
Eco storm	○	○	○	○	○	○	●	○
PTFE membrane	○	○	○	○	○	○	●	○
Flexible PV panels	○	○	○	○	○	○	○	●
PVC coated polyester fabrics	○	○	○	○	●	○	●	○
Metal membranes	●	●	○	○	●	○	○	○
Glass membranes	○	●	○	●	○	●	○	○

Tab. 6 numerical comparison tables

High ● medium ● low ○

4

MEMBRANE STRUCTURES

Membrane structures might seem like an odd concept in the solid build environment we know today, but it is one of the oldest forms of constructing shelters. Fabrics were used to construct tents. These were light, temporary structures. Ideal for early nomad cultures. The uses for membranes evolved from nomad tents - military campaign tents - ship sails - tensile roofs for amphitheatres like the Roman Colosseum - parasol structures. After this tent structures became more mainstream in modern society in

the form of circus tents (Llorens, 2015).

The lightness of membrane structures can make the spans and volumes enormous. Membranes are ideally suited for minimalistic architecture, but it has some disadvantages. They do not have much redundancy. New technologies are developed constantly, but are sometimes unproven and asks as much expertise of the engineer as the chemist. The advantages provided outweigh, however. Flexibility, mobility and a light touch on the world (Llorens, 2015).

4.1 - Types of structures

As is mentioned in the introduction, the lightness of membrane structures are one of the main advantages, but this also has some inherent disadvantages. Because of the low weight, designing against wind loads is normative. The strength of a structure is not determined by the rigidity or own weight, but by material, curvature and tension ((Knippers, 2011). Membranes in architecture always need to be tensioned in a doubly curved surface . Otherwise wind forces can cause flutter. This is rapid out of plane movement of the surface and will create a lot of noise on the scale of a building. The lifetime of the used materials are also seriously decreased through excess movement and forces (fabrics in architecture). There are other systems available and used, but not for permanent structures, and especially not for residential or office applications.

Pre-stressed structures can be roughly divided into two types. The mechanically pre-stressed structures or the pneumatically pre-stressed structures. Each will be explained in the rest of this sub-chapter

Mechanically pre-stressed systems

Mechanically pre-stressed systems are put under stress by direct forces of the structure. This is done through the use of weights or tension cables and can take a variation of fundamental shapes. These types will be explained.

Saddle shaped surfaces

These surfaces are created when the support points of the membrane alternate from high to low, as shown in figure 53. The tension created at the edge of the membrane, by being stretched up and down, stresses the whole surface. Stiff arches can be incorporated into this shape, but they have to be placed with equal forces on both sides for a stable structure (Bechthold, 2008).

Ridge and valley shaped surfaces

Ridge and valley shaped surfaces can be seen as elongated saddle shaped surfaces. They are typically created three sets of tensioned cable running parallel of each other of which the middle cable is fixed on a high point on either end. The two outer cables are fixed at four low corners. A number of these shapes can be replicated next to

each other within the same surface (Bechthold, 2008).

Point supported shaped surface

A surface type common in umbrella's or circus tents. This shape is created through one or more high points in a centralized location of the membrane. All other points, of which there need to be at least three, are fixed a at lower supports (Bechthold, 2008).

Braced surface

When a surface is fixed around its entire perimeter it is a braced surface. Braced surfaces can be applied in one of the above mentioned shapes, but also in planar surfaces. However, these are not completely rigid and need more stress to achieve the same stability (Llorens, 2015).

Pneumatically pre-stressed systems

Pneumatically pre-stressed systems are put under stress by a difference in pressure on both sides of the membrane. The gas with a higher pressure will push on the membrane, creating a uniformly distributed load. This is done by either increasing the pressure or decreasing it on the inside of the structure. Higher inside pressure will make the membrane curve outwards. Inwards curves are the result of a lower pressure. The shapes created are synclastic in shape. In these systems, pressure needs to be maintained at all times, which makes them inherently active systems (Kaltenbach, 2004). They can take a variation of fundamental shapes. These types will be explained.

Cushions

A membrane cushion is a system where two or more layers are clamped at the edges and filled with a higher pressure than the surrounding air. The edges are clamped to prevent the cushion from becoming a sphere, which is the natural shape it will want to make. The two outer layers will always curve in the opposite direction. The size and shape can be varied, but whole facades often are divided in multiple cushions. In orthogonal shapes corners are critical points. The shape of the membrane layers must be designed with the inflated volume in mind or corners should be avoided (Bechthold, 2008).

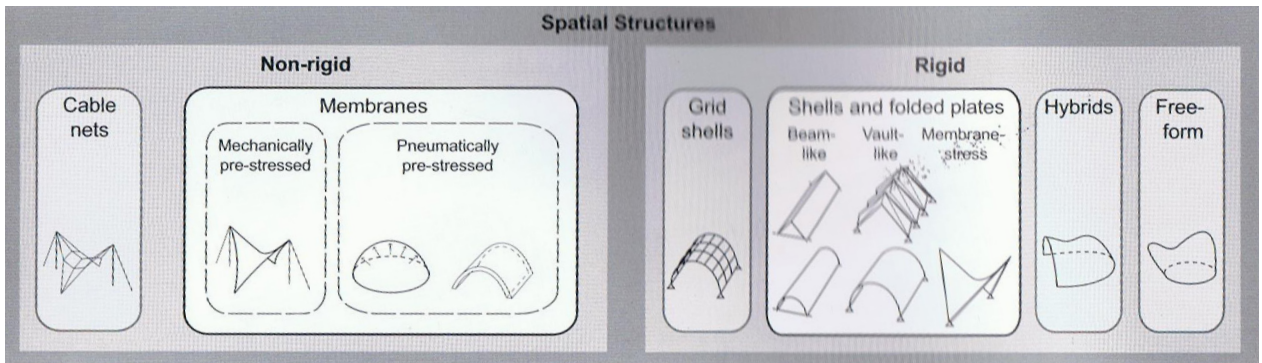


Fig. 52 spatial structures

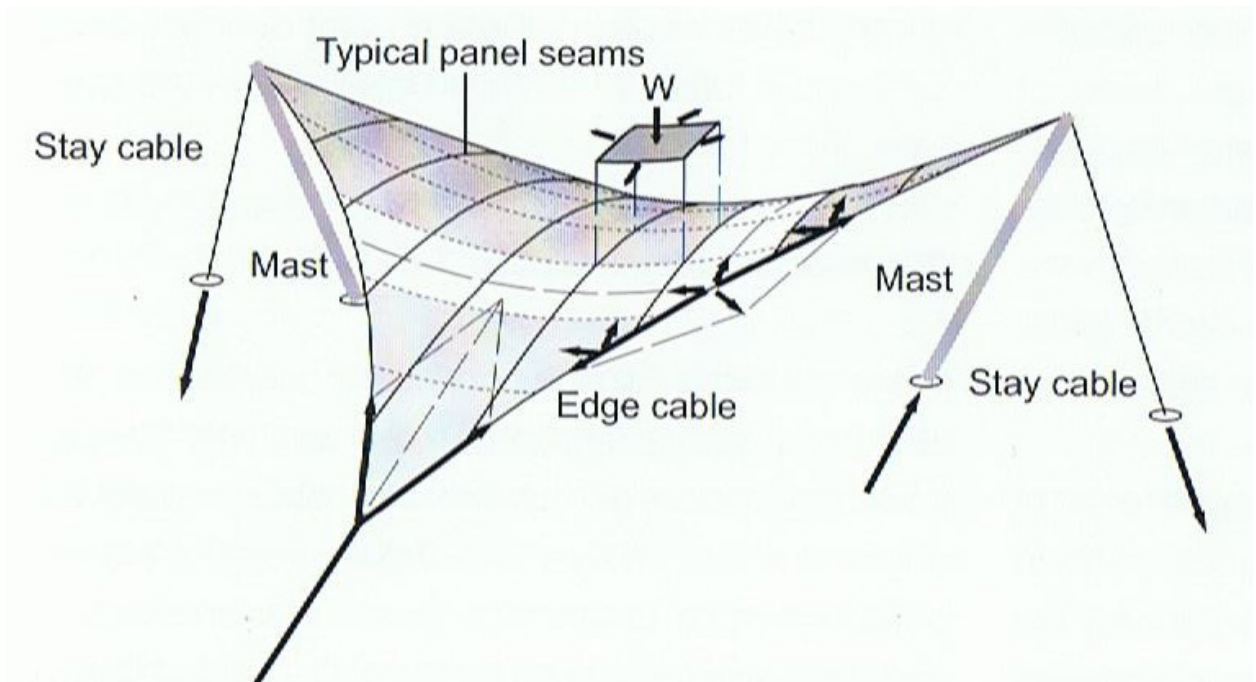


Fig. 53 saddle shaped surface

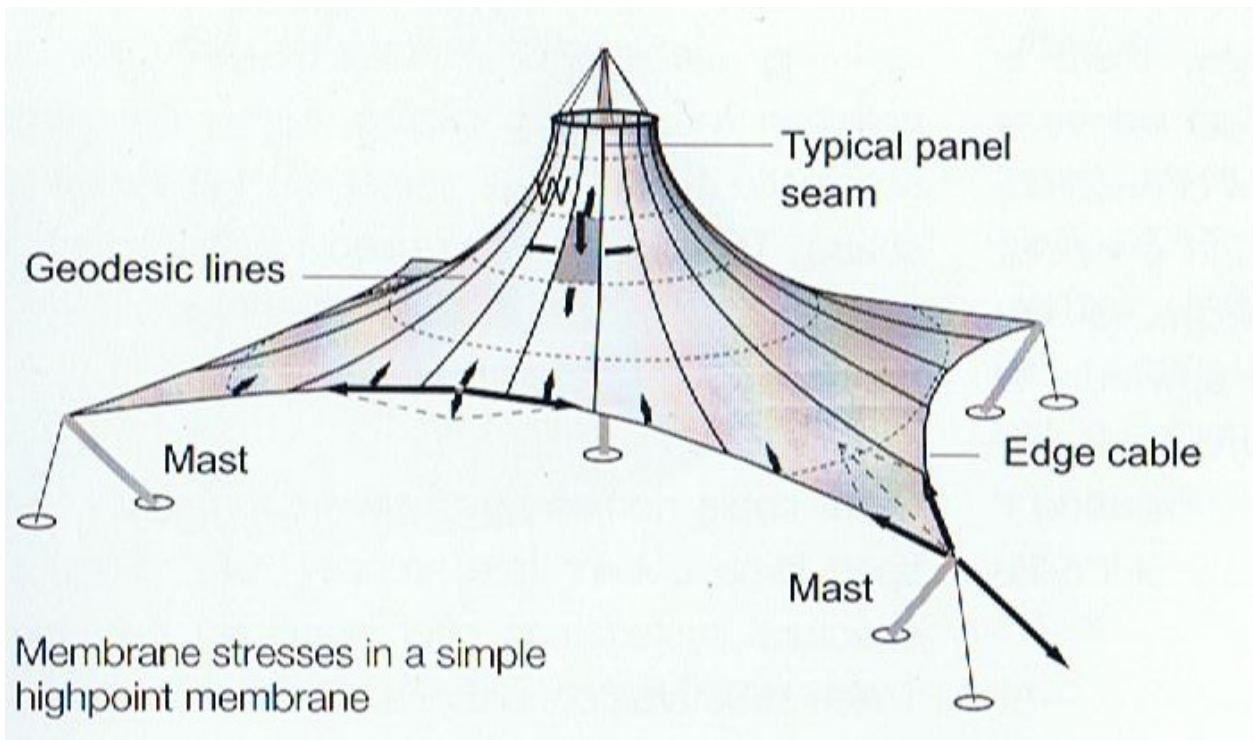


Fig. 54 point supported shaped surface

Tubes

Tubes are inflatable cushions with a spherical cross-section and an indefinite length. They can be used in structural applications as reinforcement of membranes or as a surface, by linking many next to each other (Bechthold, 2008).

Hybrid systems

Hybrid systems use both pneumatic and mechanical means for providing stress in the structure. Most of these systems use mechanical means for taking tension and pneumatically means for taking pressure forces in a structure. This can be for instance a tubular inflatable with cables containing its expansion (Llorens, 2015). Membrane structures are very delicate, compared.

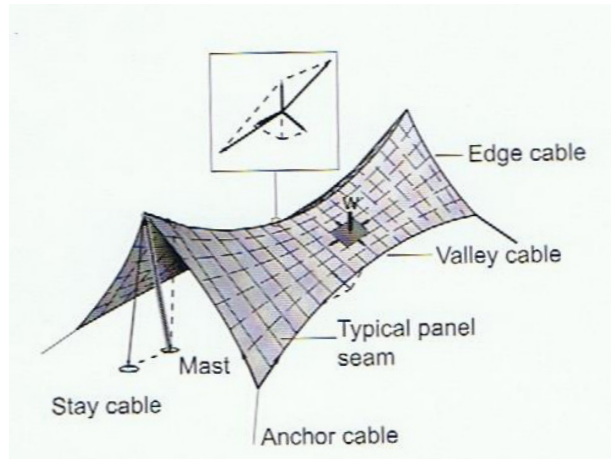


Fig. 55 ridge and valley shaped surface

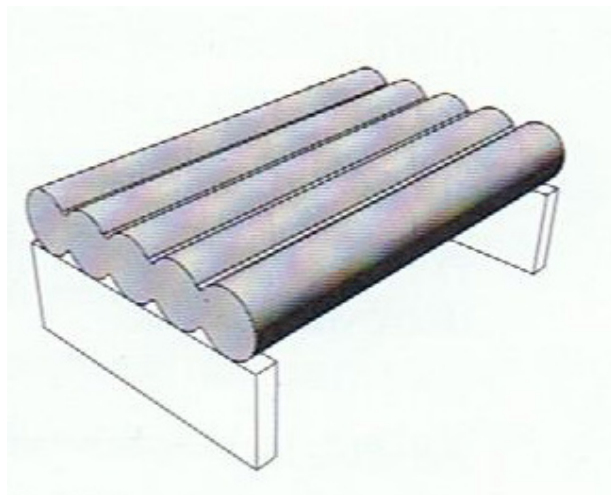


Fig. 56 tube

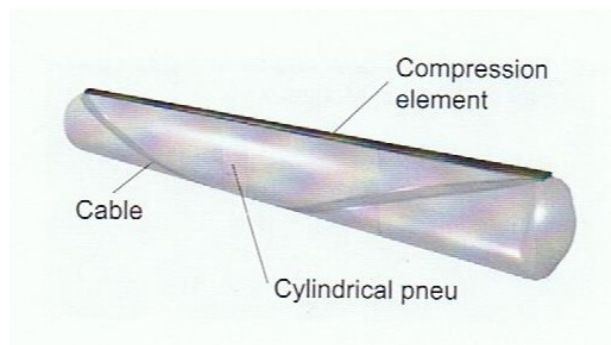


Fig. 57 Hybrid system

4.2 - Points of attention

to structures made from more rigid materials. The fact that they aren't as common also creates a lack of experience in building membrane structures. Some of the points of attention in developing a membrane structure can be identified by past experience. The most critical will be listed below (Llorens, 2015).

Tearing of the fabric

- o Proper fabric needs to be chosen for the mechanical and wind loads.
- o The geometry should be correct to properly divide the forces over the surface. Imbalance can lead to point loads and failure.
- o Detailing should prevent any and all sharp edges capable of damaging the fabric.
- o Maintenance should prevent unexpected loads or attacks on the surface.

Standing water

- o Geometry should prevent valleys and aid water runoff.
- o Maintenance on drainage should be regular.

Wrinkles

- o Manufacturing conditions should be to standards of applied location to prevent warp after placement.
- o Proper geometry and detailing should prevent wrinkling and therefore standing water, point loads and wind induced fluttering.

Corrosion of connections

- o Use anticorrosion protection on unfavourable connections.
- o Maintain open connections regularly. Corrosion can etch in membranes, which cuts into the membrane or affects its properties.

4.3 - Reference projects

Membrane structures are being built more and more. Many kinds of are realized, but most often it is used as sun shading, a second skin façade or for unclimatized areas. Few structures actually use membranes as the building physical separation of inside and outside as a building envelope. Of the ones that do, a small selection will be shown here, to serve as reference of what is possible.

The reference projects are:

- o The Eden project
Nicholas Grimshaw & Partners, London, UK, 2000
- o Cellophane house
Kieran Timberlake Associates, New York, USA, 2008
- o Môme – Experimental house
Kengo Kuma & associates, Memu, Japan, 2011
- o Thermohall
Rubb, Stockholm, Sweden, 2011

The Eden project

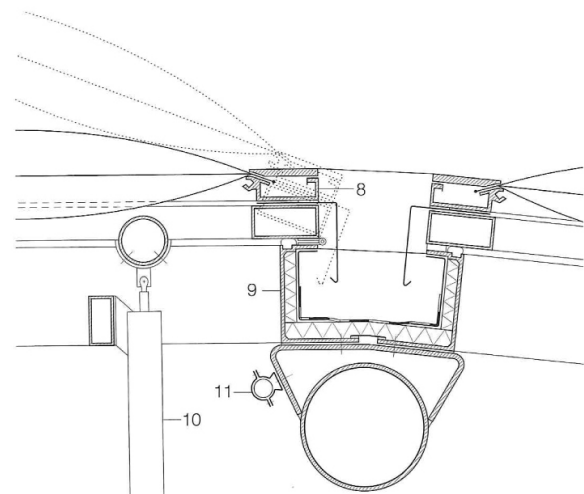
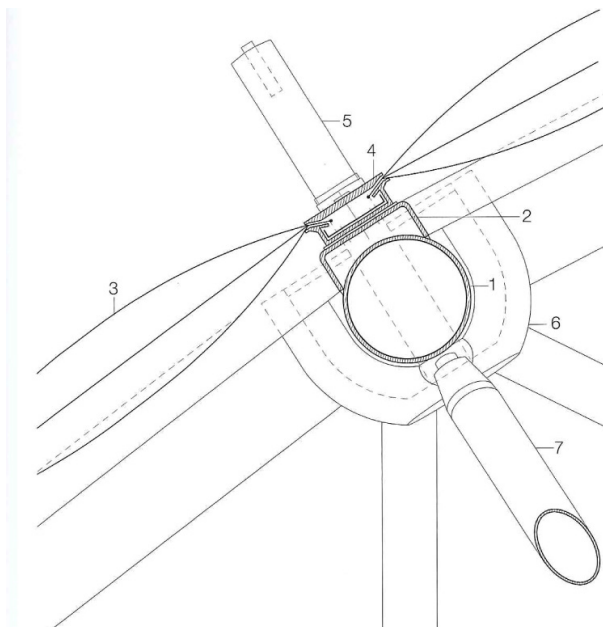
Architect: Nicholas Grimshaw & Partners
Location: Cornwall, UK
Realisation: 2000

The Eden project is a complex of structures, designed to house a number of exotic flora in so called 'biomes'. The most striking features are the five giant transparent domes. Three are connected, to create the biggest space of the complex, containing the Rainforest biome. The other two connect to house the Mediterranean biome (www.edenproject.com).

The design of the biome domes was based on efficiency. In shape and material. The domes have a hex-tri-hex structure made from steel tubes and plug-in joints, that are designed for ease of transport and assembly (www.grimshaw.com). The largest frame spans a gap of over 124m.

For the envelope, traditional glass was avoided, because of its weight. The building envelope is made from triple layered ETFE membrane of which the biggest panel is over 9 meters. These are extremely light weight, require little detailing and can achieve a U value of 1.96 W/mK. The edges of each cushion, where the ETFE is connected, are far thinner however, which means a lower overall heat resistance is achieved (www.onart.com). This can be seen in the detailing. Compressors are used to maintain pressure at all times.

The result of the ETFE envelope and steel construction is a building that is lighter than the air it holds (www.grimshaw.com).



- 1 Ø 400.6 mm steel tube
- 2 6 mm sheet steel bent to shape
- 3 three-layer inflated ETFE cushion
- 4 aluminium clamping strip
- 5 Ø 70 mm steel cylinder as safety rail
- 6 cast-steel node
- 7 Ø 89 mm tubular diagonal member
- 8 extruded-aluminium frame to opening flap
- 9 thermal insulation, steel section;
composite sheet-metal and plastic-sheet gutter
- 10 pneumatically operated cylindrical opening shaft
- 11 high-pressure-air tube for operating flap

Fig. 58 detail etfe cushion eden project



Fig. 59 birds eye view eden project



Fig. 60 Eden project under construction

Cellophane house

Architect: Kieran Timberlake Associates
Location: New York, USA
Realisation: 2008

The Cellophane house is a building designed for the museum of modern art, fabricating the modern dwelling exhibit in New York. Out of all contestants, it was one of five to be actually built and temporarily stationed in New York. The challenge was to design the prefabricated house of the future, with five stories, bedrooms, bathrooms, living and dining spaces. It was built with an aluminium structure with steel connections. Made for ease of assembly and disassembly. The building was built in parts on an offsite location and then put together in blocks.

The building envelop is made from a system called Smartwrap. It is a lightweight, energy-gathering building envelope made from multiple layers of plastic that are wrapped around the structural frame. In this case, the Smartwrap consists of four layers, stretched over the aluminium frame: the outer weather barrier, the second layer with photovoltaic cells, a third layer with UV resistant coatings, for solar control, and an inner layer of plane plastic. Ventilation between layers cools in summer, but stopping ventilation can insulate during winter. Thermal data isn't measured however.

All layer are made from PET plastic, normally used for boat sails and soda bottles. This type of plastic was chosen because it's colourless, transparent and inexpensive. It also has high chemical resistance and mechanical strength. Early prototypes fixed the flexible PV panels through adhesives, but new technologies are able to print the PV panels and necessary wires on the PET directly. PCM's or OLED's can also be integrated for added functionality, like heat storage and information display (www.kierantimberlake.com).



Fig. 61 Cellophane house



Fig. 62 Smartwrap



Fig. 63 Cellophane house interior

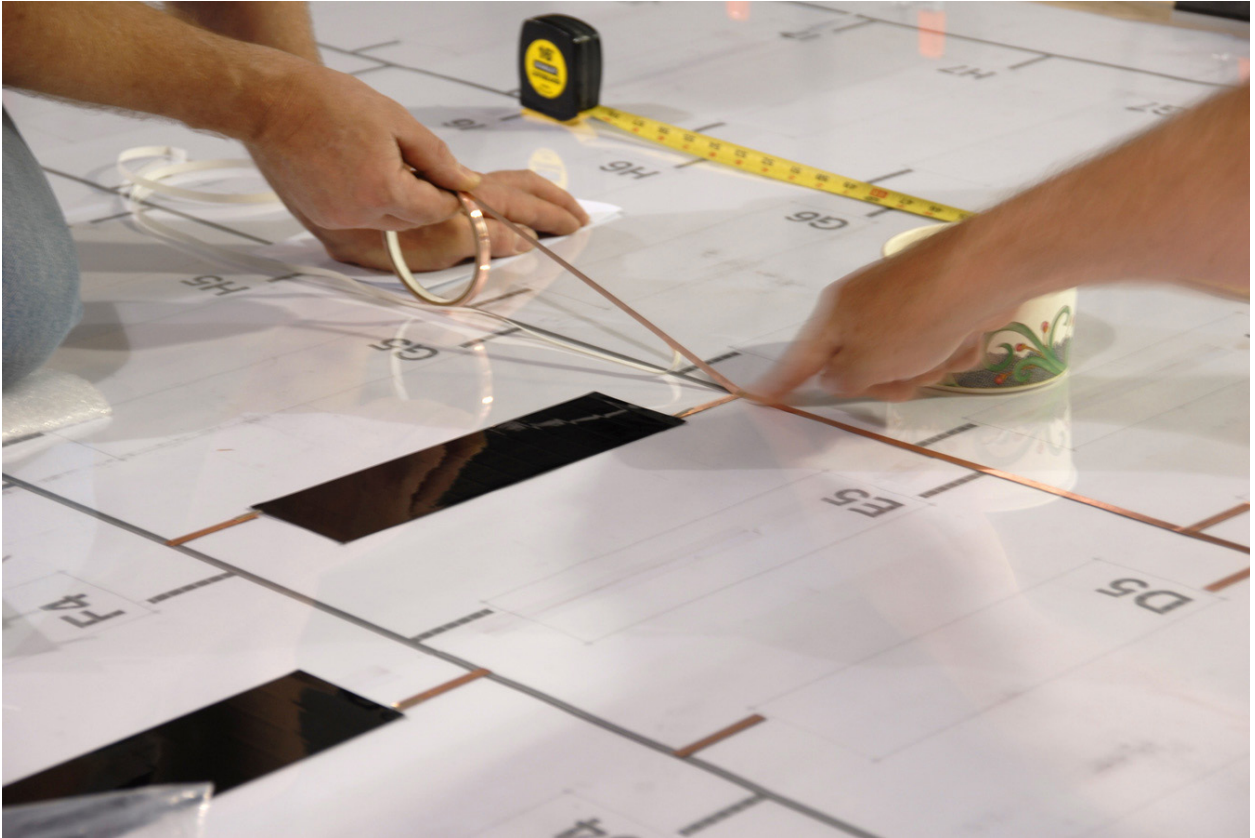


Fig. 64 Smartwrap assembly

Villa arena mall

Architect: Benthem Crouwel architecten
Location: Amsterdam, the Netherlands
Realisation: 2001

The villa arena mall has a roof of ETFE membrane cushions. The cushions are on a slanted roof and have triangle shapes. Half are lightly patterned the other half has heavy patterning. the cushions are supported with a tubular steel construction. Ingeniously the edge tubes also function as the pipes towards the inflation pump, which is connected to the cushion by a flexible tube. Excess air can escape via a release valve. There is no safety measure for water in a deflated cushion. Probably not necessary because the roof is slanted. The cushions are connected through a clamping connection. On the outside the clamp is protected against birds by wires. The slant of the roof is not enough to get water over every bump and ridge, which leads to a slightly wrinkled and dirty outer detail (www.arcam.nl).

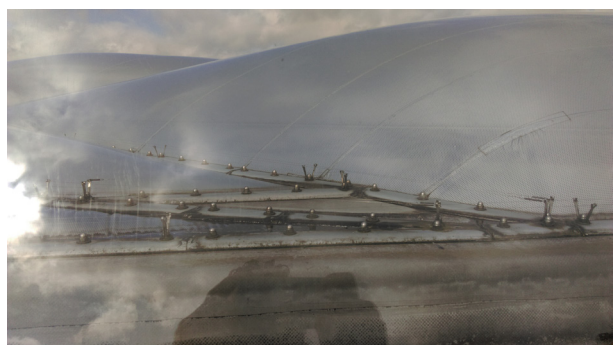
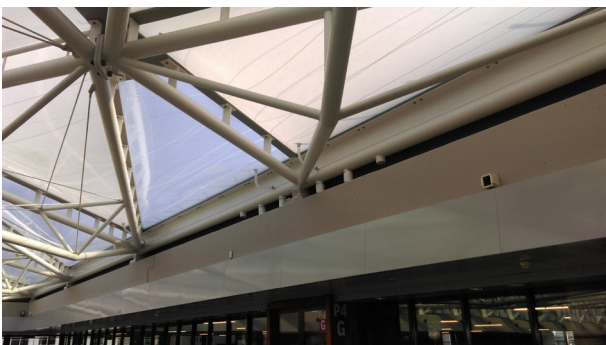
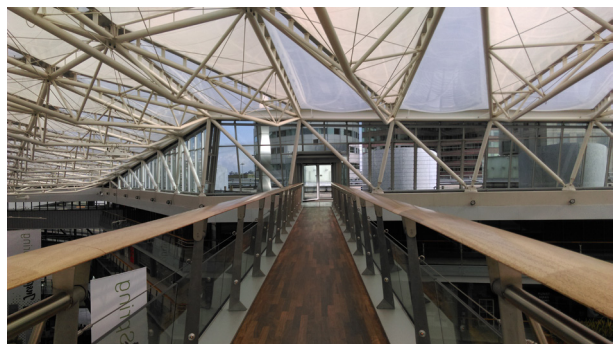


Fig. 65 collage villa arena mall



Fig. 66 villa arena ETFE cushion air supply



Fig. 67 villa arena ETFE cushion structural knot



Fig. 68 villa arena ETFE cushion roof

Même – Experimental house

Architect: Kengo Kuma & associates
Location: Memu, Japan
Realisation: 2011

This house was commissioned by the LXIL JS Foundation research sustainable living and future housing. The architect interpreted this by designing a lightweight house that embodies the concept of living in light.

The carrying structure is completely made from wood covered by an outer membrane of polyester with fluorocarbon coating. The inner membrane is a removable glass fibre cloth. They have introduced this adaptability to be able to change the insulation or other fabric layers according to their experimental needs. Recycled PET insulation is put in-between the membranes. All layers and materials are translucent

Heat between the layers can be ventilated along the floor as a kind of floor heating. It has been proven that this system can be comfortable for a couple of days in winter (www.kkaa.co.jp).



Fig. 69 même at night

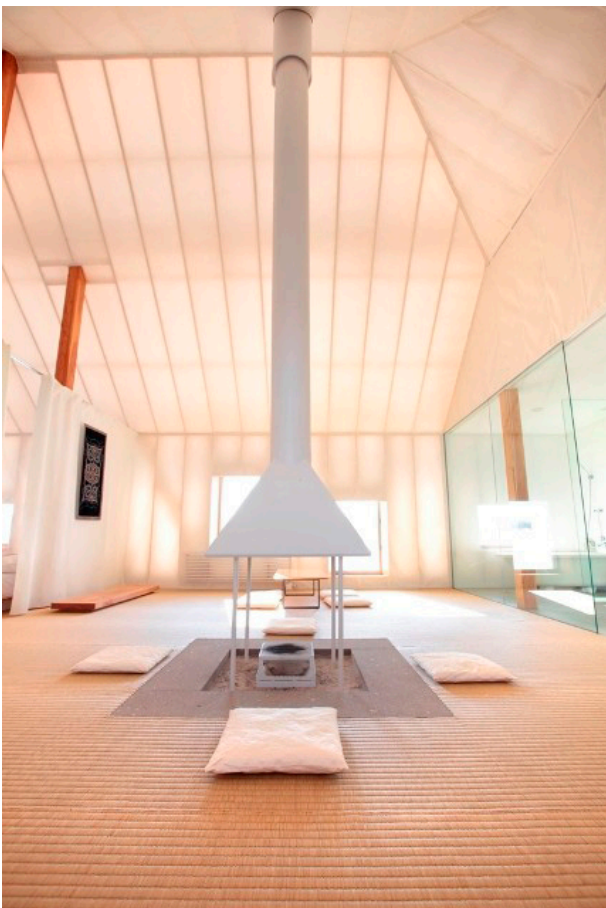


Fig. 70 même interior



Fig. 71 même wall construction

Thermohall

Engineers: Rubb
Location: Stockholm, Sweden
Realisation: 2011

The thermohall isn't actually a single structure, but a system sold by Rubb for insulated storage buildings. This means it isn't suited for residential or office applications, but the fact that it is one of the few mass produced insulating membrane systems is interesting.

The thermohall system uses a double layered cladding of heavy duty PVC membranes filled with glass wool insulation, which can be seen in the figures. This envelope is typically fixed on a steel frame structure. The end result is a system that can insulate up to a U value of 0.19 W/m²K with a thickness of 200mm.

Aircraft organizations are the prime customers. The membrane system is lightweight, which makes large hangars cheaper to build. The improved insulation value, in comparison with uninsulated panels used in some other hangar systems, is also a positive addition for delicate airplane parts (www.rubbuk.com).



Fig. 72 thermohall wall section



Fig. 73 thermohall

Others



Fig. 74 BMW Dynaform pavilion, ibz+L, Bollinger + Grohmann, Frankfurt, Germany, 2001



Fig. 75 UBPA B3-2 pavilion, Studio Archea, Shanghai, China, 2010



Fig. 76 Membrane house, F.O.B.A., Tokyo, Japan, 2000



Fig. 77 A.P.P.P. church, Royal Haskoning, Maassluis, Netherlands, 2007



Fig. 78 Allianz Arena, Herzog & de Meuron, Munich, Germany, 2005



Fig. 79 Zenith strassburg, FUKSAS, Strassburg, Germany, 2016



Fig. 80 Islazul, L35 Arquitectos, Madrid, Spain, 2010



Fig. 81 London Olympic shooting venues, Magma architecture, London, UK, 2011

5

UNITIZED CURTAIN WALLS

Building envelopes are constructed in a large variety of ways. Some are load bearing like the solid wall or walls with a skeletal structure. Some others depend on an interior structure for bearing the load and are only skins for protecting the inside from outside influences. Curtain walls fall under the latter group. A curtain wall is a non-loadbearing external wall attached to a framed structure, often one that is prefabricated (www.dictionary.com). The first curtain walls were designed by Walter Gropius around 1926 according to a desire for a functional and

industrial building envelope with large glass surfaces for light to enter.

Quickly, developments led to systems that were completely fabricated in offsite factories and assembled in units, which had increased building speed and factory quality as an advantage. The so called unitized curtain wall. (Murray, 2009).

During the years, curtain walls have developed and become far more advanced with many different systems available.

5.1 - Curtain wall types

The curtain walls can thus be divided in two main groups according to the way they are constructed and applied on a building. The division is between stick systems and unitized curtain walls.

Stick system curtain walls

These types of curtain walls are constructed on site using posts and beams that are fixed to the structural floors. The posts are fixed at the top and allow movement at the bottom to prevent buckling. Cladding is filled in at a later stage to meet aesthetic and functional demands (Barf, 2010).

Advantages

- o Standard systems applicable on almost any building.
- o Contractors are familiar with the systems.
- o Applicable in small scale.

Disadvantages

- o Low quality control.
- o Requires exterior scaffolding

Unitized curtain wall systems

Unitized systems are completely fabricated at an offsite factory and only need to be assembled on supports that are fixed on the structural floors. The systems are floor height and are less wide than their height is measured. They have the necessary structural posts and beams integrated in the panel together with the cladding. The advantages make them highly efficient in repetitive structures like skyscrapers. Extra planning costs, does negate the advantages in small scale applications (Barf, 2010).

Advantages

- o Guaranteed production quality.
- o Rapid assembly.
- o Low labour requirements on site.
- o No need for exterior cranes.

Disadvantages

- o Higher planning and developments costs on small scale.
- o Needs skilled contractors during application.

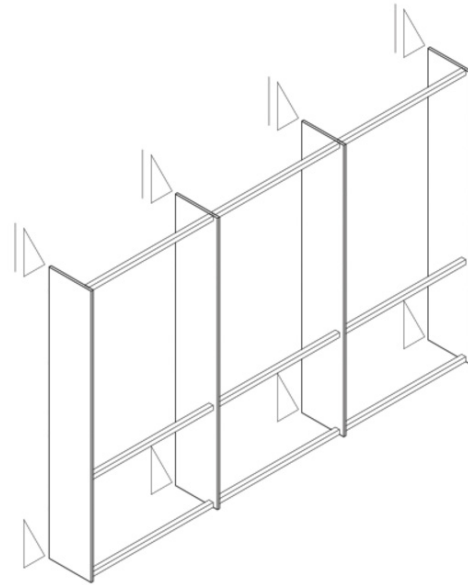


Fig. 82 Stick system step 1

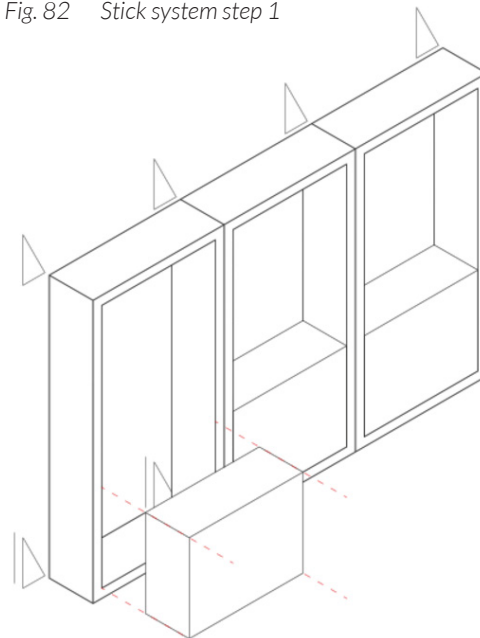


Fig. 83 Stick system step 2

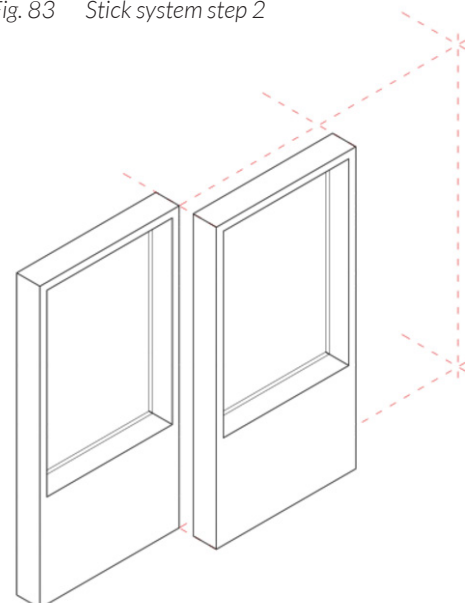


Fig. 84 unitized curtain wall

5.2 - Unitized systems

Unitized curtain wall systems, as explained in the previous chapter, consist from four key elements that combine to make the envelope (Murray, 2009). Below the elements will be explained along a façade panel from the seven more London project (Barf, 2010). Afterwards, details from well-known systems are analysed.

Building elements

Frame

Number one indicates the frame of the unitized panel. It is the main carrying structure of the entire panel and should therefore offer strength and stability against loads experienced on the building façade and during construction. Simultaneously the frame will function as the interlocking profiles that connect the individual panels to each other (Barf, 2010).

This part is often made from aluminium. It can be extruded and processed easily into the intricate shapes required from façade detailing. Steel frames are also possible, when a stronger material is required, but profiling is limited.

Cladding

The cladding is the main surface of the system and is filled in-between the frame. Glass is used most often for transparency and light. This panel has a closed part, however. This is in front of the

floor, because transparency is unnecessary at this location and extra insulation is more appropriate (Barf, 2010). The cladding can also add to the structure and stiffness of the frame. Especially four edge adhered structural glazing, which is only possible in prefabricated systems (Murray, 2009).

Seals

Numbers two, three and five point at sealants and gaskets. These are important parts for making the system air and water tight. They should be designed with freedom of movement and the placement in mind (Barf, 2010).

Exterior additions

The outer layer of the system contains optional elements like sun shading, safety features or purely aesthetical items. This case has vertical sun shading added (Barf, 2010).

Support points

Different supports are possible. For example rail system, which allow movement and a higher degree of tolerance, but they are superfluous in a well-planned building construction. Most systems currently in use, use smaller adjustable mounts as shown in the figure at number 7 (Barf, 2010).

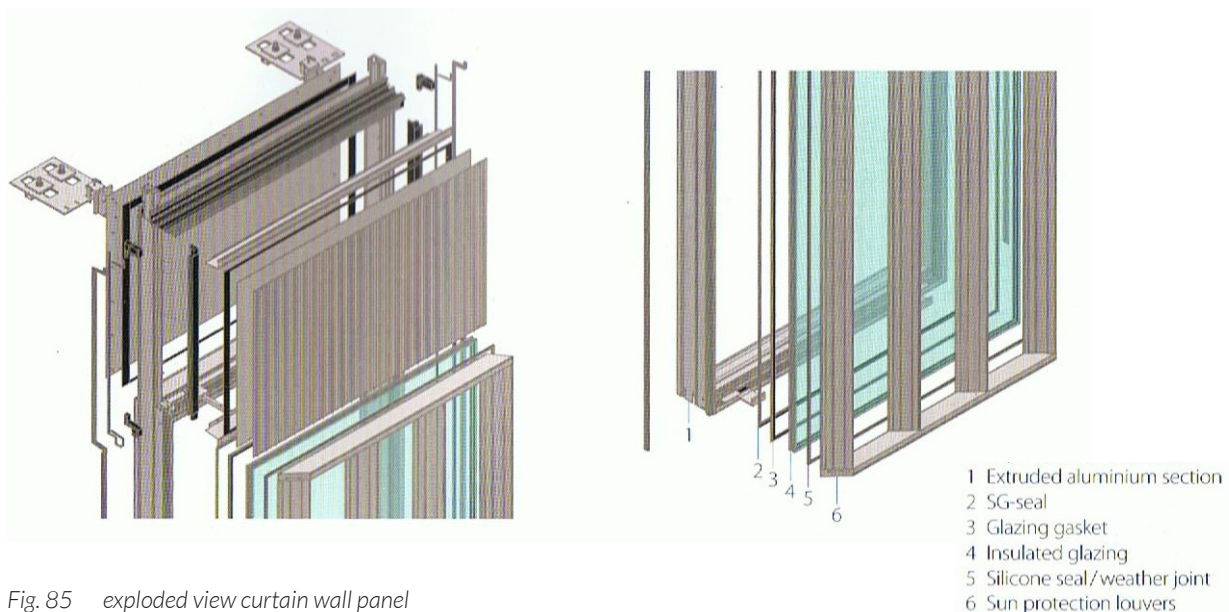


Fig. 85 exploded view curtain wall panel

53 - Detailing

The most basic detailing of a unitized envelop can be seen in figure 87 (Murray, 2009). This is the basis of many other systems, but they are more advanced and detailed according to demands for durability and sustainability. Every supplier has their own variation in design, but the principle stays roughly the same.

Figure 88 shows a detail of a system supplied by Rynaers aluminium N.V. (www.reynaers.com). The gasket shown at number eight seals the gap between the two components and the extra insulation at number seven prevents heat from escaping or entering through the vulnerable connection point. The rest of the detail speaks for itself. The result of that detail can be seen in figure 86.

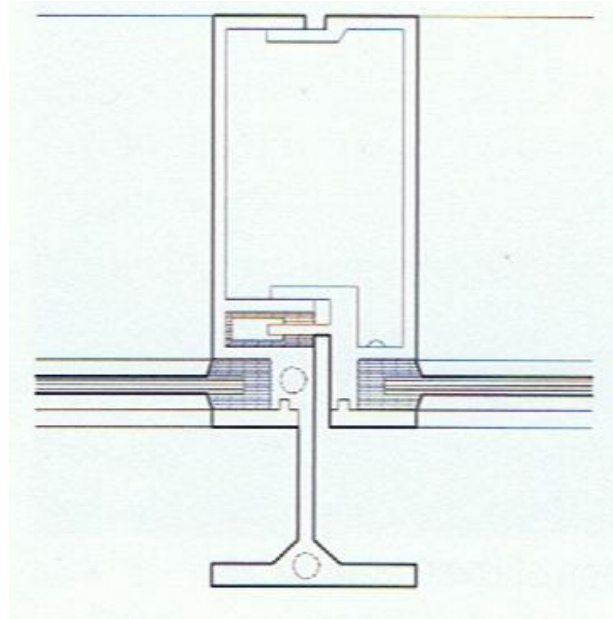
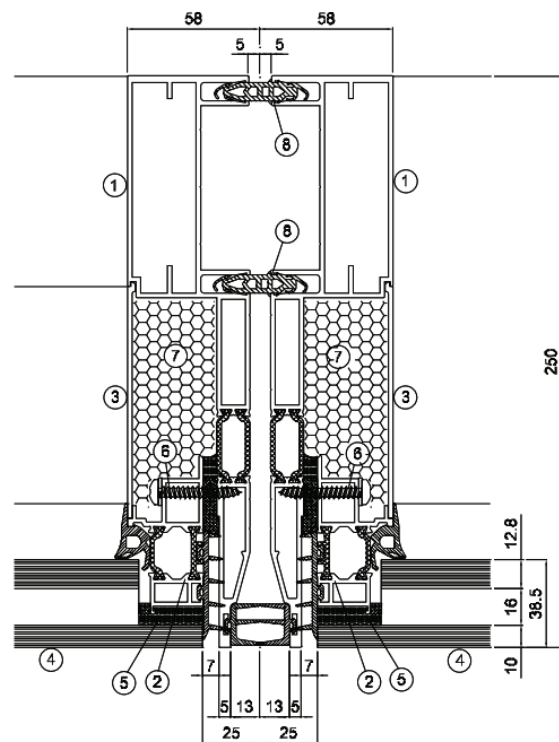


Fig. 87 facade detail cornering glass works



Fig. 86 Hofdatorg facade



- | | |
|------------------------------|-------------------------------|
| ① Outer frame | ⑤ Structural silicone sealant |
| ② Thermal broken glass frame | ⑥ Screw fixation |
| ③ Clips profile | ⑦ Insulation |
| ④ Vision glass | ⑧ EPDM linking gasket |

Fig. 88 Rynaers facade detail of Hofdatorg

5.4 - Installation

Installation of the systems can be done with a smaller crane that can be setup on a upper floor. There is no need for large external cranes or scaffolding, which is one the advantages of unitized curtain wall systems (Barf, 2010).

Figure 89 shows the assembly procedure of their systems. Before the step shown at the first figure the panels are stored inside, waiting to be assembled. They are always stored with the glass facing up to prevent damage. The panels are lifted on the loops at the end of the panels and turned around outside. Afterwards they are slid over the supports, which are placed and set in advance. Finally, adjustments are made to set the panel perfectly and the system is ready to receive the next one.

5.5 - Reference projects

There are almost uncountable buildings that have unitized curtain walls, that is how functional the system is for large scale buildings. Here are a few examples picked from this large pool, to serve as reference of what is possible.

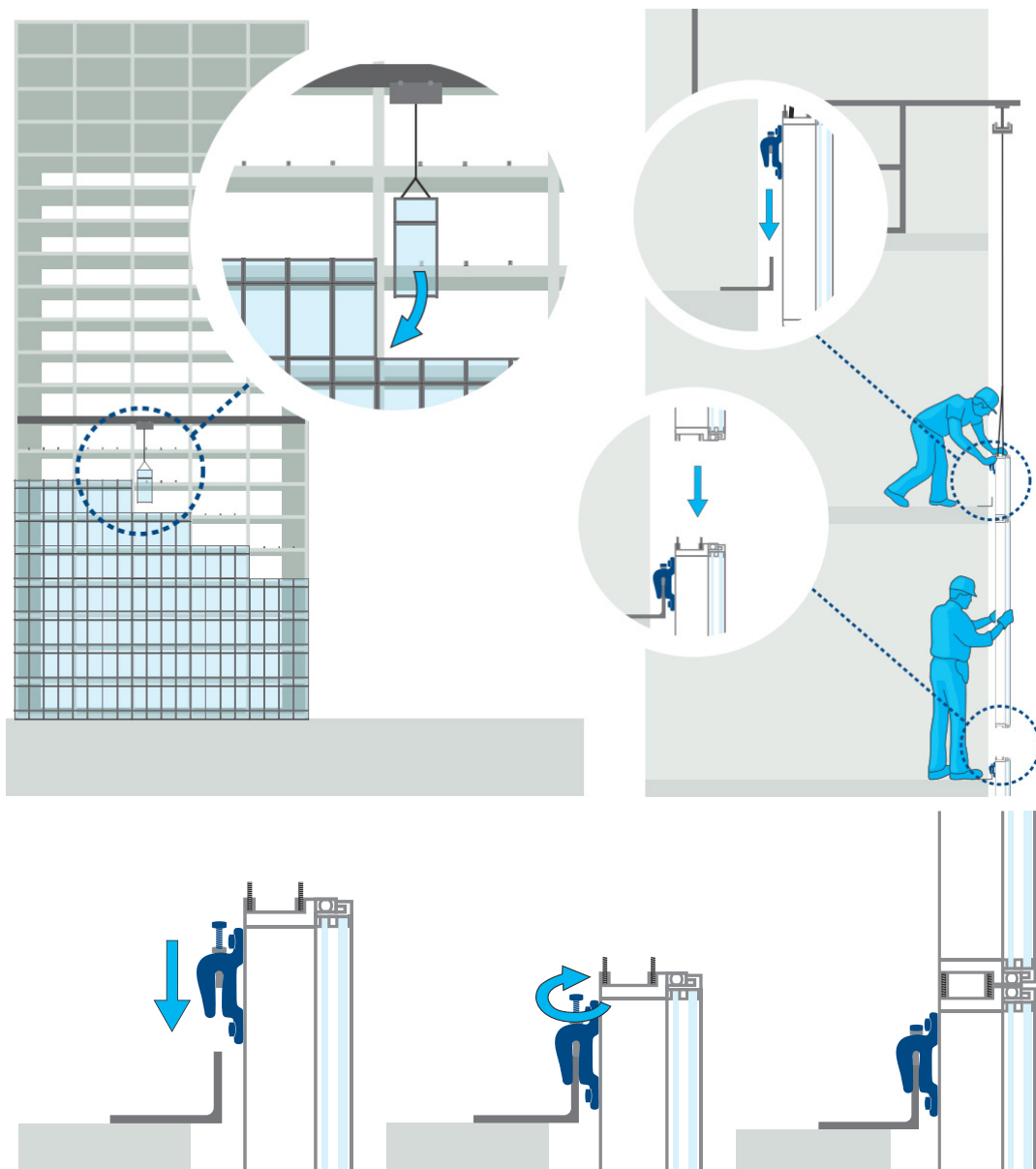


Fig. 89 Rynaers facade installation guide

Trutec building

Architect: Barkow Leibinger
Location: Seoul, Korea
Realisation: 2006

The Trutec building was to be the first building for a new digital media city and is a building that is characterized by its unique abstract visual effects. The curtain wall visually captures the surrounding context, through reflections in its many angles. Resulting in a kaleidoscope of light and colour.

The envelope is a custom prefabricated unitized system from aluminium and glass with a reflective low emission coating. Each panel is made from a set of non-orthogonal pieces put out of plane of the façade. The whole façade surprisingly only has three types of panels. One flat plain panel. A flat 2D panel with the division in it. And a 3D panel, which is turned upside down to create variation.

The panels were fabricated with CNC digital technology to precisely cut and assemble the complex shapes. Resulting in a technically challenging and aesthetically pleasing envelope (Murray, 2009).

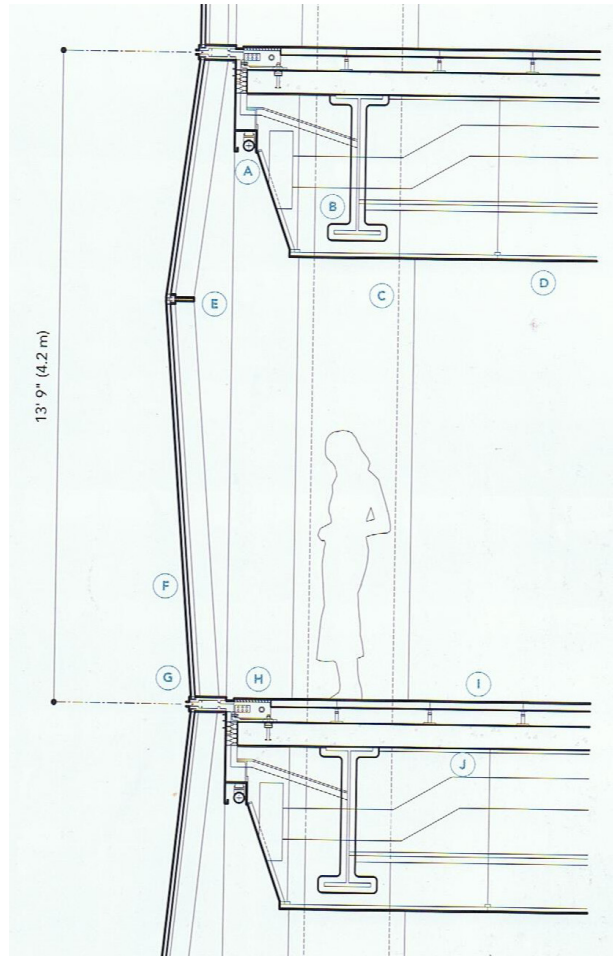


Fig. 90 section Trutec building

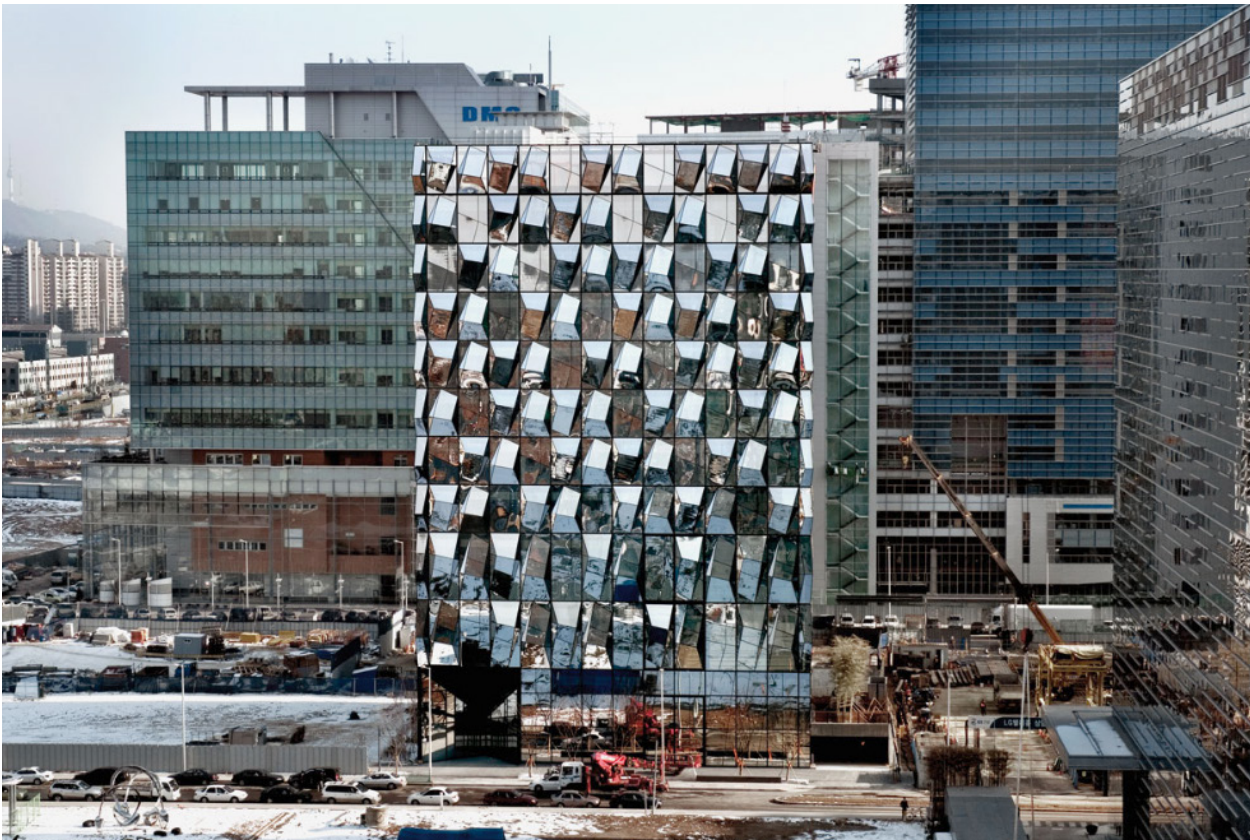


Fig. 91 Trutec building

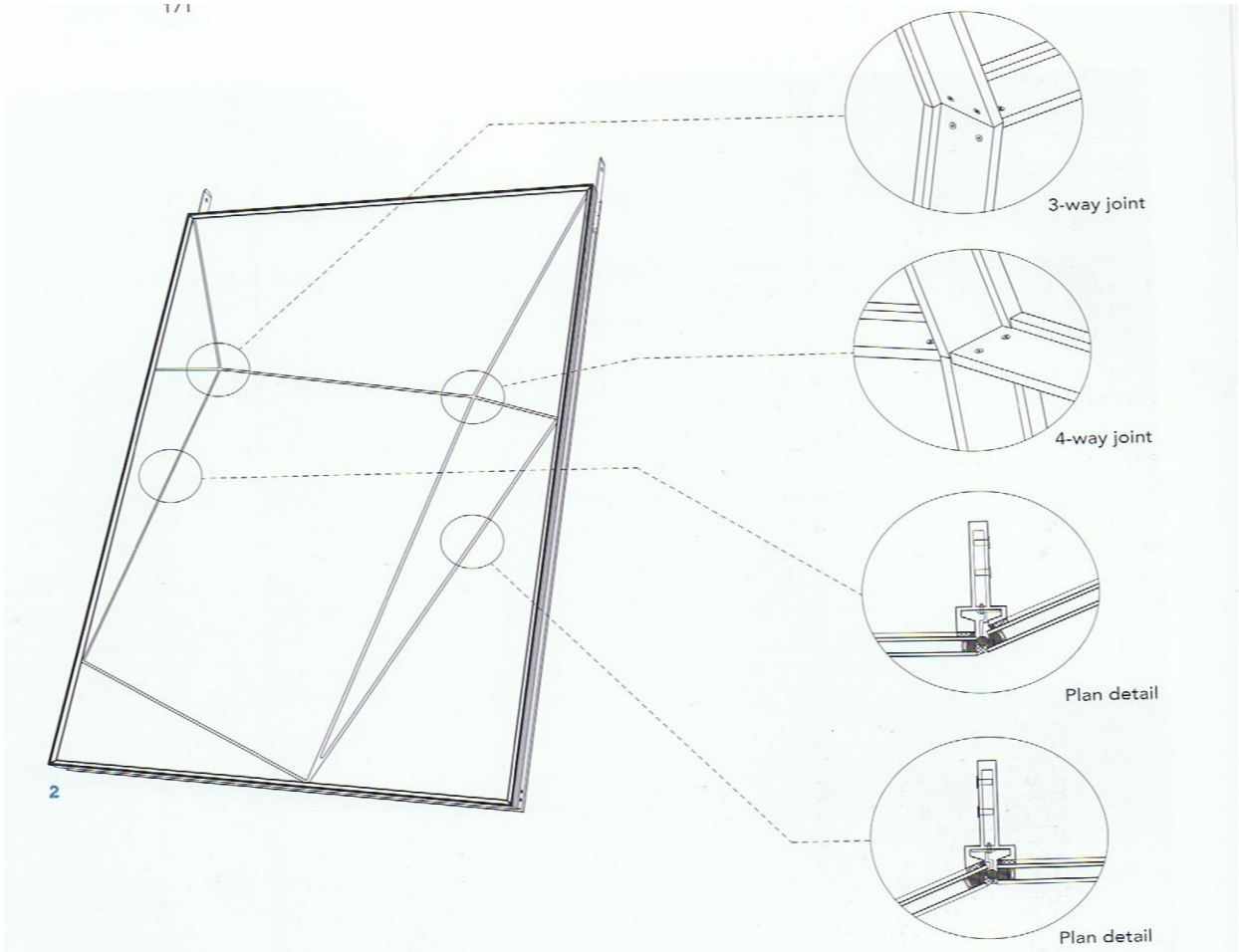


Fig. 92 Unitized curtain wall details Trutec building



Fig. 93 Interior Trutec building

Melvin J and Claire Levine hall

Architect: Kieran Timberlake associates
Location: Philadelphia, USA
Realisation: 2001

Melvin j and Claire Levine hall is an extension of the Weis tech building of the Pennsylvania university. It is one of the first active double wall concepts in the United States. Designed to contrast against the masonry of the surrounding buildings.

To achieve this light appearance without resorting to dark coloured low-e coatings or sun shading, which current sustainability demands dictate in similar situations, a different approach was needed. 18 custom units were created with a double glass layer. The outside layer is of insulated glass. The inner layer is single glazing. When the sun heats the cavity in winter, heat can be ventilated through the Hvac system. When extra heat isn't needed the air can be taken away. Electronically controlled blinds further decrease the change of overheating (Murray, 2009).

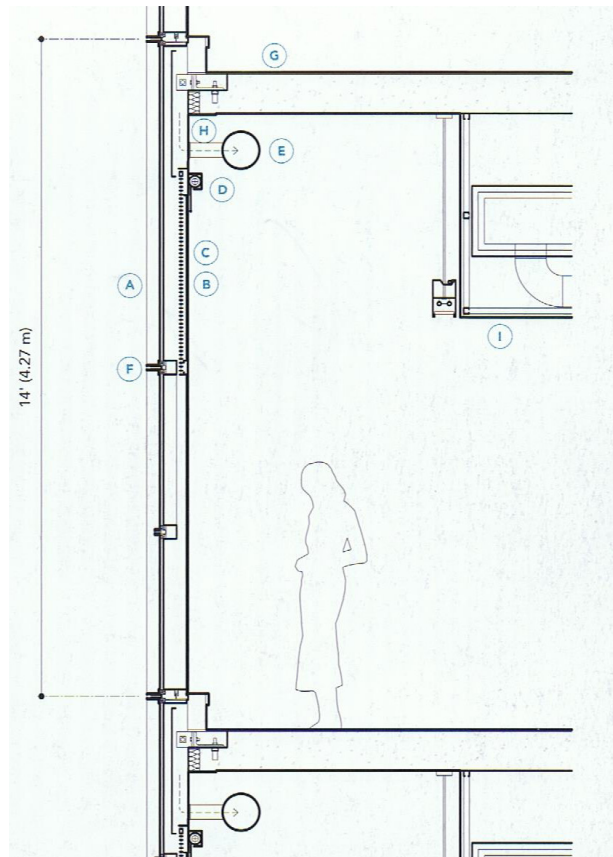


Fig. 94 section MJaCL hall



Fig. 95 MJaCL hall

Others



Fig. 96 Reflections at Keppel bay, Studio Daniel Libeskind & DCA architects, Singapore, Republic of Singapore, 2011



Fig. 97 The new York times building, Renzo Piano, New York, 2007



Fig. 99 Blue tower, Bernard Tschumi, new York, 2007



Fig. 100 BAspire tower, Hadi Samaan, Doha, Qatar, 2007

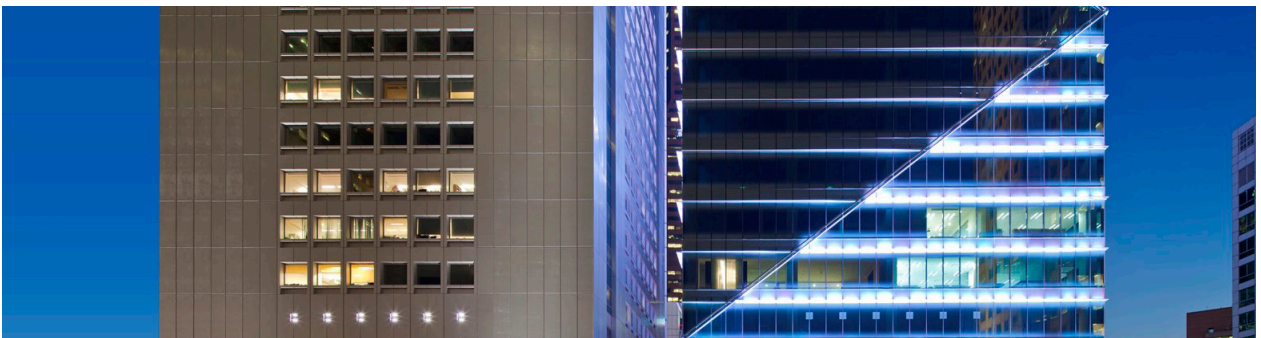


Fig. 98 One Raffles place, SAA architects, Singapore, Republic of Singapore, 2012



SKETCH DESIGNS

6.1 - Solution pathways

After the literature research phase enough information has been gathered to start thinking about possible solutions for the design task and visual answers to the research questions.

Solution pathways were created through the use of the results of the literature study. It helped in analysing the research results of all design aspects and as a brainstorm of design opportunities. It visualizes subjects where many solutions are available and where innovation is necessary.

The pathways do not deliver a complete design however, but possible solutions to key parts. The design will be developed in the next chapter.

A number of subjects have been explored in this method. They can be found in the appendix. The picture below shows one example of the stress system pathway.

This figure shows which options are available for

keeping the membrane stretched and wrinkle free. This can be done pneumatically or mechanically, like shown in chapter 4. Each of these options can be developed in more specific solutions.

The design other aspects that are developed into pathways are:

- Stress systems
- Connections
- Shape
- Colour
- Unitized system
- Thermal break
- Fire resistance
- Thermal insulation
- Ventilation
- Sunshading
- Transparency
- Acoustic insulation
- Safety
- Other functions

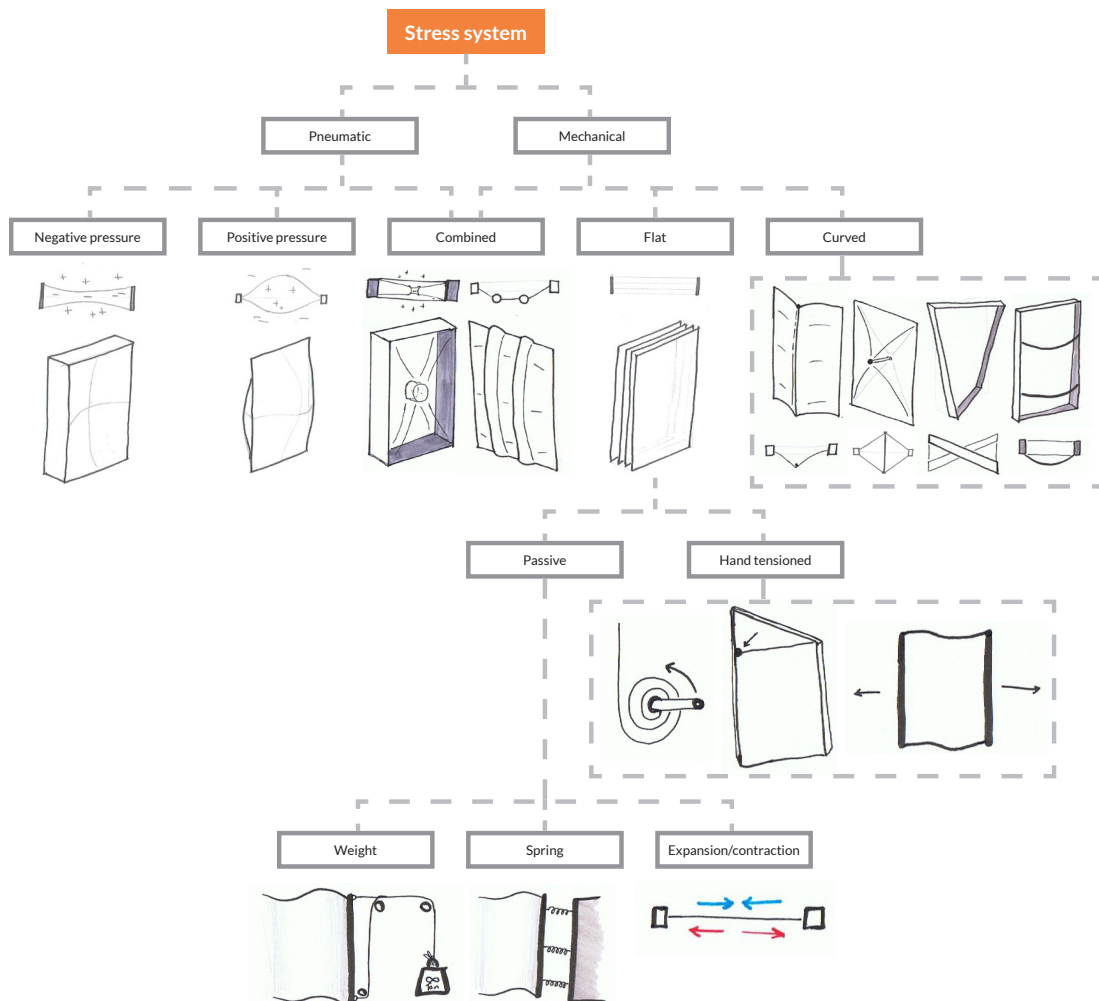
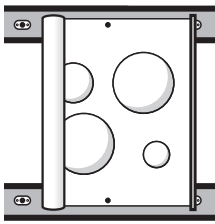


Fig. 111 Mindmap example

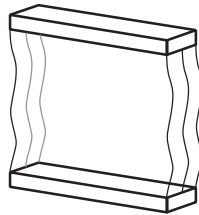
6.2 - Draft designs

The pathways provided a clear analysis of available options and gave direction to design ideas. The designs are not directly related to, but heavily inspired by the pathways. The designs tried to fill the gaps found in some subjects or tried to use the few solutions available effectively. The pathways do not deliver a complete design

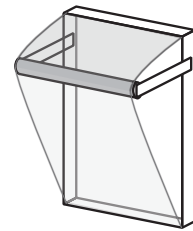
however, but possible solutions to key parts. These parts were developed into ten designs. Which can be seen in the figure below and are explained in the following pages. Each design will be explained shortly. Pictures will visualize the ideas and a list will be compiled of the positive and negative aspects of each design.



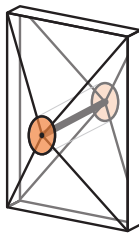
Rollable envelope



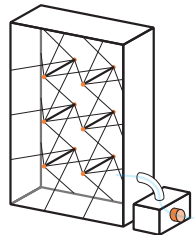
Fold-out façade



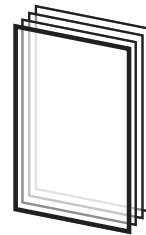
Shaped shading



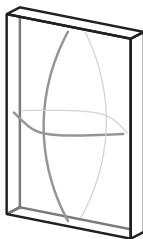
Mechanical cushion



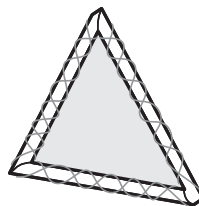
Unitized vacuum



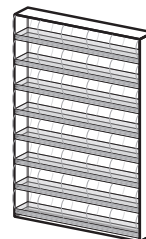
Media façade



Shaped inflatable



Structural tubes



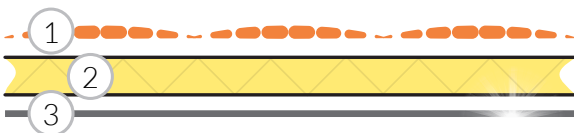
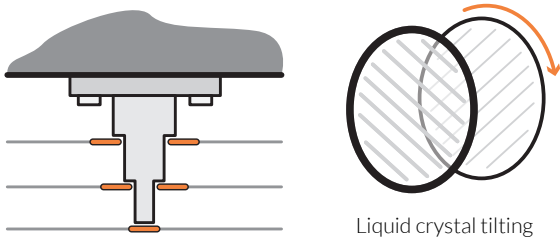
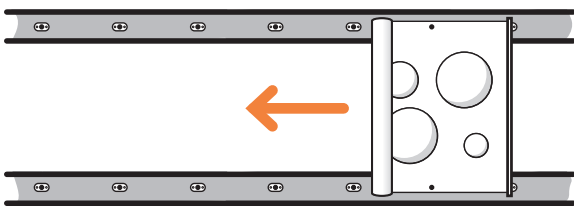
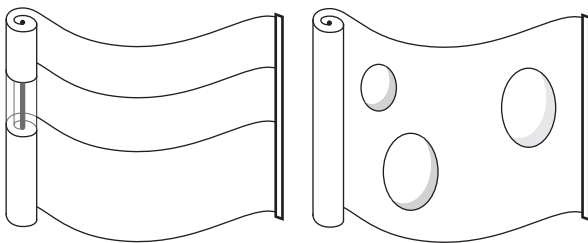
Selective inflation

Fig. 112 draft designs overview

Rollable envelope

The flexibility of membrane materials open up a number of possibilities in designing a unitized system. This concept uses this fact to have the envelope delivered in a roll and then rolled out along the façade and fixed to supports on the structural floors.

- + Increased size
- + Unit weight same as current systems
- + Far lighter per square meter
- + Faster building speed
- Challenging horizontal detailing
- Can't have rigid parts in horizontal direction



- 1- PCM mesh fabric
- 2- Spaceloft
- 3- Metalized Mylar



Fig. 113 rollable envelope draft design

Fold-out facade

This concept also uses the flexible nature of membrane materials to make an envelope with specialized advantages. The top and bottom bars connect, stretch and hold the units multiple layers of ETFE. Similar to the smartwrap system. The vertical directions stay flexible.

- + Lightweight
- + Small transport size
- + Possibly no vertical view interruption
- Challenging vertical connection detail

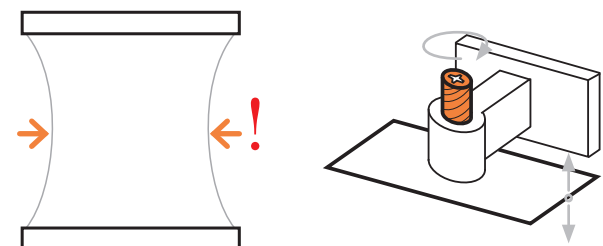
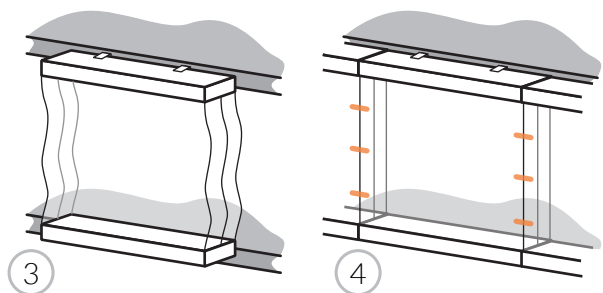
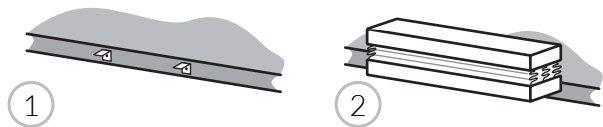
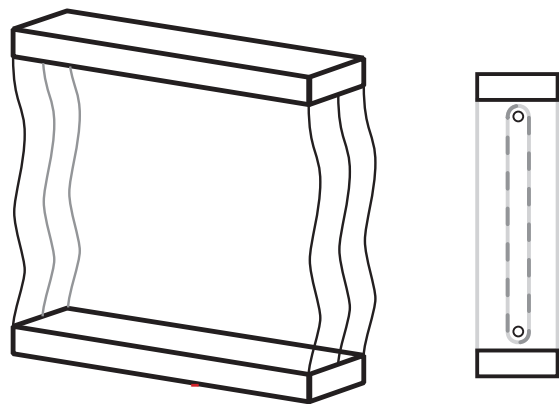


Fig. 114 fold-out facade draft design

Shaped shading

The previous concept could be used in a slightly different configuration. In this concept the panels have a frame which pushes the flexible envelope outwards, this creating tension. The shape and roll can be used very well for shading purposes.

- + Directional shading
- + Visually adaptive
- + Creates new dimensionality in the façade
- Extremely challenging vertical and side details

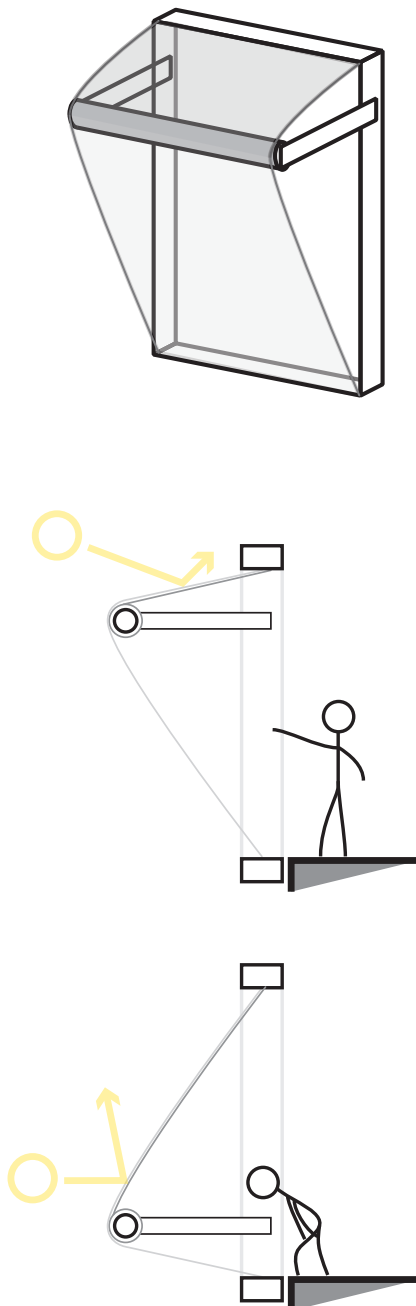


Fig. 115 shaped shading draft design

Mechanical cushion

One of the principal methods of applying membrane materials is in the form of a cushion. However, pressure based systems could be unfavourable in high-rise applications. A bar in the middle of the cushion, like shown in this concept, is a means of creating a cushion with mechanical means.

- + High volume shape
- + Mechanical system
- + Easily tensioned
- + Adaptive shape, limited
- Physical obstruction in middle
- Angular shape

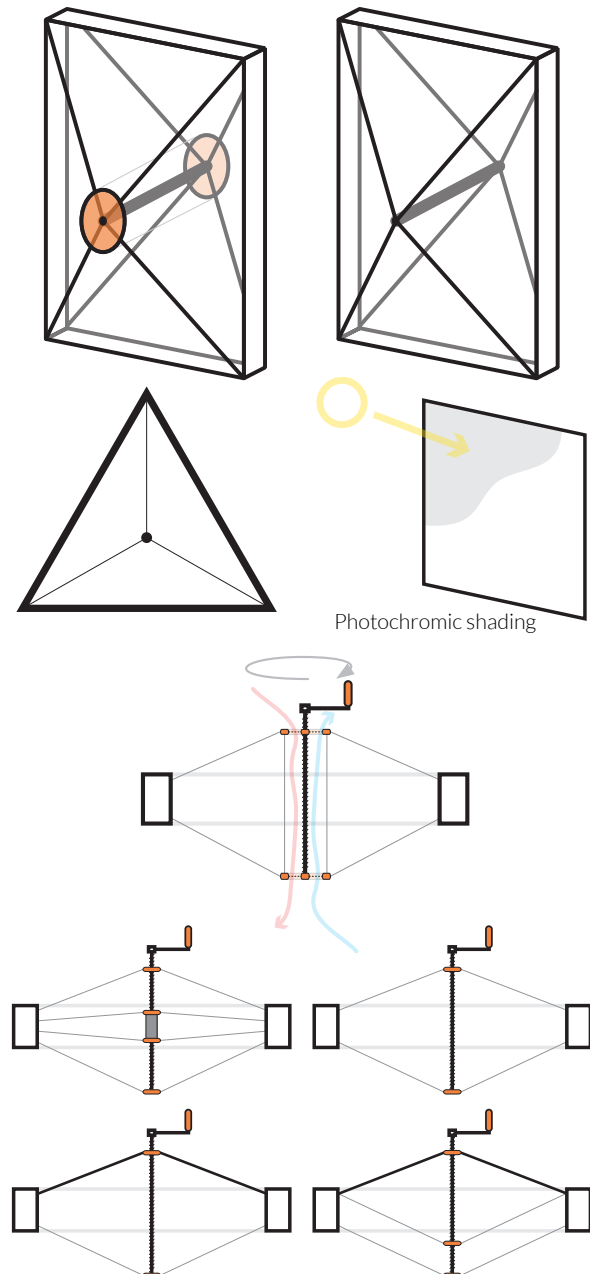


Fig. 116 mechanical cushion draft design

Unitized vacuum

A system that is pressure based is this unitized vacuum concept. It uses negative pressure to create tension in the membrane. To prevent the membranes from getting too close, a number of spacers need to be installed. The low pressures inside provides no medium for thermal and acoustic transport, but it is hard to achieve.

- + Good sound/thermal properties
- High pressure/forces in system
- Obstructions in unit

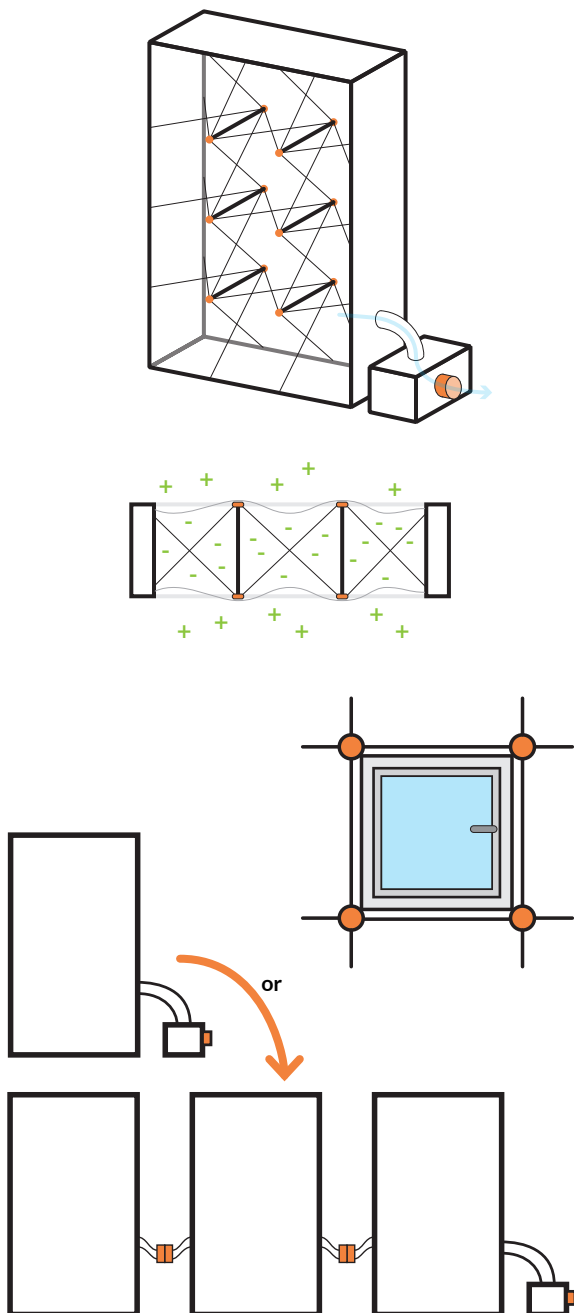


Fig. 117 unitized vacuum draft design

Media facade

Technology has made many things possible in current society. Thin and light membrane structures aren't only good for building technology applications, but could provide interior functionality as well. This concept uses transparent OLED technology on ultra-thin glass for a super light media facade.

- + Media facade
- + Functional screen
- + Relatively good acoustic insulation
- Very expensive

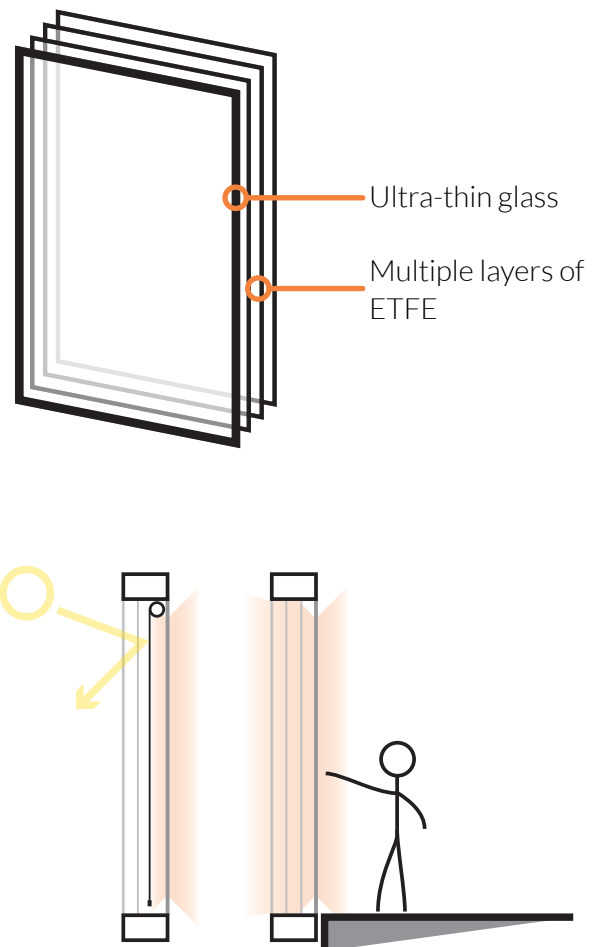


Fig. 118 media facade draft design

Shaped inflatable

One of the advantages of a pressure based membrane system is that its forces are divided over the whole membrane equally. This means that the most complex shapes could still be achieved without a complex arrangement of supports. The shapes could be designed for high acoustical insulation and cut with high precision with computer aided cutting techniques.

- + Possibly more effective acoustical insulation
- + Shaped fixed sunshading
- Pressure system
- Not consistent in shape

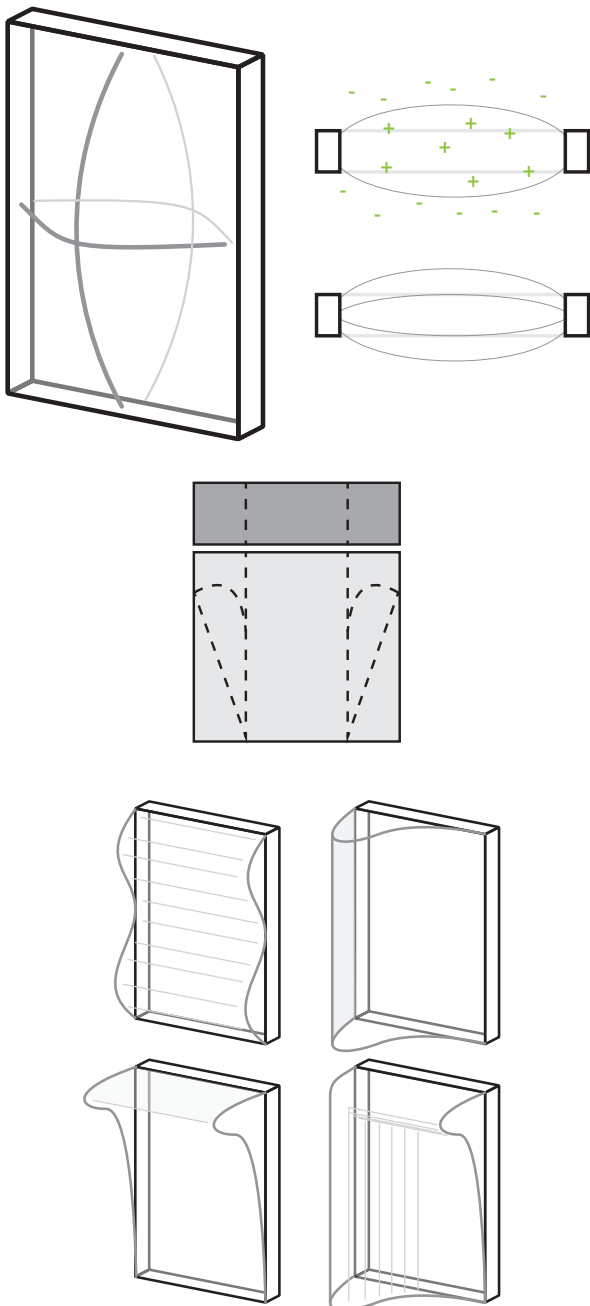


Fig. 119 shaped inflatable draft design

Structural tubes

Using pressure in smaller areas of the envelope, in tubes for instance, makes higher pressures more viable. The higher pressure results in a more rigid pressure container, which can be used for structural applications. In this concept the pressurized tubes take part in the structural system, because of which the structure can be even thinner.

- + Lightweight
- + Very few visual obstructions
- High pressure necessary
- Pressure is critical for function

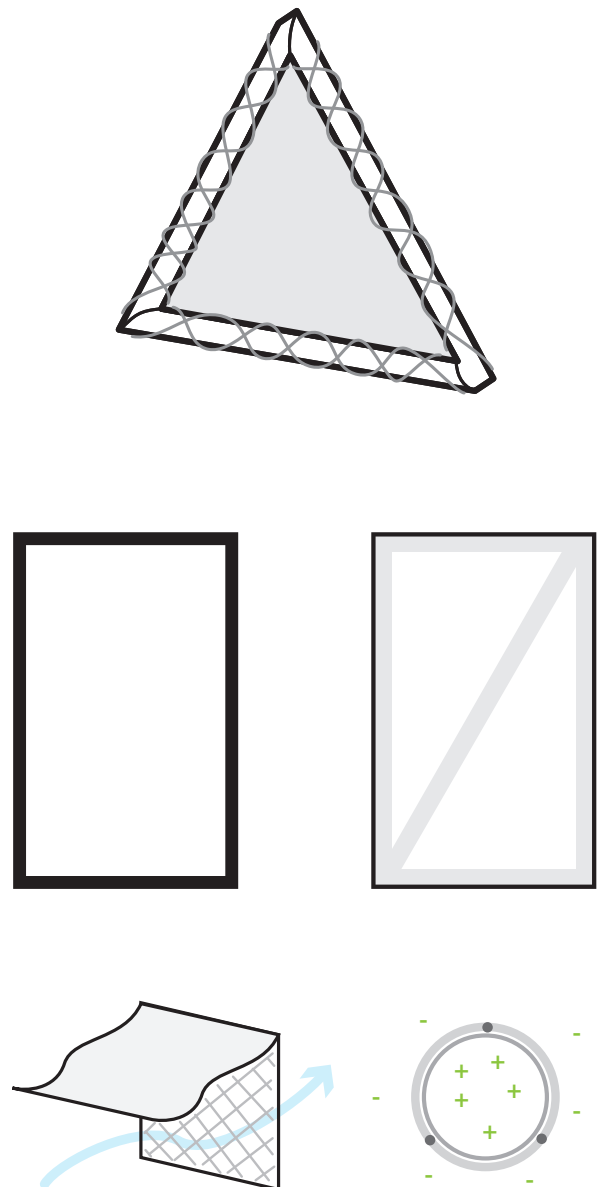


Fig. 120 structural tubes draft design

Selective inflation

Tubes can also be applied in a non-structural way. The smaller compartments could for instance be inflated and deflated at will, creating a panel which is adaptive in shape and function. Inflation and deflation could reveal sun shading or make way for other functionality.

+ Highly adaptive

- Not tensioned in vertical direction
- A lot of moving parts
- Pressure system

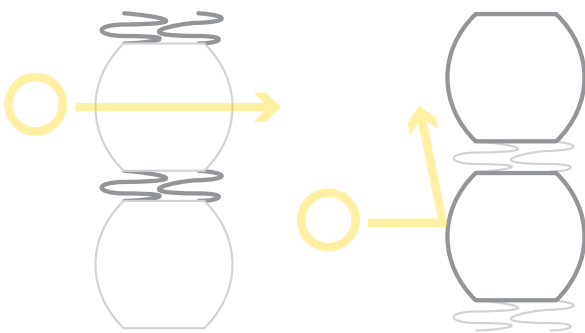
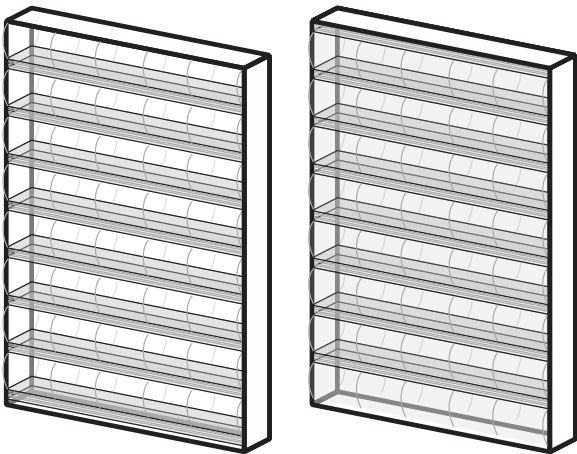
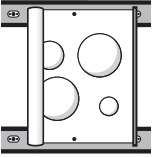
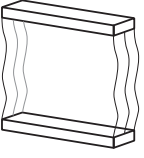
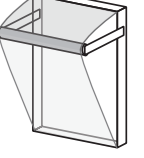
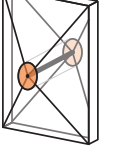
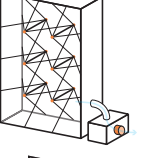
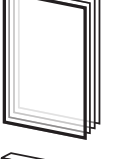
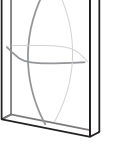
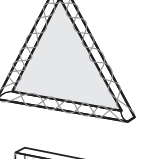
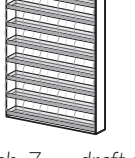


Fig. 121 selective inflation draft design

6.3 - Summary

	Thermal insulation	Solar radiation	Transparency	Acoustic insulation	Ventilation	Shape	Adaptivity	Powered	Lightweight	Feasibility
		+		○	○			×	+	
	○	+	+	○	○	○	○	×	+	+
	○	+	+	○	○	+	+	<		○
	○		○	○	+	+	+	×	○	+
	++		○	++		○		<	○	
	○	+	+	+	○	○		×		
	○	+	+	○	○	++	○	<	○	○
		○	+		○	+	○	<	++	
		+			○	+	+	<	○	

Tab. 7 draft design summary

6.4 - Further development

Three concepts will be chosen to be further developed in the next design phase.

Fold-out facade and mechanical cushion have been given the most points and will therefore be the first and second choice. According to the points, 'shaped inflatable' should be the third concept, but this concept is very similar to mechanical cushion.

Despite what the points dictate I also see a lot of potential in unitized vacuum, because this is the only concept that has an inherent advantage over Acoustics, which research has shown, will be a difficult property to achieve. It isn't a good idea for many reasons, but if these are overcome, the system could be exceptional. Unitized vacuum will be the third concept to be elaborated.

		Thermal insulation	Solar radiation	Transparency	Acoustic insulation	Ventilation	Shape	Adaptivity	Powered	Lightweight	Feasibility
-2		-	+	-	○	○	-	-	✗	+	-
+5		○	+	+	○	○	○	○	✗	+	+
+2		○	+	+	○	○	+	+	✓	-	○
+4		○	-	○	○	+	+	+	✗	○	+
-3		+	-	○	+	-	○	-	✓	○	
+1		○	+	+	+	○	○	-	✗	-	-
+3		○	+	+	○	○	+	○	✓	○	○
0		-	○	+	-	○	+	○	✓	+	-
-3		-	+	-	-	○	+	+	✓	○	

Tab. 8 draft design conclusion



PRELIMINARY DESIGNS

Resulting from the draft design phase, three designs have been concluded to be most plausible for the desired functions and are therefore going

to be further developed in the second design phase, which is the preliminary design phase.

7.1 - Fold-out facade

The fold-out façade is a concept where the horizontal structure is rigid, but the vertical parts are not. Because of this the whole façade can be folded up and down. This saves space during transportation and could achieve a revolutionary way of building a unitized curtain wall.

figure 124 shows how the basic design will look and the flexibility. The façade will have multiple layers of a transparent membrane between two rigid connection frames. However, during application on the structure the shape will be twisted to form a saddle shaped double curved surface, as shown in figure 125. This for stability and tensioning. As can be seen in figure 126, the layers can be designed to achieve many important properties, desired of a façade.

The concept results in many positive properties. It is lightweight, the view is almost uninterrupted and conventional solar shading can be easily applied. However, because of this the vertical detailing is made very difficult. The vertical connection needs to be made airtight and highly flexible at the same time. At the same time the forces on the connection are great because of the pre-tensioning needed in the membrane. The deformation shown in figure 126 needs to be prevented. figure 127 shows a possible solutions for the connection and how the panel could be built. The build steps are:

- 1 – Support connections will be fixed to the structural floors or beams.
- 2 – The rolled up membrane unit will be placed on the lower support and connected.
- 3 – The unit will be unrolled and loosely fixed to the upper support. Afterwards a semi-circular metal strip will be inserted in a pocket in the vertical edge.
- 4 – After the next panel is installed the metal strips of both panels interlock and are twisted. The twist ensures an airtight seal and tensions the membrane simultaneously.

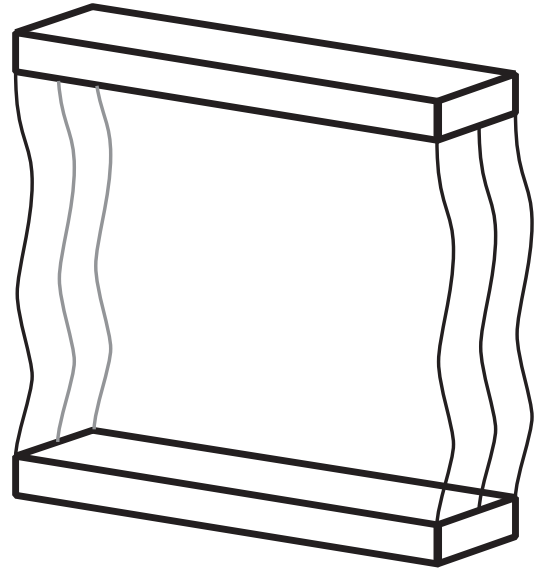


Fig. 124 unfolded facade

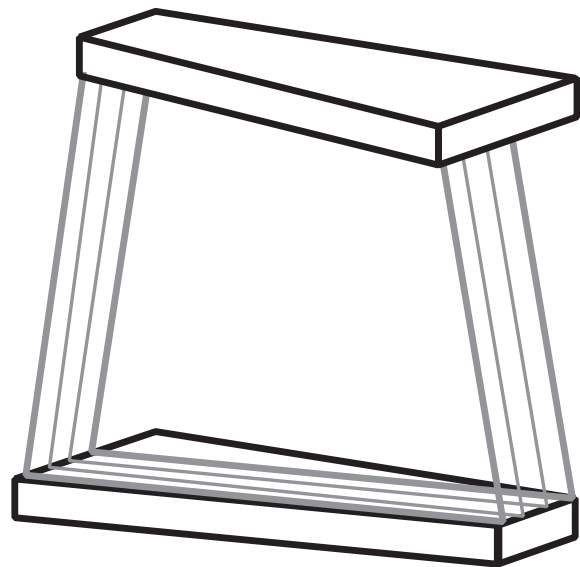


Fig. 125 stretched in saddle shape

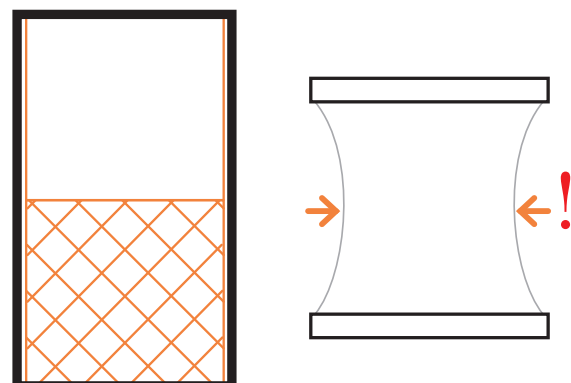
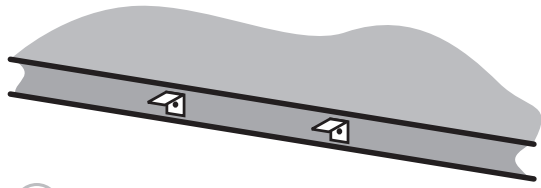
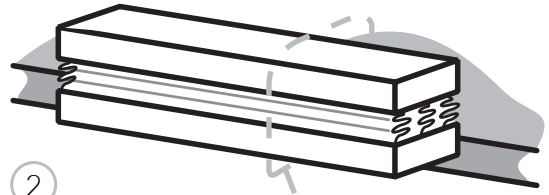


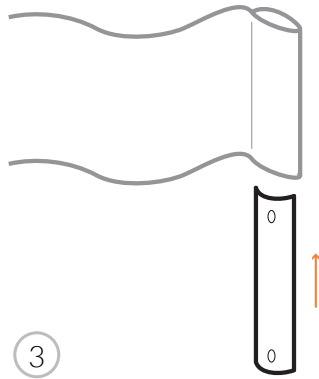
Fig. 126 safety net and deformation



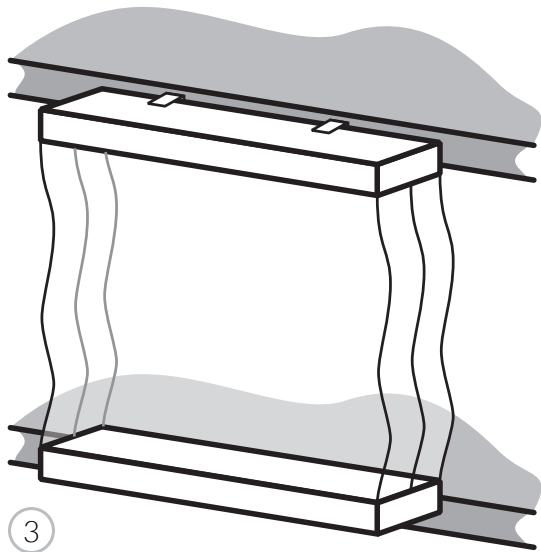
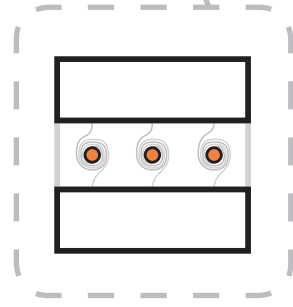
1



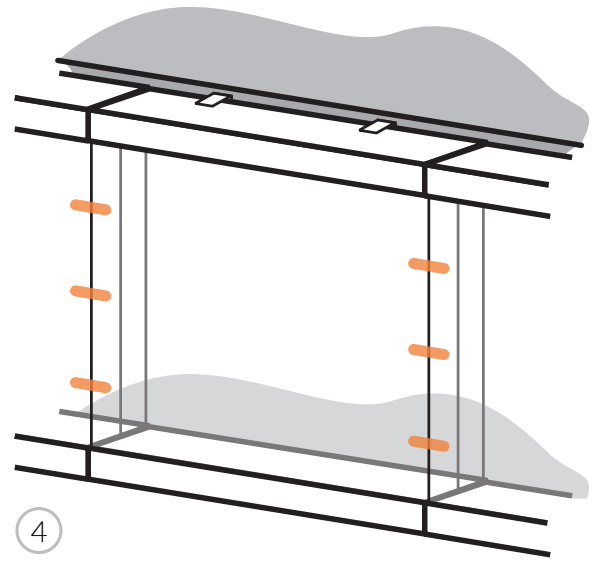
2



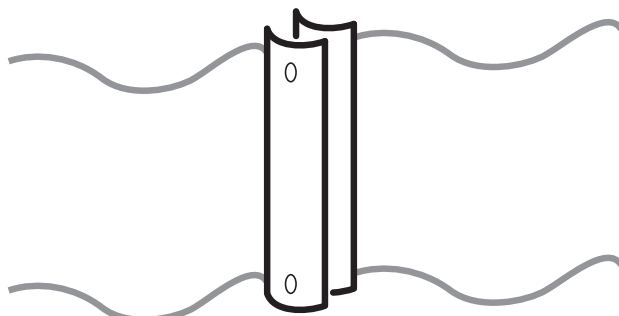
3



3



4



4



Fig. 127 fold-out facade build order

figure 130 shows a sketch detail that could possibly realize the concept. The many layers, described in figure 128 are held in keder clamps, spaced with thermal breaks. The outer layer flows over a roll to hide the connection from view and provide a connectionless appearance from outside.

Two simple mock-ups were made to see the design and reveal any unsuspected flaws. The models were made from 6 mm mdf wood and polyethen

bags. The model representing a facade panel was 19 by 19 cm. The connection model was 7.5 by 40 cm.

During construction the plastic seemed hard to tension properly and would crease if a rectangular foil was used. Extra thick rods were used in the connection model and a slot system for tensioning the other model, fixed the issues. In the end, the rolling connection worked well. It was airtight and easy to apply.

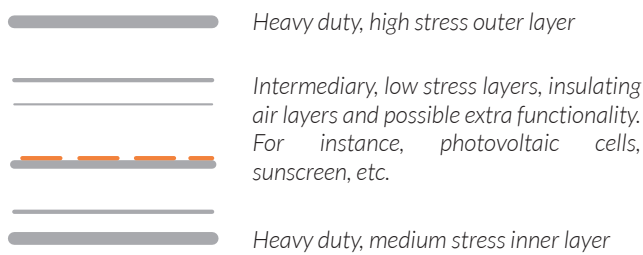


Fig. 128 fold-out layers and their purpose

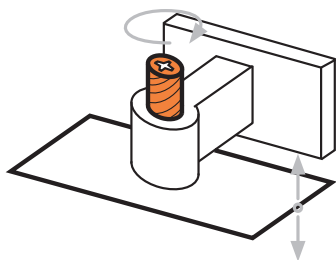


Fig. 129 fold-out adjustable panel support

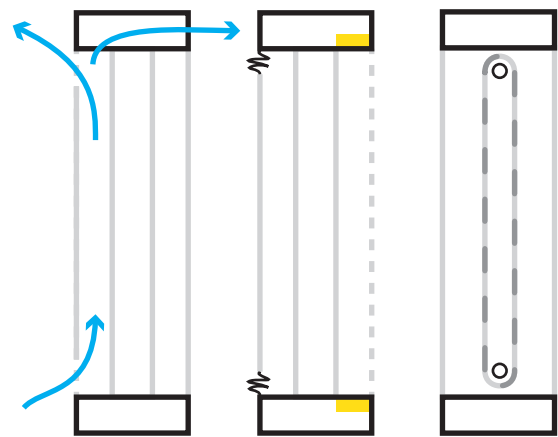


Fig. 131 layered ventilation, insulation and sunshading

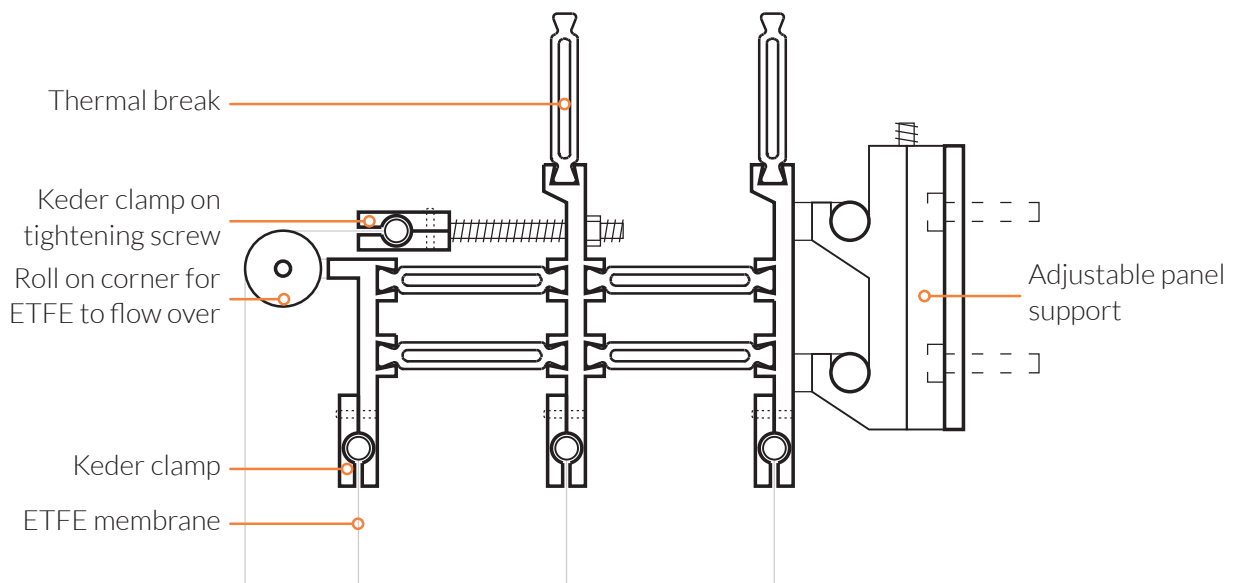


Fig. 130 sketch detail upper connection vertical section



Fig. 132 fold-out facade mock-up front



Fig. 134 fold-out facade mock-up side



Fig. 135 fold-out facade roll seal close



Fig. 133 fold-out facade mock-up roll seal

7.2 - Mechanical cushion

The mechanical cushion uses the same design principle as the much used inflatable cushions, but it realizes this shape through mechanical means instead of pressure. Because of this the whole system is far less vulnerable to leaks of any kind and also isn't reliable to any power source. All of this while retaining most of the advantages of the a pneumatic cushion.

The system kept in the required shape by a frame and a bar that pushes in the middle. This can be designed in many shapes. Square like in figure 137. Or hexagonal like in figure 136. The hexagonal shape is more difficult to apply in a unitized panel, but the shape approximates a circle the most. This means that the membrane is stretched equally around its circumference, which decreases creases.

The infill of the frame will be multiple layers of a transparent membrane material and possibly a circular window. The window is important for getting direct contact and ventilation to the outside environment. In this and the shape the window resembles a porthole in many ways. Which is a nice reference to the sail in the name of the reference building. The window acts as the pressure bar for tensioning the membrane as well. Within these design boundaries many configurations are possible, which can be seen in figure 138. Two extra layers can be added in the middle for extra insulation. Or the inner membrane can be replaced by a cable for extra strength and transparency. An adaptive layer could be moved to the front or the middle for shading purposes or adaptive insulation.

In all these situations extra strength might be needed for protection against failure or people falling out of the window. Reinforcement could be applied like shown in figure 139.

The pressure rod in the middle does increase the complexity of sun shading however, A single screen rolled down by gravity wouldn't work in this situation anymore. Mainly because there is something in the way in the middle. Also because of the polygonal shape.

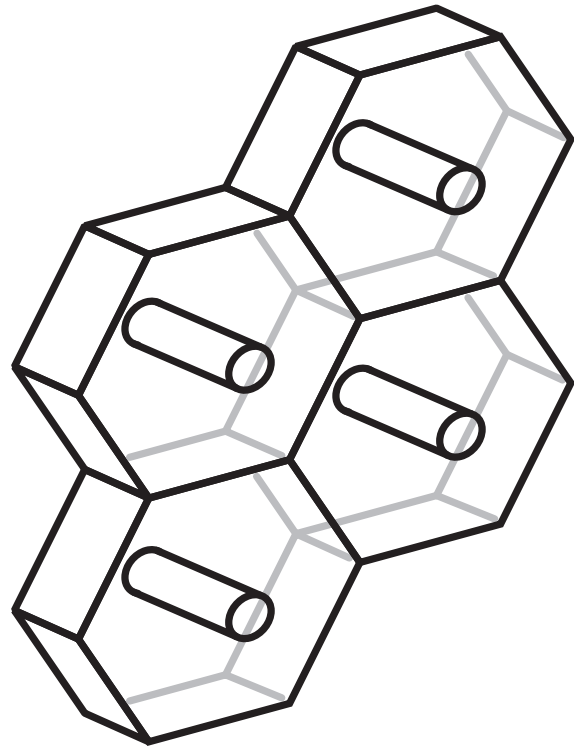


Fig. 136 hexagonal mechanical cushion with portholes

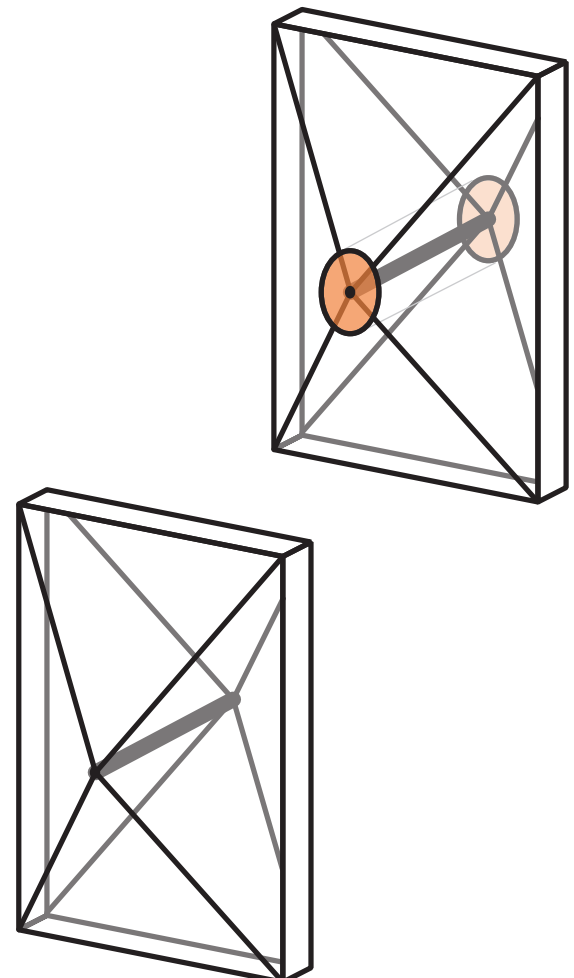


Fig. 137 square mechanical cushion with/without portholes

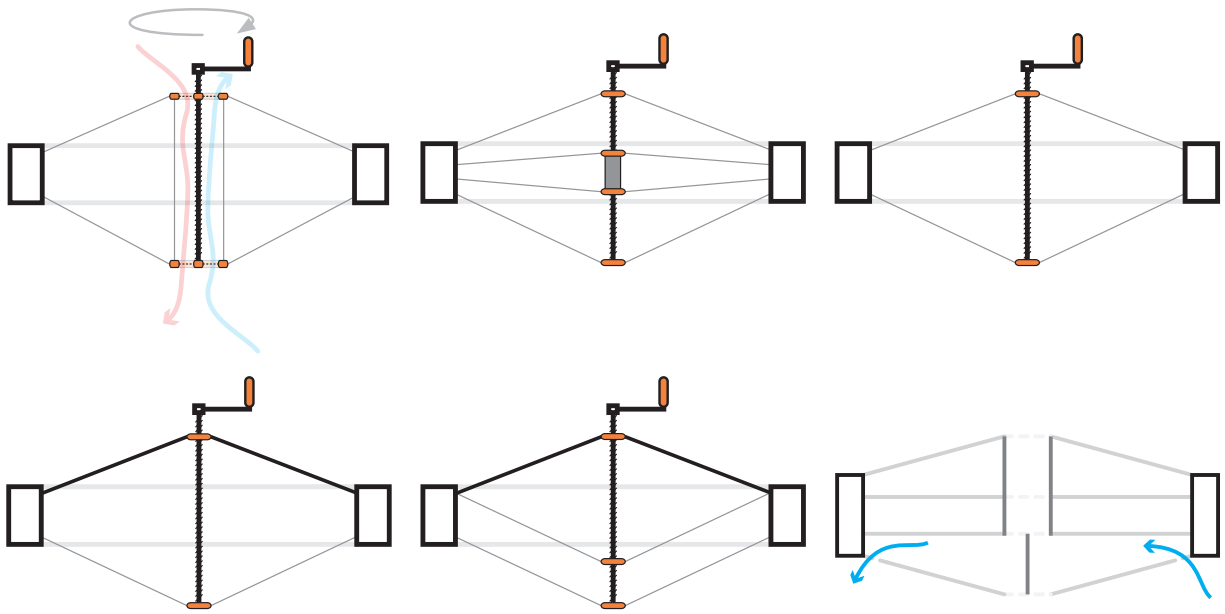


Fig. 138 membrane configurations

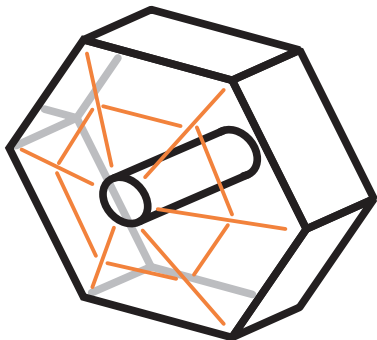


Fig. 139 tube support lattice

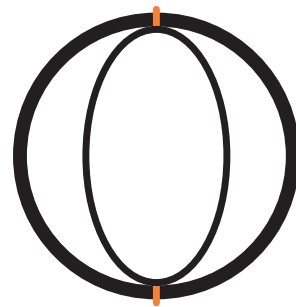


Fig. 140 window valve

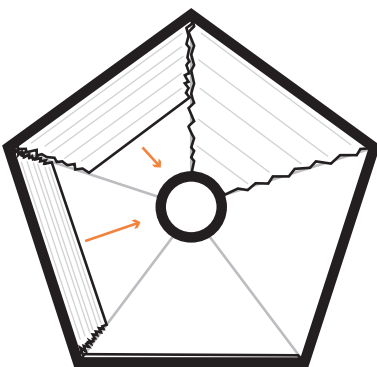


Fig. 141 radial sunscreen

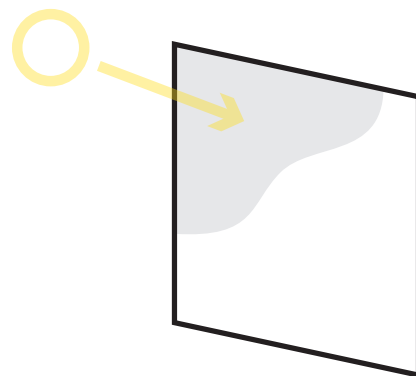


Fig. 142 photochromic shading

The lower detail shows the middle connection, where the porthole and push rod are located. The membrane is punctured and reinforced by a metal ring. This ring has a ledge on which an acrylic tube can slide on. It will stay in place because of the internal pressures. This pressure is created by the stress mechanism. It can be adjusted later if needed.

A mock-up has been created to see the membrane flow and how the tensioning of the push rod would work. This model was mostly created with the same materials as the previous one and is a

hexagon with sides of 10 by 4cm. The middle is 11cm deep. Wires, a nut and bolt were needed additionally to provide the tension. The bolt is hidden in a hole drilled in the stick. Hot glue appeared to be enough to keep the foil in place. The rod worked well and could be easily adjusted, but needed to be centred manually during extension. The forces wanted to push it out of the way. Clearly defined creases also formed, because of the angular shape, but this can easily be fixed by a pre-formed membrane. The result was a well stressed membrane surface with an adjustable surface.

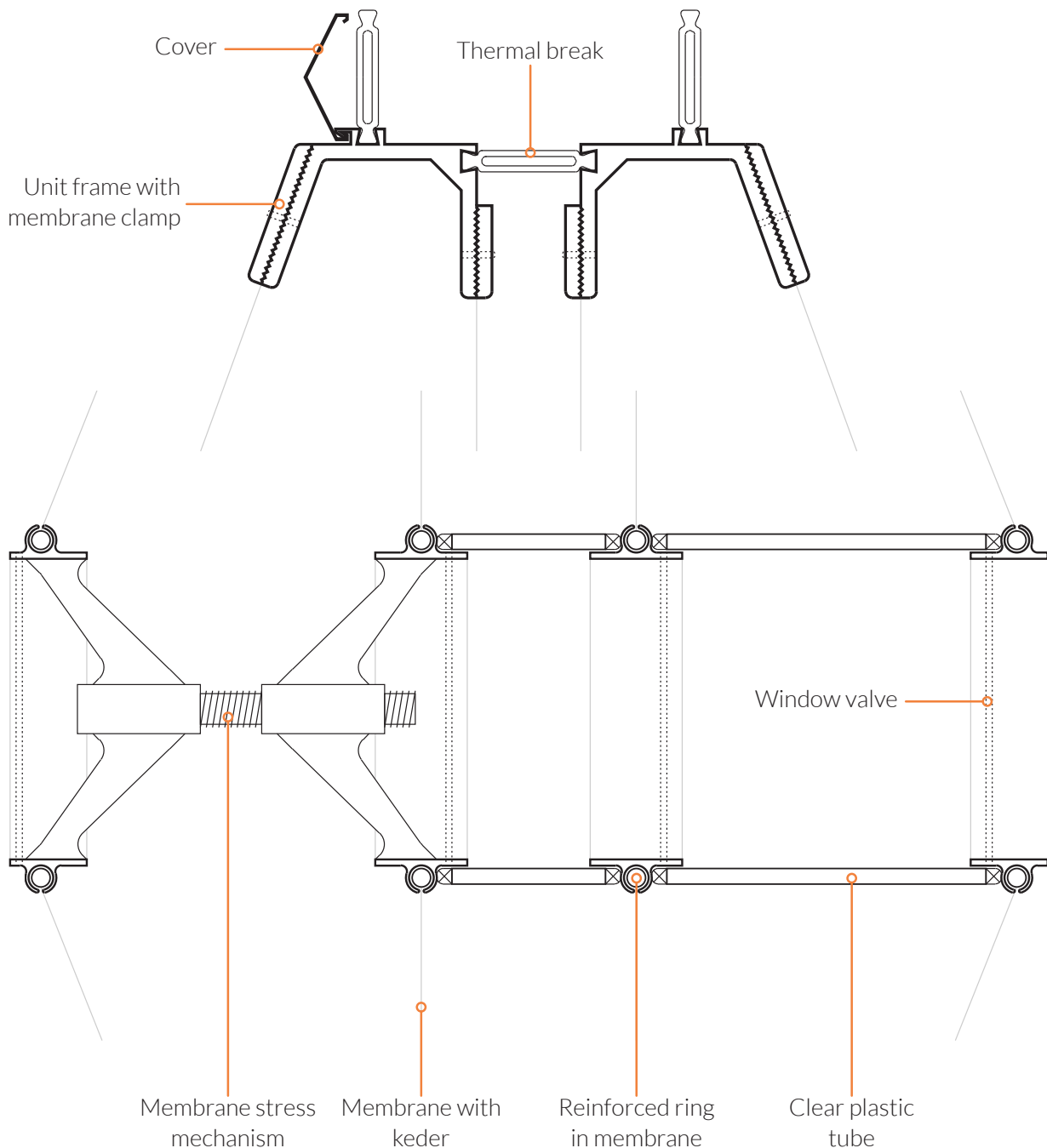


Fig. 143 sketch detail mechanical cushion upper and middle vertical section



Fig. 144 mechanical cushion mock-up



Fig. 145 mechanical cushion mock-up close

7.3 - Unitized vacuum

The unitized vacuum is a pressure based system. Not one that uses positive pressure to form a cushion, like the membrane cushions that are often used, but this system uses a lower pressure inside the cushion to get better properties. Acoustical insulation and thermal insulation could both increase significantly, but this depends on the pressure used. The lower the pressure the better the improvement. However, this is practically impossible. Mainly because of the forces that will be generated. Air pressure from inside will be lower than outside. This difference will push on the vacuum to fill in difference. The calculations that will be done later in this chapter will go into more detail about this subject.

The difficulty to overcome the extreme forces led to a low score in the draft design phase, but the high potential in both thermal and acoustical insulation granted it a place in following design phases.

The forces that push on the membrane need to be kept at bay. If this isn't done the membranes will touch and no vacuum will be left. To realize this distance a number of techniques can be used. These techniques include solid mass, linear support or point support. They are all included in the appendix. In this design there has been chosen for point supports, because they are least obtrusive for the view and they have the lowest surface area for leaking sound and heat. How this might look in a rectangular panel can be seen in figure 147. The point supports or outside influences might puncture through the membrane however. Reinforcement, like shown in figure 148 could be added to prevent this.

Ventilation of the building can be done through a grid above the façade unit or through a window. The flexibility of the membrane makes it possible to bend the entire panel, like shown in figure 150. In this situation the structure should keep the membrane at the correct spacing, as is visualized in figure 152.

Sun shading is difficult however, because of the many spacers that come in-between the membranes. The cannot be removed or pass halfway. figure 153 shows a solution with many small sunshading devices on each spacer could be

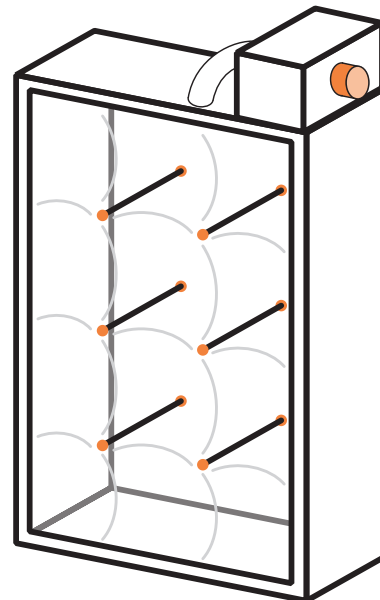


Fig. 146 unitized vacuum panel

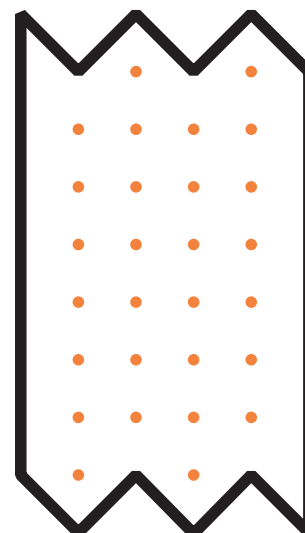


Fig. 147 shaped frame

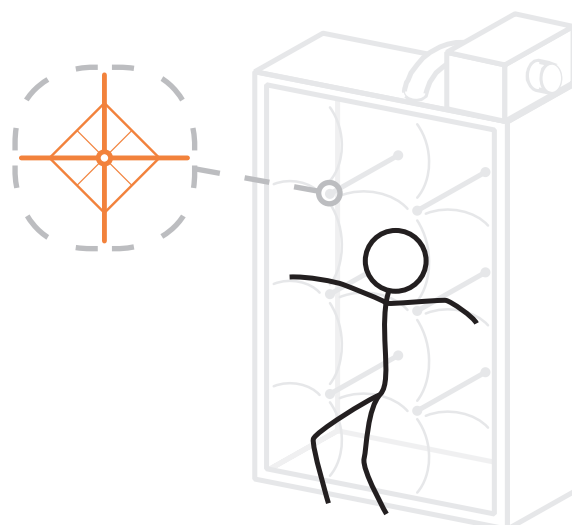


Fig. 148 local membrane reinforcement

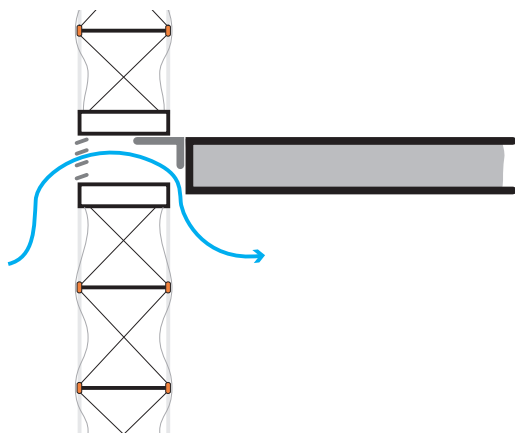


Fig. 149 ventilation grid placement

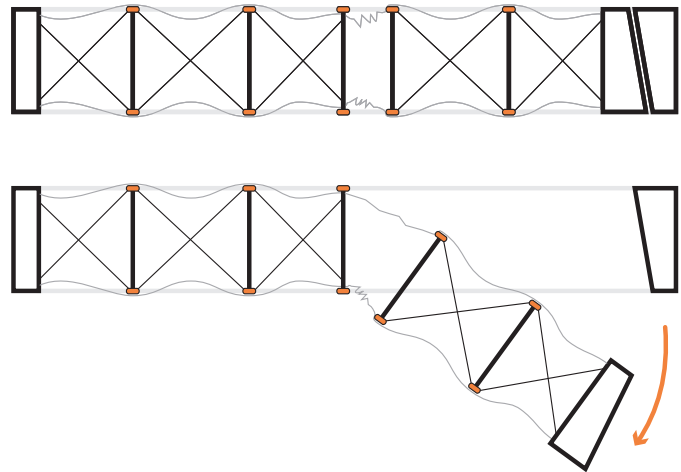


Fig. 150 operable window section horizontal section

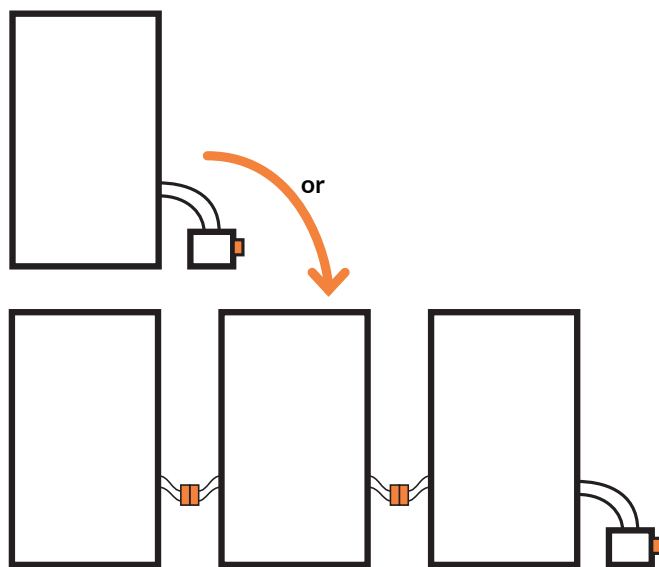


Fig. 151 serial vacuum pump connection

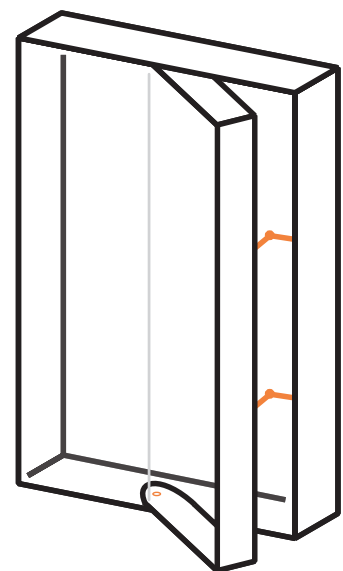


Fig. 152 operable window section

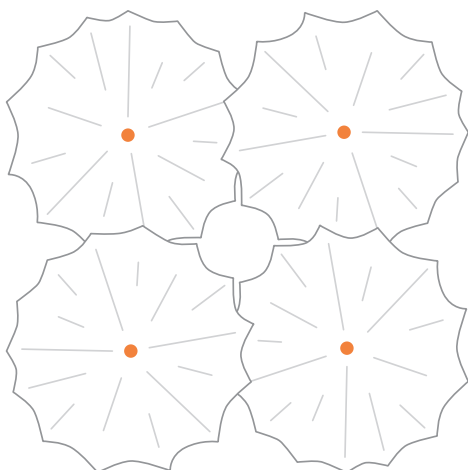


Fig. 153 bi-metal umbrella shading



a solution. For instance bi-metal umbrellas that will open with heat of excess sunshine.

In order to get the least amount of risk for leaks and have a strong frame for carrying the pressure loads an inner frame will be constructed over which an ETFE bag will be pulled and fixed. This setup will then be clamped inside and exterior frame. Similar to a glass window that is clamped in its frame. In this system it is important to get the spacers at the correct location. To achieve this they will be guided by plastic rings glued on the ETFE beforehand.

To see the function of the unitized vacuum concept a mock-up was built. It used wires, tensioned over an mdf frame of 13 by 13 by 4 cm, to temporarily keep the pine stick spacers in place. A bag of polyethene plastic was placed over it and was meant to be depressurized. This was however more difficult than expected and because of leaks the lowered pressure didn't last long. The short amount of time did show the effect of the spacers and how well the membrane flowed.

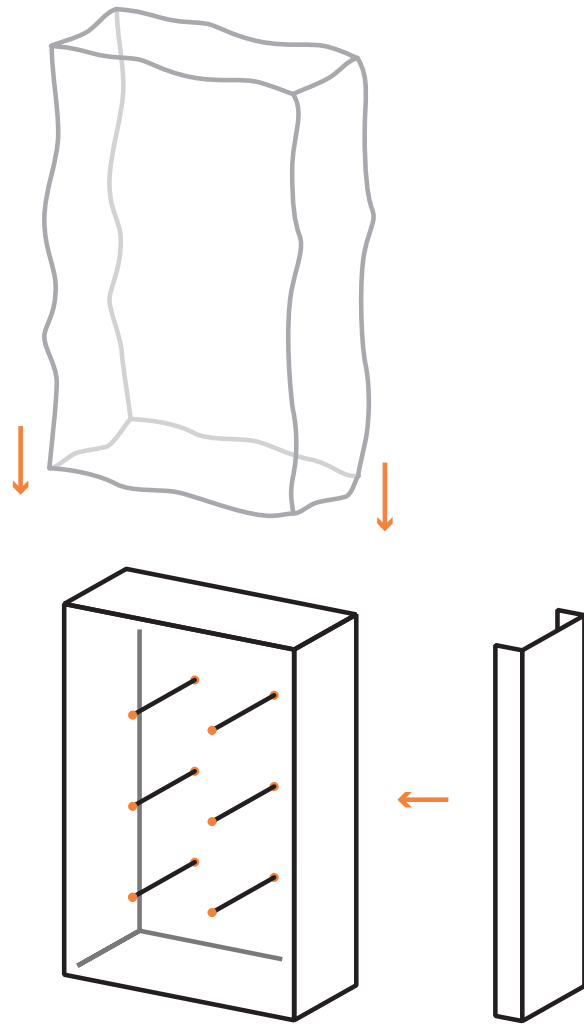


Fig. 154 unitized vacuum build order

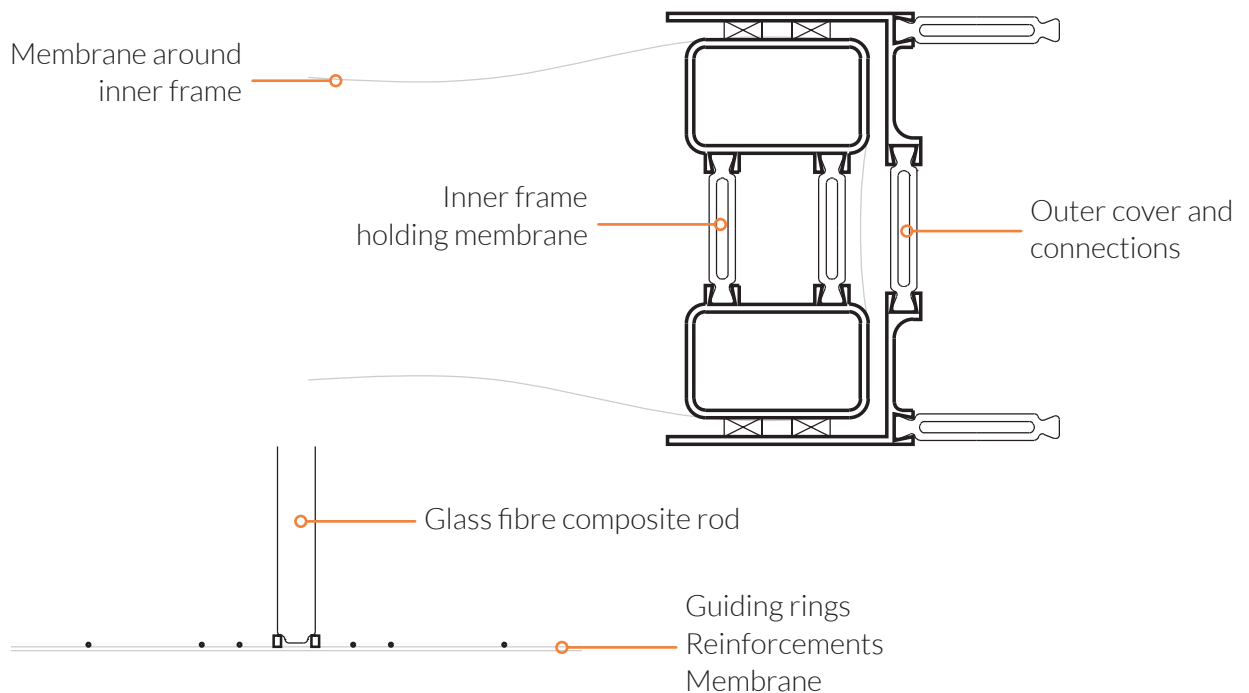


Fig. 155 unitized vacuum details vertical connection and membrane



Fig. 156 unitized vacuum mock-up



Fig. 157 unitized vacuum mock-up reinforcement

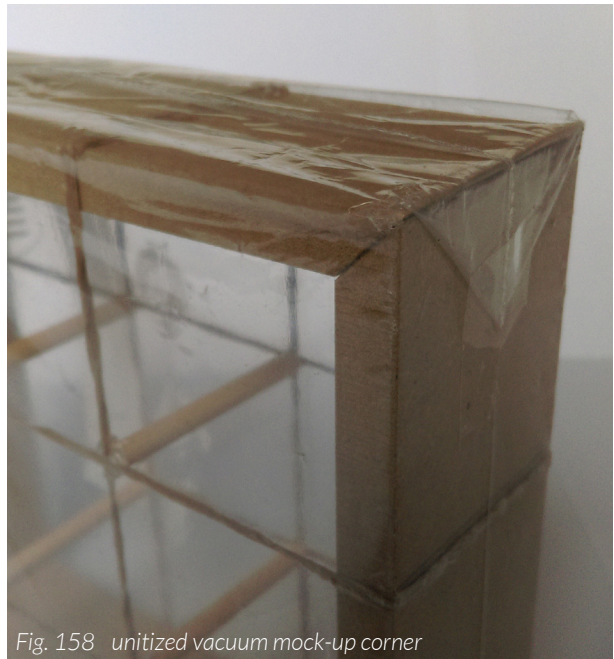


Fig. 158 unitized vacuum mock-up corner

8

**NUMERICAL
EVALUATIONS**

8.1 - Calculation assumptions

Up until this point the designs have been based on rules of thumb or literature that claimed the effectiveness of a certain method. To further develop the designs and make a choice of final design, more precise values need to be calculated for the properties of the designs.

A process of numerical evaluations and tests will be used to determine the properties of the designs. The process is visualized in figure 159.

Calculations are done by hand according to information supplied by the TU Delft lectures building physics and other literature. (Bokel, 2015), (Nederlof, et al, 2015), (van der Linden, 2011), (Welleman, 2006) & (Charbonneau, 2011)

Before calculations could be made, some assumptions had been done considering size material and other properties. These assumptions were:

- The panel size used in the calculations is 3000 x 1000 mm. With a cavity width of 50 mm.

- The membranes used are one layer of 2 mm ETFE on either side. The membrane is without low emissive coatings or any other kind.

- The heat resistance of the window frame has been assumed to be 1.2 m²K/W.

- A safety factor of 10% was applied to all materials used.

- A lowered pressure will be used in the case of the unitized vacuum concept. However, this will not be a true vacuum. A true vacuum is practically impossible. Even outer space isn't truly empty. Pressures and vacuums can be categorized as the following (Knaack, 2008):

Atmospheric pressure	= 1 bar
Low/coarse vacuum	= 10 ⁻³ bar
Medium/fine vacuum	= 10 ⁻³ -10 ⁻⁶ bar
High vacuum	= 10 ⁻⁶ -10 ⁻¹⁰ bar
Ultra-high vacuum	= <10 ⁻¹⁰ bar

Considering this a pressure of 1 atmosphere is used for the normal cavity and a pressure of 0.1 atmosphere is used for the evacuated cavity. This value is based on the recommended values mentioned in the book 'deflatables' (Knaack, 2008). In this book they have done pressure tests with similar membranes. It will be used for the initial calculations and some comparisons.

The following pages will give a summary of the calculations done for the preliminary designs. The detailed calculations used can be found in the appendix.

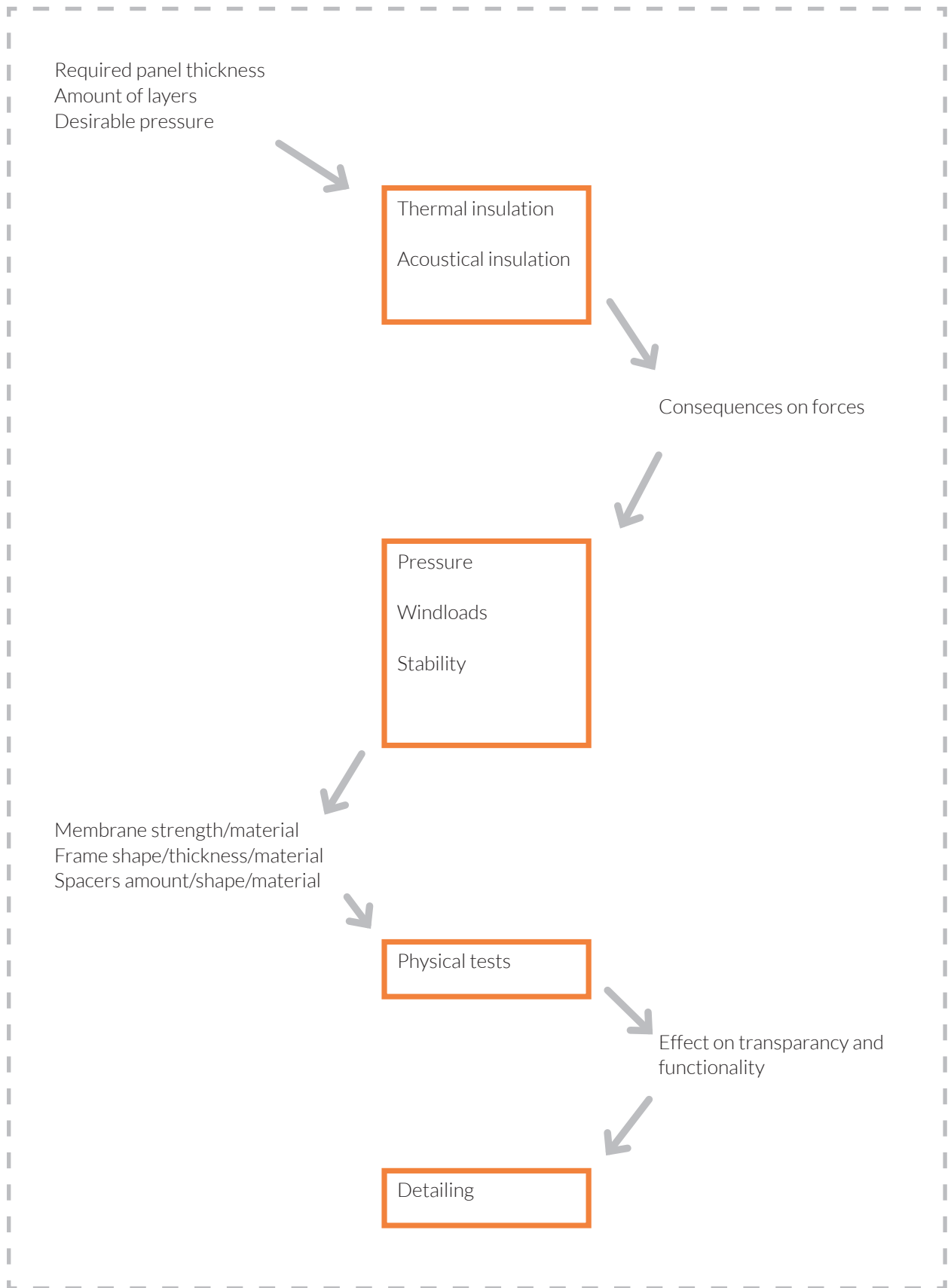


Fig. 159 validation timeline

8.2 - Thermal insulation

Thermal insulation through a cavity construction, like the membrane layers used in the designs, are calculated by heat loss through radiation convection and conduction. A single normal pressure cavity and a vacuum cavity of 5 cm is calculated. The results and method are explained below for each part.

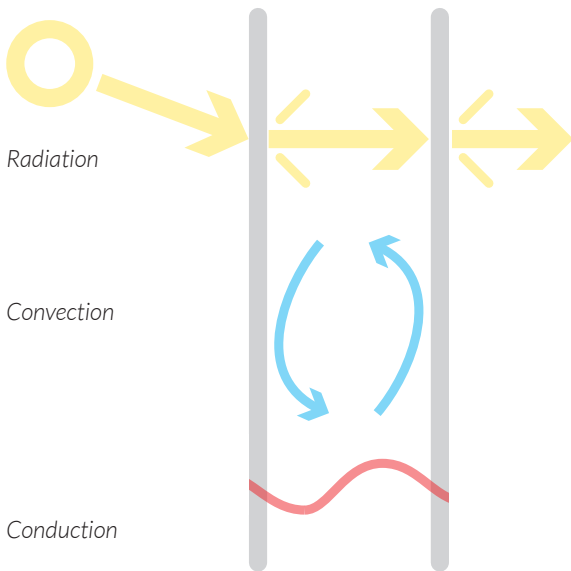


Fig. 160 heat flows

Conduction

Air has a fairly high insulation value. Heat loss through conduction is therefore not that high in atmospheric conditions, but it could be increased.

In a lowered pressure condition the conduction should be lower, but calculations done show a different result at the pressures used. Figure 161 shows the calculation results of conductivity ratio at a lowered pressure. The orange arrow is the used pressure. This is clearly not low enough for a lowered conduction value. So the conductivity ratio of both calculated cavities are the same.

Convection

Convective heat loss is high because the cavity width is large enough for full convection to take place.

For the lowered pressure condition is unchanged. Convection happens when a temperature difference on both sides of the cavity heat up or cool down part of the air through conduction. The change in density as a consequence of the temperature difference causes the air to flow, with the hotter air wanting to float on the colder air. This flow is sustained through continued change of temperature of the air through conduction of the air that moved to the opposite side.

In this coarse vacuum, conduction stays unchanged and the following pressure difference also still occurs. This leads me to conclude that convection in general stays unchanged in this situation. Therefore standard values can be applied in calculating heat loss through convection.

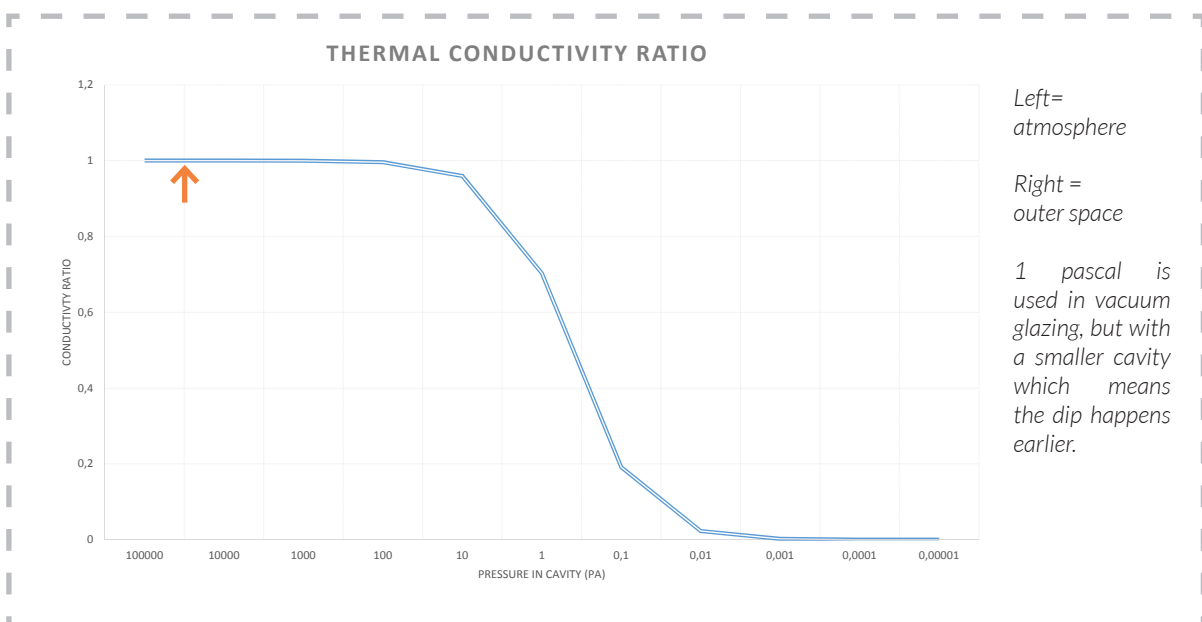


Fig. 161 unitized vacuum conductivity improvement

Radiation

Heat loss is very high through radiation, because no coatings have been applied. Low-e coatings have been developed for membrane materials (www.transmetra.ch). Mostly metalized versions for sunshading, but selective transparent low-e coatings for ETFE exist as well. These were developed by Hightex for the Dolce Vita Tejo shopping mall near Lisbon in Portugal. These coatings can reduce emissivity to around 0.3 (Pohl, 2010).

Heat resistance value, Single cavity results

Combined R_c value of $0.466 \text{ m}^2\text{K/W}$ for the normal cavity and a combined R_c value of $0.465 \text{ m}^2\text{K/W}$ for the evacuated cavity. This value is because the evacuation doesn't help and in any positive way, but the spacers still form a heat leak.

The greatest heat leak is caused by radiation through the cavity. This is $4.42 \text{ W/m}^2\text{K}$. This can be lowered through the use of low-e coatings and could therefore raise the R_c value. The second highest leak is through convection in the cavity. Cavities could be layered to multiply the amount of insulation, but a lower transparency will be the result.

Air cavity	$0.466 \text{ m}^2\text{K/W}$
Evacuated cavity	$0.465 \text{ m}^2\text{K/W}$

Multi cavity with low-e coatings

To reach similar insulation values as seen in high-end glazing systems, multiple cavities need to be created and low-e coatings need to be used. With the use of a double cavity that has a low-e coating on both sides of the middle layer and spacers that reach halfway a R_c value can be achieved of $0.89 \text{ m}^2\text{K/W}$. This is even better to air filled double glazing with low-e coating $0.65 \text{ m}^2\text{K/W}$ (www.pilkington.co.uk).

A fourth layer could even get the R_c value up to $1.14 \text{ m}^2\text{K/W}$, which is comparable to air filled triple glazing with low-e coating of $1.25 \text{ m}^2\text{K/W}$.

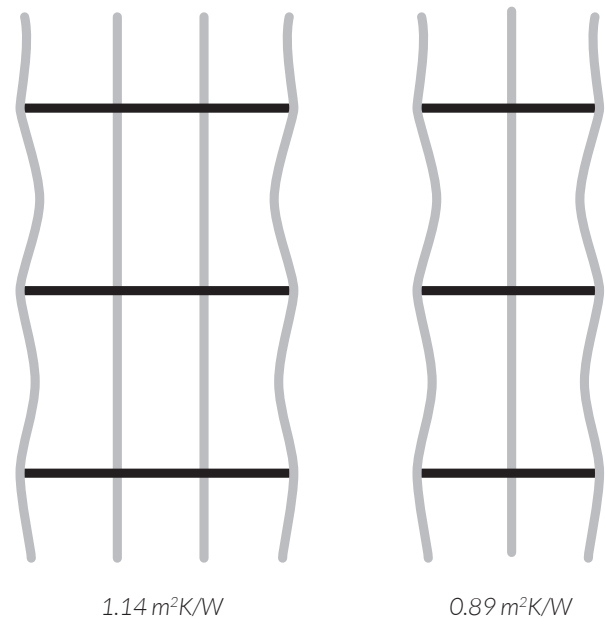


Fig. 162 Multi-layer cavities

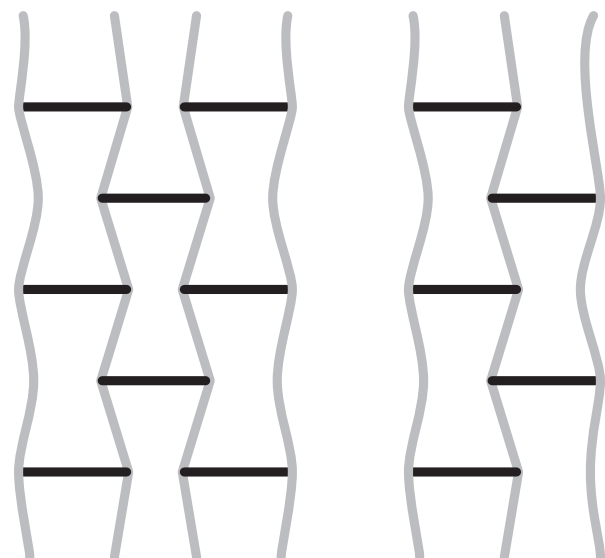


Fig. 163 Multi-layer cavities non-continuous spacers

8.3 - Therm simulation

Hand calculations have identified the ineffectiveness of the light vacuum in the membrane cavities. It has also taken into account the heat leak, caused by the spacers. However the hand calculations are representative of a linear model. Horizontal transport of heat from the spacers is not taken into account. Therefore the calculation software 'Therm' has been used to research more precisely the insulation values of the cavities with spacers.

Therm is a calculation software that calculates thermal insulation and heat transport in a two dimensional surface, instead of the single dimension calculated by hand. The heat transport in this additional dimension is important to investigate in the thermal impact of the many spacers needed in the vacuum panel. The calculations are also far more precise and incremental. Making it possible to generate a heat map of the facade panel.

The figures on the next page show two models and the results of these models. The left model is a window with three cavities contained by four membranes. The membranes are coated with a low-e coating so that each cavity has one coated and one un-coated surface. The right model is a similar situation, but glass fibre reinforced composite spacers are added to the setup.

Results

The model without spacers has a U-value of 0.79 W/m²K. This is even better than the insulation values calculated by hand, but this was to be expected, since there aren't any spacers.

The model with non-continuous spacers has a U-value of 1.17 W/m²K. Unfortunately this is lower than the calculated value of 0.88 W/m²K. However, this can be easily explained, because the real situation is not the same as is calculated in the Therm simulation. The simple model without spacers doesn't consider the spacers. The model with the spacers sees them as big solid lines, which isn't the real situation either. This fault is caused by the two-dimensional nature of the model drawings used in therm. Therefore the calculated value is something more in the middle of both the cavity with and without spacers. This result is in a u-value of 0.98 W/m²K and is more in

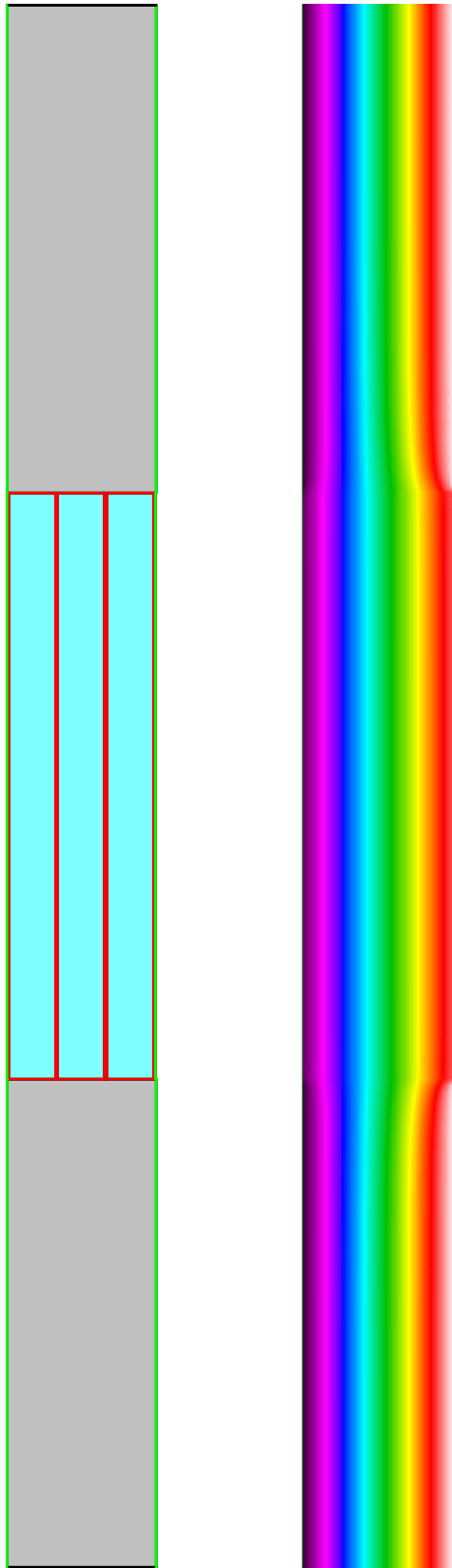
line with the results of the hand calculations.

Besides checking the insulation values calculated by hand, by comparing them to the Therm results, the goal of the model was to identify the effect of heat transport in plane of the facade panel, caused by the spacers. The heat map in figure 165, generated by Therm, can be analysed to see if any heat transport occurs.

The result is that there is barely any anomalous heat transport in plane of the facade panel. The cavities don't insulate very well, because of the high convection. The spacers are therefore relatively not that bad. The main insulating factor within the cavities is caused by the low-e coating on the surface of the membranes, but the spacers have such a low surface area that they do not disturb this very much.

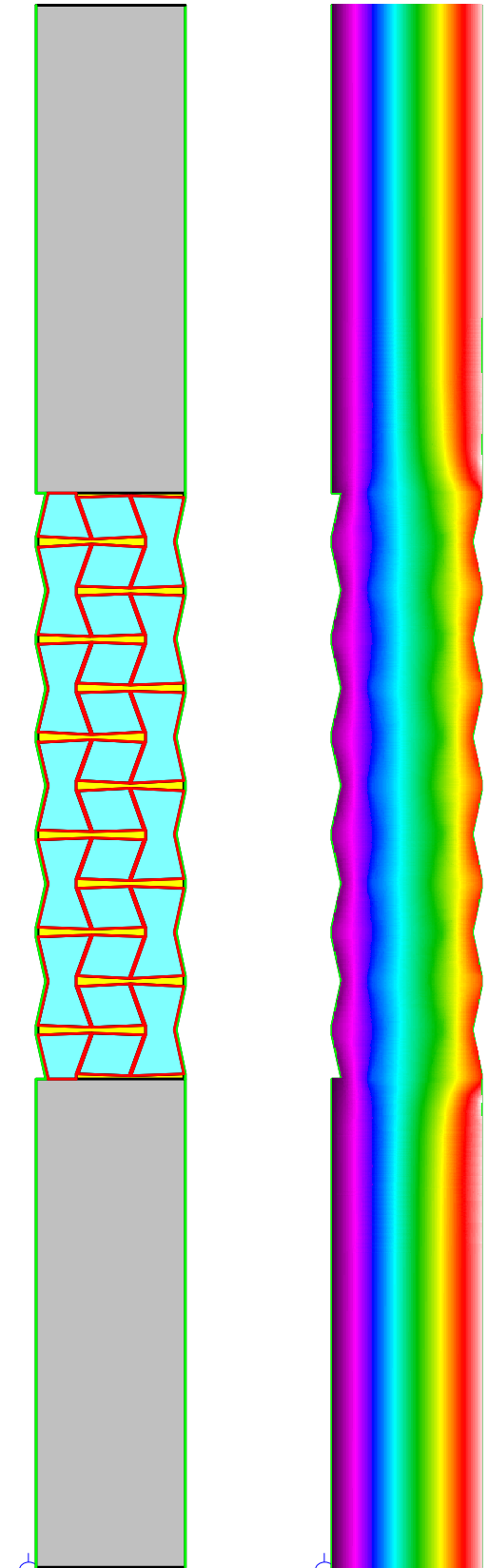
Therm model details

Height opening	800 mm
Depth	150 mm 3 x 50 mm cavity
ETFE	4 x 1 mm
Conductivity	0.24 W/mK
Emissivity	0.90
Coating emissivity	0.30
Spacers	100 mm
Conductivity	0.71 W/mK
Emissivity	0.90
Mesh parameter	6
Estimated error	7.9 %



U-value = 0.79 W/m²K

Fig. 164 Multi-layer cavities



U-value = 1.17 W/m²K

Fig. 165 M.I.c. non-continuous spacers

8.4 - Acoustic insulation

A normal cavity was calculated (Nederlof et al, 2015) and didn't work well, but the vacuum cavity is therefore especially interesting.

Some literature has revealed that calculations and measurements have already been done pertaining vacuum acoustics. These are however not membrane vacuums, but vacuum glass. Nijs (Nijs, 2003) states that distance holders are very detrimental to the effectivity of the system in an acoustic sense. A test done by them showed the spacers and vacuum combined are just as good as normal atmospheric pressure without spacers.

Results

The graph in figure 166 shows all the acoustical results that have been gathered of the many situations that have been calculated. The important ones to consider are the yellow line, which indicates a normal atmospheric cavity, and the light blue line, which indicates the evacuated cavity with spacers.

In short, the evacuated cavity is a far better insulator of sound. There is a large advantage at low and medium frequencies. The improvement in this range is up to 35 dB. The mass spring resonance is also more advantageous at 126 dB. The differences in the higher frequency ranges is minimal however, because of the effect of the spacers. If a double layered system can prevent this sound leak another improvement can be made.

Why these results are so different compared to the result given in the literature is because of the flexibility of the membranes that are used to separate the vacuum. The spacers leak a lot of sound because they are solid rods. The downside is that in a rigid structure much sound hitting the surface of the façade is transported to the spacers to be leaked through. In the case of membranes the flexible foil doesn't have the stiffness to transfer the sound to the spacers. So, the sound leak caused by the spacers stays very minimal. The effect can only be clearly seen in the very high frequency ranges.

Multi cavity vacuum

This method describes the calculation of a single cavity wall. Multiple cavities could be used however for improved properties. This increases the complexity to a point where it is difficult to calculate the values properly by hand. An excel calculator (Nederlof, et al, 2015) was used to get the graph as seen in figure 166 at the dark blue and green lines. This graph represents a double cavity of 50 mm each. The calculator was made for calculating double cavities without any spacers. This was impossible to add afterwards, therefore the spacers inside the cavity haven't been taken into account in these two calculations

It is also possible to create a cavity where the spacers go halfway, as can be seen in figure 163. The sound cannot be transmitted from one side to the other through a solid material. The flexible ETFE in between is not stiff enough to transfer the sound from spacer to spacer. In this situation the sound leaks through the spacers will be much lower. It is highly likely to see a similar insulation value for the spacers as was calculated in a single cavity situation.

Acoustic insulation value.

Single cavity vacuum vs. atmospheric

Low tones	20 dB improvement
Mid tones	40 dB improvement
High tones	00 dB improvement

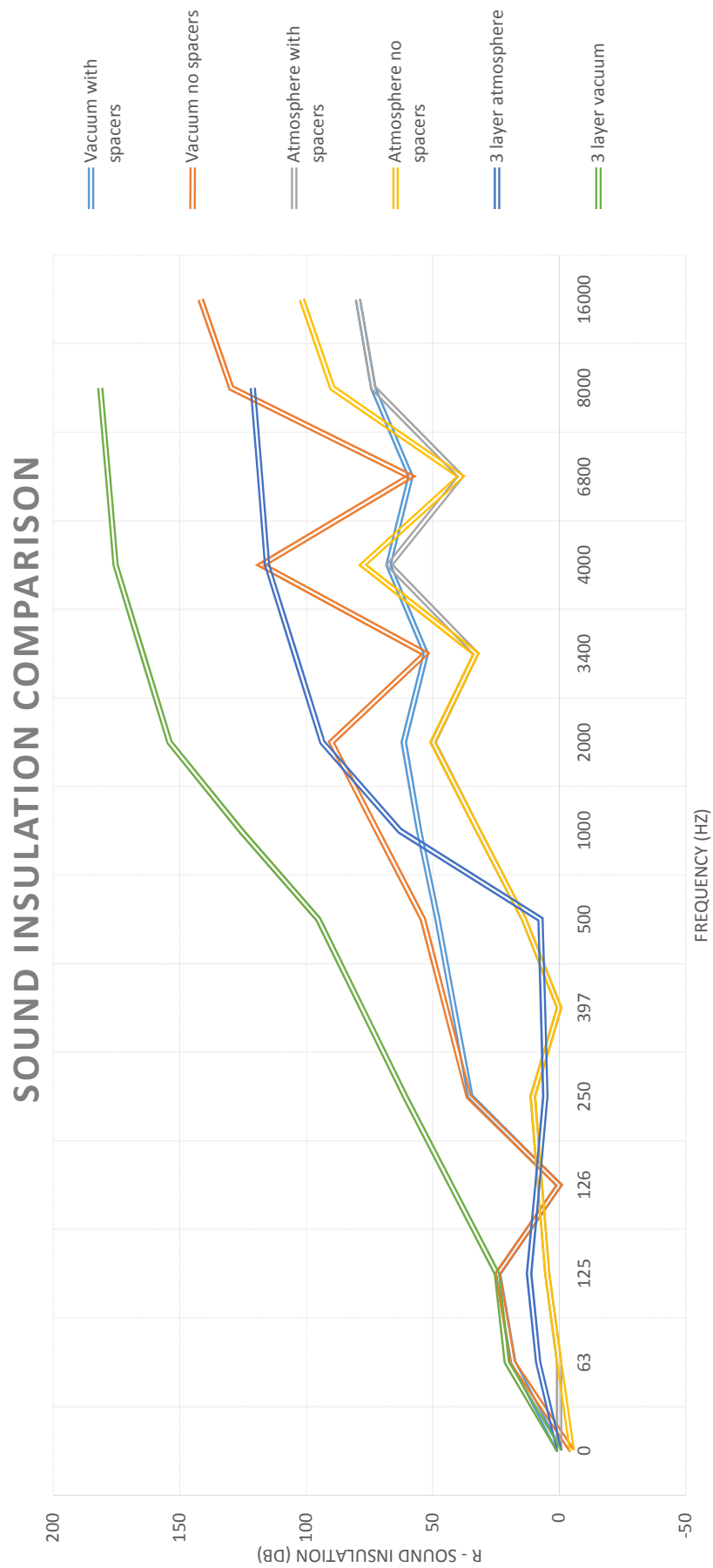


Fig. 166 calculations acoustical insulation results

8.5 - Forces

The forces that act on a façade are various and can become really high, especially in the unitized vacuum concept. Here the pressure difference pushes on the membrane while it is kept apart by small sticks. Therefore, the forces have only been calculated for the evacuated cavity, because here the forces are exceptionally high and special considerations need to be taken.

A number of steps have been taken to calculate the strength needed of a couple of different parts. The sub-chapters below look at each individually.

Internal and external forces

The first step was to identify the forces acting on the membrane and the frame. Pressure caused by the evacuated cavity and wind have been taken into account. The weight of the frame is negligible compared to this, so will only be taken into account when calculating the outer frame.

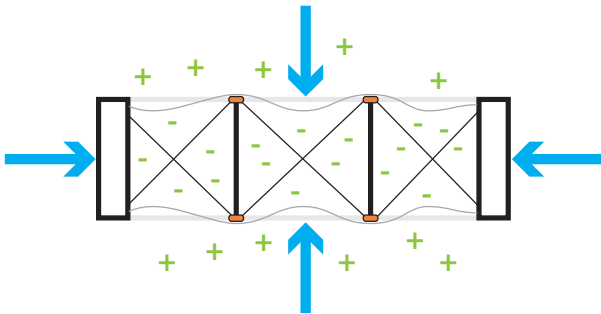


Fig. 167 evacuated cavity pressure

Beside the pressure difference of 0.9 atmosphere pushing on the membrane the wind pressure needs to be added. At the chosen location in Singapore wind speeds of 10m/s are sometimes present in heavy monsoon wind surges. The heaviest recorded was however 25m/s in 2010. This storm is so fierce that forces on the membrane almost double, but the membrane should not be able to fail under this pressure. Therefore this is the benchmark.



Fig. 168 spacer puncturing through membrane

The forces pushing on the membrane and the strength of the membrane dictate the amount of spacers that need to be placed inside and how big these spacers need to be to prevent the spacers from puncturing through. The graphs show the difference in the amount of spacers needed, indicated in the hart to hart space between the spacers, and the diameter of the spacer head. Both the medium and high wind speeds are given.

Distance between spacers compared to surface area spacer needed at monsoon wind speeds of 10 m/s.

Spacing (mm)	Diameter (mm)
50	1
100	7
150	25
200	50

Tab. 9 calculation results spacer size 10m/s windspeed

Distance between spacers compared to surface area spacer needed at maximum wind speeds of 25 m/s.

Spacing (mm)	Diameter (mm)
50	1
100	10
150	40
200	80

Tab. 10 calculation results spacer size 25m/s windspeed

Mock-up tests, that will be shown later in this research report, show however that a distance larger than 150 mm is more pleasing to the eye. At high wind speeds, this doesn't seem practical however.

Spacer pattern

The pattern at which the spacers are placed also

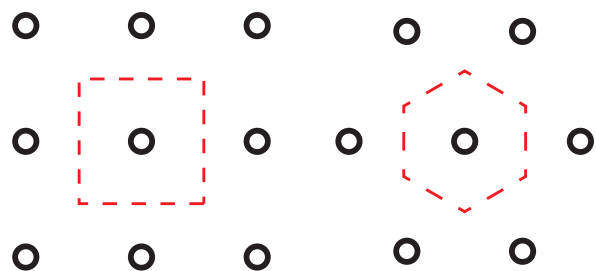


Fig. 171 spacer pattern load area

8.6 - Gas permeability

The increased pressure on the membranes could cause air and water to pass through the membrane to equalize the difference. How much gas passes through is determined by the gas permeability. To keep the heightened properties of the evacuated cavity the pressure needs to stay low. Any gas that enters needs to be pumped out again.

Calculations show that through the membranes of the panel a total of 1.35 litres per hour of air infiltrates into the cavity. This is far too much to just leave alone. Pumps can however pump this out easily. Tiny vacuum pumps can pump out one litre of gas per minute (www.iprototype.nl). This is much more than is needed for a single panel. The pumps are even small enough to be hidden inside the frame

Water infiltration could also happen. When a full panel is submerged under water around eight grams of water would infiltrate per day.

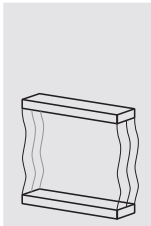
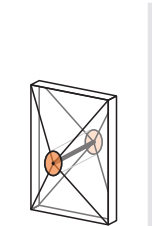
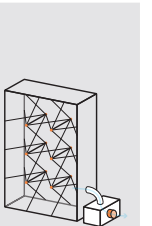
Air infiltration	1.35 L/h
Water infiltration	0.33 g/h

8.7 - Conclusion

Each concept has their advantages and disadvantages, as can be seen in the table below. The mechanical cushion is the most practical solution. It is easily tensioned and relatively simple to construct. The fold-out façade could provide the most open view for inhabitants of the apartments. However, both have very bad thermal and acoustical properties. The unitized vacuum is a challenging concept with high structural and material demands. It can however lead to a building envelope that has superior

building physical qualities when compared to the other concepts.

Because of the advantages mentioned, the challenge and innovation present in the unitized vacuum led to this concept to be the choice for further development. The next chapters will develop a final design along further calculation and physical tests, based on the unitized vacuum concept.

Summary conclusion			
			
Thermal insulation (W/m ² K)	0.79	0.81	0.88
Acoustic insulation (dB)	see graph	relative -5	relative +40
Powered	NO	NO	NO
Feasibility	○	+	—

Tab. 11 summary conclusion numerical evaluation



PHYSICAL VALIDATION

9.1 - Vacuum spacer mock-ups

A number of points of attention have been identified by the calculations. The acoustic insulation calculations showed that point spacers would be most beneficial acoustically. The force calculations showed how much force would be on the membranes, which is difficult to support on point supports. However, view is still an important criteria for a comfortable facade.

These three properties need to be in balance to create a comfortable, functional and safe building envelope. This balance can be created through many designs. Large spacers could be applied far apart, because their larger surface area causes less puncture force on the membrane. However, the larger spacers are more visible and could disturb the view. Another design option with smaller and many spacers could also be used, but this would again have a very different appearance. Like this many more options are available that also consider patterns, materials and reinforcement.

Physical tests have been done to test the different design options available with point supports. The tests will primarily look at the appearance and view through the vacuum membrane system. Stiffness and practicality will also be considered. However, most was learned through building the mock-ups and working with the materials.

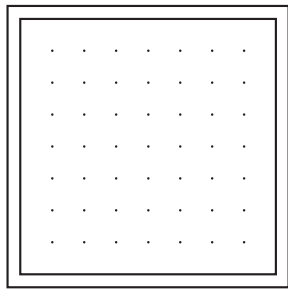
The designs that have been tested are shown in the figure on the next page.

Test setup

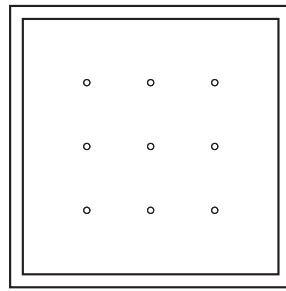
The spacers have been made from solid wooden rods of different sizes. They have been placed inside a wooden frame of 0.5 by 0.5 meters. Before testing, the spacers were placed in the required pattern by sticking them through an extra membrane that was tensioned in the middle. Tearing of this membrane appeared to be an issue, so this was often reinforced by clear tape.

After the correct design was set up they have been placed inside a vacuum travel bag. This bag is made from clear plastic, has a vacuum proof seal and has a valve that can be operated with an ordinary vacuum cleaner. The excess space inside the bag, around the mock-up, was filled by foam to keep the membrane tensioned as much as possible.

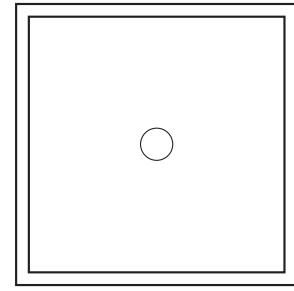
When the installation was complete the bag was evacuated of air and pictures were taken to document the process. Manually pressing on the deflated mock-up was used to very roughly determine the stiffness. All test methods are highly subjective, because they are based on my judgement, but they are helpful nonetheless.



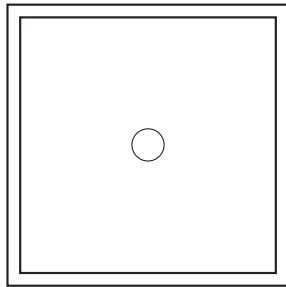
Small grid



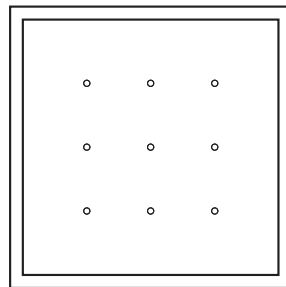
Medium grid



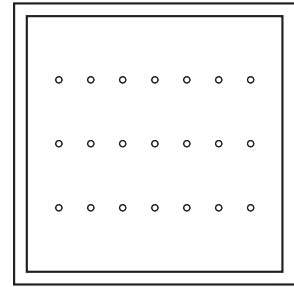
Large grid



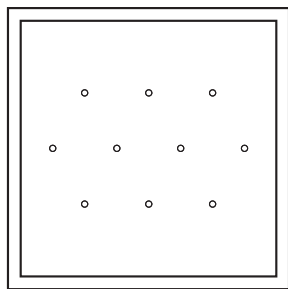
Large grid tube



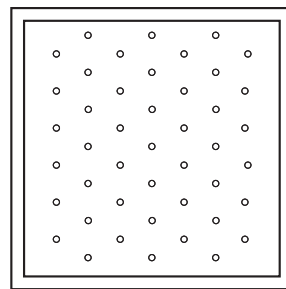
Transparent grid



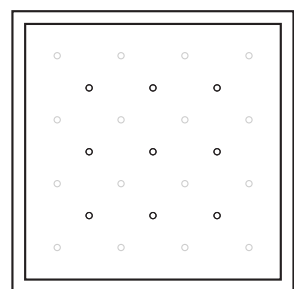
Linear grid



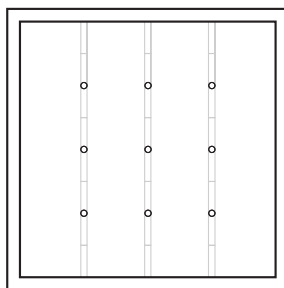
Large hexagon grid



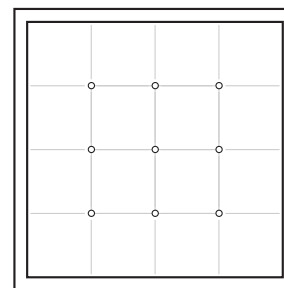
Small hexagon grid



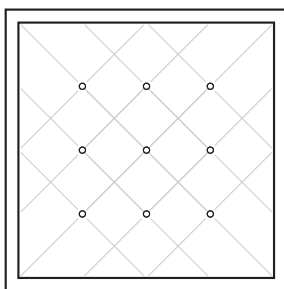
Non-continuous



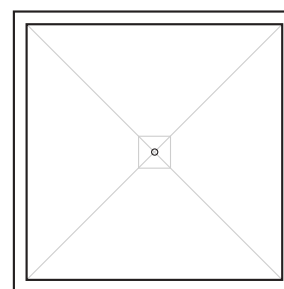
Slanted spacers



Reinforced medium grid



Diagonal reinforcement



Membrane reinforcement

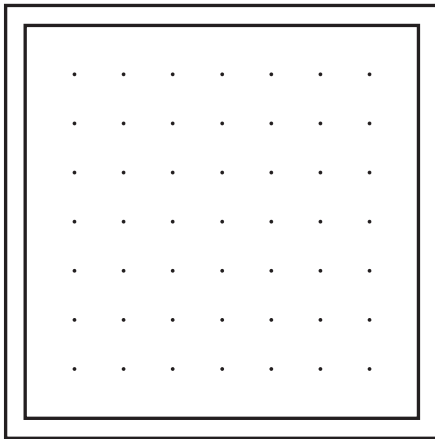
Fig. 175 vacuum spacer mock-up designs

Small grid

The small grid has many spacers that are very small in size in a square grid.

The spacers were difficult to centre, because they wanted to avoid the force put on them. Therefore the spacers needed to be adjusted after evacuation, but this didn't go well everywhere as can be seen in some pictures.

The view through this design is nice from a distance and at a quick glance, because the tiny spacers are hard to see. However, on closer inspection there are too many to ignore. There isn't a view to be found without any spacers, which feels a bit claustrophobic



Diameter of spacers 2 mm
Distance between spacers 50 mm

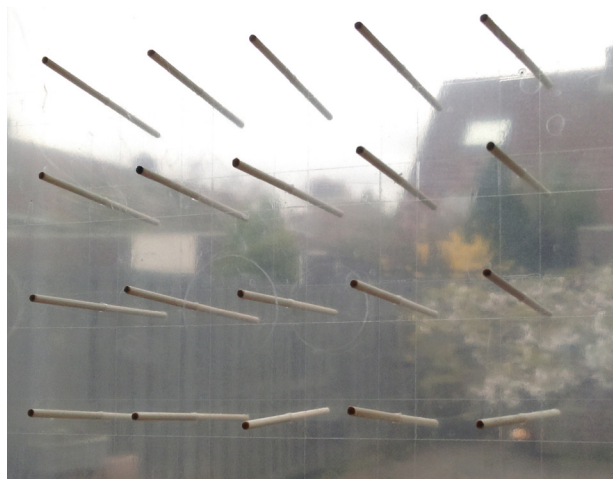


Fig. 176 collage test small grid



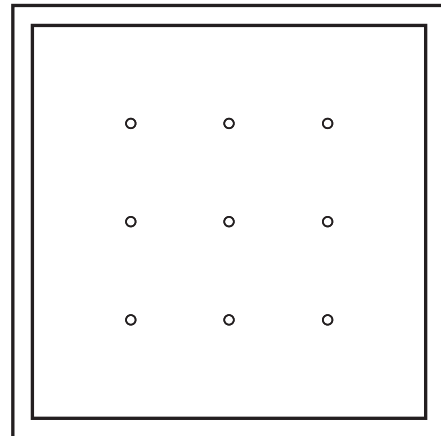
Fig. 177 collage test medium grid

Medium grid

The medium grid has an average amount of spacers that are ten centimetres apart in a square grid. The same practical issues as in the small grid apply, but they are far easier to handle because the size of the spacers is reasonable.

The view is good. The larger distance between the spacers makes the viewer able to find a view without spacers if he/she stands close enough. However, the spacers cannot be ignored as easily.

After this test I can conclude that the stiffness of this kind of setup appears to be determined by the pressure only. The higher forces on the membrane keep the panel in its place. The higher the pressure on the membrane, the more force is necessary to move it.



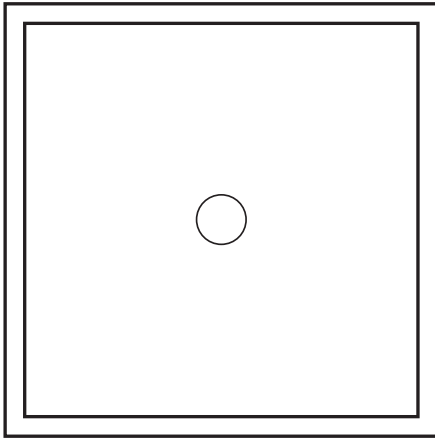
Diameter of spacers	10 mm
Distance between spacers	100 mm



Large grid

The large grid has very few spacers that are far apart in a square grid. The larger spacers are more easily identified, which makes them easier to filter them visually at close range, but are individually more obtrusive. They cannot be ignored and become a design object in the façade. A simple rod will not suffice anymore. They need to be nice to look at. The greater space between the rods is also nicer.

In this test the flow of the membrane is very apparent, because the larger distance means a larger deformation of the membrane. The uneven load and deformation causes the membrane to crease around the spacer in a star like pattern. The shortest distance between supports deform the least and therefore create ridges.



Diameter of spacers 40 mm
Distance between spacers 200 mm

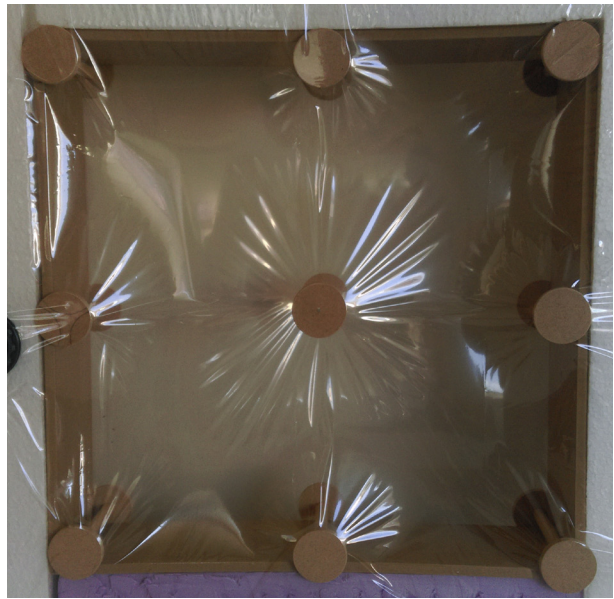
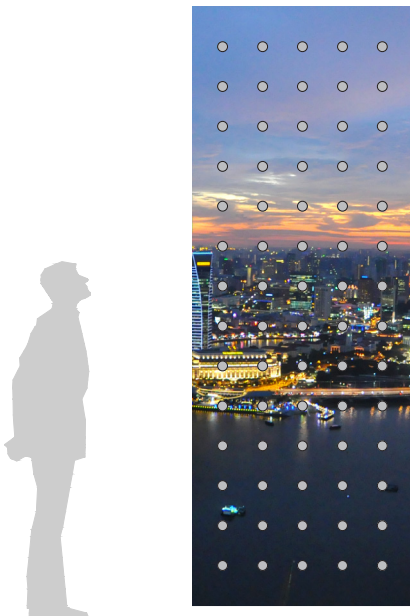


Fig. 178. Collage test small grid

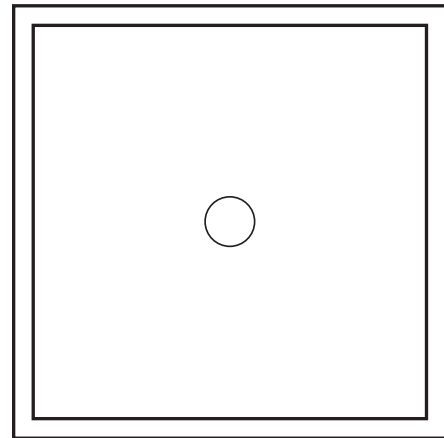


Large grid tube

This test is similar to the large grid, but the spacer is replaced by a tube instead of a rod with circular plates. This was designed to improve the view.

The view is indeed improved, but only when you look straight at the façade panel. This situation will not occur very often in practical situations. Almost every window and therefore spacer will be looked at at an angle. Then the view is worse.

The view becomes worse, because the tube is wide over the whole length. The other spacers are very thin in the middle and can therefore be more easily looked past.



Diameter of spacers

40 mm

Distance between spacers

200 mm

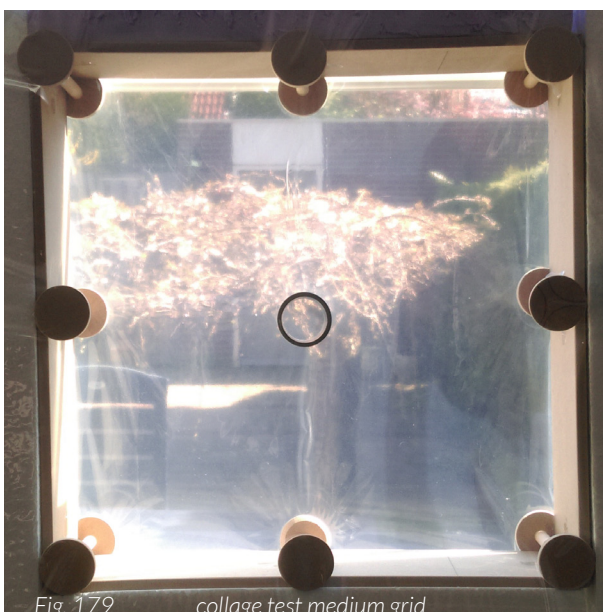


Fig. 179

collage test medium grid

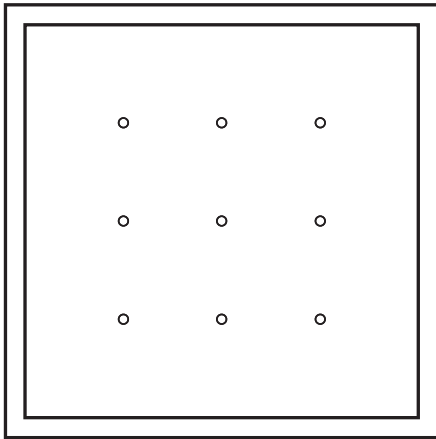


Transparent grid

This test is similar to the medium grid, but the spacers are replaced by transparent rods. This was designed to improve the view.

The transparent rods do appear to be less obvious. They can still be clearly seen, because light reflects bright white on them. The view is more pleasant. They act like chameleons. Taking on the colour of the background and blending in a bit at a quick glance. Not at closer inspection however.

The downside is that this is that this transparent material is far less stiff and therefore needs to be bigger to carry the same loads.



Diameter of spacers 10 mm
Distance between spacers 100 mm



Fig. 180 collage test small grid

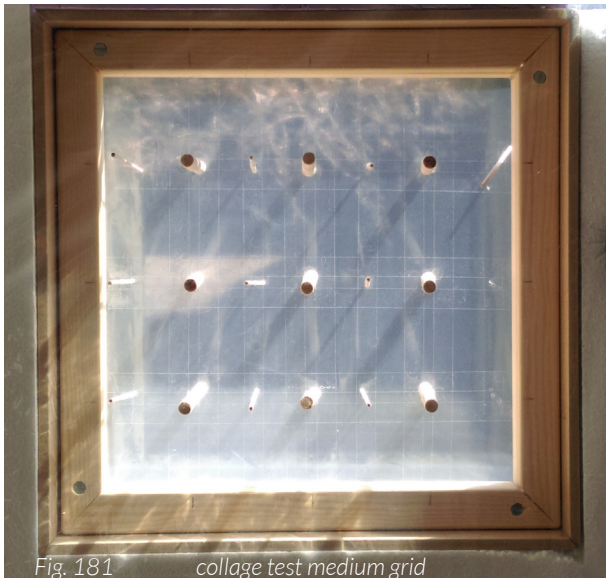
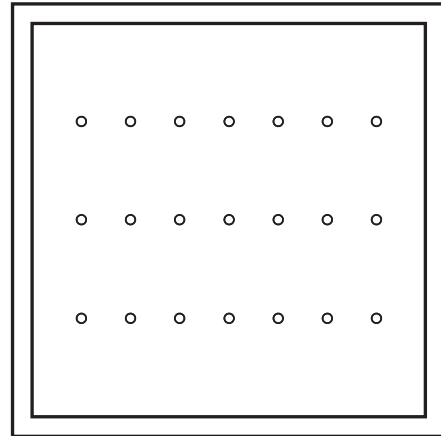


Fig. 181 collage test medium grid

Linear grid

The linear grid the same spacing as the medium grid in vertical direction and the same as the small grid in horizontal direction. This was designed to improve membrane flow. The flow is far more linear in this situation. Ridges of low stress form in the short direction, while the other direction has a smooth curve. This imbalance in force did lead to a puncture in the membrane. The small rods at the edges poked a hole, because they were on the edges. Here was a slightly larger gap, because the frame didn't fit well.

In case of the view. The mind forms horizontal lines of open view as, which is pleasant. This already happened at the square grids, but is more clear in this design.



Diameter of spacers	10 mm
Distance between spacers	100 mm
	50 mm

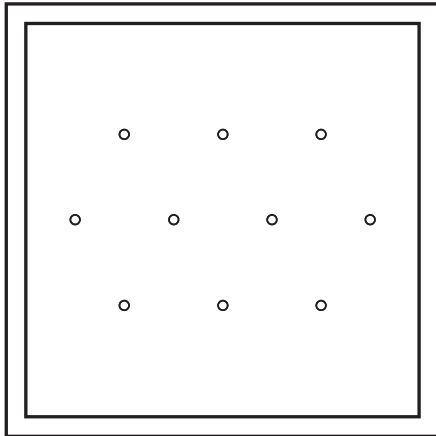


Medium hexagon grid

The medium hexagon grid uses the same spacers and distance as the medium grid, but the pattern is offset to form triangles. This was designed to improve membrane flow.

There was more room in the vacuum bag in one direction compared to the other. Because of this the creases formed diamond shapes instead of triangles, but it is clear that the forces are more equally distributed.

The view is a bit more obstructed vertically, because straight lines cannot be drawn anymore. The horizontal bars stay however. The same distance between spacers insured the same quality up close as well.



Diameter of spacers 10 mm
Distance between spacers 100 mm

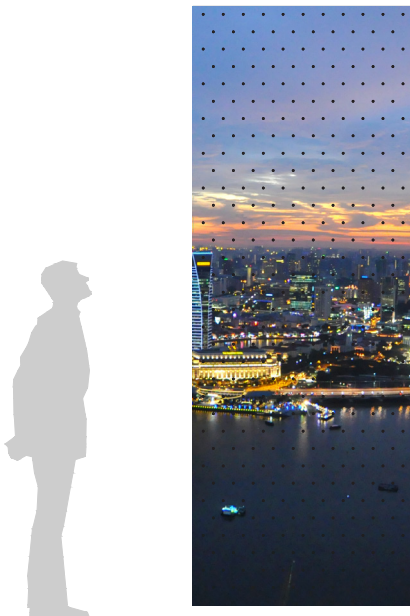


Fig. 182 collage test small grid

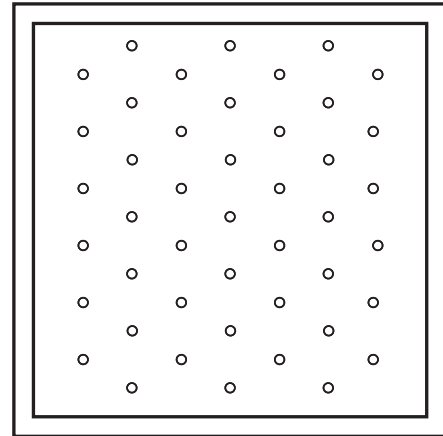


Small hexagon grid

This grid is similar to the medium hexagon grid, but with more closely packed rods and smaller rods.

The view becomes very hectic. This pattern isn't as recognisable as the square grid. This makes it very hard to feel comfortable with.

Again, keeping the rods straight was an issue. The small spacers are very difficult to control and steer. They are inadvisable to use in any practical situation.



Diameter of spacers	10 mm
Distance between spacers	50 mm



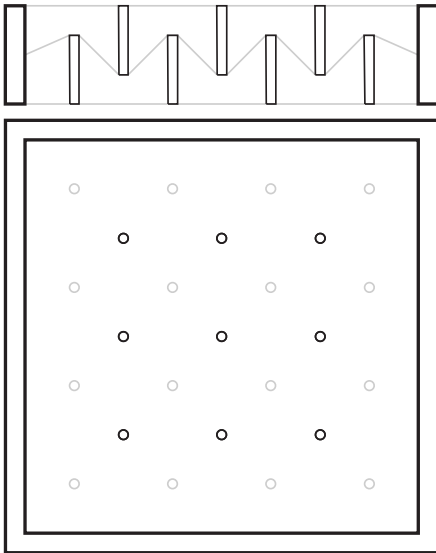
Fig. 183 collage test medium grid



Non-continuous

This design has spacers that are connected to an extra layer halfway the cavity. Both sides apply a spacer pattern similar to the medium grid, but one side will be shifted to be the farthest distance from the other. This was designed to lower the heat and acoustical leak caused by the spacers.

The connection to the middle layer led to a failure. Fortunately, extra reinforcement with clear tape fixed prevented another failure in a new model. The building physical properties of this design will probably be far superior to every other tested design, but twice as much spacers are needed to support the membrane. The view suffers because of this.



Diameter of spacers 10 mm
 Distance between spacers 100 mm



Fig. 184 collage test small-grid

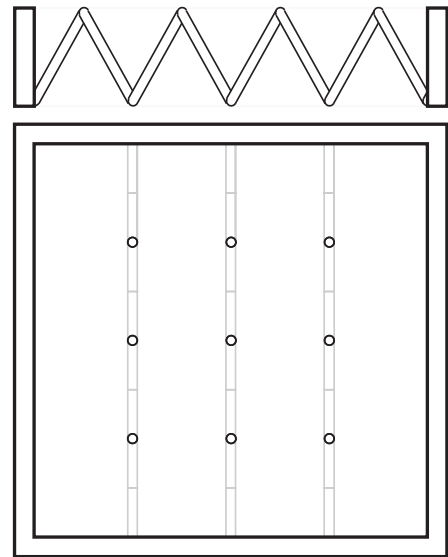


Fig. 185 collage test medium grid

Slanted spacers

This design placed the spacers diagonally in the cavity and connected them. This could give the façade more stability.

The greater stability was definitely achieved, but this stability is still depended on the pressure. However, this dependency is far less than in the other designs. The spacers create triangles of which two sides are rigid, but one is a membrane. It hasn't been calculated, but the extra length of the spacers should mean that they need to be bigger. The resultant appearance is very linear in the direction the spacers are placed. I personally didn't like the jagged appearance.



Diameter of spacers

10 mm

Distance between spacers

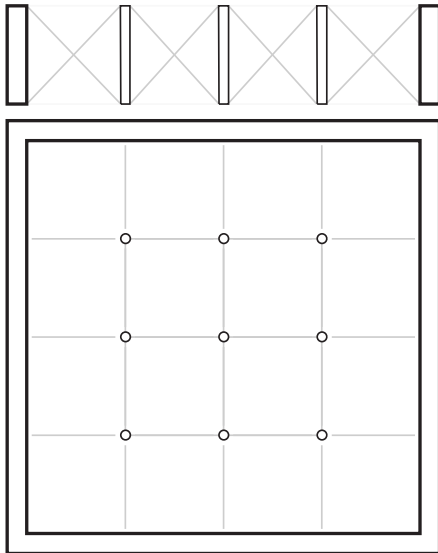
100 mm



Reinforced medium grid

The medium grid has been reinforced by nylon wire that has been laced through the spacers. This was designed to distribute the forces on the membrane better and gain some stability.

Because the wires were only laced through the spacers and not fixed, the stability didn't improve very much. The wires couldn't really pull on the other spacers enough. The small amount that it could do was clearly helpful. The second picture shows a situation where the middle spacer is pushed. This force also results in the other spacers taking some of the force and displacing. This only happened in this test.



Diameter of spacers 10 mm
Distance between spacers 100 mm

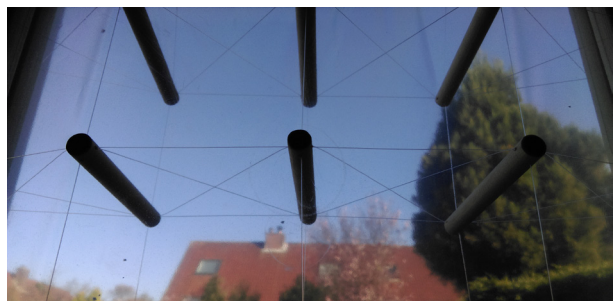
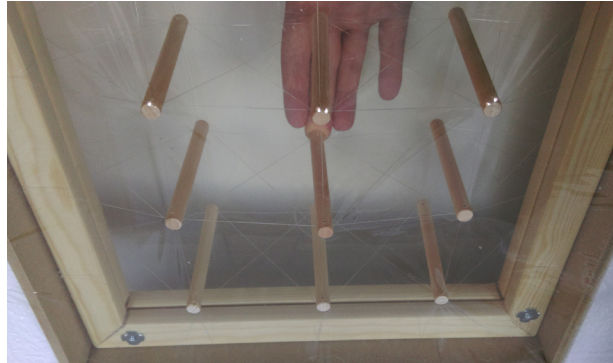
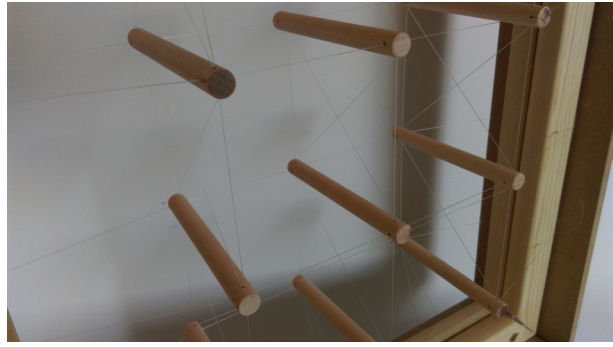


Fig. 186 collage test small grid



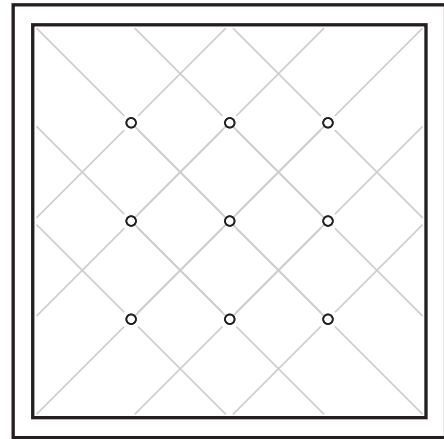
Fig. 187 collage test medium grid

Diagonal reinforcement

The previous test showed that the location of the reinforcement was exactly at the areas where the least force is on the membrane. Therefore this test will lace the wires in a diagonal pattern to support the membrane at the lowest points.

This reinforcement resulted in the flattest membrane of all the tests, which is very promising. However, the pattern does obstruct the view more than the other medium grids.

Structurally the diagonal reinforcement is both positive and negative. They give extra stability, but the angle at which they need to be fixed is more difficult to realize.



Diameter of spacers

10 mm

Distance between spacers

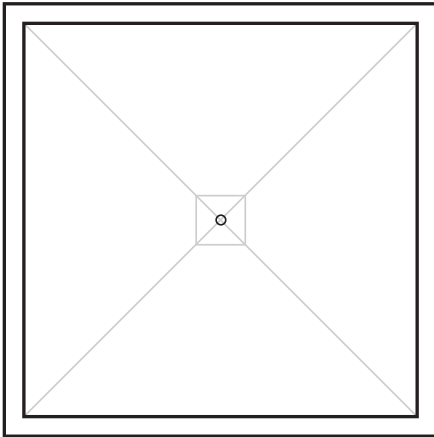
100 mm



Reinforced membrane

This final test is not one done in the same setup and evacuated cavity, but only a strength test. Nylon wires are adhered on the membrane with hot glue to give them more strength at specific locations. A point force was then applied to the reinforced and unreinforced membrane to observe any difference.

It is clear in the pictures that the 'dent' in the reinforced membrane is larger and more shallow than in the unreinforced membrane. This means that the forces have been spread out over a wider area, which is positive. I believe that in a situation where non-elastic materials, like glassfiber, are used as reinforcement, and they are fixed more properly, then the deformation will be non-existent.



Diameter of spacers	10 mm
Distance between spacers	200 mm

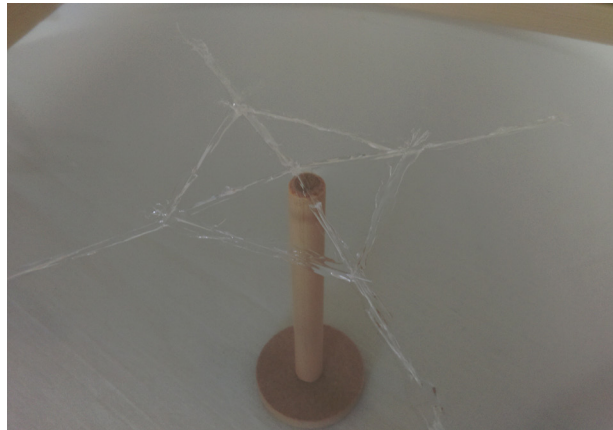
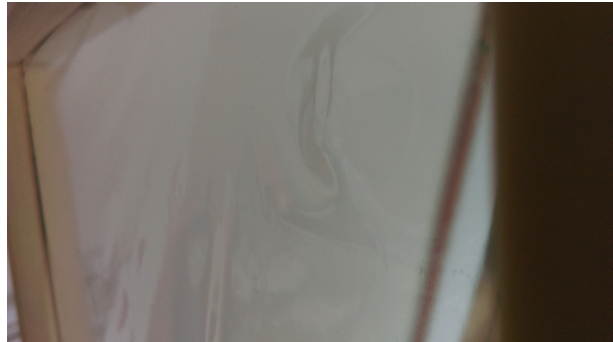
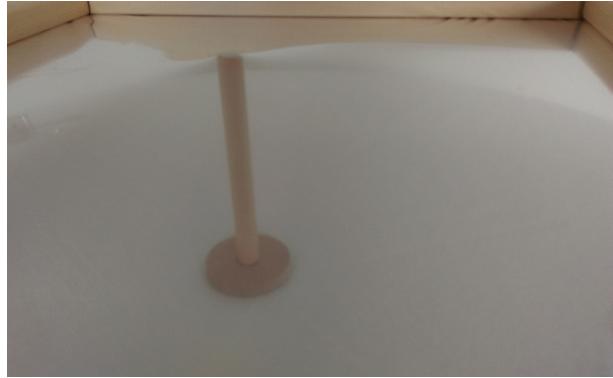


Fig. 188 collage test small grid



Conclusion mock-ups

Out of all the tests that have been done the large grid was visually most pleasing to me. This is a personal opinion so this could be different for other, which is very reasonable. Calculations show however that at high wind speeds this is not a plausible configuration. The forces would be too great and even larger spacers needs to be used. My second choice was the medium grid, which was visually pleasant.

For better forced distribution this grid will be shifted to the hexagonal medium grid. This grid will be combined with diagonal reinforcement to create the most supportive spacer configuration. The reinforcement can be applied in a few different amounts, shown in figure 189. Two diagonally running wires were chosen to be sufficient enough, highlighted in orange, because they are connected in the shortest distance and would probably carry all the force and make the third on irrelevant.

To improve the building physical properties the design will also use the non-continuous spacer design for minimising both the acoustic and thermal leak.

None of the rigidity solutions will be used, because this was deemed unnecessary at the pressures applied on the membrane envelope.

The design is not finished yet. Further development opportunities have also been discovered. A way of placing and centring the spacers needs to be found. A method for adding the membrane reinforcement needs to be developed. And the rest of the panel needs to be designed. This was just the start.

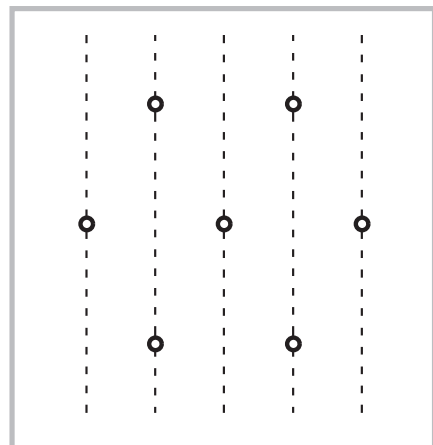
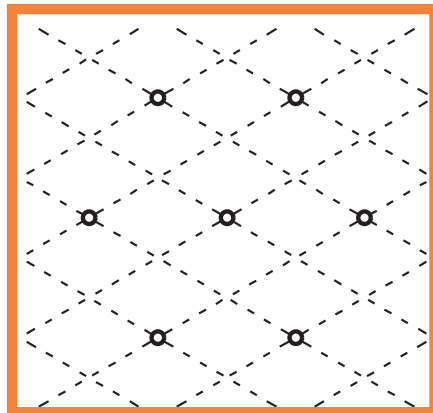
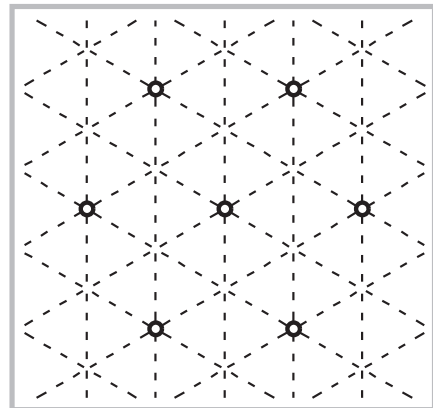
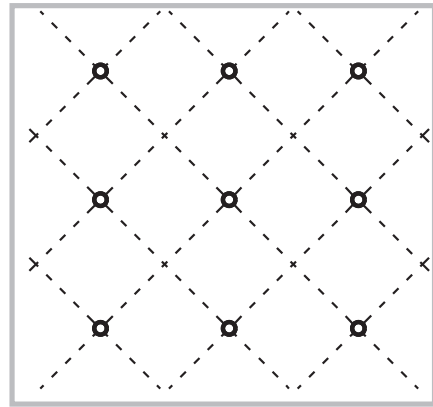


Fig. 189 hexagonal grid reinforcement patterns

9.2 - Vacuum acoustics tests

The acoustical performance of the façade has been calculated by hand, but the system is still untested and the calculations used could be inappropriate for the system. Or unknown variables could play a part. Therefore a practical test will be done to physically test the acoustical performance against air-born sound of a vacuum membrane panel.

The test was supposed to be performed in a lab specifically designed for this purpose. The lab is shown in figure 190. Two rooms are completely acoustically decoupled except for one hole of 1.25 by 1.5 meters. Here the test panel will be placed. In one of the room an omnidirectional sound source will transmit white noise. This is a noise containing all relevant frequencies. The sound will be measured in the other room, to measure the effectiveness of the panel

Building the large test panel

The vacuum membrane panel that was supposed to be tested is not the final design, but a simplified version. The final design was too thick for the lab setup, which had a maximum depth of ten centimetres, and building it properly required professional equipment that was unavailable within the given time. The test panel has only one cavity of ten centimetres, with continuous spacers. This simplified version could however give enough results to identify the effectiveness of the vacuum. This result could be calculated with and extrapolated to give a more precise indication of the effectiveness of the final design.

Figure 191 shows the large panel that was built. It is 1240 by 1490 millimetres in size, so it will fit nicely in the test room. The frame had to be very strong to cope with the tons of air pressure that could possibly be applied at the desired pressure level that the test required. A steel frame would be ideal for this, but hasn't been chosen because weight and other practical issues. This proved to be an unwise choice, because the frame wasn't strong enough and had to be reinforced with steel rods afterwards.

The 257 spacers within have been made from wooden rods 18 millimetres in diameter. The rods were placed in a hexagonal pattern, as the theory dictates is the most efficient way. To keep

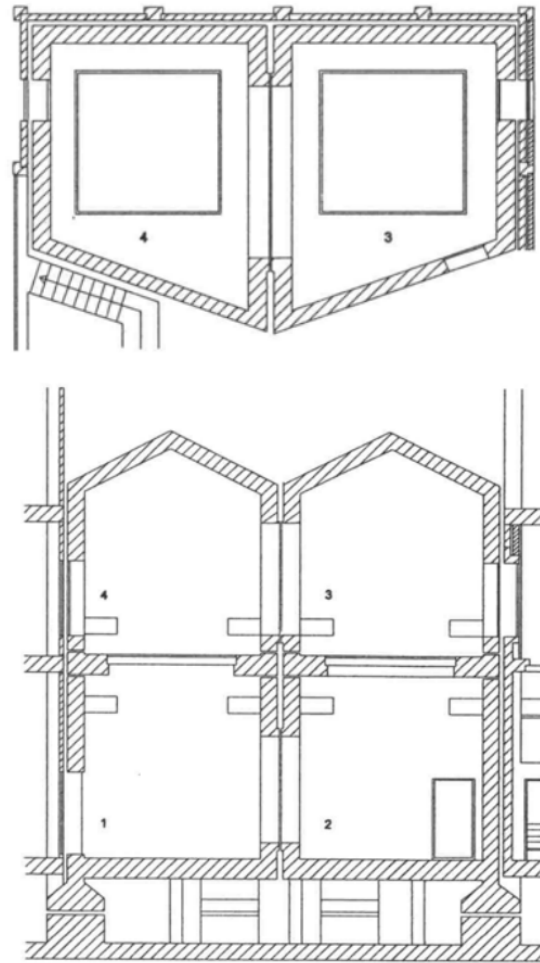


Fig. 190 acoustic test lab

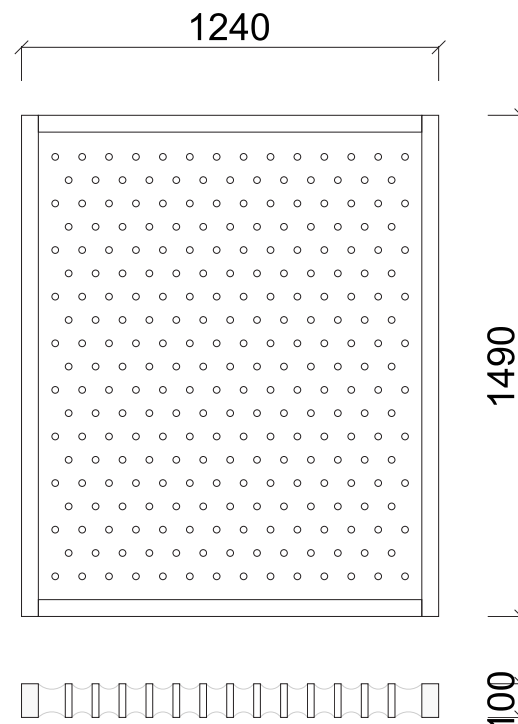


Fig. 191 tested vacuum membrane panel

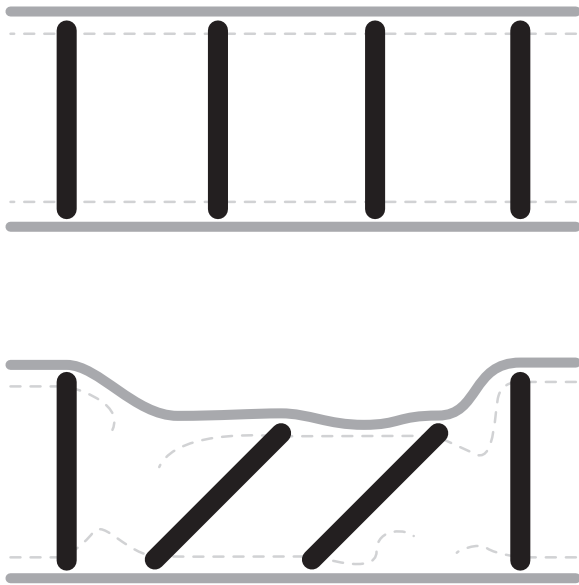


Fig. 192 failure schematic

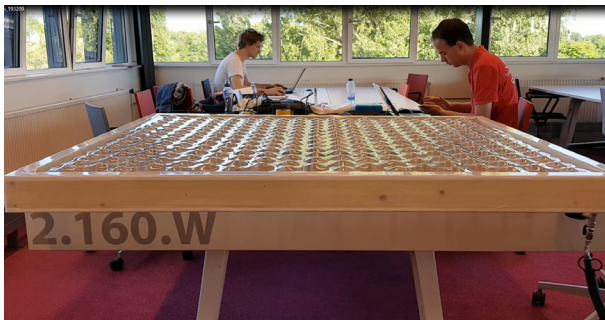


Fig. 193 still from failure footage

the spacers in the correct position an elaborate wire mesh has been fixed on the frame by staples. The spacers have grooves in them to be held in the correct place.

The most important piece of the test panel, is of course the membrane. 300 micrometre thick foils of ETFE have been used. This is one of the thickest foils available and should be strong enough to hold the required pressure, without stretching or tearing. The membrane was fixed to the frame with abundant use of tape.

Test panel failure

After the whole panel was finished, a final airtightness check was done to ensure everything worked properly for the actual acoustics tests. During this test the pressure was slowly lowered from 1 Bar to 0.6 Bar. At this point the panel violently imploded.

After close inspection and review of footage taken of the check, the flaw in the panel was identified. The spacers, that were meant to keep the membranes apart, fell over. Figure 192 shows a schematic of the situation. The membrane was also badly damaged and punctured, but this was caused by the imbalance in forces after the collapse. The spacer tests done in chapter 9.1 didn't predict this event, because that test was done with far lower pressure and another kind of plastic membrane. That membrane had a lot more stretch and shaped itself over the spacer tip, locking it in place. ETFE is far more stiffer and doesn't elongated much under force, which is why it was chosen for the membrane envelope, but this also prevented it from locking in place and let it slip out of the way if any spacer isn't perfectly aligned perpendicular to the membrane, which is impossible to do by hand.

The wires used to fix the spacers also increased the size of the failure area. The failure probably started at one spacer, but the wires connected many more to this one and pulled them all down with it.

Building the small test panel

After the failure of the large test panel a replacement test was found. The large panel was too badly damaged and only small parts could be recovered. With these small parts another smaller panel was created. To prevent another failure the spacers were fixed in another way. Figure 196 shows a schematical detail of the new spacer fixing method. A piece of ETFE is glued and nailed to each spacer tip. This provides a large surface, which can subsequently be taped to the inside of the membrane. Because of the smaller size it was also more viable to draw out the exact location of each spacer and place the by hand, which should result in less deviation in alignment. This proved to give enough grip for each spacer to prevent any slipping.

Acoustical measurements

The measurements were done in the product development test lab, with the help of a speaker box setup. The test is really unreliable, but considering the circumstances could at least give an indication of the effectiveness of the vacuum membrane envelope. Figure 194 shows the room and the test setup. The box is a plywood box with an integrated speaker on the inside, which emits white noise.. One side of the box is uncovered. Here the tested panel is placed. By measuring the difference in sound pressure level between the inside and outside of the box, the sound insulation value of the test panel can be identified.

Before measuring the panel sound levels, the reverberation time and sound absorption of the room need to be identified. This is required for calculating the sound insulation after the test. Where this was done can be seen in figure 195. A measurement device was used to measure the reverberation time. The device does need a loud trigger to initiate the measurement and to hear the properties of the room. The trigger is simply, popping a balloon. This was done two times on three location to get proper results of which an average could be taken.

The panel was tested afterwards on top of the testbox. Multiple tests have been done at different pressures inside the test panel to divide the load on the panel and to see the effectiveness of the panel at the different pressures. The pressures

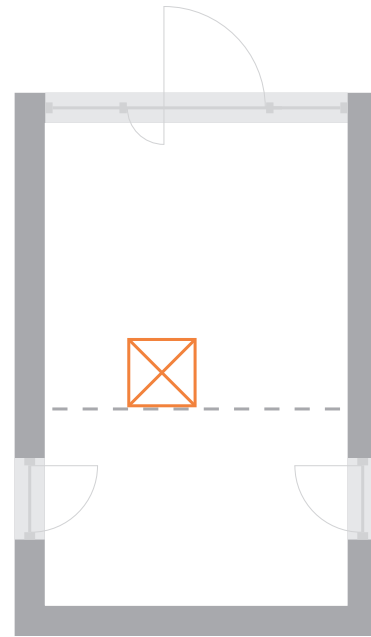


Fig. 194 Test space and testbox location

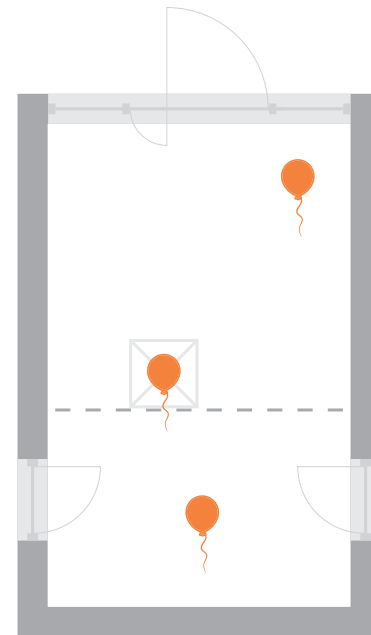


Fig. 195 Test space and balloon test location

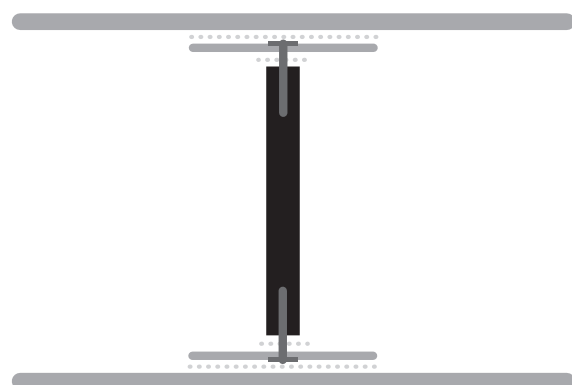


Fig. 196 Schematic detail spacer connection

that were planned to be measured were 1.0, 0.8, 0.6, 0.4, 0.2 and 0.1 Bar. A nine millimetre MDF plate has also been tested to function as a baseline test, to which the membrane envelope can be compared to. Each situation was tested four times. Of the four tests, two times the measurement has been taken inside the box and two outside the box.

However, disaster struck again. The brand new vacuum pump broke down after the tests at 0.6 Bar had been completed. So data could only be gathered up to this point. The test model did hold up very well this time.

Test results

The limited results have been gathered and filtered of any flawed measurements. The data was then calculated using equations that can be found in the appendix, resulting in the graph that can be seen in figure 197. The graph shows the sound insulation value of the entire box. This includes the plywood of the box itself and of course the tested panel.

The results are inconclusive. A curve can be recognized that dips around 200 Hertz and shakily rises afterwards. However, this is the same for the MDF, which should be absolutely different. The results of the pressures that were measured also dance around each other without any correlation,

while a minor, but steady increase or decrease of insulation was expected. Any peaks, both positive and negative are therefore also unreliable, because not enough measurements have been done to completely rule out measurement flaws and because they happen suddenly without any correlation to the rest of the measurements.

There are a number of factors that could have led to these inconclusive results. Either, the test setup isn't very reliable. The box itself is also measured and might have some unforeseen acoustical leaks. The room it was tested in was also not built for this purpose and was surrounded by traffic, which could all affect the measurements.

The test panel was also not tested to the required pressure levels. The calculations done in chapter 7 showed that the acoustical performance increases on a logarithmic scale. This means that it will very slowly improve at first and will improve dramatically every power of ten. That is why the desired pressure was ten percent of normal pressure. The minor differences that could be noticed at the relatively high pressures could just be not enough to notice in this setup.

That the panel simply doesn't work could also still be a possibility, because of the untested concept of the design. Future study should definitively be done on this subject to know it definitively.

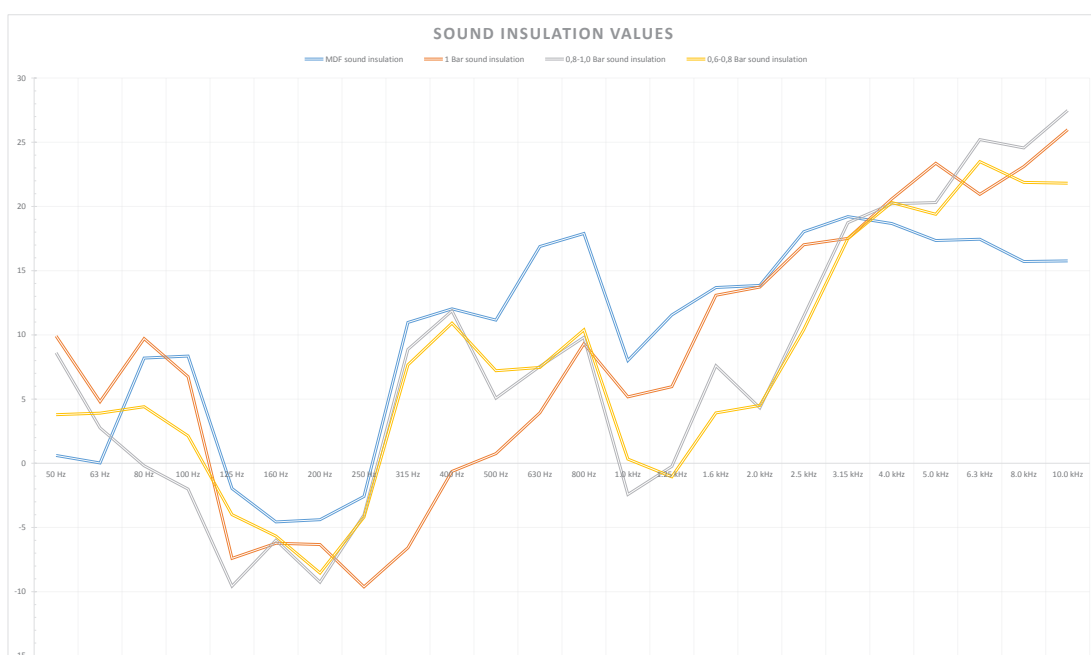


Fig. 197 test results

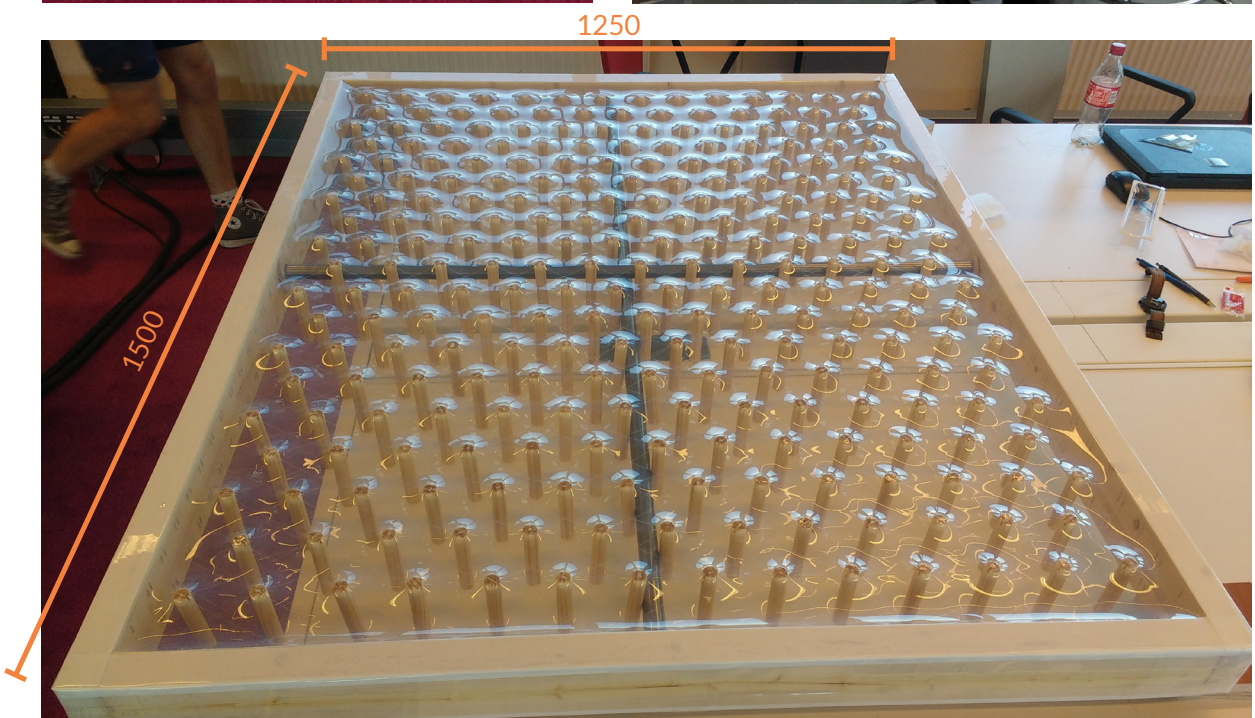
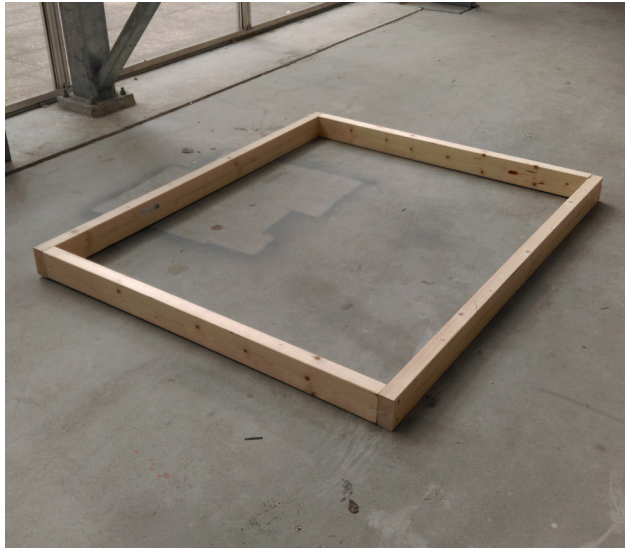
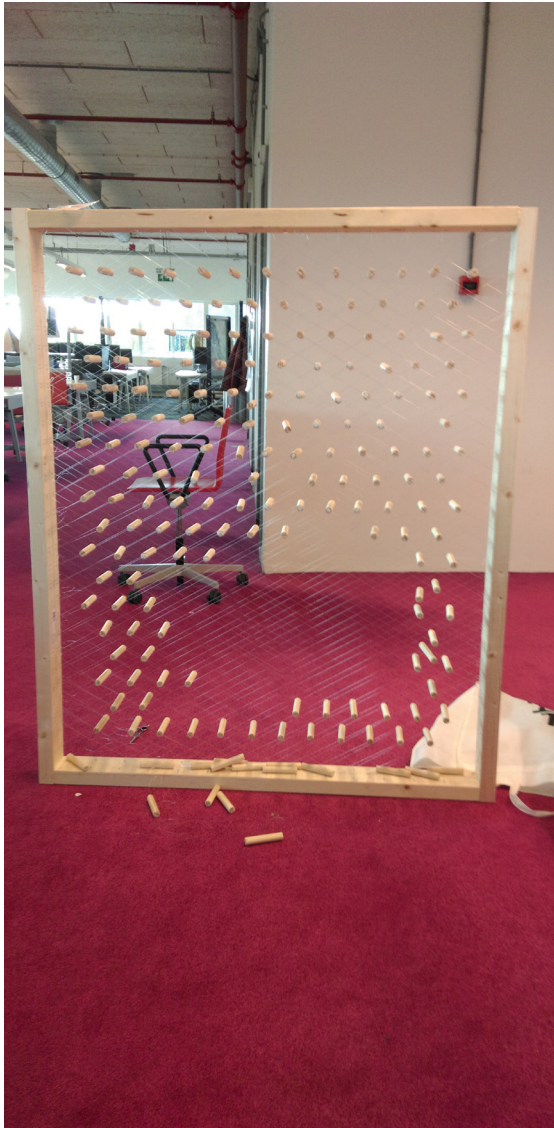


Fig. 198 collage of building the large panel

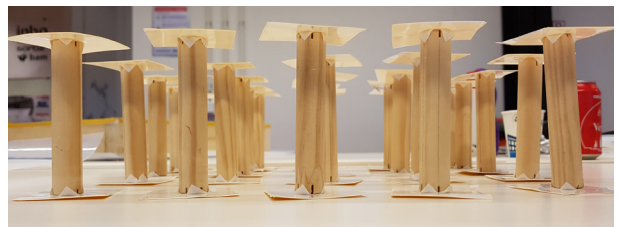
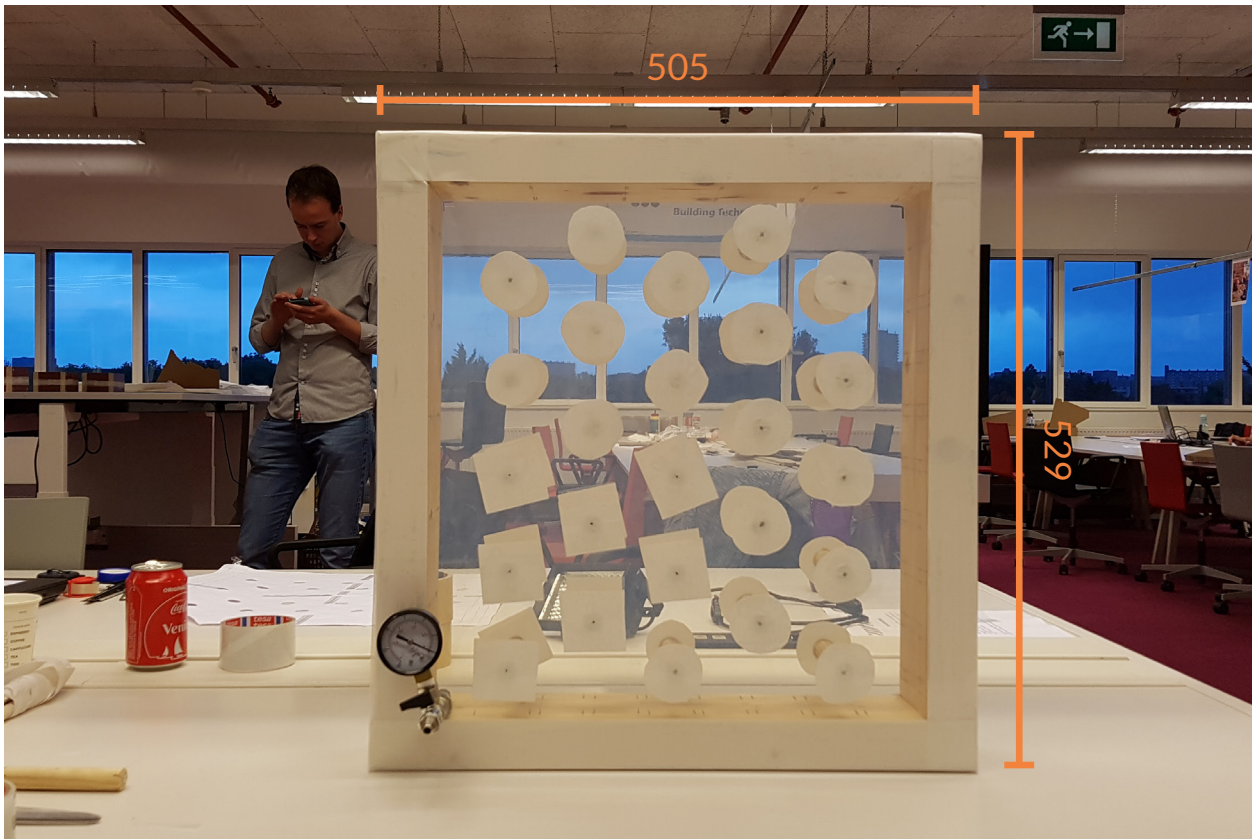


Fig. 199 collage of building and testing the small panel

10

FINAL DESIGN

10.1 - The design

A properly functioning unitized membrane envelope should have sufficient values to every aspect mentioned in figure 3 in the literature study. This design should even add to this to create a more suitable façade for the build environment of the future. To try to achieve this with membrane materials all the work on the previous pages has been done. After all previous design phases and research done through literature, mock-ups and physical tests a final design can be created.

The design was based on the vacuum membrane envelope concept and has gone through a couple of iterations, because despite the research done a lot of design options are available. These designs based on the final concept can be found in the appendix.

The actual final design can be seen in the figures on this page. It has a distinct hexagonal shape and has a lot going on over the whole surface. Every aspect of the design has been purposefully chosen and this will be explained in the rest of this chapter. Research done concluded that each design aspect had a most optimal solution.

This sub-chapter will explain the design by focussing on different parts or design aspects. The subjects along which the design will be explained can be seen in figure 201. The subjects are:

- Membranes
- Spacers
- Shading
- Panel
- Frame
- Additional design aspects

They will be discussed and explained in that order.

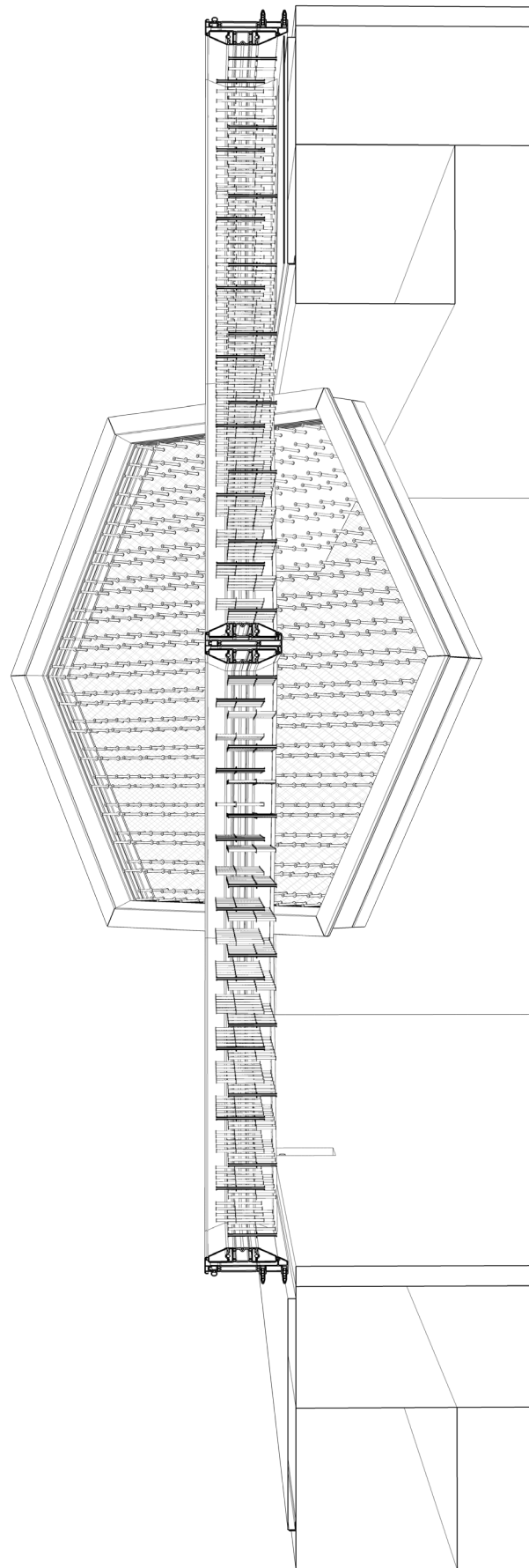


Fig. 200 final design section

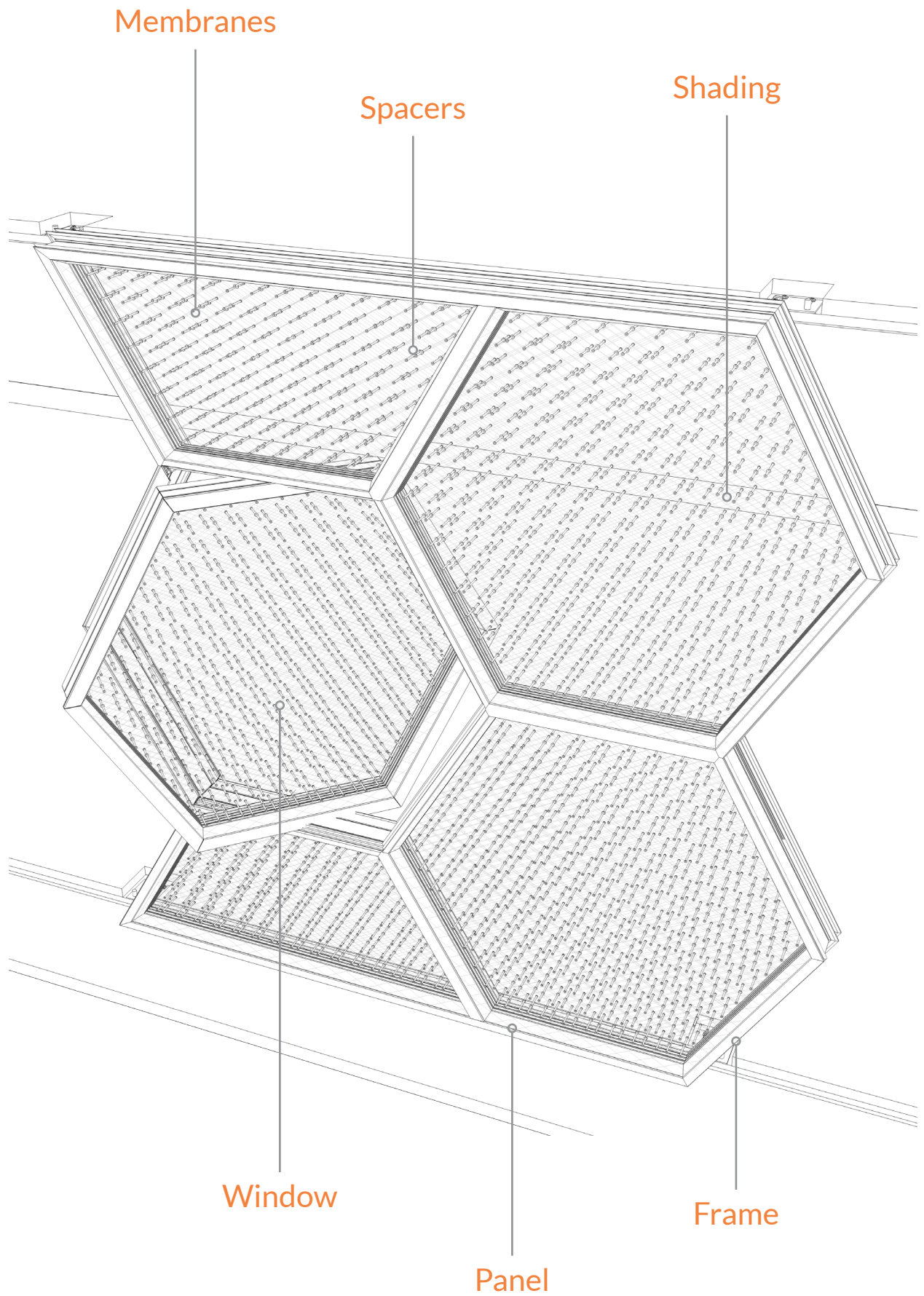


Fig. 201 final design isometric view

10.2 - Membranes

The main components of the unitized membrane envelope are of course the membranes. They create the barrier between inside and outside and in this case hold the light vacuum. The envelope consists of four membrane layers that create three cavities, as can be seen in figure 194. This amount has been specifically chosen to create similar thermal properties compared to conventional triple glazing, as was explained in chapter 7.4. The outer and inner cavities have a depth of 50mm. The middle cavity has a depth of 70mm. The difference is purposefully created to prevent acoustic resonance between all three cavities at the same time. The outer cavity will house a sun shading system for solar control. It will be explained later.

The cavities are air tight as a whole and are evacuated of air together. The air pressure will be lowered to 0.1 Bar. This is ten percent of normal atmospheric pressure and will increase acoustic performance significantly. However, the evacuated cavities will create enormous inward pressure, which needs to be held by a heavier frame and spacers to keep the membranes separated. Both will be explained later.

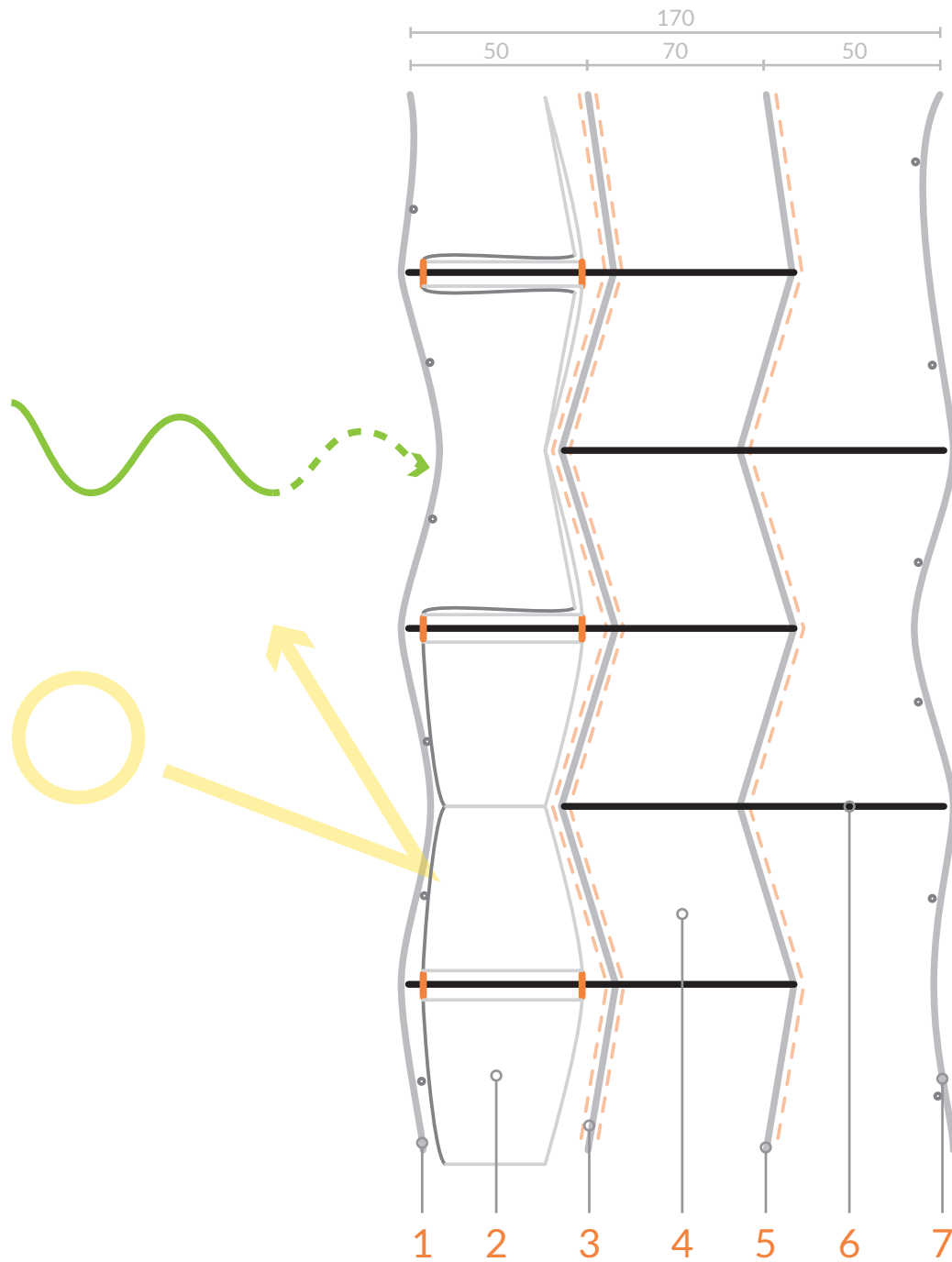
All four membranes will be from 0.3 mm thick ETFE foil. ETFE is already used very often in membrane building applications because it is very transparent, strong and durable. Because of these reasons this design will use it as well, however in the 0.3 mm variant, which is relatively thick. This thickness is needed to prevent it from tearing or being punctured through by the spacers.

Further reinforcement is applied in the form of thickened ETFE disks and glass fibres. The ETFE disks are heat welded on at the spacer contact points. Here the highest stress will occur. The

glass fibres are placed in a custom pattern that spans diagonally over the spacers to reinforce the membrane at the spacer location, but also support the location where the most deformation will happen. This support will result in a flatter surface and thereby less, creases and more uniform properties. The glass fibres are welded between another strip of ETFE. The glass fibres can also be inserted during the production of the ETFE foil, but this will result in a less uniform surface and therefore in a loss of transparency. The glass fibres are not only applied for reinforcement of specific areas, but mainly for preventing creep. This is a slow process of elongation through prolonged stress. Polymers like ETFE suffer from this, but glass doesn't, which makes it an ideal reinforcement material.

The membranes will also be coated by a low-e coating with an emissivity factor of 0.3. This makes it possible to achieve the aforementioned thermal properties. The coating is uncommon on ETFE foil, but possible and relatively expensive compared to other solutions, because a pattern printed on the foil would suffice in most situations, but because high transparency is desired in this case a coating is the better solution.

A single coated ETFE foil is very transparent to visible light with a light transmission factor of 95%. This is even better than some types of coated glass panes. When applied in four layers with sunshading an adaptive light transmission factor between 77%-10% can be achieved. Unfortunately this doesn't result in the same transparency as glass would. ETFE and most other polymer foils scatter the light slightly. This means the picture quality will be slightly vague, as can be seen in the mock-up at the end of this chapter.



1 - Glass fibre reinforced ETFE 0.3 mm with ETFE reinforcement at spacer points

2 - Sunshading system

3 - Glass fibre reinforced ETFE 0.3 mm with ETFE reinforcement at spacer points and low-e coating on both sides

4 - Low vacuum at 0.1 Bar

5 - Glass fibre reinforced ETFE 0.3 mm with ETFE reinforcement at spacer points and low-e coating on one side

6 - Spacers

7 - Glass fibre reinforced ETFE 0.3 mm with ETFE reinforcement at spacer points

Fig. 202 membrane layers schematic

10.3 - Spacers

The spacers are one of the most important parts in the design to make the vacuum function. The forces created by the vacuum will push the membranes together until no space is left anymore, this will negate all effectiveness of the vacuum and is therefore obviously unwanted.

Many spacer designs are possible. The researched options can be found in the appendix. Acoustic calculations showed that point supported spacers would be most beneficial acoustically, because they have the lowest surface area to leak sound through. However, a design without spacers would be even better. This could be possible if the membranes are placed far enough from each other and the forces created by the membrane pulling inwards is held by the frame. The calculation in chapter 7.4 showed however that the forces involved make this impractical. The more spacers are applied, the shorter the distance the membrane needs to span. This does not only lighten the load on the membrane at connection, but also lessens the stress on the frame, because the inwards force will be less.

A combination of the strength of the frame, the strength of the membrane and the applied loads dictated the amount of spacers needed. The final design will use spacers that have a distance between each other from heart to heart of 100 mm. This way the load on the membrane and the frame is within acceptable parameters, but the view through the envelope is severely affected.

The pattern in which the spacers are applied also determines the amount of force on the membrane and the force distribution through the membrane.

The mock-ups in chapter 9.1 researched this in detail and concluded that a hexagonal or triangle pattern, like shown in figure 204 would be the most optimal solution. This pattern even results in 7% less force per spacer.

In an effort to decrease the thermal and acoustical leak caused by the spacers a design where a single spacer never travels continuously through every layer has been applied. The spacers will be clamped between the intermediate layers to be set in the correct pattern. Thermally this doesn't improve the situation much, because twice as much spacers are needed, but acoustically improvement is more significant, because the heavy drop in sound insulation at higher frequencies will be greatly decreased. This also comes at the cost of decreased view through the envelope.

The spacers are made from a glass fibre composite material, This has a very high strength and a relatively low thermal conductivity. They are specifically designed to create only the required surfaces. and be minimal in all other dimensions. Figure 203 shows what is possible. The ends and a part in the middle need to have a large circumference for supporting the membrane in as large an area as possible. Calculations show that this needs to be at least a diameter of 10 mm. The middle of the spacer can be far thinner, because here the size is determined by the buckling force. The small length results in a very low buckling force. Because only the circumference supports the membrane the spacer can also be hollow. All this results in the spacers in figure 205.

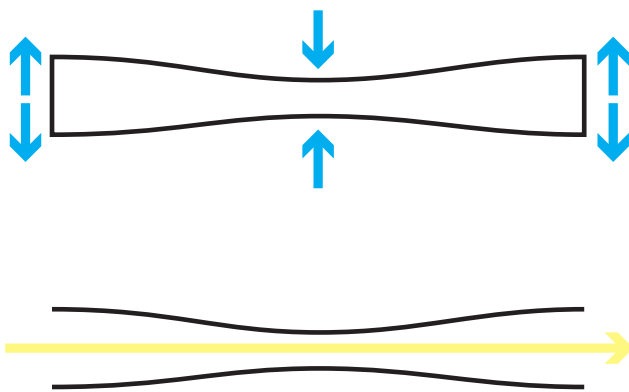


Fig. 203 spacers design conditions

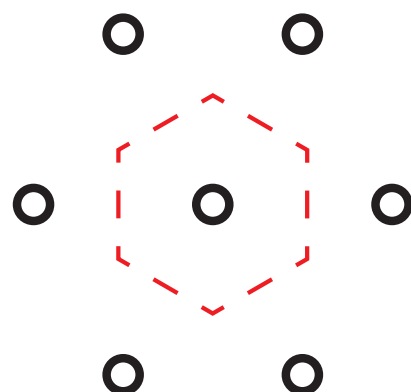


Fig. 204 load area per spacer

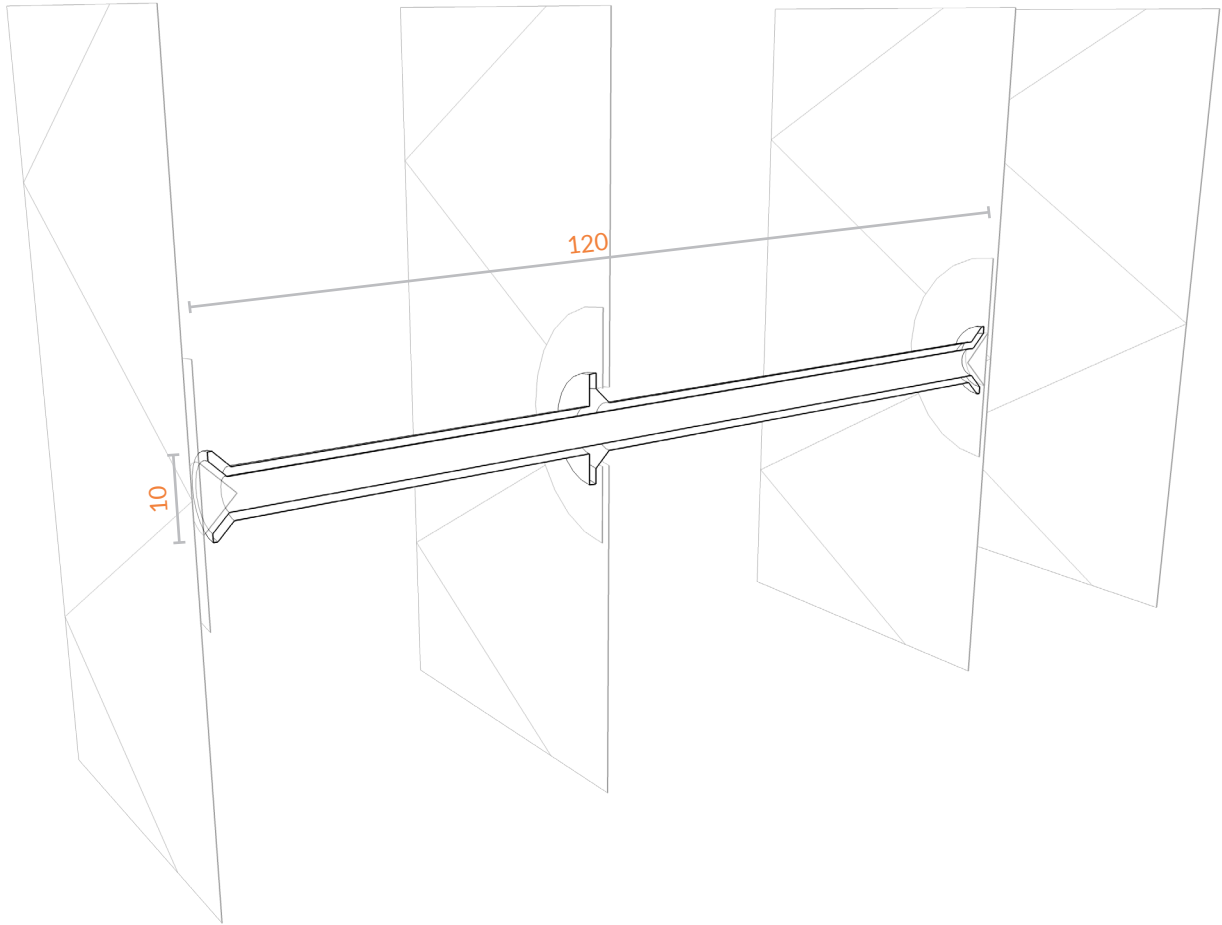


Fig. 205 Spacer detail

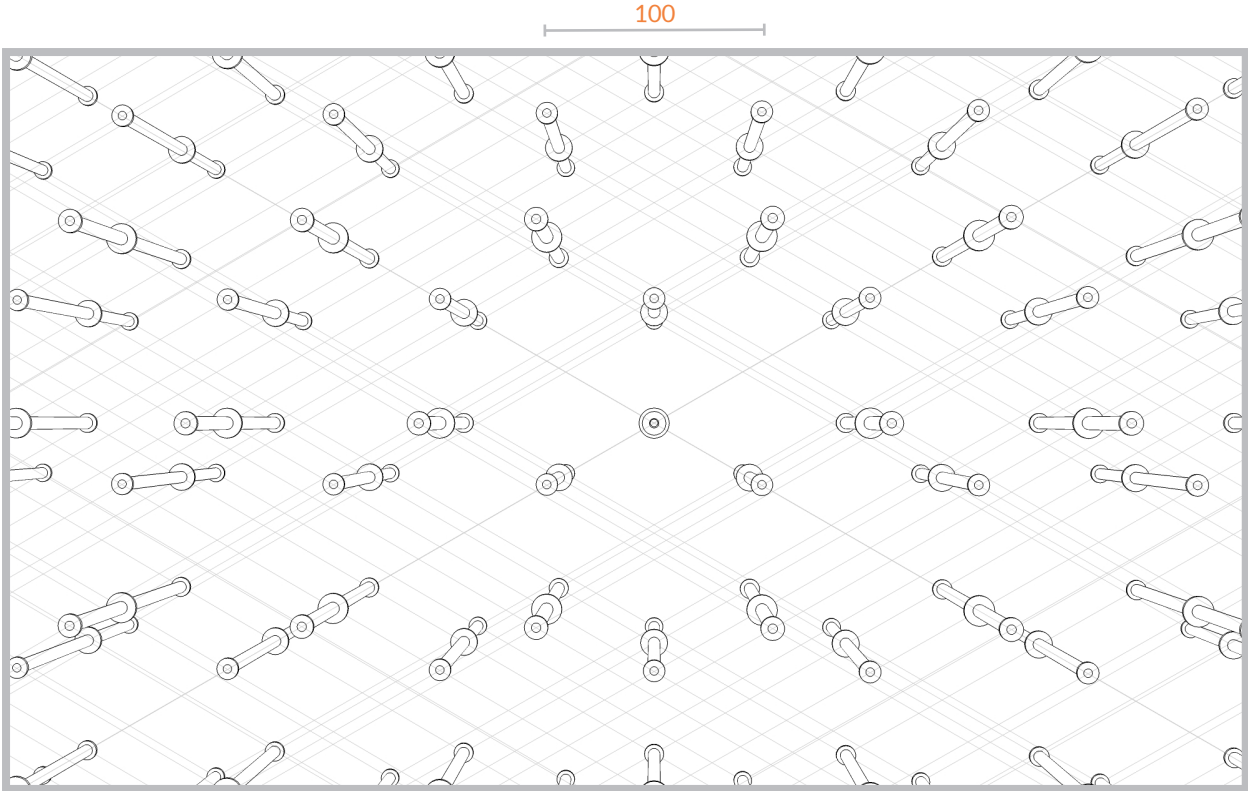


Fig. 206 spacer and reinforcement pattern

10.4 - Sunshading

The unitized membrane envelope will be applied on the Sail at Marina bay in Singapore. The climate in this region is of such an intensity that sun shading is an absolute requirement on a building. Any of the currently available sun shading systems for building applications can be used, but they will just be an addition and will probably not fit on the uncommon shape and will not be suitable in the extreme weather conditions present on a high-rise building in Singapore. Therefore an integrated system has been chosen out of the many available options that were researched through mindmaps. The mindmaps can be found in the appendix.

The sun shading is applied in the cavity closest to the exterior of the building. This is to keep the heat of the sun as far away from the interior as possible. The shading is a pressure based system. A rectangular pocket will be placed inside the cavity. The spacers are very convenient in this situation, because they provide ideal mounting brackets, as indicated with the orange strips in figure 208. The pocket has one side with a reflective coating on it and is transparent on all other sides. Letting in a tiny bit of air in the pocket means that it will have a higher pressure compared to the vacuum it resides in, expand, and present the opaque part to the outside surface and therefore close the façade to sunshine.

Only one liter of air is more than enough for the whole panel, because it is present inside the vacuum. When the shading isn't needed anymore the air can be evacuated by the vacuum pump. The deflated pocket changes shape so the reflective part is horizontal and will reflect extra

light inside. The connection to the spacers rigid sides will ensure proper deflation.

To test the theoretical effectiveness, in practice, a model has been created. The model is made from thin polyethylene plastic that has been folded and glued in a box. One side was painted white to function as the shading part of the design. The box has an aluminium tube for an air supply and was placed and fixed in a wire suspended setup with spacers. The setup isn't the final design, but serves to test the principle. The whole construct was placed in a vacuum bag, similar to the test done in chapter 9.1.

The pictures in figure 209 show the effectiveness of the shading. The first picture clearly has a rectangle of shadow behind it. Light is being blocked or reflected effectively by the shading. Comparatively, the second picture doesn't have the same shadow behind it. The edges of the shading can still be identified, but it is not truly shaded. The light source of the room is very low in this situation, so the horizontal shading in the second picture is almost invisible. With a high light source, they would still function as horizontal louvers.

The model also revealed the exact way a box like this changes shape. Figure 208 shows how the shading changes from one situation to another.

Conveniently, the shading system is a pressure based system that can even work on the same pump as the rest of the panel. The valve control system can be seen in figure 207.

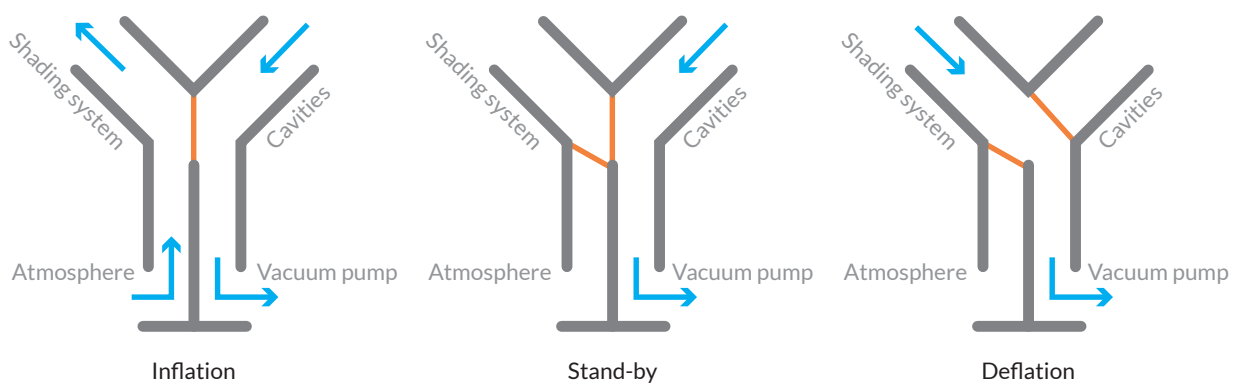


Fig. 207 valve control settings

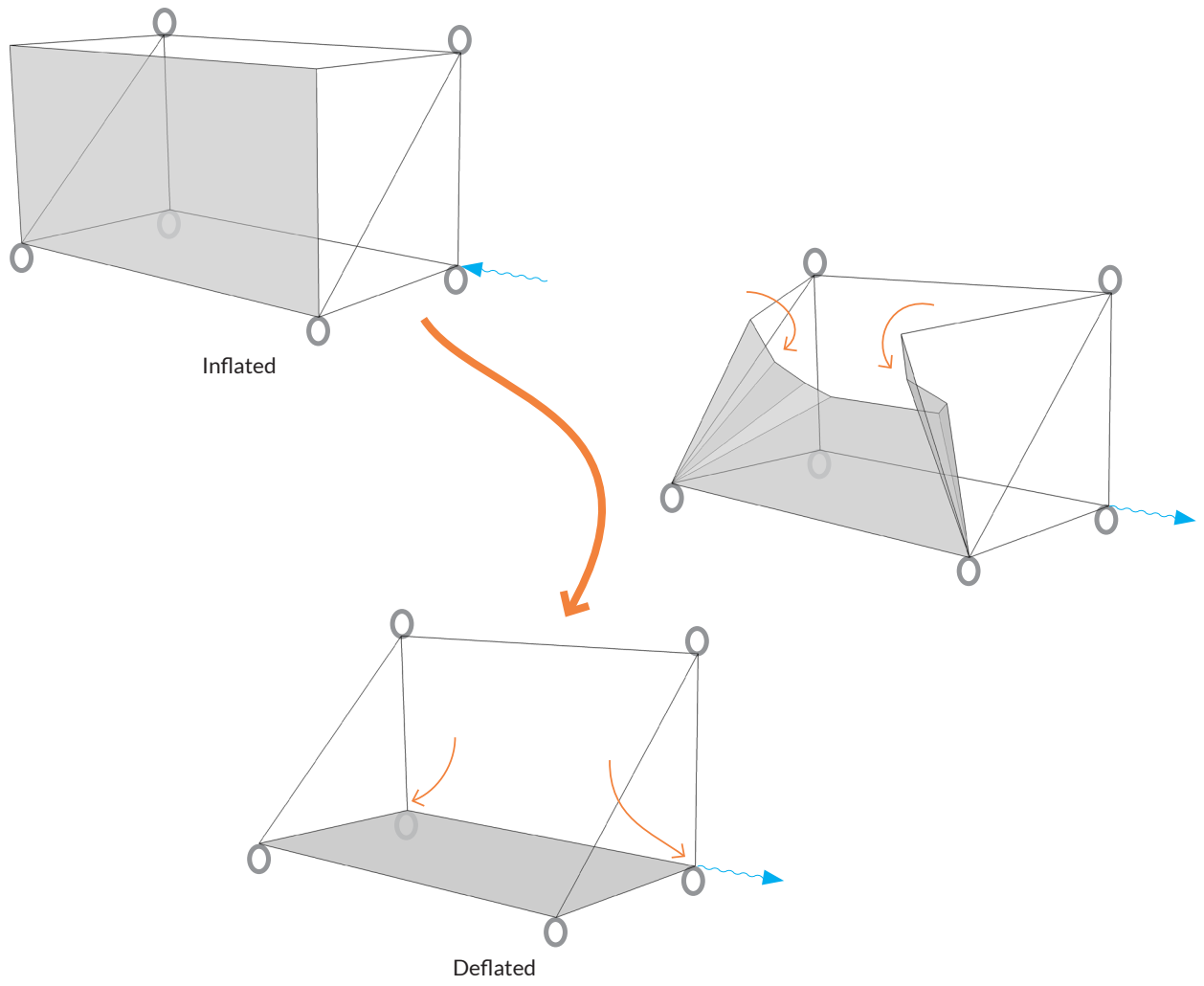


Fig. 208 sun shading



Fig. 209 sun shading

10.5 - Panel

The unitized envelope is made up out of many smaller units. Each unit has a main frame that connects to the building. Within this frame are a number of separate panels clamped in like windows. The division was primarily made to divide the load of the vacuum on the frame and strengthen the frame. It also creates redundancy in the evacuated chambers.

Each panel has its own inner frame in which all the aforementioned parts are contained. The middle layers are clamped inside it and over it the membranes are sealed airtight. The inner frame

is the main structural support against the forces of the vacuum. To strengthen it against the forces and for a smoother membrane flow a hexagonal shape has been designed. It approximates a circle, which is an ideal shape considering pressure vessels. The short ribs can be far thinner and current detailing minimizes the deflection to lower than 8 mm under even the heaviest storms.

The panels are not completely self-sufficient however, because they are connected to a central pump system, contained within the main frame.

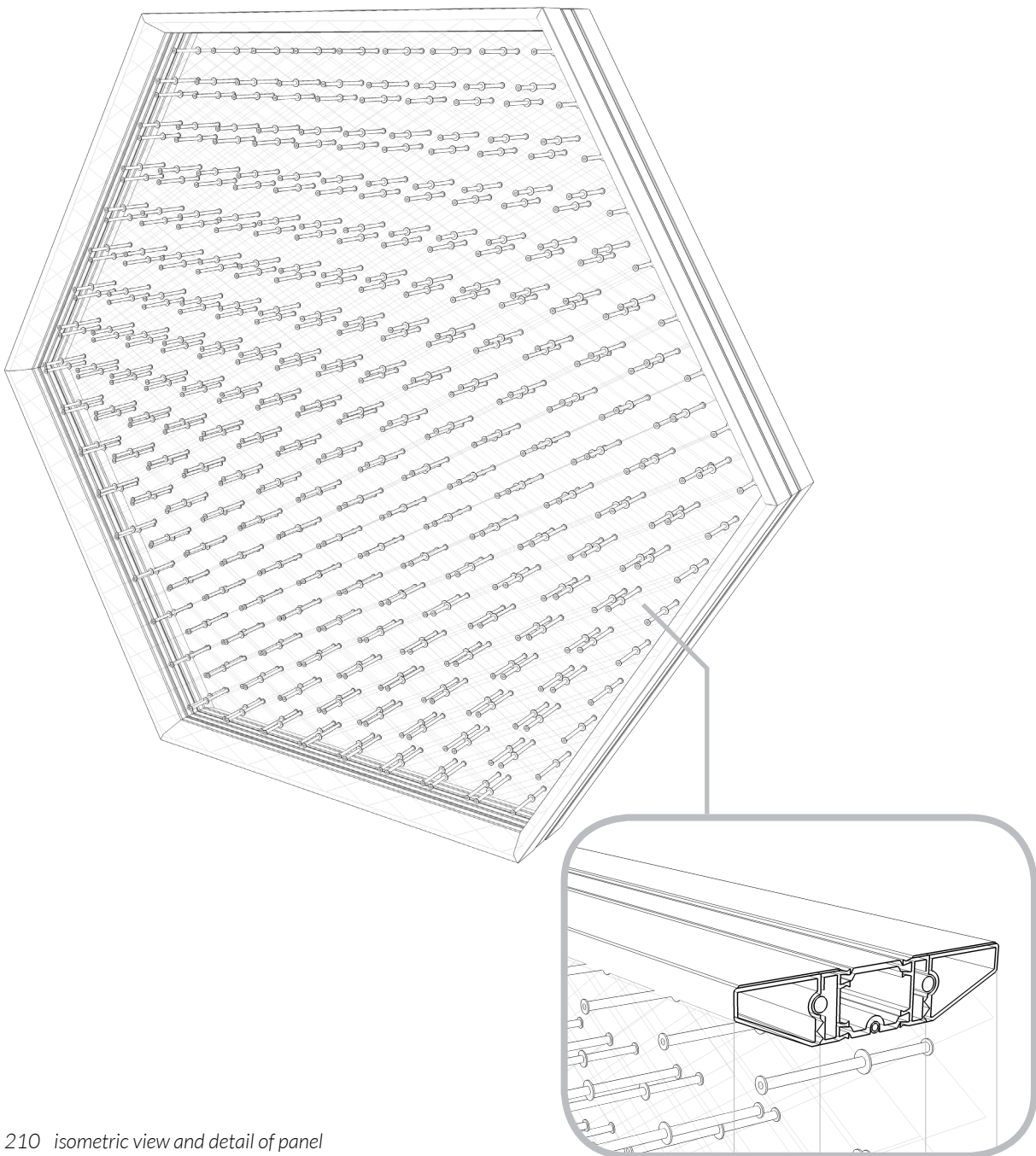


Fig. 210 isometric view and detail of panel

10.6 - Frame

As mentioned in the previous text, the frame holds the individual panels and connects them to the building. The hexagonal shape is continued in this frame by placing two vertical rows next to each other on one frame, but it cuts off to a straight line at floor height for connection and freedom of movement.

Because each panel already has a heavy inner frame the main frame can be a bit lighter. The detailing shows that the depth that is needed for the system is used to its full effect to lend strength to the frame.

All this material does make for a heavy frame. To alleviate this a little bit, and to improve thermal properties, the frame is made from glass fibre

reinforced polymers. This material is far lighter than steel or aluminium resulting in a frame that is only half the weight with negligible loss in strength.

Thermal breaks are also applied in the frame even though this is uncommon in plastic frames. However, the full depth of the frame isn't needed for strength so the slight improvement in thermal performance the thermal breaks do give are always helpful.

The frame pieces are extruded and will therefore be straight pieces. To create the required shape, special corner pieces will be bolted together and glued inside the corners. This will create an invisible moment fixed connection.

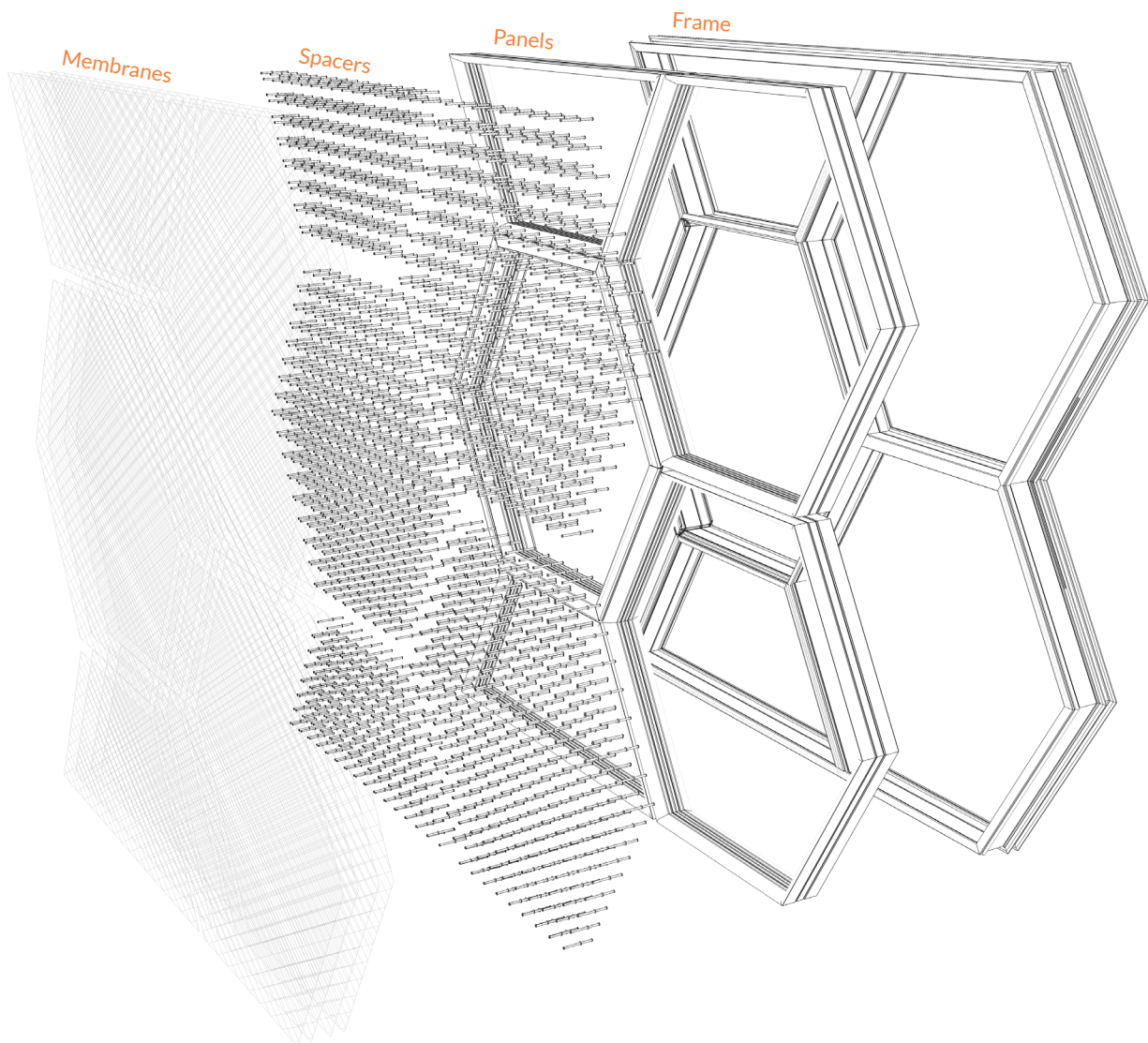


Fig. 211 exploded view of unit parts

10.7 - Additional design aspects

Window

The façade currently on the Sail at marina bay has windows in it. Occupants will have a drastically higher comfort level because of this. Especially considering the hot and humid environment. Therefore, a window has been one of the façade requirements from the start.

In the unitized membrane envelope each unit has a window in it. It is placed exactly in the middle of the height of the panel and is one full hexagon in size. The window operates like a pivot window with a vertical pivot axle in the middle. For safety reasons the pivot is limited to a maximum turning point of 24°. This amount keeps the maximum opening of the window below 125mm, which is the minimal size needed for a small child to fall out. The limit also slightly lessens the damage that can be caused by high wind forces. Removing the window entirely would prevent all damage, but you could expect the windows to be closed during a storm. So it would be unnecessary to make such a precautions.

The panel contained within the frame is a smaller version of the other, but continues the exact same

pattern in its spacers. A flexible tube inside the pivot point connects the evacuation pump to the panel.

Air evacuation system

In an ideally closed system with an impenetrable surface, no air would ever escape. However, leaks will probably occur and even the membrane is porous enough to leak around 100 litres of air each day if heavy storm winds push on it, which was calculated in chapter 8.6. Therefore each unit will have a vacuum pump that keeps the pressure constant

Each panel will be evacuated by a unit centralized pump. The pump will be a mini vacuum pump of 38 x 60 x 87 mm with a 12W power requirement. A pump like this can suck up to 12-15 litre of air per minute, which is more than enough. The pump is small enough to be placed in the frame of the panel and will evacuate air from the panel directly to the outside.

In this situation the pump needs to run for eight minutes in a worst case scenario. Ideally the pump should run a few seconds every hour, but

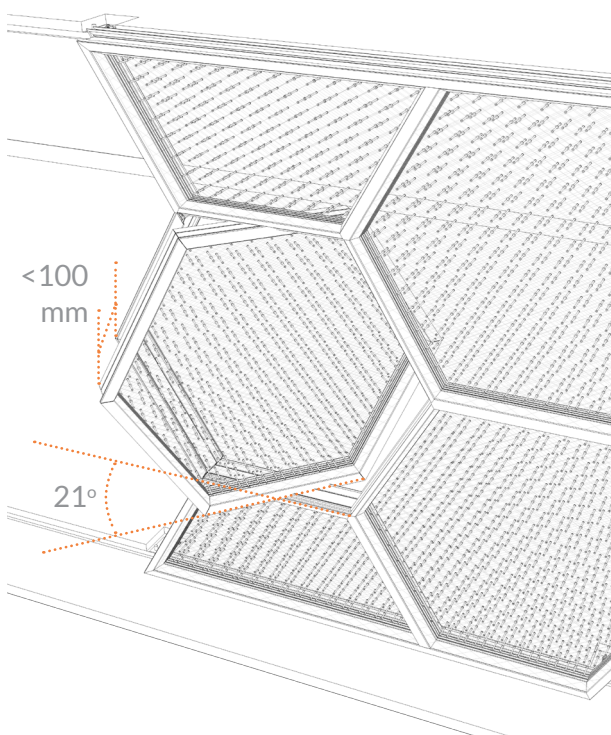


Fig. 212 window placement in unitized facade

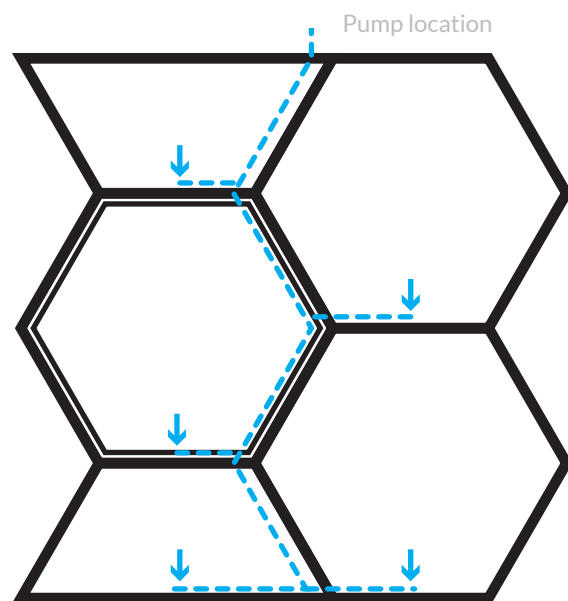


Fig. 213 Air evacuation pipes and pump location

the sound of the active pump can be annoying in the evening. If the pump won't run in the evening the pressure will rise to 0.17 Bar overnight. This is not extremely bad, but unwanted nonetheless

The required power for this is so low, and the amount of sun in Singapore so high, that a thinfilm photovoltaic cell of only 10 cm² is needed to power it for a whole day. The energy does need to be stored in batteries however and the PV cells do not work as effectively on the north façade, but extra solar cells fixed to the frames of the other facades can make up the difference. Extra energy needed for sensors and control systems are negligible.

Fire

In case of fire the thin membrane doesn't offer much protection at all. The membrane won't drip or cause any harm, but fire transfer from lower apartments is a hazard. The spacers will stay in place for a little while because of the glass fibres.

To protect against fire transfer one of the membranes in the parapet will be replaced by polyethylene terephthalate, also known as Mylar,

instead of ETFE. The Mylar has a far higher heat resistance and will not melt through. It is also a bit stronger than ETFE so the parapet will provide extra protection for falling occupants. However, Mylar is translucent so will not provide the same transparency and will change the view from outside.

Weight

One of the advantages of a membrane envelope is its low weight. The unitized membrane envelope is a bit heavier than common membrane envelopes however, because it needs a heavier frame. Common unitized facades are around 200 Kg for a panel of 1500 x 3200 mm. The unitized membrane envelope is 203 Kg, but has a size of 3200 x 3150. So this is twice as light per square meter. This is still a sufficient improvement.

If more transparency is wished for, the window can be replaced by a glass window. This does increase the weight significantly. The window frame weighs 33 Kg. A Glass window of similar size will weigh 65 Kg. The advantages and disadvantages should be weighed carefully in this situation.

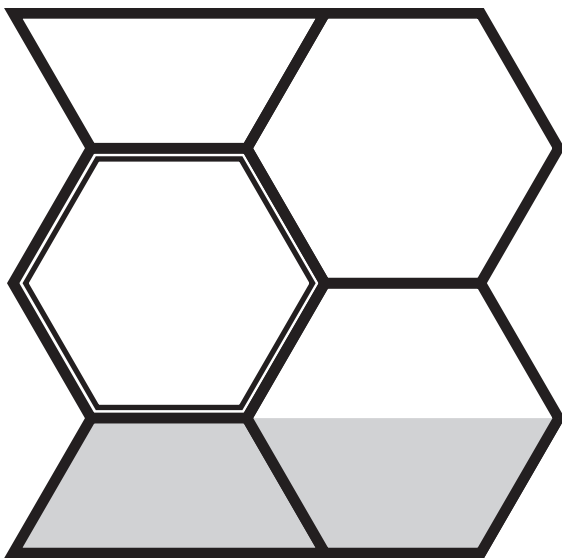


Fig. 214 Mylar parapet

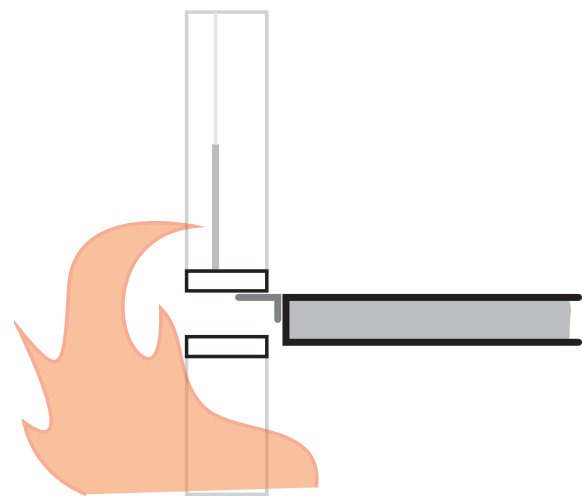
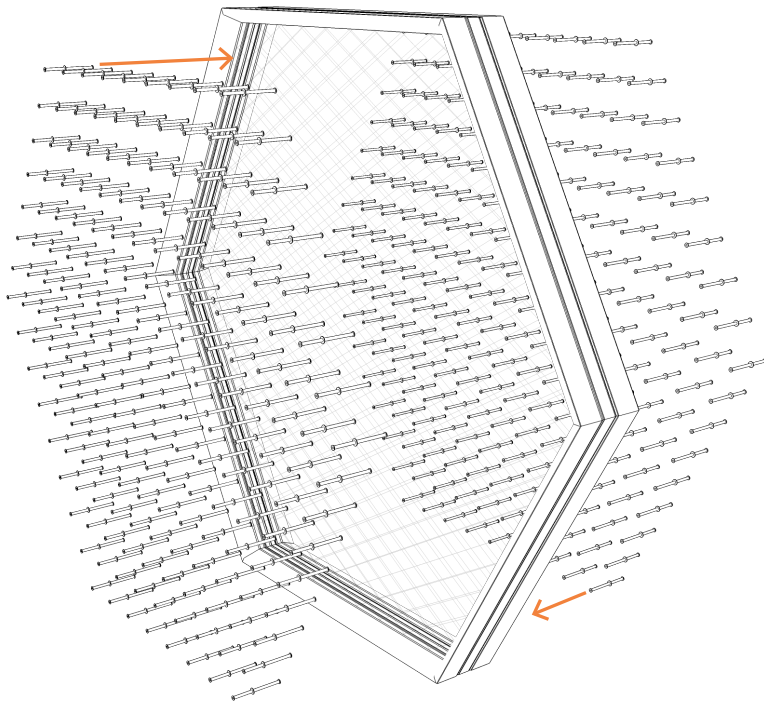
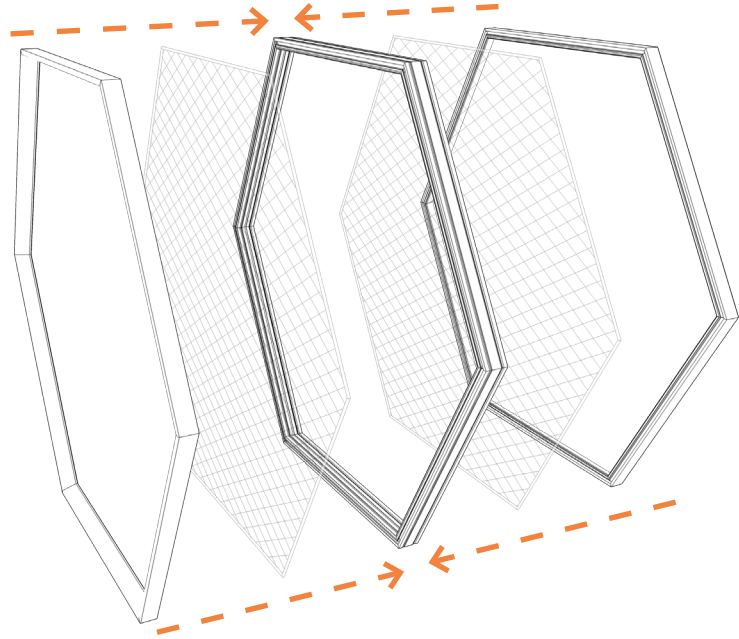


Fig. 215 vertical fire transfer between apartments

10.8 - Build order

Step 1

The two membranes in the middle are spanned and pre-stressed inbetween in the inner frame. The membranes have glass fibre reinforcement added beforehand and holes cut into them. The inner frame is in three parts and has keder rails to facilitate a proper connection. The screws connecting the pieces can be screwed through holes in the side of the frame. Afterwards the holes can be sealed with a lid, this isn't necessary for the view, because they will be covered, but will prevent the membrane from cutting apart on the edge.

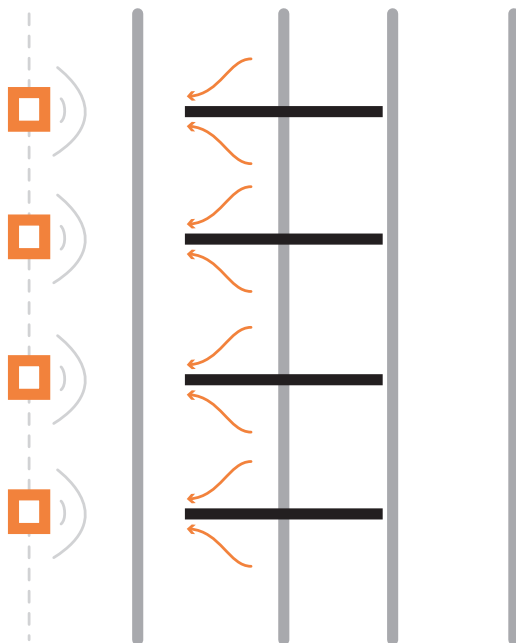
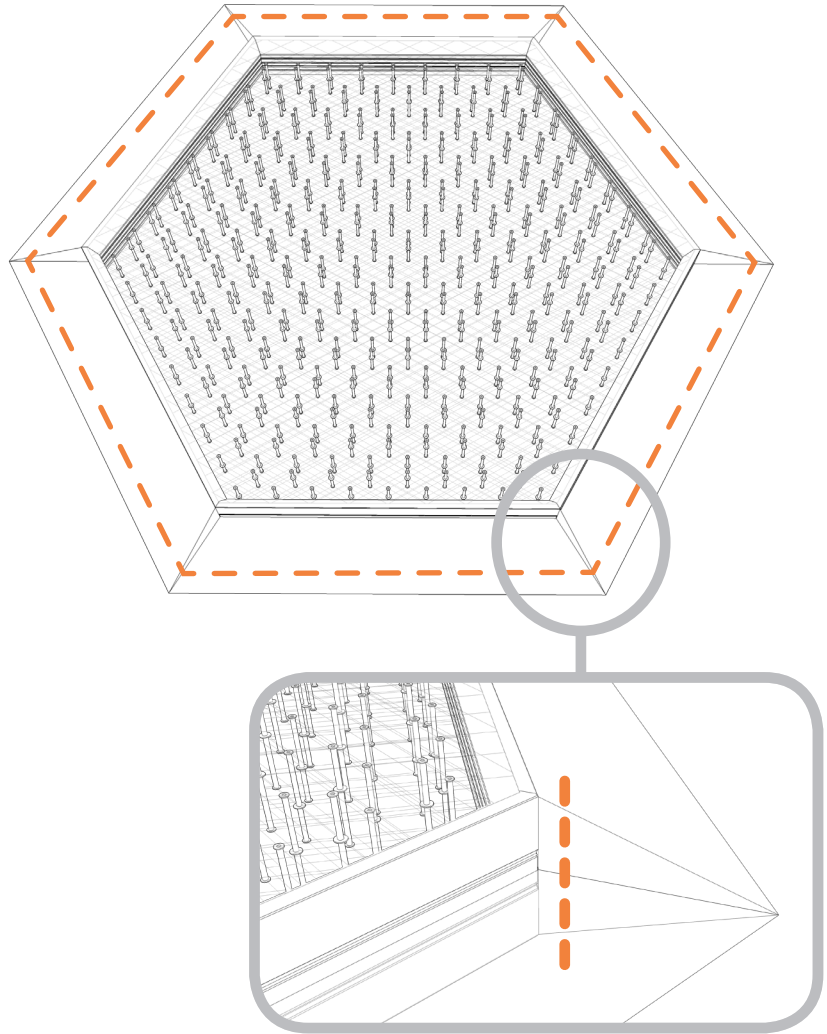


Step 2

Secondly, the spacers are inserted in the holes in the membranes. They will stay at roughly the right place, but the panel needs to stand up straight to prevent one side of falling out.

Step 3

The outer membrane will have glass fibre and ETFE reinforcement fixed on it before placing it over the inner frame. Both sides will be heat welded to each other by pressure and heat. The combination will result in a better more flexible weld that is not as heavily deteriorated by too much heat. The weld will be continuous around the whole circumference. Afterwards the irregular corners are folded together and welded again to create the required hexagonal shape. It doesn't matter that this method isn't pre-stressed, because the pressure will do that and the extra material will create dimples in the surface. The curved shape is necessary to create less tension in the membrane.

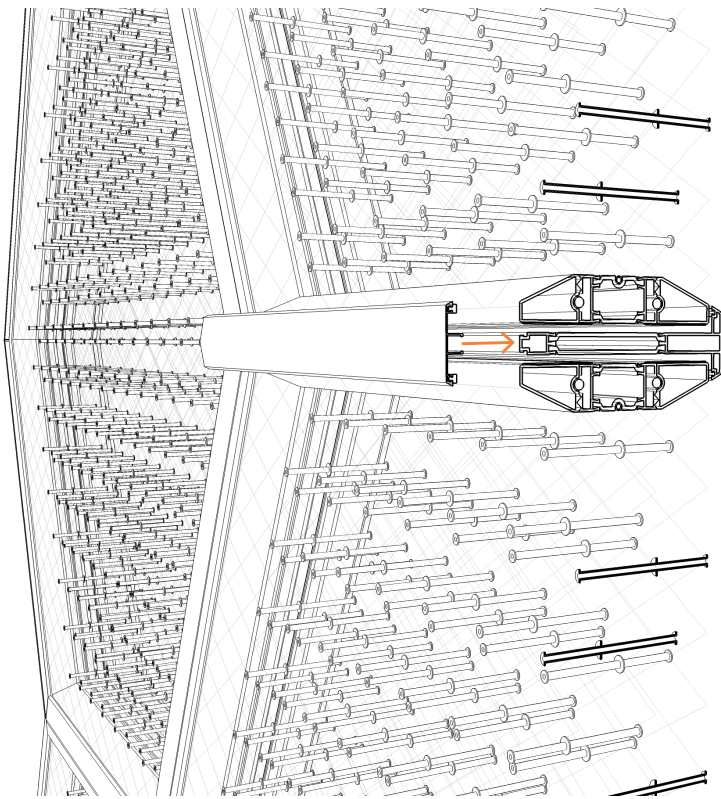
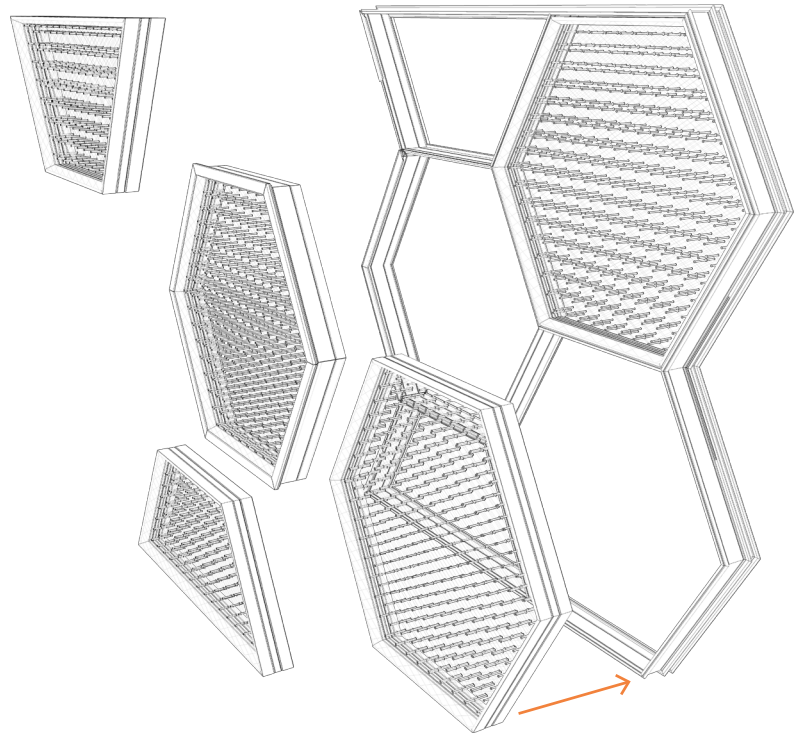


Step 4

Magnets are used in the required pattern to get the spacers in exactly where they are needed without being able to reach them. When the required pattern is achieved a slight under pressure will secure them in place.

Step 5

Brackets in the main frame will be set to place the panels on. Afterwards all the panels are placed inside the main frame.

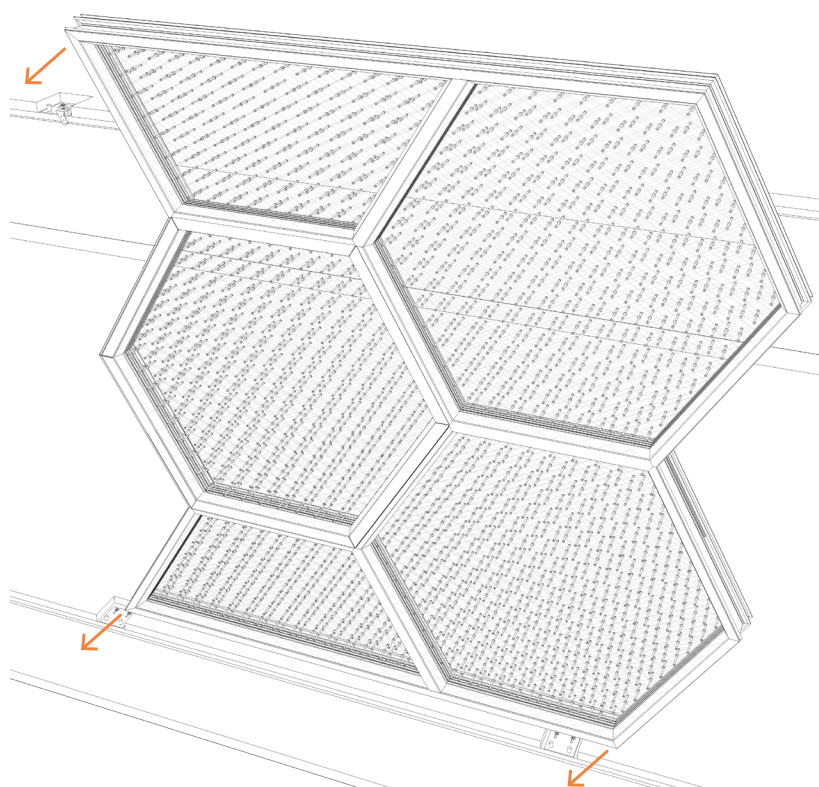
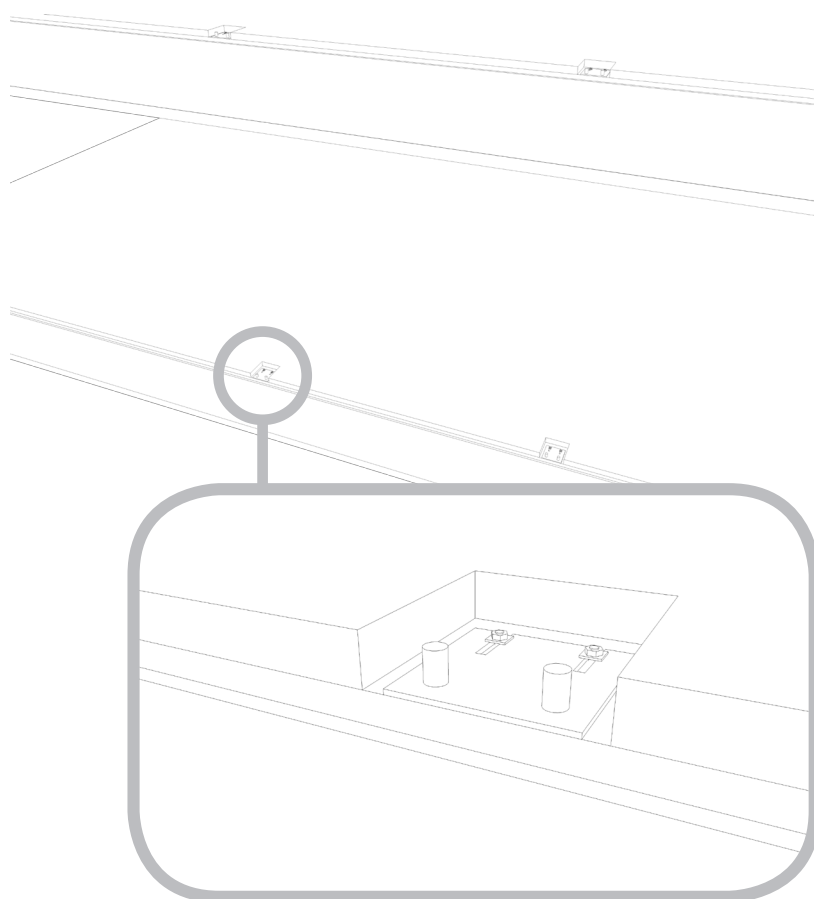


Step 6

A clamp seal will be clicked on the frame from the outside to fix the panels in their final position. This concludes the assembly phase in the factory. Afterwards final assembly will take place on site.

Step 7

The following step will take place on site. There the supports need to be fixed and set to receive the façade units. Soft insulation will also be placed in front of the beam and floor



Step 8

The final step is to place the panel in a diagonal manner on the supports and set the screws so the panel is fixed on the perfect place.

10.9 - The south-east facade

The Sail at Marina Bay has a very distinct shape, because the south-east façade of the building is slightly curved and the South-West corner of this façade is curved in vertical direction as well. The original façade achieves this curve along the profile of the building by cutting the glass of the façade in the specific shaped needed for the application. However, this isn't possible when applying the unitized membrane envelope. The spacers in the façade need to be in a specific pattern to be able to carry the vacuum. The hexagonal shapes need be kept in the façade.

Therefore, the curve seen in the profile will be replaced by a pixelated look. The hexagons will be stacked and create a curve step by step. This results in the new profile of the building that is shown in figure 215.

Around the corner of this building the façade continues for only a few meters before creating the back of the building. This part of the façade, connecting the front and the back of the building, will be made from straight pieces that follow the pixelated edge. This results in an angular and serrated façade, but creates the best shape to connect the two façades, without compromising the functionality of the unitized membrane envelope.

Another key part of the façade is where the apartments are separated from each other. Here the division wall needs to connect to the façade and create a soundproof seal. The Sail at Marina Bay has very thick columns where this is possible. As can be seen in figure 217. When the façade end is exactly in front of the column it fits along the whole side of the panel. The seal can then easily be made against the frame without pushing against the membrane.

At this building the façade coincidentally fit exactly between the columns, within the tolerances of the connection seals. However, this will not always be the case. The shape freedom of the system does allow for one or more rows of spacers to be removed in a façade. As long as the six corners are kept. Because of this, the designer can play with the size of the panel and make it fit.

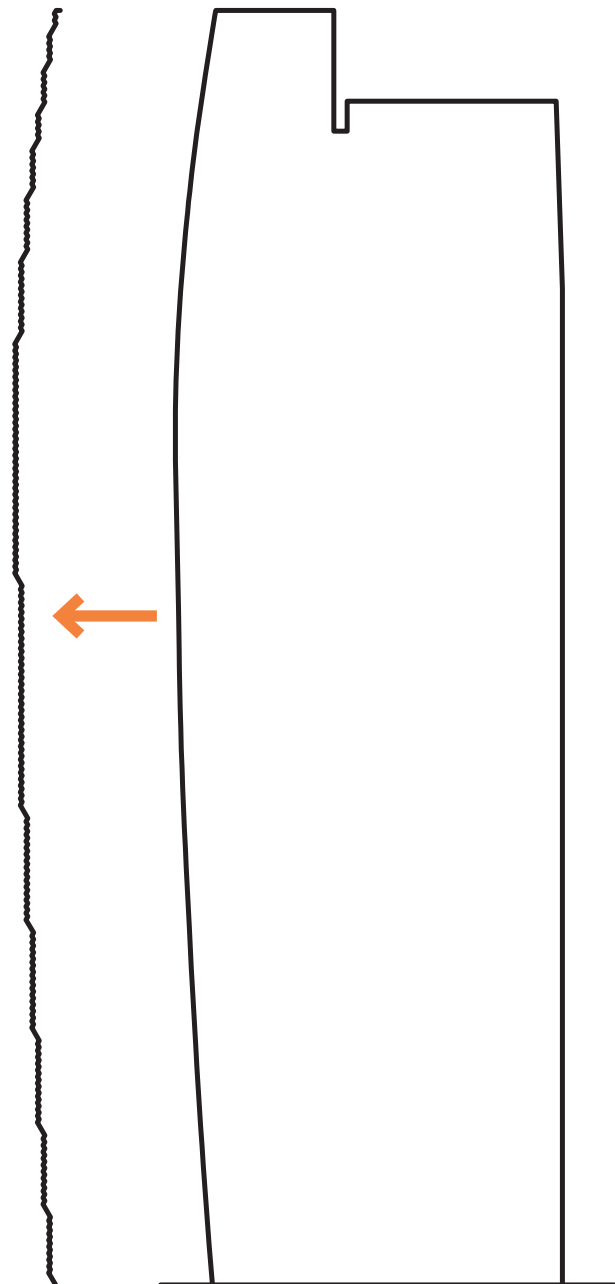


Fig. 215 building edge shape

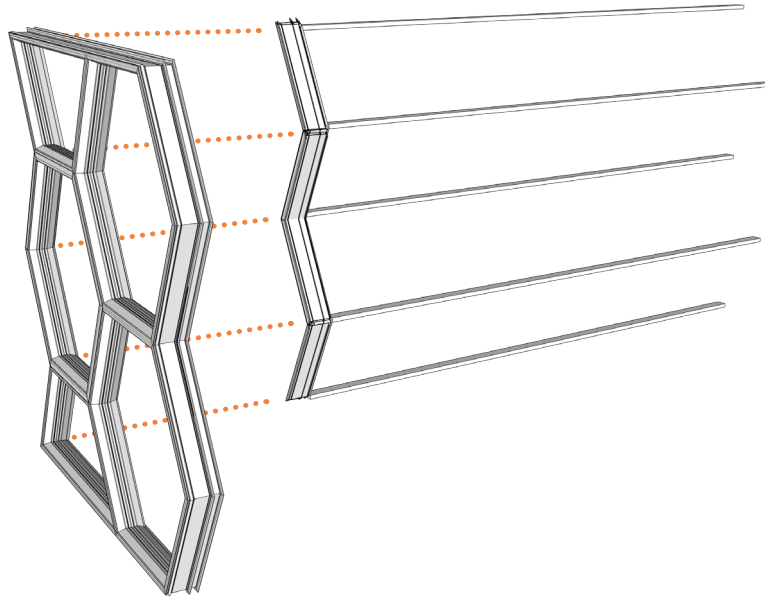


Fig. 216 building corner

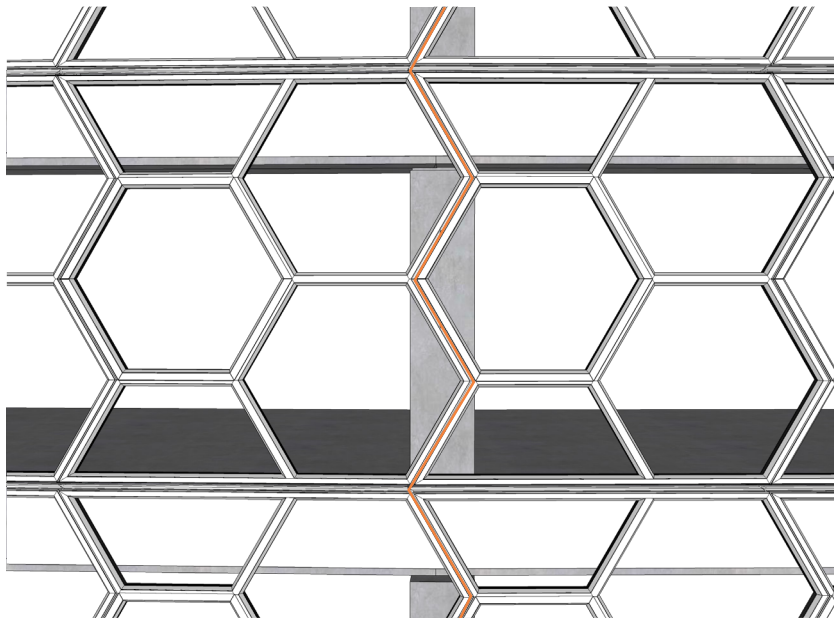


Fig. 217 apartment division wall

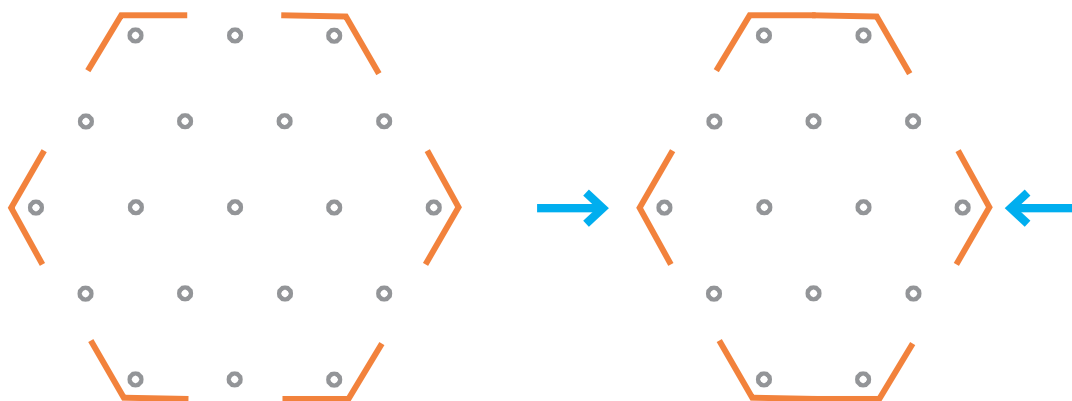
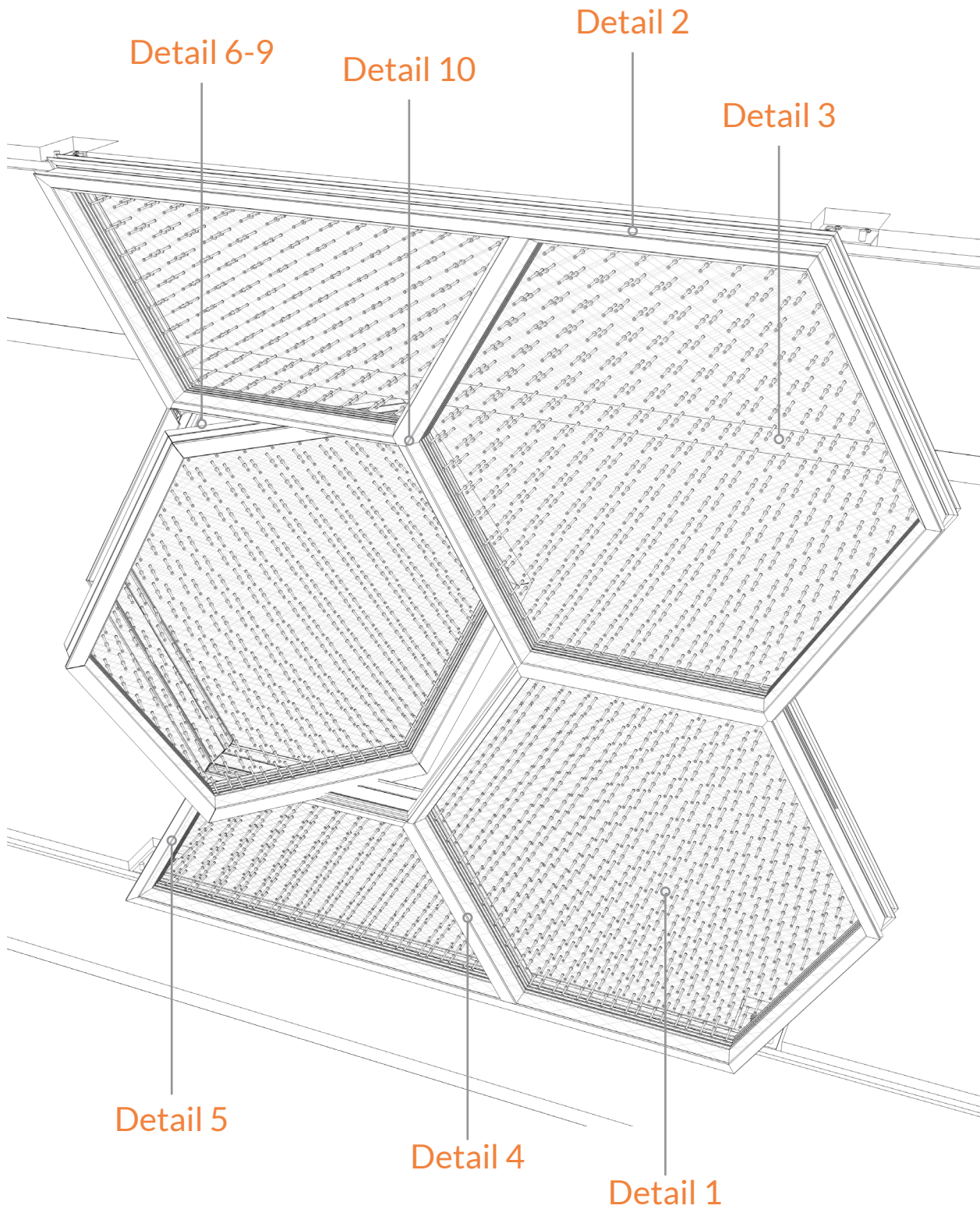


Fig. 218 facade pattern shape freedom

10.10 - Construction details

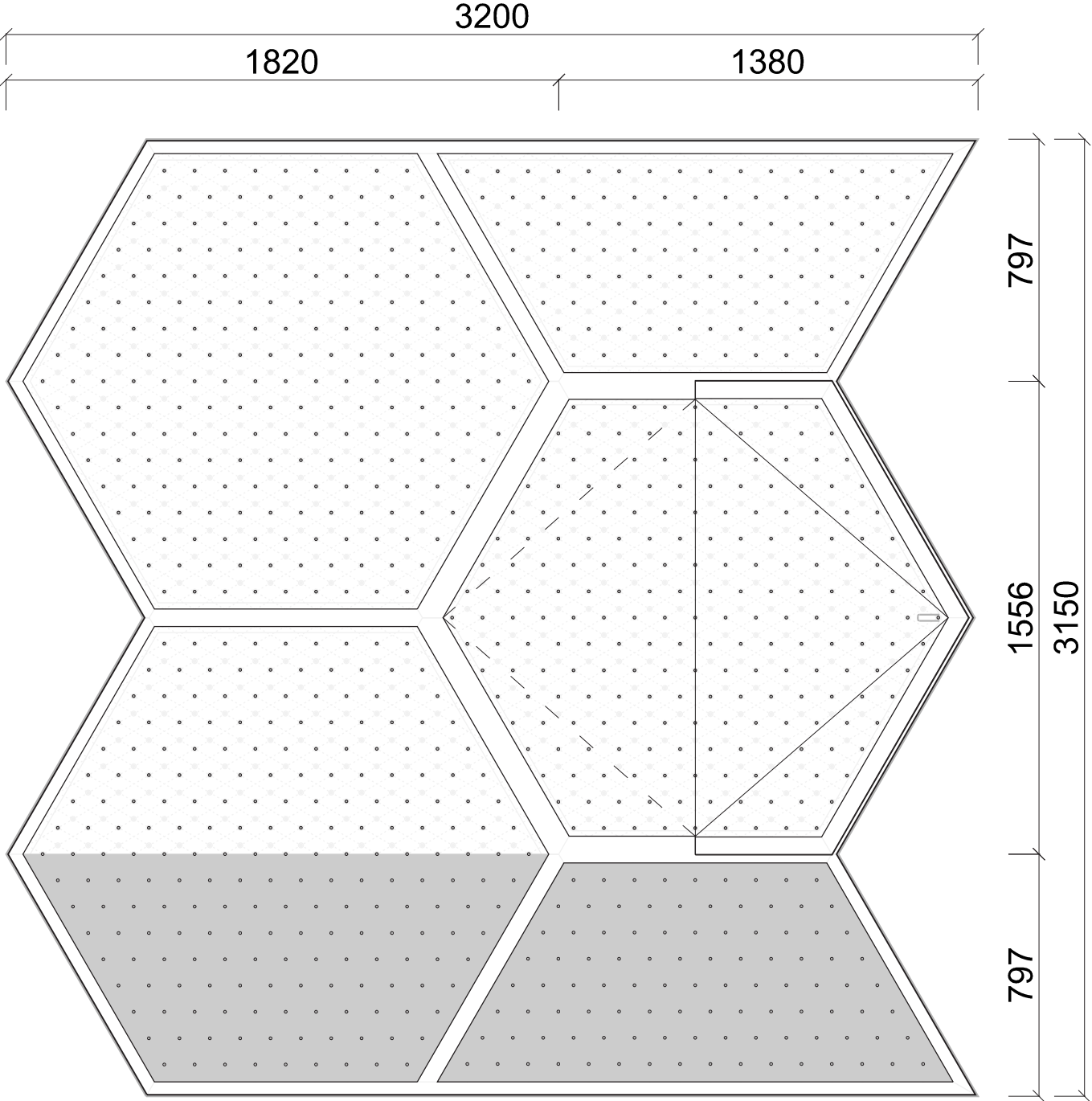
The following pages contain technical drawings of the unitized membrane envelope.

The drawings shown are facade views, sections and the details indicated below



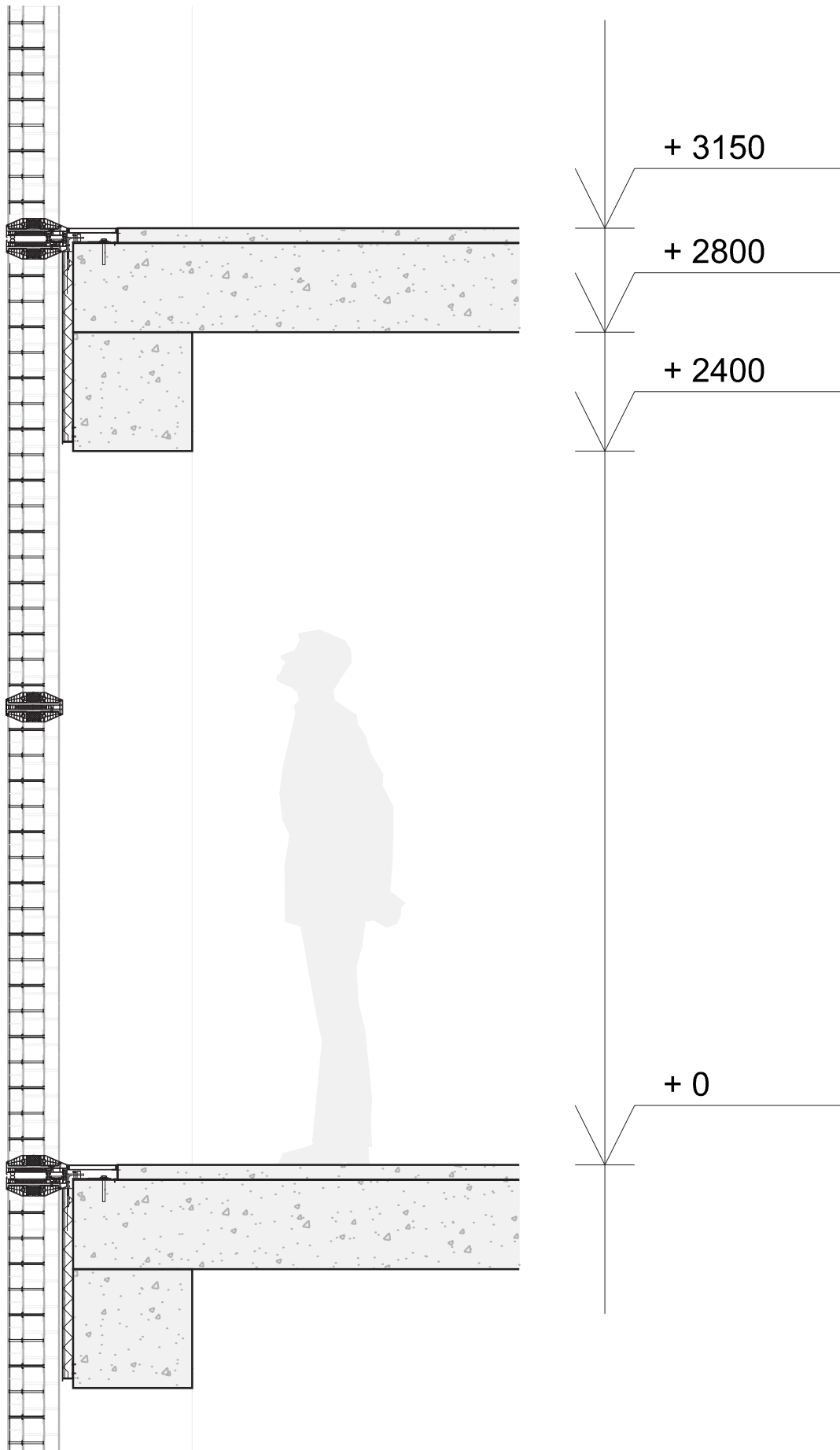
Front view

1:20



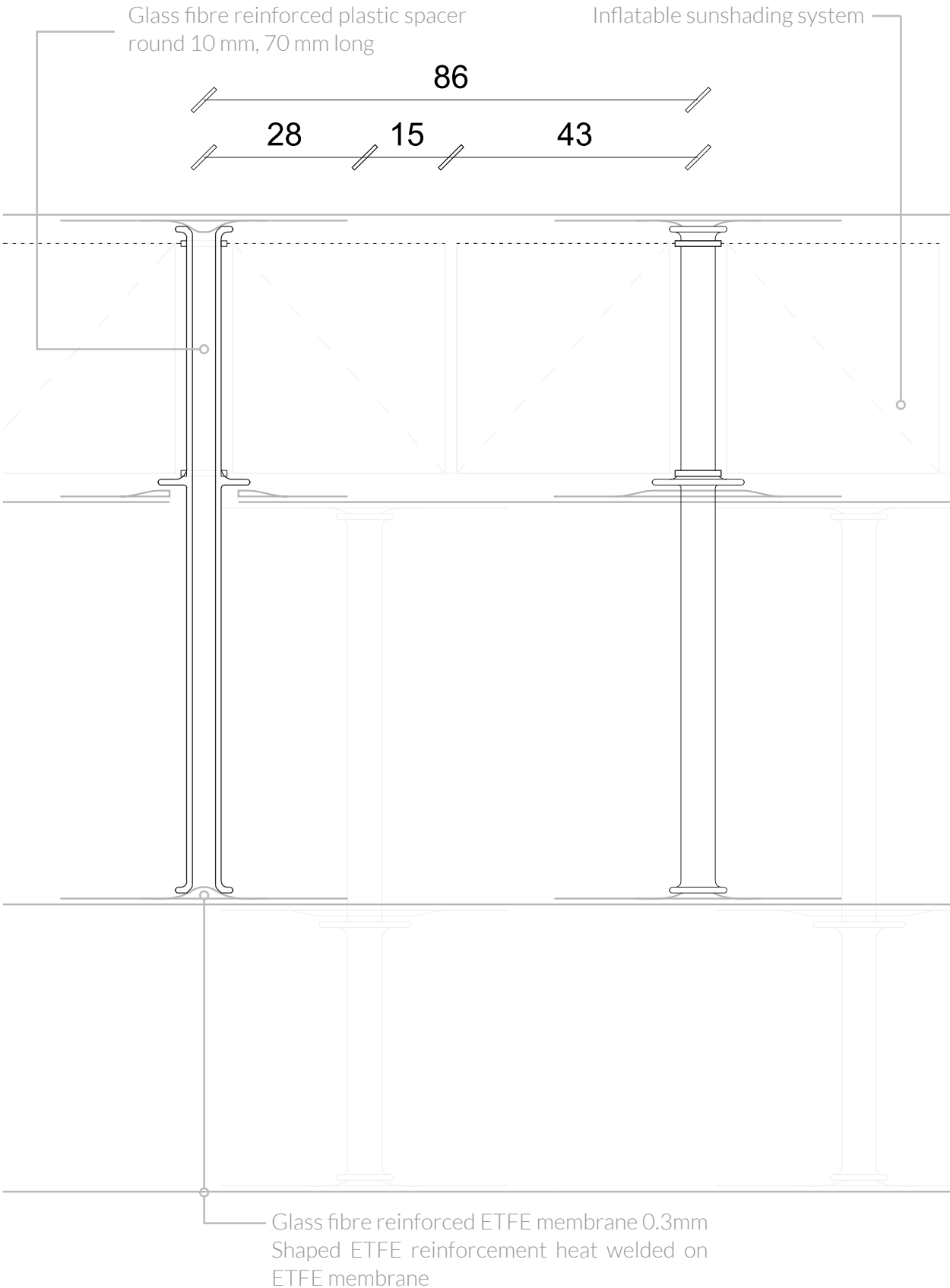
Section

1:20



Detail 1

Membranes and spacers - vertical - 1:1



Detail 2

Unit to floor connection - vertical - 1:2

- A Glass fibre reinforced plastic window frame 170x36 mm
Insulated thermal break 46x35 mm
Keder clamp
Perforation for air evacuation
Pneumatic sun shading air tube
Anti-slip rubber strip

- B Glass fibre reinforced plastic unit frame 205x43 mm
Insulated thermal break 102x16 mm
Ribbed vacuum tube
Weather and window clamp seal
Window seal
Glass fibre reinforced plastic window clamp click profile

- C Expanding gasket
Sliding air gasket

- D Glass fibre reinforced plastic spacer round 10 mm, 70 mm long

- E Glass fibre reinforced ETFE membrane 0.3mm
Shaped ETFE reinforcement heat welded on ETFE membrane

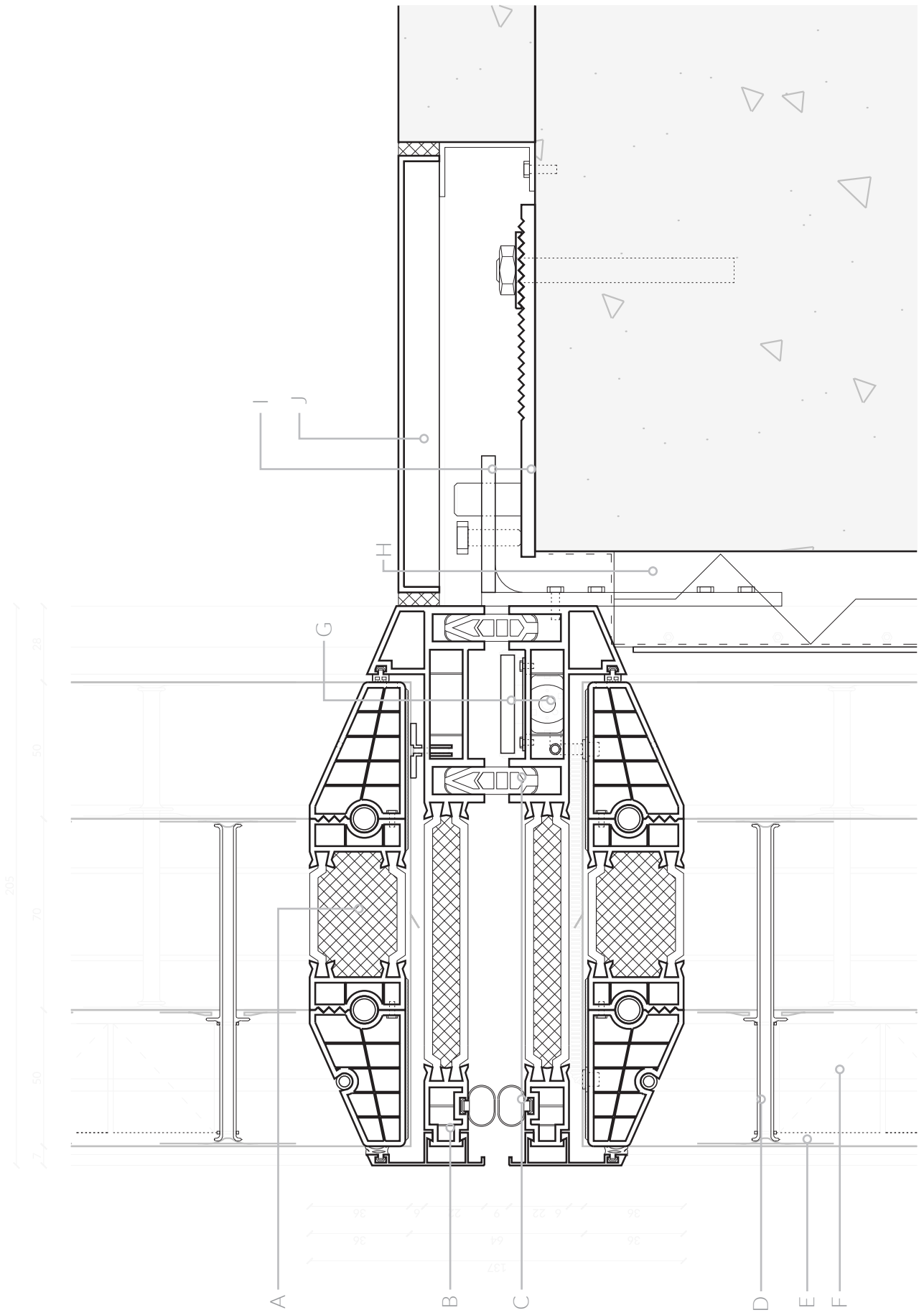
- F Inflatable sunshading system

- G Adjustable foot for setting window frame
Hoist plate on hinge folded in, bolted to frame
Vacuum pump 12V 20x12x80 mm
Ribbed vacuum tube

- H Mineral wool insulation
Glass fibre reinforced plastic plate bolted to frame

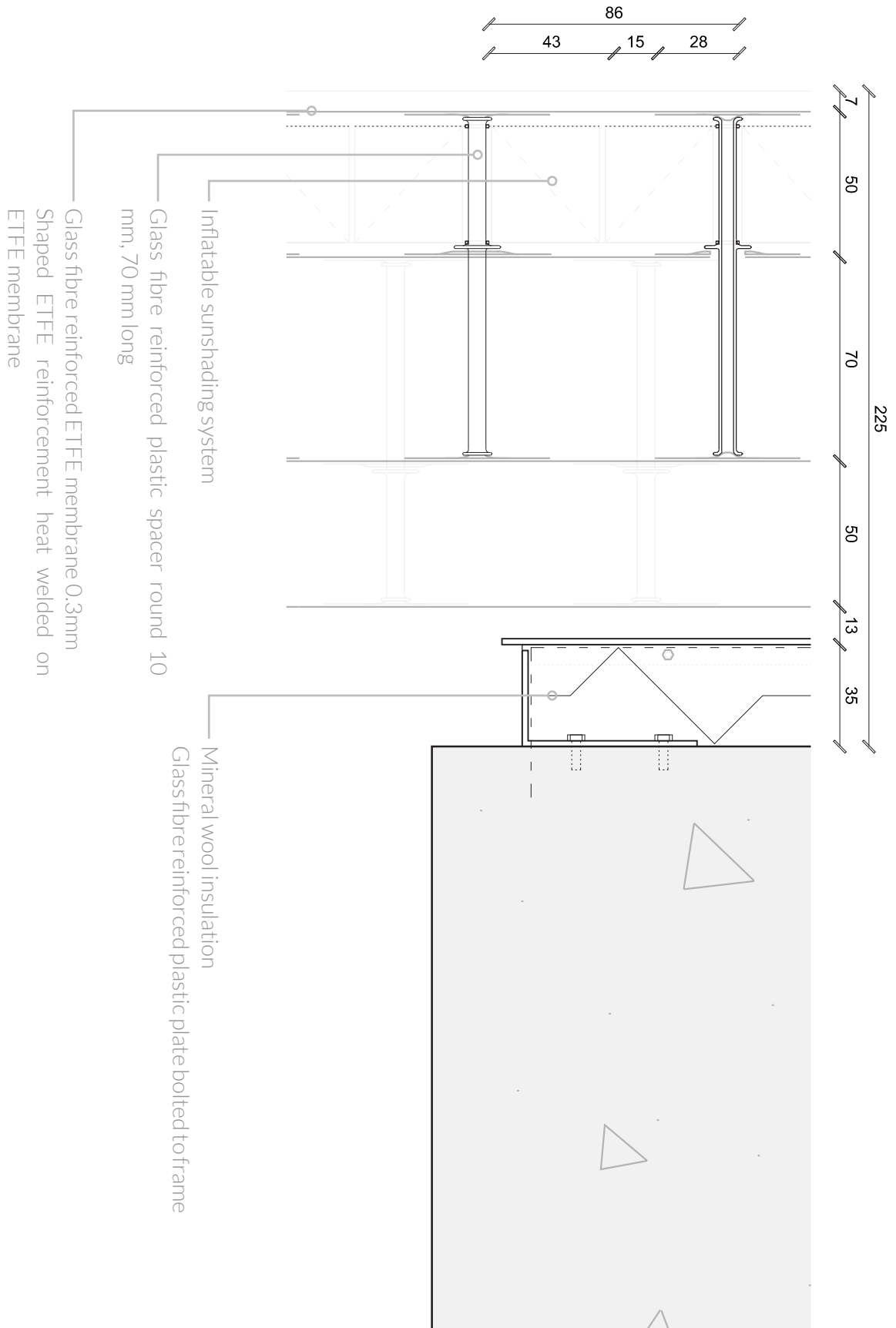
- I Steel support profile with setting bolt, bolted to side of frame
Support plate with setting pin

- J Aluminium covering plate, sealed at edges



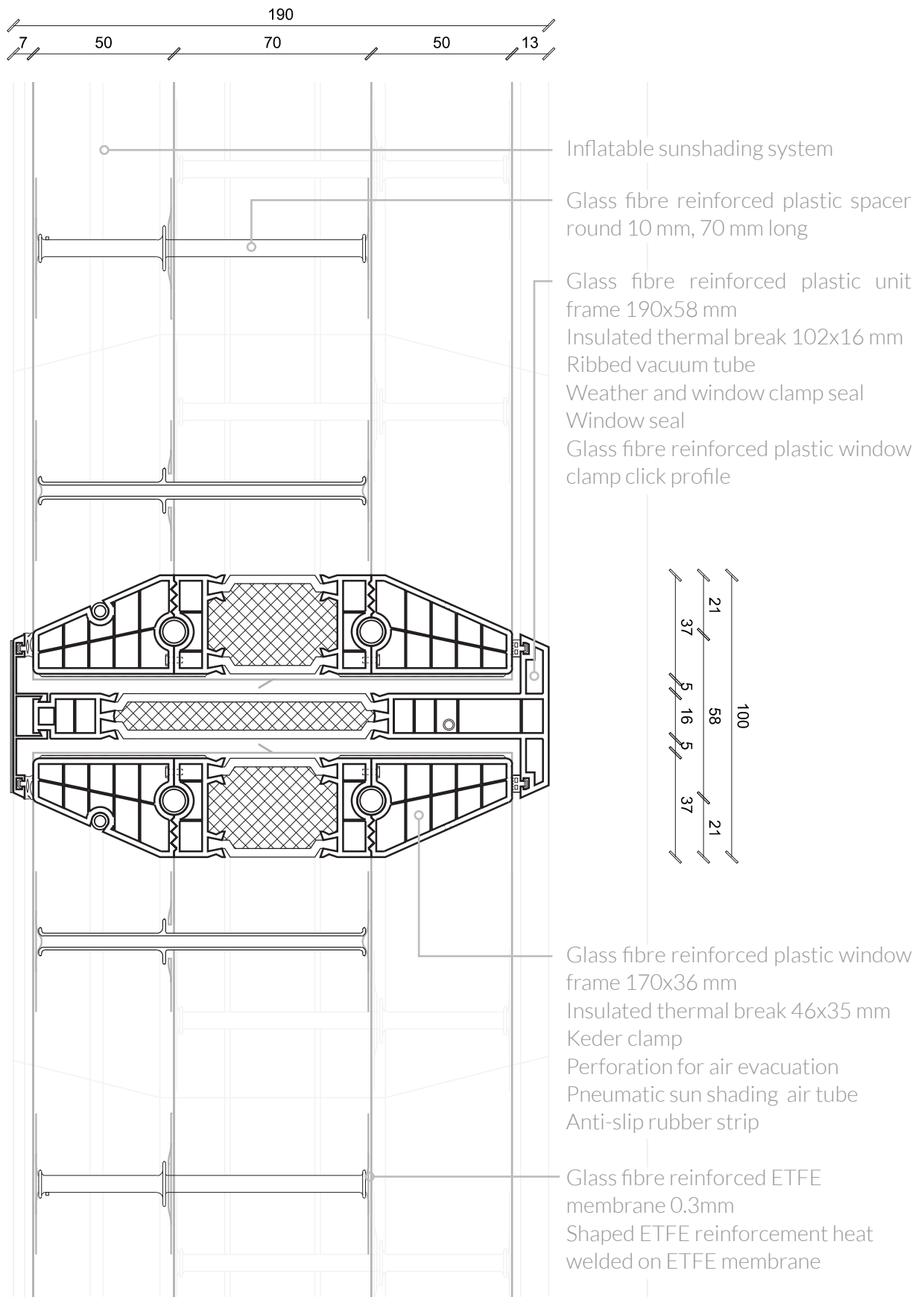
Detail 3

Unit in front of column - vertical - 1:2



Detail 4

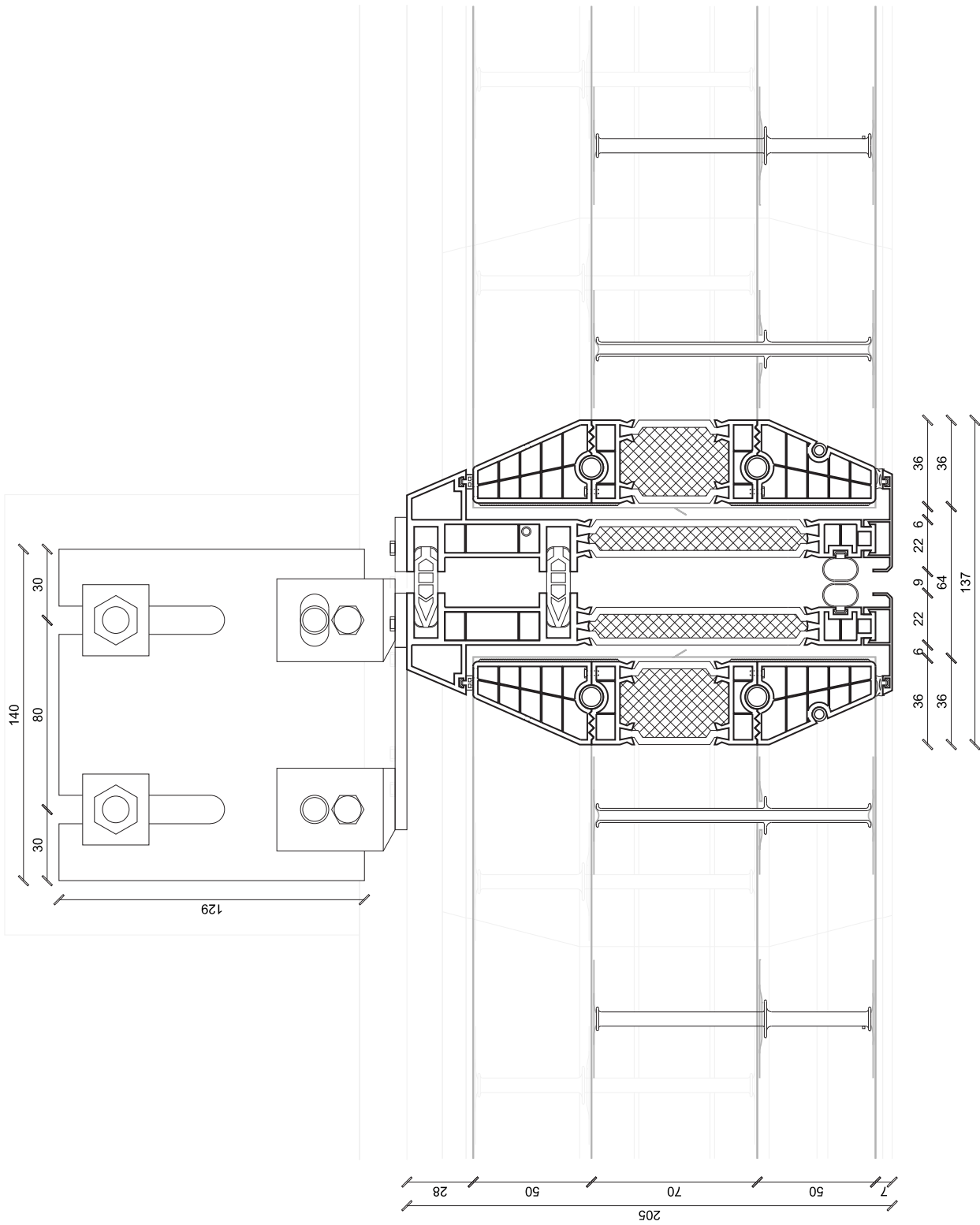
Panel connection to main frame - horizontal - 1:2



Detail 5

Unit connection - horizontal - >1:2

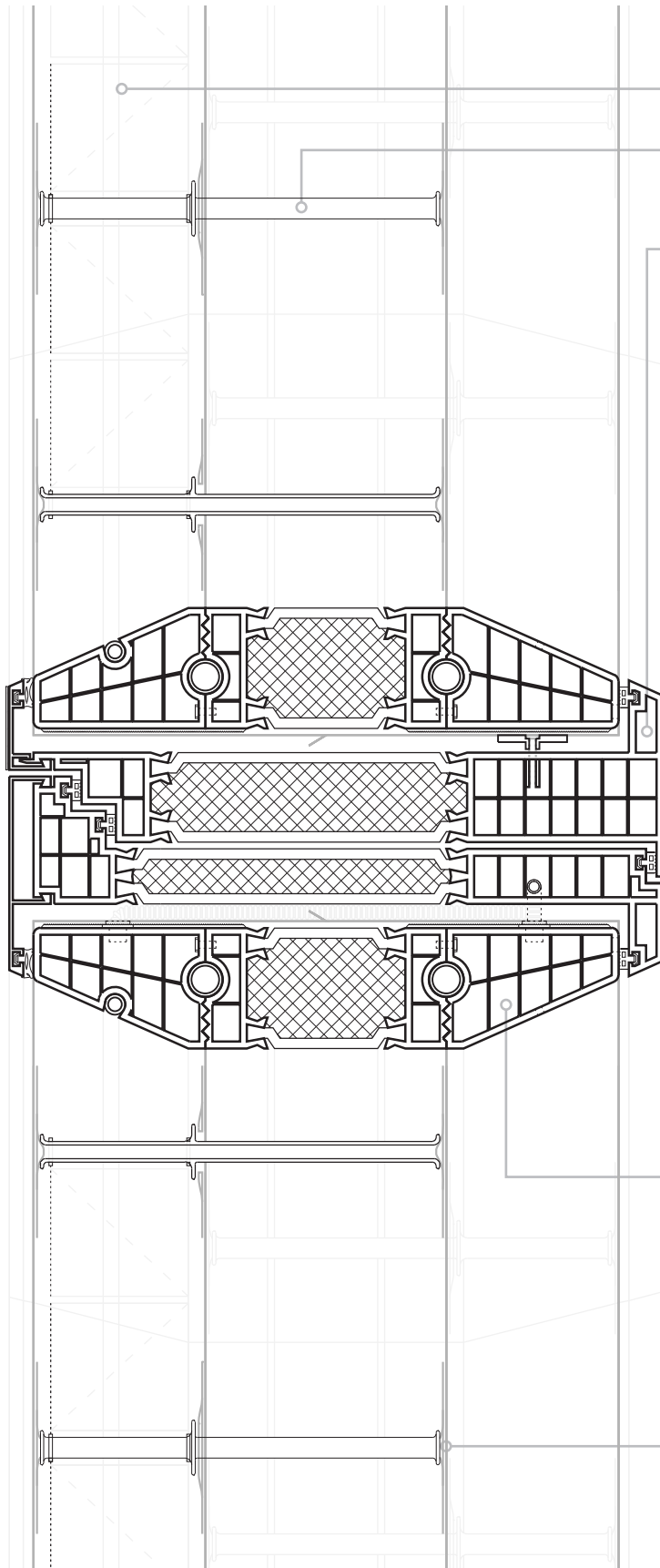
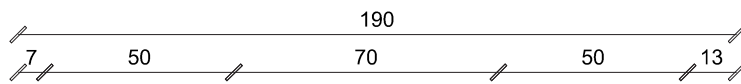
See detail two for detail description



* please refer to detail 2 for detail text

Detail 6

Window frame - vertical top - 1:2



Inflatable sunshading system

Glass fibre reinforced plastic spacer
round 10 mm, 70 mm long

Glass fibre reinforced plastic unit
frame 190x86 mm

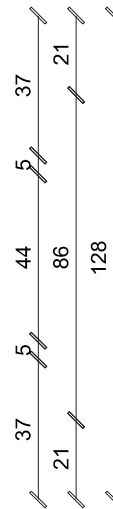
Insulated thermal break 102x44 mm

Ribbed vacuum tube

Weather and window clamp seal

Window seal

Glass fibre reinforced plastic window
clamp click profile



Glass fibre reinforced plastic window
frame 170x36 mm

Insulated thermal break 46x35 mm

Keder clamp

Perforation for air evacuation

Pneumatic sun shading air tube

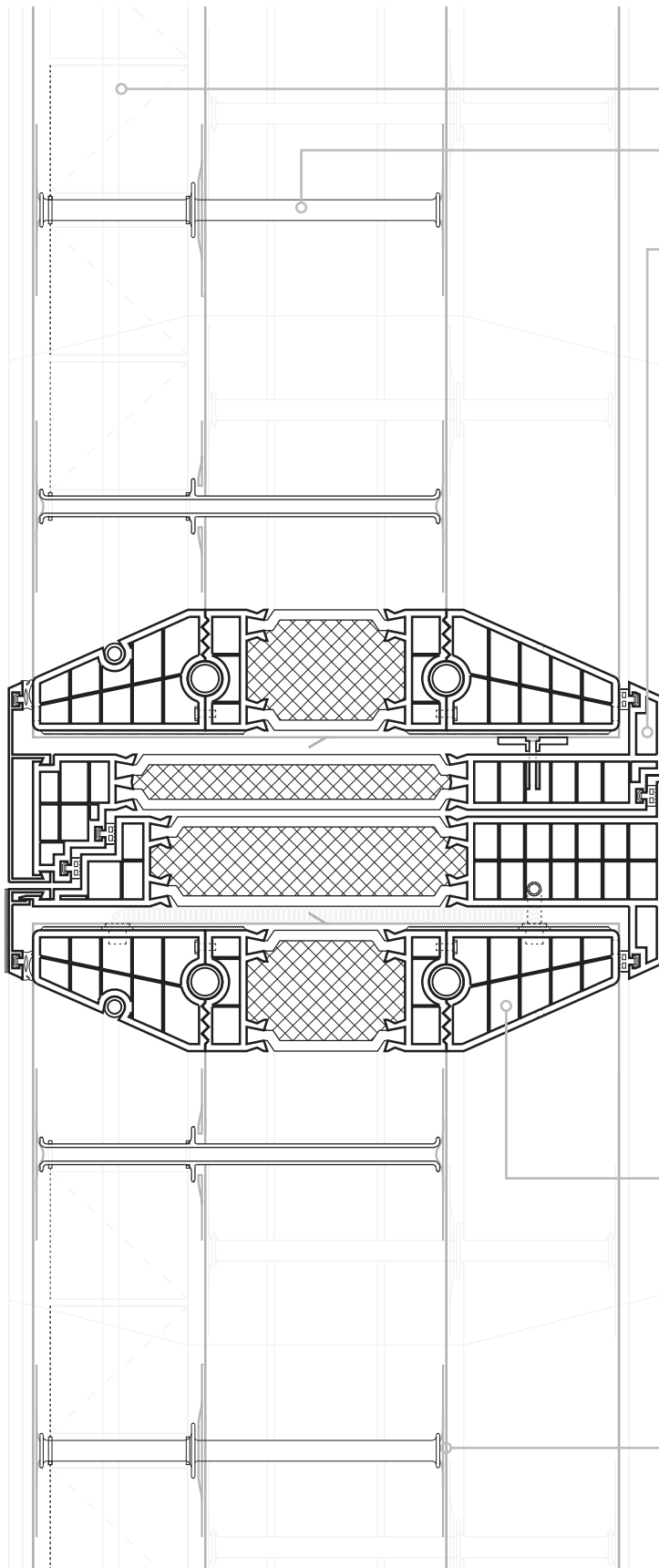
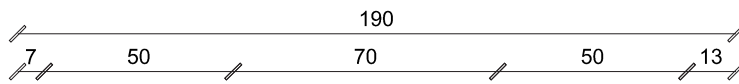
Anti-slip rubber strip

Glass fibre reinforced ETFE
membrane 0.3mm

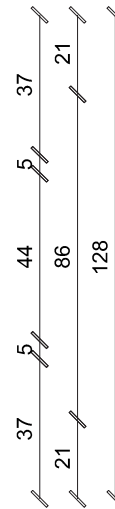
Shaped ETFE reinforcement heat
welded on ETFE membrane

Detail 7

Window frame - vertical bottom - 1:2



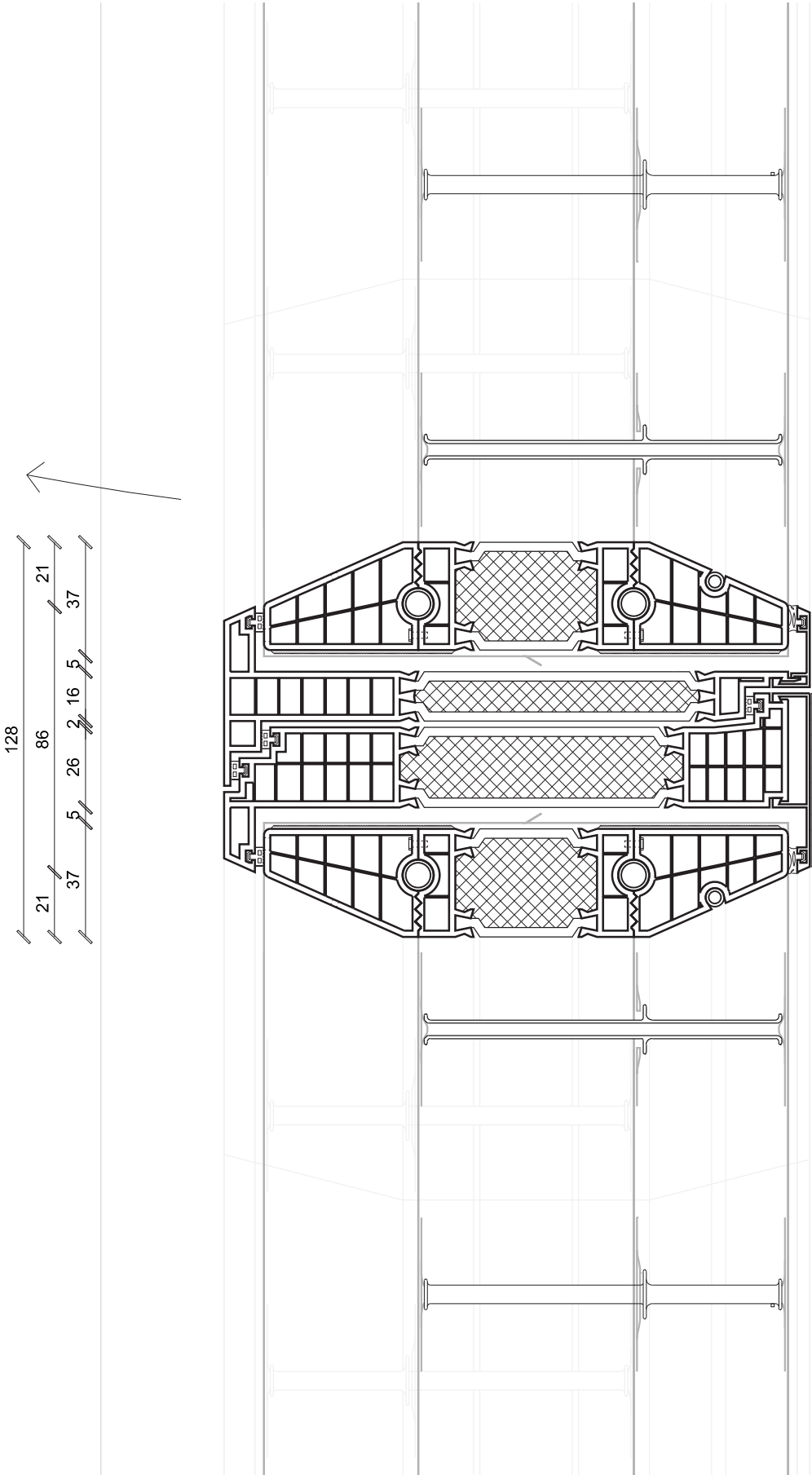
- Inflatable sunshading system
- Glass fibre reinforced plastic spacer round 10 mm, 70 mm long
- Glass fibre reinforced plastic unit frame 190x86 mm
- Insulated thermal break 102x44 mm
- Ribbed vacuum tube
- Weather and window clamp seal
- Window seal
- Glass fibre reinforced plastic window clamp click profile



- Glass fibre reinforced plastic window frame 170x36 mm
- Insulated thermal break 46x35 mm
- Keder clamp
- Perforation for air evacuation
- Pneumatic sun shading air tube
- Anti-slip rubber strip
- Glass fibre reinforced ETFE membrane 0.3mm
- Shaped ETFE reinforcement heat welded on ETFE membrane

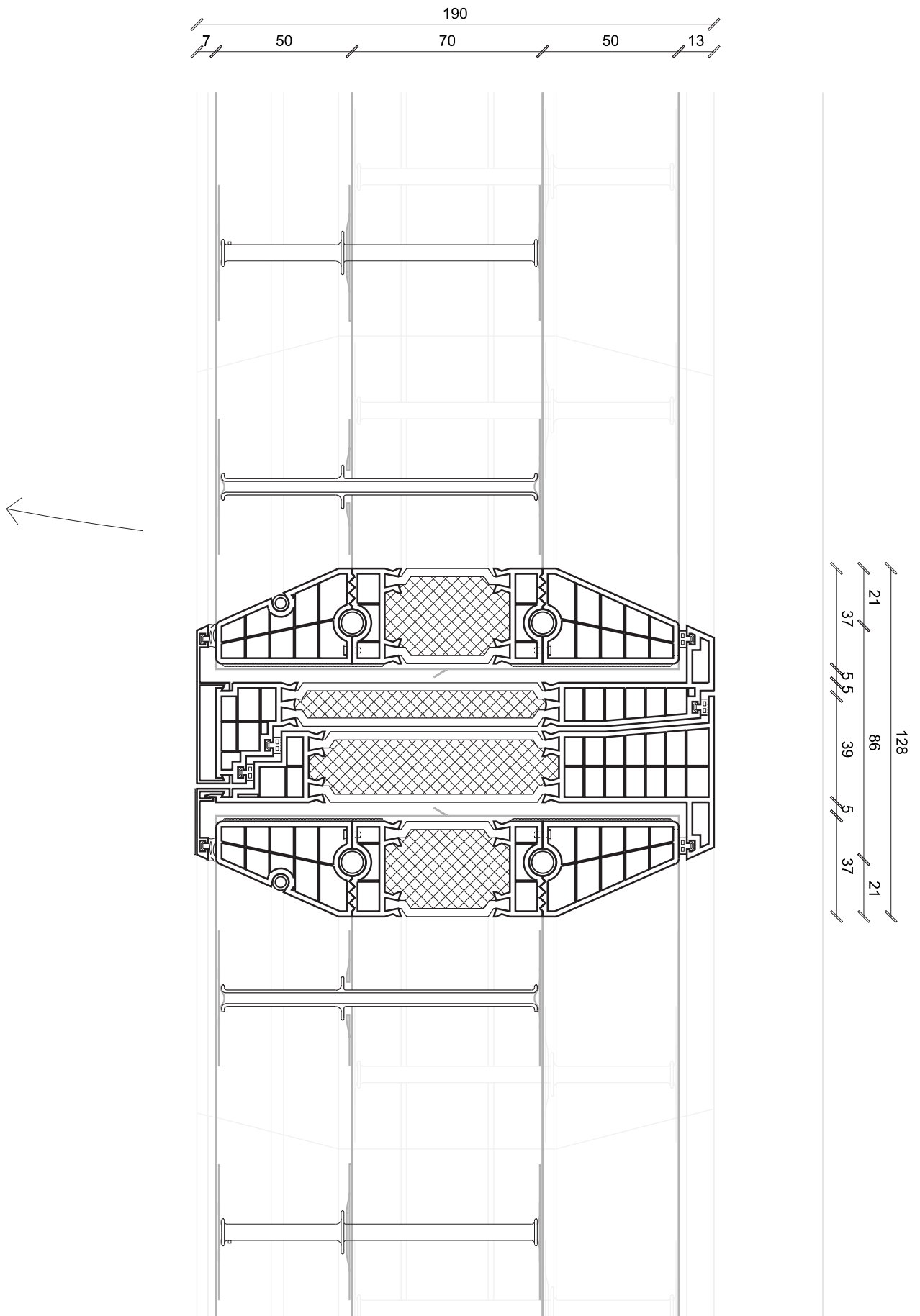
Detail 8

Window frame - horizontal left - 1:2



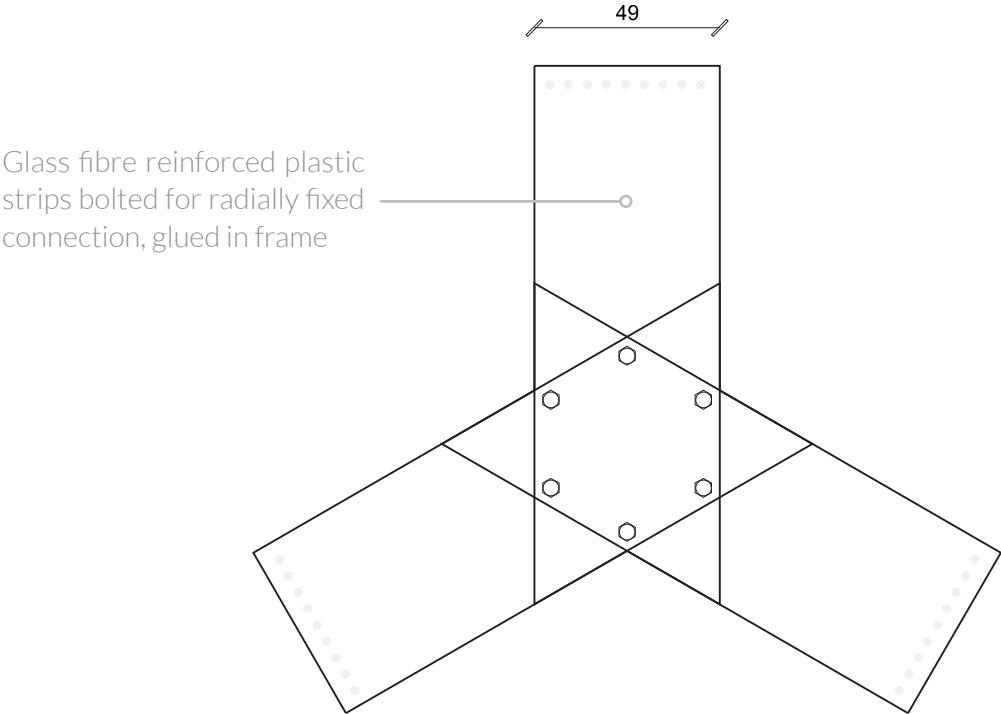
Detail 9

Window frame - horizontal right - 1:2



Detail 10

Moment fixed connection piece - 1:2



10.11 - Visual comfort

The final design has a lot of detailed parts that work together to make the vacuum membrane envelope work, but they also have a very great influence on the overall appearance of the façade. Especially on the viewing comfort of the façade. ETFE isn't completely transparent. It is a bit 'milky'. The design even uses four extra thick layers, together with wire reinforcement and spacers. To visualize the view through the façade a visual mock-up has been made. It is a 1:1 scale model of the façade. However, it doesn't have the size of a full sized façade, but is more like a bathroom window.

Figure 219 shows the mock-up that is built with louvres, representing the sunshading. Figure 220 shows the model without sunshading. From a distance, especially in the pictures directed at the sky, it doesn't look very transparent. However, this is because you have a reference. This reference makes it look less transparent. For instance, insulated glass isn't fully transparent either, but you don't notice it in the frame and on a large surface. Holding a small plate of glass will look green or blue. You can't expect the membrane to be fully transparent, but it might be good enough for many building applications. It was interesting to see that a small piece seems less transparent than a larger surface. The large mock-up almost looked transparent. Size plays a part.

The effect of the spacers are already researched extensively in chapter 9.1. This model looks very similar in comparison to the results found there, but with the addition of the nipples. These are larger and more disturbing.

The shape in the ETFE and the material itself could deform the image viewed on the other side, but the system doesn't do this. For reference a Rubix cube has been placed on the other side of the panel. In these pictures you can clearly recognize the cube. It is blurred or deformed. Only a little bleached.

The following pages show the model and a render that shows the possible appearance and visual comfort of the Sail at Marina bay with the unitized membrane facade.

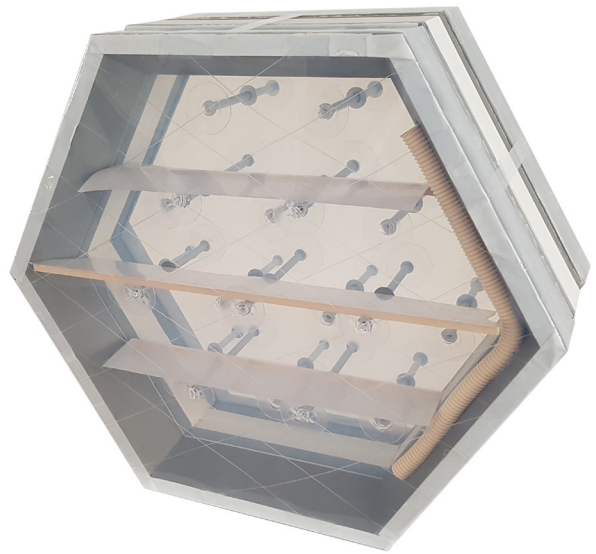
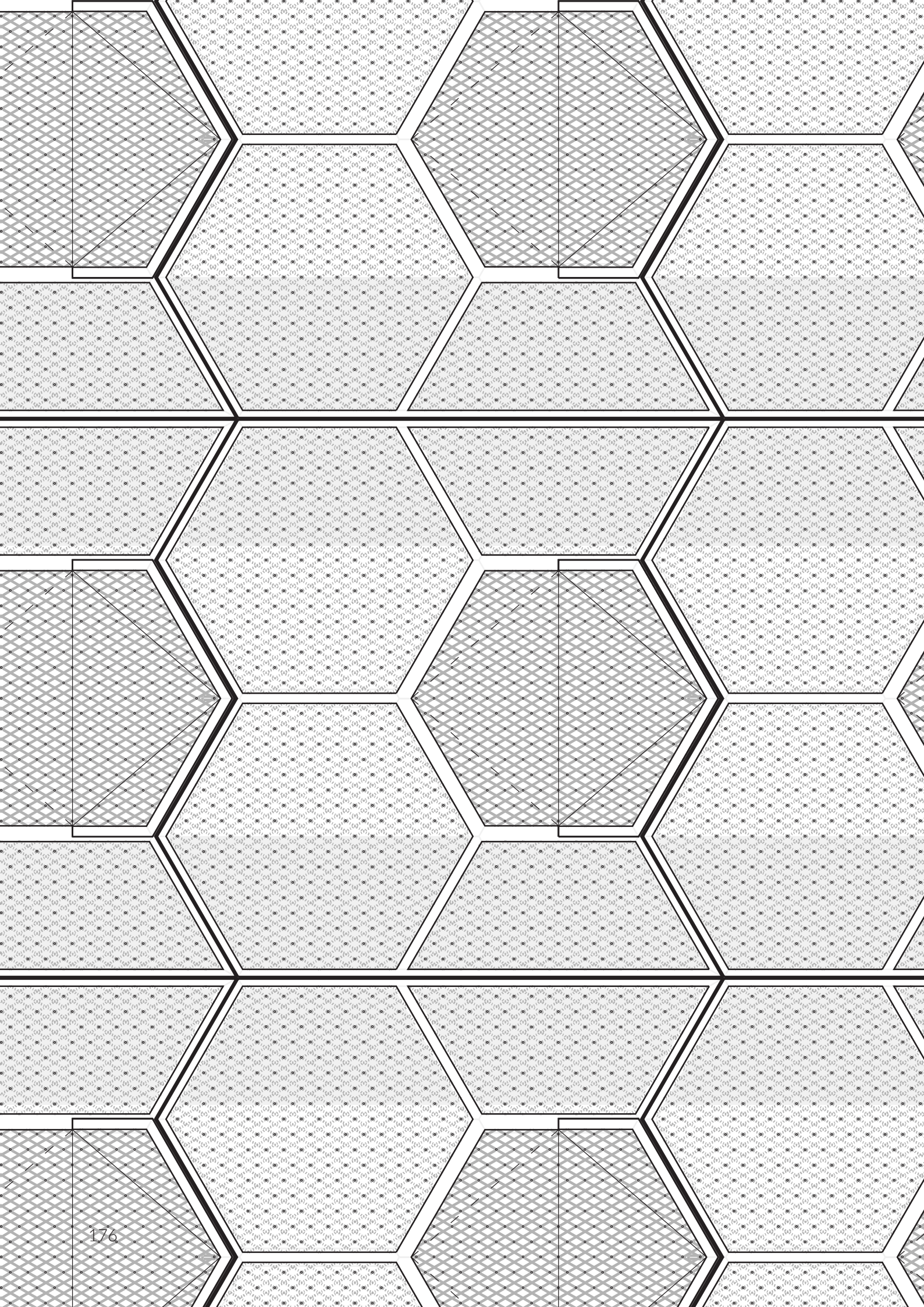
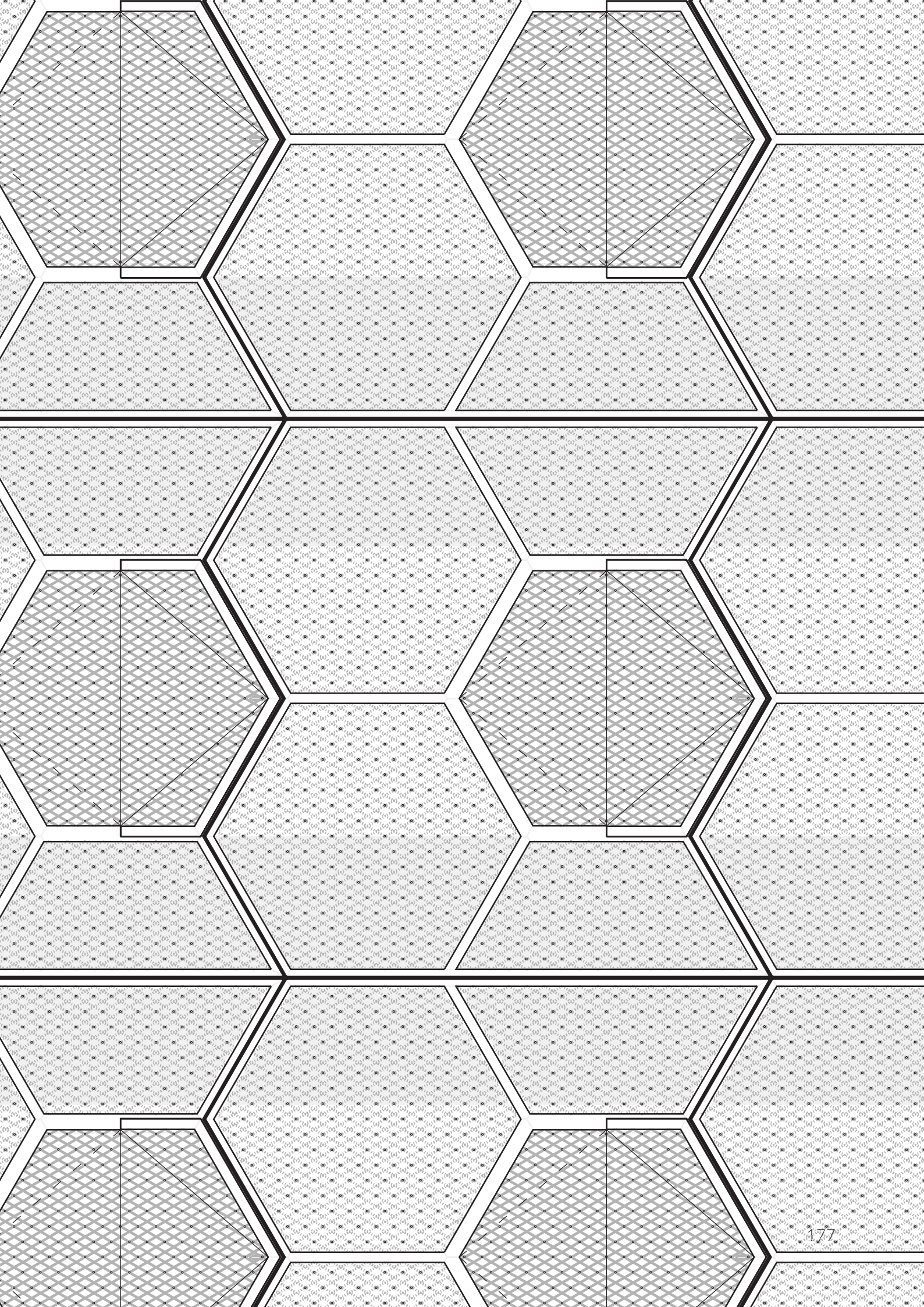


Fig. 219 collage of showmodel mock-up 1



Fig. 220 view through showmodel mock-up





11

SUSTAINABILITY REVIEW

11.1 - Introduction

This master thesis explores the possibility of realizing a building envelope, that uses membrane materials as much as possible, for a high-rise building in Singapore. The choice of this subject and thus the material, hasn't been random. Membrane materials see relatively little use in the built environment, but have specific properties that offer new opportunities in façade design. Membranes materials can be flexible, strong, lightweight and most are 100% recyclable (Lorens, 2015). These properties could lead to a more sustainable façade. Therefore, this was one of the goals in the master thesis. The master thesis is eligible for the TiSD annotation if it contributes towards sustainable development. This report will review the sustainability of the final design in the master thesis.

The main thesis report contains the development of the unitized membrane envelope. The goal for sustainability has been suppressed during development by more pressing matters like: building physics and user comfort. However, at the end a final design has been created and now it is time to check if the final design is actually more sustainable. This will be done by answering the following question:

How sustainable is the unitized membrane envelope compared to a aluminium and glass unitized façade?

Before answering this question 'sustainability' needs to be defined, because sustainability is a broad subject. The definition of sustainability can be given as:

The quality of not being harmful to the environment or depleting natural resources, and thereby supporting long term ecological balance (Collins, 2016).

This is a very broad and non-specific definition, but is quantifiable if the full lifecycle of a material or product is analysed. For materials in the built environment the lifecycle can be simplified to a few steps, which have been visualized in figure 1. Advancing through each step costs or provides a certain amount of energy. The total amount of energy cost at the end of the lifecycle of a material or product can be defined as the embodied energy.

The embodied energy will be calculated for the unitized membrane envelope and compared to a common unitized façade. Some additional aspects especially interesting for the unitized membrane envelope will also be mentioned to provide the full scope of information to answer the main question.

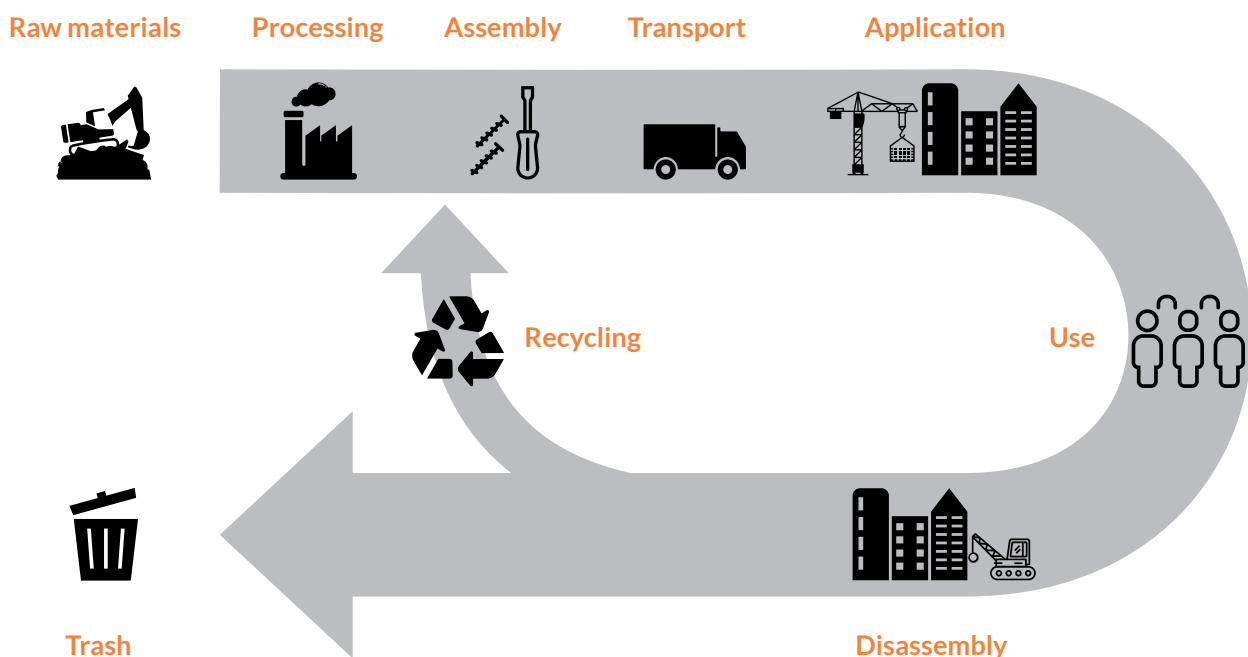


Fig. 220 lifecycle of building materials

11.2 - Embodied energy

For calculating the embodied energy the CES edupack 2016 material database has been used. The calculation done is very rough however, because the exact locations from where the materials are mined, manufacture, assembled and are transported to are not taken into account. For comparison a random distance has been used. Also, not every material of the façade is calculated. These are materials like gaskets and glues. I assume that these are the same in either of the two facades that are compared so don't need to be analysed to see the difference. Only the main building components are taken into account.

To represent a 'common' façade for the comparison data an Alcoa unitized façade element with an aluminium frame and double glazing has been used. The datasheet of the façade can be found in the appendix. Two units have exactly the same surface area as one unit of the unitized membrane envelope. Therefore, two common units are compared to one membrane units.

The results are visualized in figure 2. They show that the unitized membrane envelope has a higher embodied energy of 28.000 MJ, compared to the common façade, with an embodied energy of 26.000 MJ. What is immediately clear is that this isn't even determined for the most part by the façade infill, but by the frame of the façade. In both cases the frames cost more than four times the amount of energy, compared to the rest of the materials. Because of the enormous forces of the vacuum, the unitized membrane envelope requires a thicker and therefore heavier frame. This extra material costs more energy, but this is offset by the use of glass fibre reinforced polymers. Compared to aluminium, this material has a lower embodied energy per Kg. The end result is almost the same energy cost in the frames.

Even though the infill of the frames have a relatively low impact in both cases, this is where the difference in environmental impact is made, in this comparison. Ignoring the frame, the infill can be compared separately. A single layer ETFE

indeed has a low embodied energy. However, in this case there are four extra thick layers, supplemented by a lot of glass fibre reinforced spacers. The result is a higher embodied energy than an insulated double glazing window.

Figure 2 also shows the CO² footprint. In this case the situation is reversed. This is also mainly caused by the contribution of the frames. Both aluminium and glass have a higher CO² footprint. So, if the energy used during the production of the membrane envelope could be provided by sustainable sources, it could still be considered more sustainable. However, this is currently not the case and the difference is minimal.

Lowering the embodied energy could be done most effectively by replacing the frame materials, by something more sustainable. Wood is, in the case of embodied energy, a very sustainable material. By replacing the frame with a wooden frame the embodied energy could be more than halved in both cases. However, this would have a lot of downsides. Considering for instance: maintenance, durability, and especially important in the case of the vacuum envelope, strength. When designing a façade with a low embodied energy, wood would be better solution.

Lightweight

In the embodied energy calculation, transport is also taken into account, but because the unitized membrane façade is only half the weight of the common façade additional comparisons will be made. In the embodied energy calculation a random travel distance of 100 Km by truck and 500 Km by Boat has been calculated. Here the lighter unitized membrane envelope costs only half the energy of the common façade, but this is a negligible 25.8 MJ. If travel, and its associated energy costs, are a larger issue this energy saving could stack up to something more relevant.

The light weight of the façade could also be taken into account during the design of a new building. In that case the structure can be far lighter. How

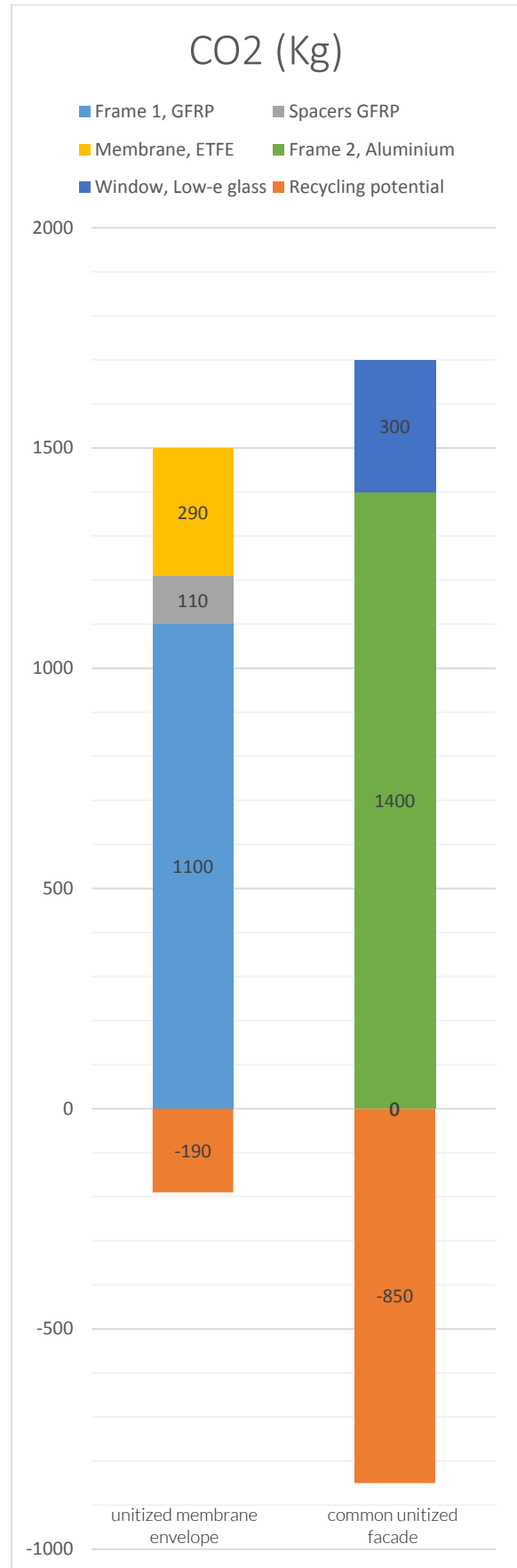
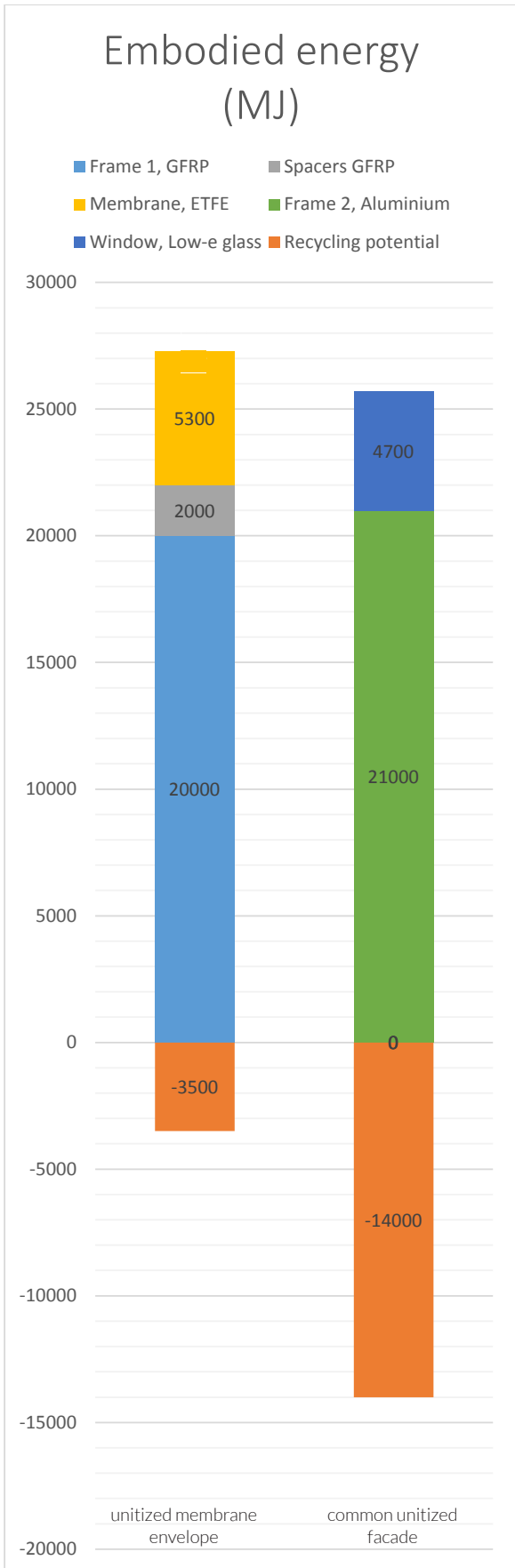


Fig. 221 embodied energy review results

much weight this would save is very specific to the building and its construction, but could be significant in the case of ultra-high-rise buildings or structures with a large cantilever.

To illustrate this point a theoretical situation can be imagined with a HEA 300 beam carrying a large part of a façade, weighing 550 tons. If this weight is halved to 275 tons, the beam can be replaced with a HEA 260 beam. This would save 15 Kg of steel, which CES shows takes 525 MJ of energy to produce. This decrease in weight and embodied energy is repeated throughout the whole building and the effect is stacked on each, because the lower floors also carry the extra weight of the upper floors.

Façade use

Energy needed to use the façade have not been taken into account in the embodied energy assessment. Both façades directly and indirectly use energy during use of the façade. The energy used by the unitized membrane envelope is the vacuum pump. This pump has to run every day for a couple of minutes to keep the required pressure. Conveniently, the same pump is used to control the sun shading integrated in the façade.

The common façade also has a sun shading device that is operated by an electric motor. Both the vacuum and sun shading motors are around the same size and will be operated the same amount of times, give or take a few minutes per day.

Indirectly the facades use energy by leaking heat or cold to the outside environment. A façade with better insulation values will leak less and consequently cost the climate insulation less energy. Both compared facades have similar insulation values.

Normally, one does not compare the loss of acoustical energy, for identifying its sustainability, but in this case the comparison will be made, because the unitized membrane envelope has far greater acoustic properties compared to the common façade. To get a glass façade that can

also insulate up to 50 dB, a specialised acoustical glass needs to be applied with four sheets of glass laminated together with a cavity in-between in a 8-1-6 – 15 – 6-1-6 relationship (Viracon, 2016). This acoustical glass pane is more than twice as heavy and has a higher embodied energy compared to the unitized membrane envelope.

Lifetime and durability

ETFE is very durable, compared to other plastics. It can be used in building applications for up to 25 years. Double glazing is often guaranteed to function between ten and fifteen years (NSG group, 2017), but glass windows have the ability to function for much longer than that. If the circumstances are right.

In the case of ETFE, this is definitely not the case. 25 Years is the absolute maximum lifetime (Lorens, 2015). When applied on the unitized membrane envelope this will probably be halved. The forces on the membrane are enormous and creep will deform the membrane over time significantly. It will also scratch quickly and therefore fade in time, because of airborne pollutants carried by strong winds. Accidental puncture could also occur. Therefore, the outer two layers will need to be replaced once to reach the 25 Year period. This has to be tested to be scientifically proven of course.

Recycling

At the end of the lifecycle of a component it can be either thrown away or recycled. ETFE can be recycled very well. The material can be recycled for 99.3 percent, with relatively low energy cost, even with coatings on the material. Comparatively, glass is very hard to recycle, because of the metal low-e coatings on it. Glass used for windows is not recycled, but often down cycled. However, most energy is in the frames. In this case the glass fibre reinforced polymers aren't recyclable. The aluminium is, but at great energy cost. This is evident in the high energy returns possible shown in figure 2.

11.3 - Conclusion

After analysing each part of the lifecycle of the unitized membrane envelope, which can be seen in figure 3, an answer can be given to the question asked at the start of this report.

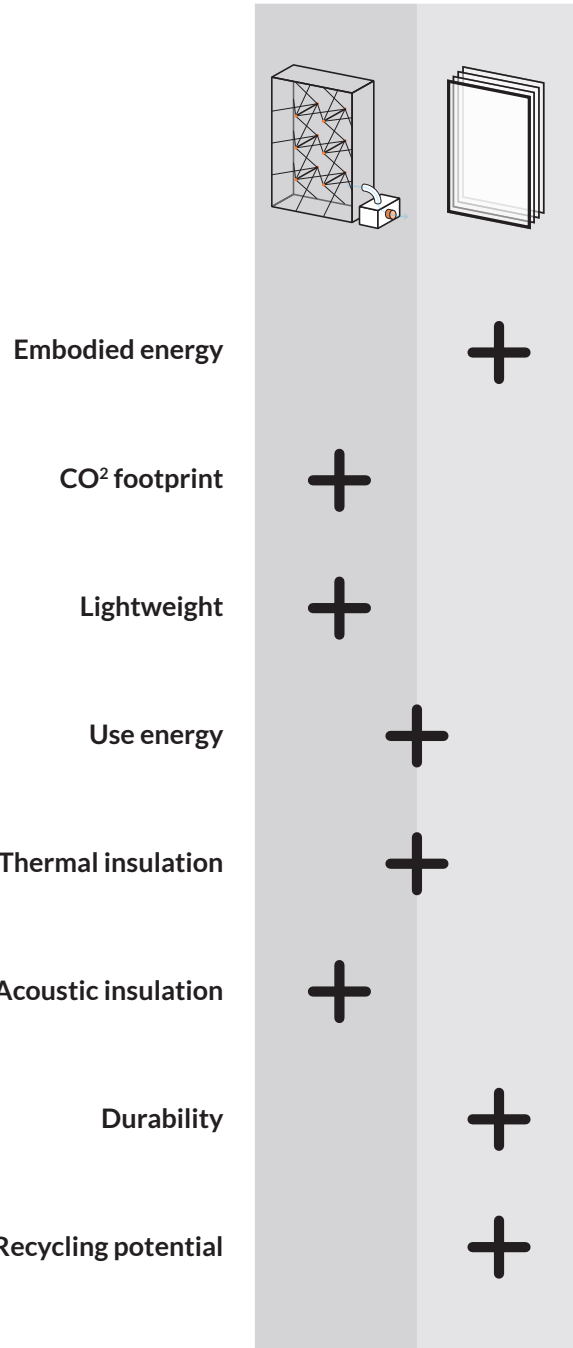
How sustainable is the unitized membrane envelope compared to a aluminium and glass unitized façade?

The answer to the question is a little bit unexpected. When looking at the sustainability of an individual foil of ETFE and comparing this with a sheet of glass, the superiority of ETFE seems very clear. The ETFE has a lower CO² footprint, embodied energy and is extremely lightweight. However, this comparison ignores what ETFE needs to function on a building, similar to what a glass façade does. The ETFE needs a heavy frame, because it can't carry itself and at least multiple layers to increase its thermal and acoustical properties.

Now that a design has been made and this has been compared to a common glass curtain wall, the advantages of ETFE are not so obvious anymore. In this case a vacuum was used inside a triple cavity to increase its thermal and acoustical properties. This required an even heavier frame, spacers and four layers of ETFE.

However, the unitized membrane envelope does have its advantages. The acoustical properties are far higher. A glass façade with similar acoustical properties will have a higher embodied energy. The unitized membrane envelope is also far lighter. This requires less supportive structure, is easier to transport and mount. However, the energy saved by this is negligible compared to the energy needed to produce the panel.

In a situations where extra facilities for mounting the ETFE are already present, where less thermal and acoustical properties are allowed or where lightweight is absolutely necessary, ETFE can still be a very useful and effective material. However, this is just not the case in a high-rise façade system. Common façade systems are just as effective, and aren't really sustainable either. A façade system with a wooden frame could be more effective.



Tab. 12 comparison results

12

**CONCLUSIONS AND
REFLECTION**

12.1 - Conclusion

The goal of this research was to find an innovative new envelope that is an adaptive unitized façade, specifically designed to utilize the advantages of membrane envelopes for high rise buildings in Singapore. According to the research framework this goal was approached with a number of smaller questions. Answers to which have mostly been found during the literature study, done at the start of this research. Together, the answers have identify the different aspects of the main goal and thereby formulated a design goal which could be filled in to answer the main question.

The design has been made, but to evaluate if it truly meets the requirements set by the main- and sub-goals it will be tested against them. The goals pertaining to the final design are:

- Designing towards the required façade properties dictated by the exterior climate and indoor comfort demands.
- Exploring applications of membrane materials.
- Exploring applications of unitized façade systems.
- Discovering the advantages of membrane envelopes compared to commonly used unitized façade systems.

Site-specific design

The literature study identified the sometimes extreme weather conditions present at Singapore. Building typology of high-rise buildings and the indoor comfort requirements of the area were also researched to take into account every aspect of the site. Together this formed a set of boundary conditions to which the newly designed façade was to be tested.

This set of conditions had a large impact on the design process, resulting in quick elimination of the more outlandish concepts at the start of the design process. The final design has a sun shading system and a window, but this would probably also be the case when the design would have been done for other locations. The main challenge lay in the heavy wind loads that put an even higher

load on the already stressed vacuum panels. The resulting reinforcements in the design were therefore necessary, but these could be mostly removed if another location was chosen. This would be advisable for this inherently fragile design.

Membrane materials

Many technical fabrics and membrane materials have been identified in the literature study. What was interesting to note was that most materials were designed for a very specific purpose and are largely unusable for other design aspects. Therefore a combination of materials seemed to be necessary.

However, the final design ignored this suggestion and went with improving the area in-between the membranes to achieve increased properties in the required fields. Therefore the final concept was a vacuum membrane envelope. The membrane used to contain the vacuum was ETFE. This fluoropolymer is already used very often in the build environment, for good reason, because also this research found it the most suitable material. It has a very high transparency and relatively high strength. The transparency of the material allowed more layers to be placed after one another without a significant loss in light transmission. The strength of the material didn't prove enough however, because glassfibres were used to reinforce it at high stress locations.

Membrane materials were used for most of the envelope. To make this happen the true limits of the material needed to be tested, or else the vacuum would not have been possible.

Unitized façade system

The research found that unitized façade systems are dominated by glass steel and aluminium. It would already be a victory if a new system could be found that was just as effective if not better than conventional unitized facades, through the use of membrane materials.

The initial concepts, during the sketch design phase, played more with the concept of a unitized façade than the final design did. Difficulties in applying and making the system practical hindered their development and led to more

conventional ways of unitizing the envelope. Through other developments focus of the project shifted towards an envelope with high properties instead of a new kind of unitized façade. The final design is still a unitized façade however and could be applied effectively on the Sail at marina bay.

Advantages and disadvantages

Membrane materials and the building applications for these materials appeared to be lightweight, highly recyclable and flexible compared to many other materials. These advantages came at a cost of lower building physical properties and vulnerability. The advantages mentioned are the reasons this research started looking into the possibilities, but the disadvantages had to be overcome.

During the research an unexpected advantage of membrane materials had been discovered. Namely, that the flexibility of the material meant that it could work exceptionally well as acoustical insulation when it is used to contain a vacuum cavity. The whole final phase of this research revolves around making a design that fully capitalizes on this and testing the theory. In the end the theory hasn't been tested properly and is still an unknown variable in the design. This has to be looked into during further research, because it is key to the functionality of the design.

However, assuming that the acoustical theory is correct, the disadvantages of membrane materials are still present. A lot of extra attention was needed to provide enough thermal insulation. The vacuum also results in an active system that will not function without electricity, even if the requirements are very low. The vulnerability of the membrane is even higher, because it is constantly stressed to its maximum capacity. And the final design is not as lightweight as other membrane facades, because of its heavier frame. The sustainability of the facade has also been lost during the development. The necessary detailing needed for the vacuum to function has increased the embodied energy of the facade too much.

Therefore the question is: Do the advantage weigh up to the disadvantages? On the Sail at marina bay, the unitized membrane envelope could be applied effectively, but would probably

not be the most ideal in terms of comfort and functionality. Future developments could increase the systems resilience or visual comfort to make it more competitive. However, the system could be perfect for special scenarios. It doesn't have to be applied as a façade, but could also function as a recyclable sound wall for use along roads or as an interior wall. Further development could find even more uses for the system.

12.2 - Further research

The design as presented in this research report still has a lot of room for improvements. Here further research could aid in making the design even more effective or more attractive to the building market.

First, a proper acoustic test has to be done to definitively prove the effectiveness of the vacuum within the membrane envelope.

The frame and spacers are currently based on hand calculations, which are rough and have a relatively large margin of error. This has been taken into account in the design, which probably resulted in an over dimensioned and therefore heavier design. Specific structural optimizations could save a lot of weight and further increase the advantages of a membrane envelope. Structural optimization could also increase visual comfort by reducing the size of the spacers.

Ultra high strength transparent membranes could be developed to be specifically effective in the high-stress environment of a vacuum envelope. This could possibly be used to achieve a lower pressure, further enhancing the acoustic properties of the façade. Possibly even reaching beyond high vacuum where also thermal properties will be severely affected. This would be the ultimate goal of a vacuum membrane envelope.

If the Sail at marina bay would be refurbished, more development should be done on applying the membrane envelope to the whole building. The main system is clear, but this still leaves many issues to be dealt with.

12.3 - Reflection

In this reflection I would like to look back at the past couple of months and analyse my approach to the graduation project, which led to the research and design results I have at the moment. I will do this along relationships that can be identified in the project and asking the question: Did my approach work?

Answering this question can be very simple and short. Yes, the approach that is explained in the figure on the next page worked. With help of some guidance and nudges in the correct direction by my mentors. However, the final steps have not been finished yet. I cannot help but feel that another approach would have gotten better results. Maybe only slightly better, but an improvement nonetheless. This is off course easy to say after the fact, when all important question are discovered and most answers are found.

What I would have liked is to have a final design or final concept earlier in the process. This could open up more time for the testing phase before the P4. The current concept that resulted from my research has potential for another full graduation project on its own. This time wasn't left anymore when the final concept was chosen, but I would have liked to have it.

What should have been different in the approach to get the desired results could be sought in the choice of subject at graduation when choosing a lab, social context or the design phase.

Graduation lab

For me the graduation project started by choosing a graduation lab and this put me on the right or wrong path. The graduation lab I chose has a very open theme. The theme is membrane envelopes. I had the freedom to explore what a membrane envelope is in my project. This became my main guide in the development of my graduation project and in any decision making process. Because I made this decision early in the process I didn't got lost in different subjects later on, but the theme was still too broad. I believe that a more specific research question could speed up the decision making process.

Social context

The project is only superficially related to any social context. Current topics like innovation and sustainability are the core of the project and an actual location and building has been chosen to give a frame and grounded structure for the designed envelope. This influenced the decision making process heavily, but not as much as an actual project, that would be executed, would do. This wasn't strived for at the start of this graduation project.

Research and design

The methodology I used in developing my project can be seen in the figure on the following page. Put simply, I started with literature research, followed by design and research evaluation loops of numerical calculations or mock-ups. Designs were created and refined from ten designs to three designs to one final design.

The second phase of this approach has a very strong relationship between research and design. The two switch constantly. The designs were based on research. However, the research often gave multiple options, which needed to be chosen and applied by me. Therefore the final product is both a product of research and my own opinions. If this is a truly scientific method I cannot answer, but it was a very pleasurable approach for me.

I even believe that I learned more through designing and prototyping than with the initial literature study. Therefore my approach should have started with designing far earlier. A few weeks before P2 would be advisable.

Looking ahead

All in all, I think my approach was sufficient. The research and design phase was very effective, but it should have been involved a bit earlier in the process and this should be combined with a more specific theme to help in the decision making process. Almost everybody already says this and I feel nobody really listens anymore. At least I didn't truly listen. It is really important to have a good, concise theme for the graduation. Combined with an end goal where you can work towards. A clear start makes in everything going much more smoothly.

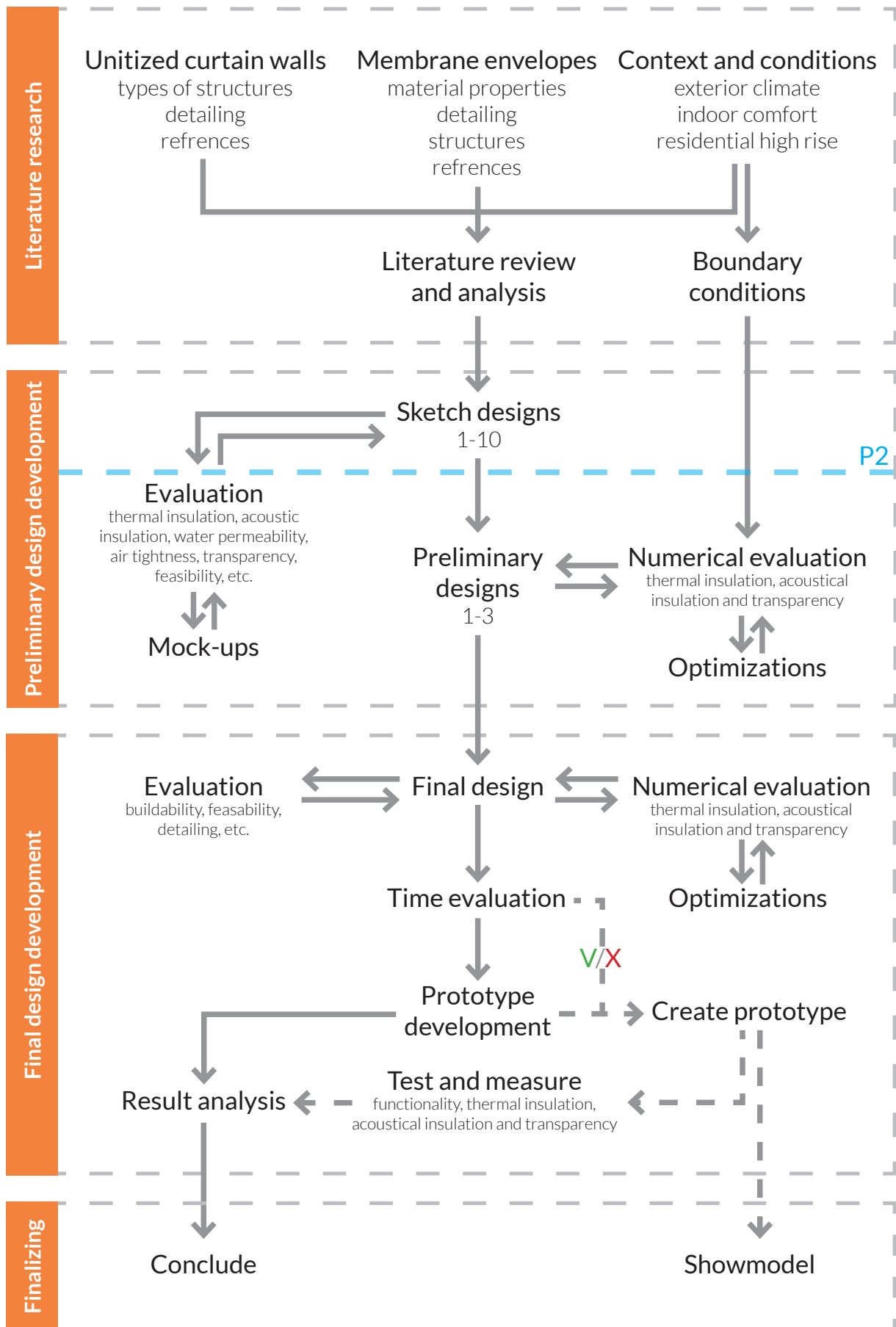


Fig. 222 graduation methodology and approach

13

BIBLIOGRAPHY

13.1 - Bibliography

- 3M. (2017). Retrieved from http://www.3m.com/3M/en_US/thinsulate-us/
- Architectuur centrum Amsterdam, (2001). Retrieved from <http://www.arcam.nl/villa-arena-winkelcentrum/>
- ASHRAE Singapore chapter (2013). Retrieved from <http://www.ashrae.org.sg/>
- Augustyniak, M. J. (2016). Tensotherm insulated tension membranem Retrieved from www.birdair.com
- Barf, H. (2010). Innovative design + construction : Manufacturing and design synergies in the building process (DETAIL development; DETAIL development). München: Institut für internationale.
- Bechthold, M. (2008). Innovative surface structures : Technology and applications. London: Taylor & Francis.
- Bluyssen, P. (2009). The indoor environment handbook : How to make buildings healthy and comfortable. London: Earthscan.
- Boduch, M., Fincher, W. (2009). Standards of human comfort: relative and absolute. Austin: Centre for sustainable development. Retrieved from: <https://repositories.lib.utexas.edu>
- Boerstra, A. C., van Hoof, J., van Weele, A. M. (2015) A new hybrid thermal guideline for the netherlands: background and development. Architectural science review.
- Bokel, R. (2015). Building physics lecture notes AR1B025D4 2015-2016 Q4. Retrieved from www.blackboard.tudelft.nl/couresAR1B025-D4. Retrieved at 25-06-2016
- Bos, P. R., & Wolters-Noordhoff (Groningen). (1981). De grote Bosatlas (49e dr. /). Groningen: Wolterordhoff.
- Bris bv, (2015). Retrieved from www.bouwbesluitonline.nl.
- Charbonneau, L. (2011). Time-dependent tensile properties of ETFE foils. Waterloo: University of Waterloo
- Collins English Dictionary. (2016) Complete & Unabridged 10th Edition. Retrieved January 6, 2017 from Dictionary.com website <http://www.dictionary.com/browse/curtain-wall>
- Du Pont de Nemours and company. (2013). Dupont Tyvek thermawrap. Retrieved from www.construction.tyvek.com
- Eden trust, the. (2016). Retrieved from <http://www.edenproject.com/>
- Garbe, T. (2008). Tents, sails, and shelter: innovations in textile architecture. Austin: Centre for sustainable development.
- Gore & associates. (2016). Retrieved from <http://www.gore-tex.nl/nl-nl/technologie/gore-tex-membraan>
- Grimshaw architects. (2003). Retrieved from <https://grimshaw.global/projects/the-eden-project-the-biomes/>
- Harvie, G. (2016). Retrieved from https://www.designingbuildings.co.uk/wiki/Thermal_comfort_in_buildings
- Horrocks, A. R., & Anand, S. (2000). Handbook of technical textiles (Woodhead publishing in textiles, 12). Boca Raton, FL: CRC Press/Woodhead Pub.
- Huntington, C. G., & Structural Engineering Institute. (2013). Tensile fabric structures : Analysis, design, and construction. Reston, Virginia: American Society of Civil Engineers.
- IPCC (2007). Retrieved from https://www.ipcc.ch/publications_and_data/ar4/wg2/en/annexessglossary-a-d.html
- Iprototype. (2017) Retrieved from <https://iprototype.nl/products/robotics/servo-motors/Vacuumpomp>

- Kaltenbach, F. (2004). *Translucent materials : Glass, plastics, metals (Detail praxis; Detail praxis)*. Birkhäuser: Edition Detail.
- Kengo Kuma and associates. (2016). Retrieved from <http://kkaa.co.jp/>
- Kierantimberlake associates. (2016). Retrieved from <http://kierantimberlake.com/pages/view/28>
- Knaack, U., Klein, T., Bilow, M. (2008). *Deflatables (Imagine, 02; Imagine, 02)*. Rotterdam: 010 Publishers.
- Knaack, U., & Engelmann, U. (2011). *Performance driven envelopes (Imagine, 03; Imagine, 03)*. Rotterdam: 010 Publishers.
- Knippers, J. (2011). *Construction manual for polymers + membranes : Materials semi-finished products form-finding design*. Ba: Birkhäuser.
- Kynol Europa GmbH, (2014). *Kynol, novoloid fibres*. Retrieved from www.kynol.de.
- Llorens, J. I. (2015). *Fabric structures in architecture (Woodhead publishing series in textiles, no. 165; Woodhead publishing in textiles, no. 165)*. Cambridge, UK: Woodhead Publishing Limited, in association with the Textile Institute.
- Mendis, P., et al. (2007). *Wind loading on tall buildings*. Melbourne: EJSE International.
- Mikron instruments company. (2000). *Table of emissivity of various surfaces*. Retrieved from www.transmetra.ch
- Murray, S. C. (2009). *Contemporary curtain wall architecture (1st ed.)*. New York: Papress.
- O'Mahony, M. (2011). *Advanced textiles for health and well-being*. New York, NY: Thames & Hud.
- Nederlof, L., Cauberg, J.J.M., Tenpierik, M.J., (2015). *Building acoustics lecture notes*. Retrieved from www.blackboard.tudelft.nl/courses/AR1B025-D4. Retrieved at 25-06-2016
- Nijs, L. (2003). *De geluidsisolatie van een vacuum isolatiepaneel*. Voorschoten: Printhouse Drukkers & Uitgevers
- Onart. (2011). *ETFE facades and roofs*. Retrieved from www.onart.com
- Peel, M. C., Finlayson, B. L., McMahon, T.A. (2007). *Updated world map of the Köppen-Geiger climate classification*. European Geosciences Union.
- Pilkington building products. (2012). *Pilkington triple and insulight window energy rating*. Retrieved from www.pilkington.co.uk
- Pohl, G. (2010). *Textiles, polymers and composites for buildings (Woodhead publishing series in textiles, no. 95)*. Oxford: Woodhead.
- Reynaers Aluminium N.V. (2014). *Unitised element facades*. Retrieved from www.reynaers.com
- Rubb building systems. (2016). Retrieved from <http://www.rubbuk.com/projects/thermohall/cks-bilservice.htm>
- Rubel, F., Kotteck, M. (2010). *Observed and projected climate shifts 1901-2100 depicted by world map of the Köppen-Geiger climate classification*. Austria: Gebrüder Borntraeger.
- Saint-Gobain. (2011). *Fabrorb acoustical membrane*. Retrieved from www.sheerfill.com
- Simmonds, P. (2015). *ASHRAE design guide for tall, super tall, and mega tall buildings*. Atlanta: ASHRAE.
- Singapore urban development authority, (2016). Retrieved from <https://www.ura.gov.sg/uol/master-plan>.
- Solarnext AG. (2011). *PV flexible*. Retrieved from www.solarnext.de
- Teijin frontier Co. (2016). Retrieved from <http://www2.teijin-frontier.com/english/sozai/specifcs/eco-storm.html>

Tubbs, M. C., Daniels, P. N., & Textile Institute (Manchester). (1991). Textile terms and definitions (9. ed.). Manchester: The Textile Institute.

van der Linden, A.C., et al. (2011) Bouwfysica (7e dr. ed.). Amersfoort: ThiemeMeulenhoff.

Verheul, R. F., Breukels, J., Ockels, W. J. (2009). Material selection and joining methods for the purpose of a high-altitude inflatable kite. California: Institute of Aeronautics and Astronautics.

Welleman, J.W. (2006). Constructiemechanica 3. Retrieved from www.blackboard.tudelft.nl

13.2 - Table of figures

Fig. 1	Created by author
Fig. 2	Canceled
Fig. 3	Created by author, based on (Knaack, 2011)
Fig. 4	Canceled
Fig. 5	(Peel, 2007)
Fig. 6	Canceled
Fig. 7	http://livingonaplane.nl/wp-content/uploads/2015/06/1_Singapore_skyline.jpg
Fig. 8	(Peel, 2007)
Fig. 9	Canceled
Fig. 10	http://unearthed.solutions/wp-content/uploads/2016/09/Santiago-Chile.jpg
Fig. 11a	http://www.duosingapore.com/design.html
Fig. 11b	http://tanjongpagarcentre.com.sg/
Fig. 11c	http://www.nbbj.com/work/sail-marina-bay/
Fig. 11d	http://images.adsttc.com/media/images/5009/2490/28ba/0d27/a700/1a7a/large_jpg/stringio.jpg?1414005557
Fig. 11e	http://www.nbbj.com/work/sail-marina-bay/
Fig. 11f	http://images.adsttc.com/media/images/5009/2490/28ba/0d27/a700/1a7a/large_jpg/stringio.jpg?1414005557
Fig. 11 g	Created by author
Fig. 11 h	http://www.nbbj.com/work/sail-marina-bay/
Fig. 12	(Mendis, 2007)
Fig. 13	Created by author, based on (www.ashrae.org.sg)
Fig. 14	http://www.caas.gov.sg/caas/en/eServices_Forms/Application_for_Aerial_Activities/map_of_Singapore.html
Fig. 15	(www.ashrae.org.sg)
Fig. 16	(www.ashrae.org.sg)
Fig. 17	Canceled
Fig. 18	(Knippers, 2011)
Fig. 19	(Knippers, 2011)
Fig. 20	Canceled
Fig. 21	http://pdf.archiexpo.com/pdf/saint-gobain-technical-fabrics-europe/esf-engineered-specialty-fabrics/72516-284383.html
Fig. 22	http://www.threadsmagazine.com/assets/uploads/posts/5152/SST1-knits-wovens-03.jpg
Fig. 23	https://is.alicdn.com/img/pb/309/152/321/321152309_517.JPG
Fig. 24	https://www.north-windsurf.com/media/transfer/img/14_sail_feature_4.jpg
Fig. 25	http://images.naldzgraphics.net/2011/12/29-blue-knitted-fabric.jpg
Fig. 26	http://i00.i.aliimg.com/img/pb/466/333/638/638333466_590.jpg
Fig. 27	http://accessnorthstructures.com/wp-content/uploads/2014/06/ETFE-welding-4-1024x685.jpg
Fig. 28	Created by author, based on (Knippers, 2011)
Fig. 29	http://mid-mountain.com/wp-content/gallery/fm-approved-products/caven_srs40.jpg
Fig. 30	https://www.sattler-global.com/ta-site-static_files/images/content/ETFE-Materialmuster1_-_400x267.jpg
Fig. 31	https://www.dickson-constant.com/nl/NL/zonwering/high-tech-doeek-voor-professioneel-gebruik
Fig. 32	http://www.dsm.com/products/dyneema/en_GB/home.html
Fig. 33	https://ae01.alicdn.com/kf/HTB1q2aILVXXXXXQaXXXq6xXFXXX1/1100D-200gsm-Yellow-font-b-Kevlar-b-font-Fabric-PARA-font-b-ARAMID-b-font-SYNTHETIC.jpg
Fig. 34	http://www.tapplastics.com/uploads/products/Clear_Mylar_Rolls-xl.jpg
Fig. 35	http://www.dupont.co.uk/content/en_gb/home/products-and-services/

personal-protective-equipment/thermal-protective/articles/protection-in-action-with-dupont-nomex--3dp-fabric/_jcr_content/bodycopy/heroimage.img.jpg/1457514919785.jpg

Fig. 36 http://www.tapplastics.com/uploads/products/Clear_Mylar_Rolls-xl.jpg

Fig. 37 <http://www.gasketsinc.com/images/products/item/1877-1.jpg?v=1425929255>

Fig. 38 <http://www.buyaerogel.com/wp-content/uploads/2013/09/spaceloft-10-mm.jpg>

Fig.39 https://www.texashomeexteriors.com/wp-content/uploads/2013/12/tmpd41c-tmp_tcm138-1637420-1.jpg

Fig. 40 <http://accessnorthstructures.com/wp-content/uploads/2014/06/ETFE-welding-4-1024x685.jpg>

Fig. 41 https://www.sattler-global.com/ta-site-static_files/images/content/ETFE-Materialmuster1_-_400x267.jpg

Fig. 42 <https://i.ytimg.com/vi/YSvPIQDnu5l/maxresdefault.jpg>

Fig. 43 <http://www.birdair.com/tensile-architecture/membrane/ptfe-fiberglass>

Fig. 44 <http://www.eccoimg.com/-/media/images/ecco/contentretainer/backgrounds/aw14/style/goretex/topbanner.jpg?w=1901>

Fig. 45 http://www.detail-online.com/fileadmin/_migrated/pics/149_500_335.jpg

Fig. 46 <https://www.dickson-constant.com/nl/NL/zonwering/symphony>

Fig. 47 <https://dir.indiamart.com/delhi/aluminum-foils.html>

Fig. 48 <https://cnet1.cbsistatic.com/img/mm13lc3hOgDbYx9fCdcOIbYTfIA=/1600x900/2016/02/17/613b62da-f4fe-4e70-950a-03225a2d2e2f/schott-ultra-thin-glass.jpg>

Fig. 49 Canceled

Fig. 50 http://www.tapplastics.com/uploads/products/Clear_Mylar_Rolls-xl.jpg

Fig. 51 Canceled

Fig. 52 (Bechthold, 2008)

Fig. 53 (Bechthold, 2008)

Fig. 54 (Bechthold, 2008)

Fig. 55 (Bechthold, 2008)

Fig. 56 (Bechthold, 2008)

Fig. 57 (Bechthold, 2008)

Fig. 58 <https://grimshaw.global/projects/the-eden-project-the-biomes/>

Fig. 59 <https://grimshaw.global/projects/the-eden-project-the-biomes/>

Fig. 60 <https://grimshaw.global/projects/the-eden-project-the-biomes/>

Fig. 61 <http://kierantimberlake.com/pages/view/28>

Fig. 62 <http://kierantimberlake.com/pages/view/28>

Fig. 63 <http://kierantimberlake.com/pages/view/28>

Fig. 64 <http://kierantimberlake.com/pages/view/28>

Fig. 65 Photo taken by author

Fig. 66 Photo taken by author

Fig. 67 Photo taken by author

Fig. 68 Photo taken by author

Fig. 69 <http://www.archdaily.com/322830/meme-experimental-house-kengo-kuma-associates>

Fig. 70 <http://www.archdaily.com/322830/meme-experimental-house-kengo-kuma-associates>

Fig. 71 <http://www.archdaily.com/322830/meme-experimental-house-kengo-kuma-associates>

Fig. 72 <http://www.rubbuk.com/projects/thermohall/cks-bilservice.htm>

Fig. 73 <http://www.rubbuk.com/projects/thermohall/cks-bilservice.htm>

Fig. 74 <http://www.franken-Architekten.de/index.php?pagetype=projectdetail&lang=en&cat=3¶m=cat¶m2=38¶m3=0&>

Fig. 75 <http://www.archea.it/en/ubpa-b3-2-pavilion-world-expo-2010/>

- Fig. 76 <http://www.detail-online.com/inspiration/single-family-house-in-tokyo-106863.html>
- Fig. 77 <http://tentech.nl/textarchproj/app/>
- Fig. 78 https://allianz-arena.com/binaries/content/gallery/allianz-arena/media/images/allianz-arena/baa_6863.jpg/baa_6863.jpg/fcbhippo%3Alargesixteentontone
- Fig. 79 <http://www.canobbio.com/zenith-strasburg-eng>
- Fig. 80 <http://tentech.nl/textarchproj/islazul/>
- Fig. 81 <https://www.dezeen.com/2012/06/12/olympic-shooting-venue-by-magma-architecture/>
- Fig. 82 (Knaack, 2011)
- Fig. 83 (Knaack, 2011)
- Fig. 84 (Knaack, 2011)
- Fig. 85 (Barf, 2010)
- Fig. 86 (Llorens, 2015)
- Fig. 87 <http://www.archdaily.com/512617/turninn-pk-arkitektar>
- Fig. 88 (www.reynaers.com)
- Fig. 89 (www.reynaers.com)
- Fig. 90 (Murray, 2009)
- Fig. 91 http://www.barkowleibinger.com/archive/view/trutec_building
- Fig. 92 (Murray, 2009)
- Fig. 93 http://www.barkowleibinger.com/archive/view/trutec_building
- Fig. 94 (Murray, 2009)
- Fig. 95 <http://kierantimberlake.com/post/view/269>
- Fig. 96 <http://www.ykkapfacade.com/completed-project-detail>
- Fig. 97 <http://www.shildan.com/project/the-new-york-times-building/>
- Fig. 98 <https://www.dezeen.com/2007/11/07/bernard-tschumis-blue-tower-opens/>
- Fig. 99 <https://skyscrapercenter.com/building/aspire-tower/535>
- Fig. 100 <http://www.ykkapfacade.com/completed-project-detail>
- Fig. 101 Created by author
- Fig. 102 http://images.adsttc.com/media/images/505d/696c/28ba/0d27/1500/034f/large_jpg/stringio.jpg?1414012085
- Fig. 103-110 Canceled
- Fig. 111 Created by author
- Fig. 112 Created by author
- Fig. 113 Created by author and http://www.mwtw.com/images/other/rhino/Baladeo/2016/PLR062_0.png
- Fig. 114 Created by author
- Fig. 115 Created by author
- Fig. 116 Created by author
- Fig. 117 Created by author
- Fig. 118 Created by author and http://www.oled-info.com/files/4DS-transparent-PMOLED-img_assist-351x263.jpg
- Fig. 119-175 Created by author
- Fig. 176-187 Created by author
- Skyline from: https://commons.wikimedia.org/wiki/File:1_Singapore_skyline.jpg
- Fig. 188 Created by author
- Fig. 189 Created by author
- Fig. 190 (TNO)
- Fig. 191-221 Created by author
- Tab. 1-12 Created by author

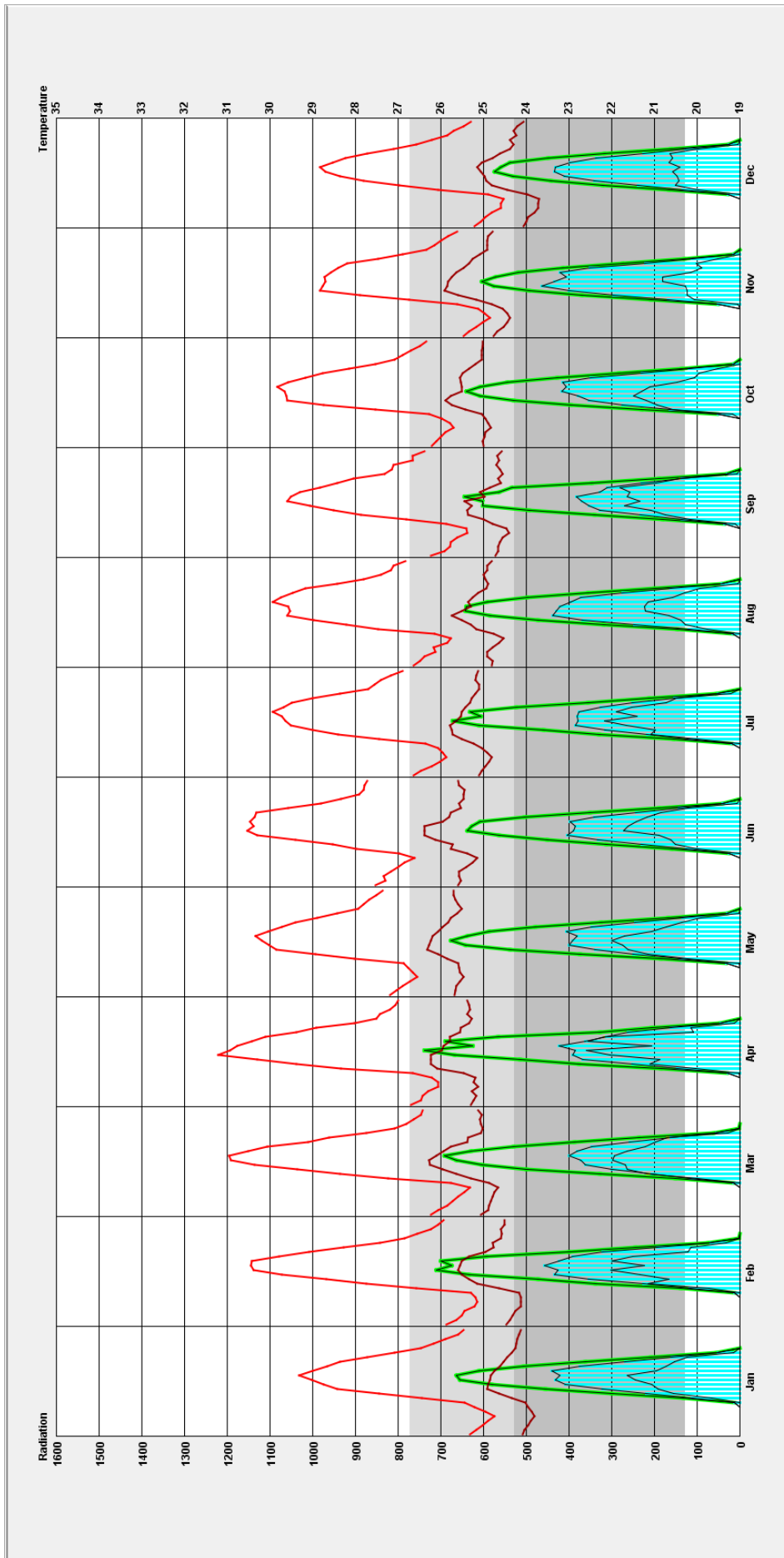
14

APPENDICES

Climate consultant data

MONTHLY MEANS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Global Horiz Radiation (Avg Hourly)	380	417	399	413	387	370	383	374	380	374	354	345	Wh/sq.m
Direct Normal Radiation (Avg Hourly)	149	169	193	189	170	158	183	129	179	140	100	119	Wh/sq.m
Diffuse Radiation (Avg Hourly)	270	286	248	261	256	252	246	272	239	265	279	262	Wh/sq.m
Global Horiz Radiation (Max Hourly)	1000	1007	1040	1027	927	881	915	951	991	1009	925	918	Wh/sq.m
Direct Normal Radiation (Max Hourly)	923	903	897	895	853	771	810	758	817	858	739	776	Wh/sq.m
Diffuse Radiation (Max Hourly)	552	524	510	504	494	466	490	497	503	508	563	526	Wh/sq.m
Global Horiz Radiation (Avg Daily Total)	4544	4994	4797	4972	4674	4471	4633	4507	4565	4479	4230	4116	Wh/sq.m
Direct Normal Radiation (Avg Daily Total)	1788	2031	2323	2284	2057	1911	2212	1554	2160	1676	1201	1424	Wh/sq.m
Diffuse Radiation (Avg Daily Total)	3224	3424	2975	3140	3096	3053	2978	3285	2873	3174	3337	3130	Wh/sq.m
Global Horiz Illumination (Avg Hourly)	43060	47304	45434	46905	44053	42046	43534	42541	43125	42553	40368	39209	lux
Direct Normal Illumination (Avg Hourly)	13054	14752	16981	16904	14516	13139	16045	10850	15459	11853	8262	10145	lux
Dry Bulb Temperature (Avg Monthly)	26	27	27	28	28	28	27	27	27	27	26	26	degrees C
Dew Point Temperature (Avg Monthly)	23	23	24	24	24	24	24	24	23	24	24	23	degrees C
Relative Humidity (Avg Monthly)	83	82	84	82	83	80	82	81	83	84	88	85	percent
Wind Direction (Monthly Mode)	30	30	30	40	0	120	190	200	150	0	0	20	degrees
Wind Speed (Avg Monthly)	3	3	1	1	1	2	2	2	1	1	1	2	m/s
Ground Temperature (Avg Monthly of 3 Depths)	27	27	27	27	27	27	27	26	26	26	26	27	degrees C

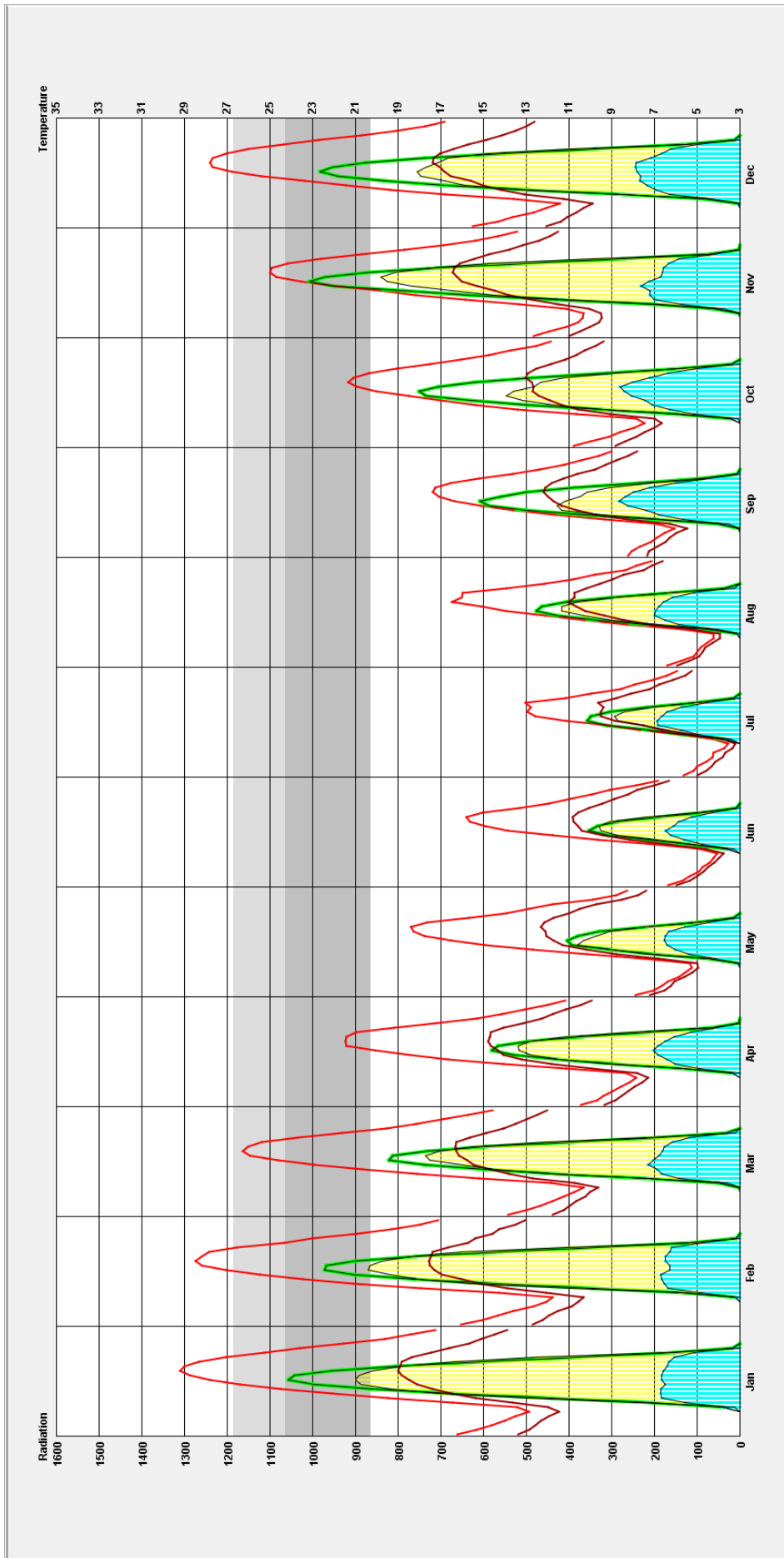
Climate consultant data Singapore



Climate consultant temperature and radiation graph Singapore

MONTHLY MEANS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Global Horiz Radiation (Avg Hourly)	589	553	459	329	235	196	203	269	346	417	544	557	Wh/sq.m
Direct Normal Radiation (Avg Hourly)	567	548	440	322	223	192	168	241	263	331	499	489	Wh/sq.m
Diffuse Radiation (Avg Hourly)	147	143	151	136	120	108	123	134	176	175	158	177	Wh/sq.m
Global Horiz Radiation (Max Hourly)	1094	1041	958	806	634	514	578	715	879	1011	1072	1097	Wh/sq.m
Direct Normal Radiation (Max Hourly)	996	958	904	863	786	737	783	768	882	957	958	973	Wh/sq.m
Diffuse Radiation (Max Hourly)	499	487	441	373	373	267	345	346	446	545	592	593	Wh/sq.m
Global Horiz Radiation (Avg Daily Total)	8227	7334	5613	3686	2420	1926	2048	2912	4090	5394	7482	7900	Wh/sq.m
Direct Normal Radiation (Avg Daily Total)	7921	7257	5385	3608	2302	1891	1697	2594	3108	4283	6854	6944	Wh/sq.m
Diffuse Radiation (Avg Daily Total)	2053	1908	1839	1516	1236	1063	1237	1455	2092	2268	2171	2513	Wh/sq.m
Global Horiz Illumination (Avg Hourly)	63832	59674	50041	36149	25757	21525	22417	29586	38030	45580	58862	60309	lux
Direct Normal Illumination (Avg Hourly)	56434	54347	43259	31131	21157	17835	15790	23232	25607	32724	49583	48452	lux
Dry Bulb Temperature (Avg Monthly)	21	20	17	14	11	9	7	9	11	14	17	20	degrees C
Dew Point Temperature (Avg Monthly)	12	10	9	9	6	5	5	5	7	6	10	9	degrees C
Relative Humidity (Avg Monthly)	60	57	64	75	79	83	85	82	77	65	67	55	percent
Wind Direction (Monthly Mode)	150	180	140	150	150	150	150	140	160	140	150	240	degrees
Wind Speed (Avg Monthly)	2	2	2	1	1	1	1	1	1	2	2	2	m/s
Ground Temperature (Avg Monthly of 3 Depths)	16	18	18	18	16	14	12	10	9	10	11	13	degrees C

Climate consultant data Santiago



Climate consultant temperature and radiation graph Santiago

ASHRAE Standard 55, current Handbook of Fundamentals Comfort Model (select Help for definitions)

1. COMFORT: (using ASHRAE Standard 55)

1.0	Winter Clothing Indoors (1.0 Clo=long pants,sweater)
0.5	Summer Clothing Indoors (.5 Clo=shorts,light top)
1.1	Activity Level Daytime (1.1 Met=sitting,reading)
90.0	Predicted Percent of People Satisfied (100 - PPD)
20.3	Comfort Lowest Winter Temp calculated by PMV model(ET* C)
24.3	Comfort Highest Winter Temp calculated by PMV model(ET* C)
26.7	Comfort Highest Summer Temp calculated by PMV model(ET* C)
84.6	Maximum Humidity calculated by PMV model (%)

2. SUN SHADING ZONE: (Defaults to Comfort Low)

23.8	Min. Dry Bulb Temperature when Need for Shading Begins (°C)
315.5	Min. Global Horiz. Radiation when Need for Shading Begins (Wh/sq.m)

3. HIGH THERMAL MASS ZONE:

8.3	Max. Outdoor Temperature Difference above Comfort High (°C)
1.7	Min. Nighttime Temperature Difference below Comfort High (°C)

4. HIGH THERMAL MASS WITH NIGHT FLUSHING ZONE:

16.7	Max. Outdoor Temperature Difference above Comfort High (°C)
1.7	Min. Nighttime Temperature Difference below Comfort High (°C)

5. DIRECT EVAPORATIVE COOLING ZONE: (Defined by Comfort Zone)

20.0	Max. Wet Bulb set by Max. Comfort Zone Wet Bulb (°C)
6.6	Min. Wet Bulb set by Min. Comfort Zone Wet Bulb (°C)

6. TWO-STAGE EVAPORATIVE COOLING ZONE:

50.0	% Efficiency of Indirect Stage
------	--------------------------------

7. NATURAL VENTILATION COOLING ZONE:

2.0	Terrain Category to modify Wind Speed (2=suburban)
0.2	Min. Indoor Velocity to Effect Indoor Comfort (m/s)
1.5	Max. Comfortable Velocity (per ASHRAE Std. 55) (m/s)

8. FAN-FORCED VENTILATION COOLING ZONE:

0.8	Max. Mechanical Ventilation Velocity (m/s)
3.0	Max. Perceived Temperature Reduction (°C) (Min Vel, Max RH, Max WB match Natural Ventilation)

9. INTERNAL HEAT GAIN ZONE (lights, people, equipment):

12.8	Balance Point Temperature below which Heating is Needed (°C)
------	--

10. PASSIVE SOLAR DIRECT GAIN LOW MASS ZONE:

157.7	Min. South Window Radiation for 5.56°C Temperature Rise (Wh/sq.m)
3.0	Thermal Time Lag for Low Mass Buildings (hours)

11. PASSIVE SOLAR DIRECT GAIN HIGH MASS ZONE:

157.7	Min. South Window Radiation for 5.56°C Temperature Rise (Wh/sq.m)
12.0	Thermal Time Lag for High Mass Buildings (hours)

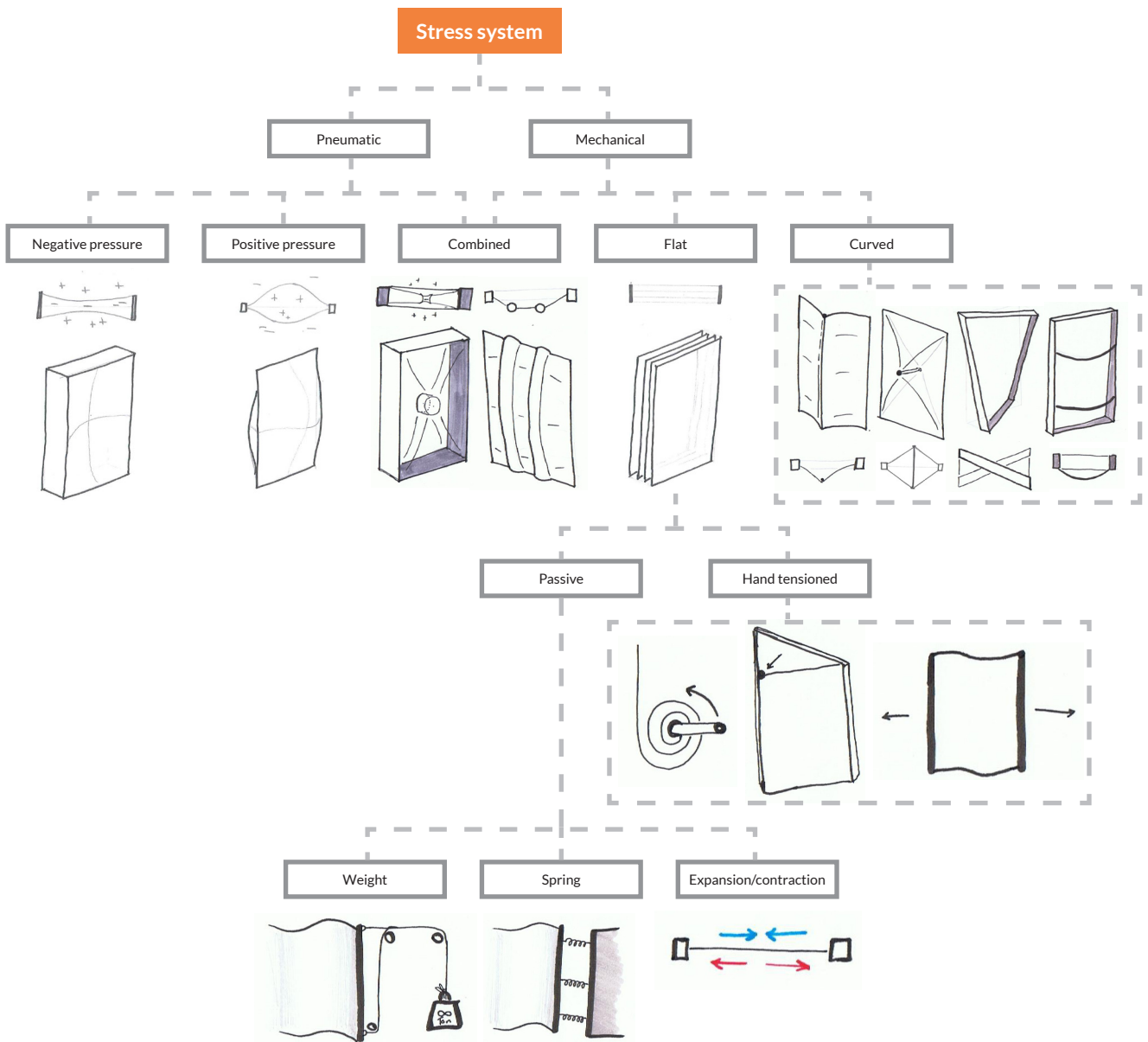
12. WIND PROTECTION OF OUTDOOR SPACES:

8.5	Velocity above which Wind Protection is Desirable (m/s)
11.1	Dry Bulb Temperature Above or Below Comfort Zone (°C)

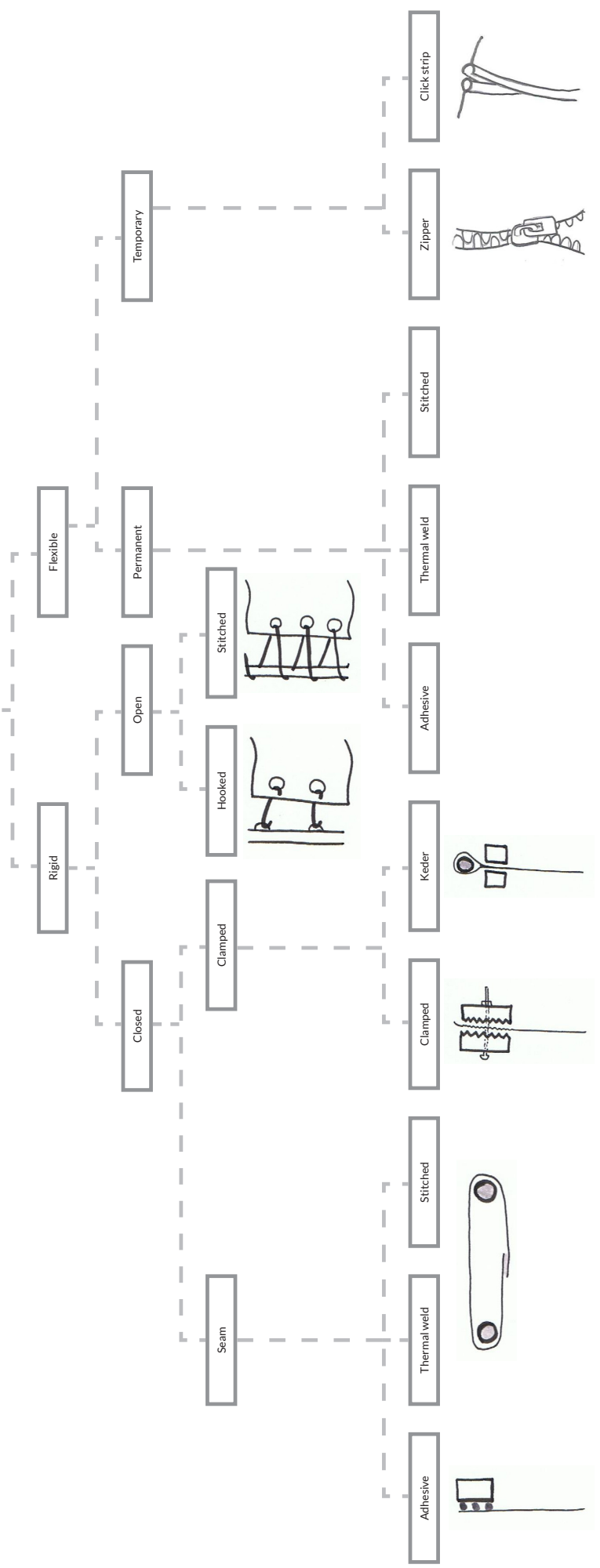
13. HUMIDIFICATION ZONE: (defined by and below Comfort Zone)

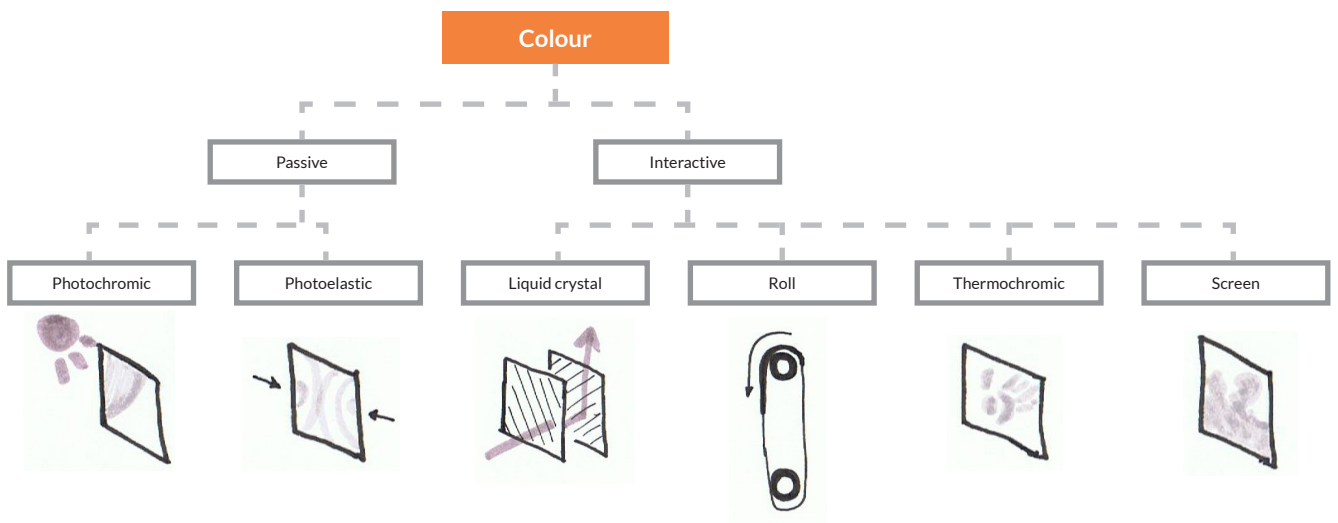
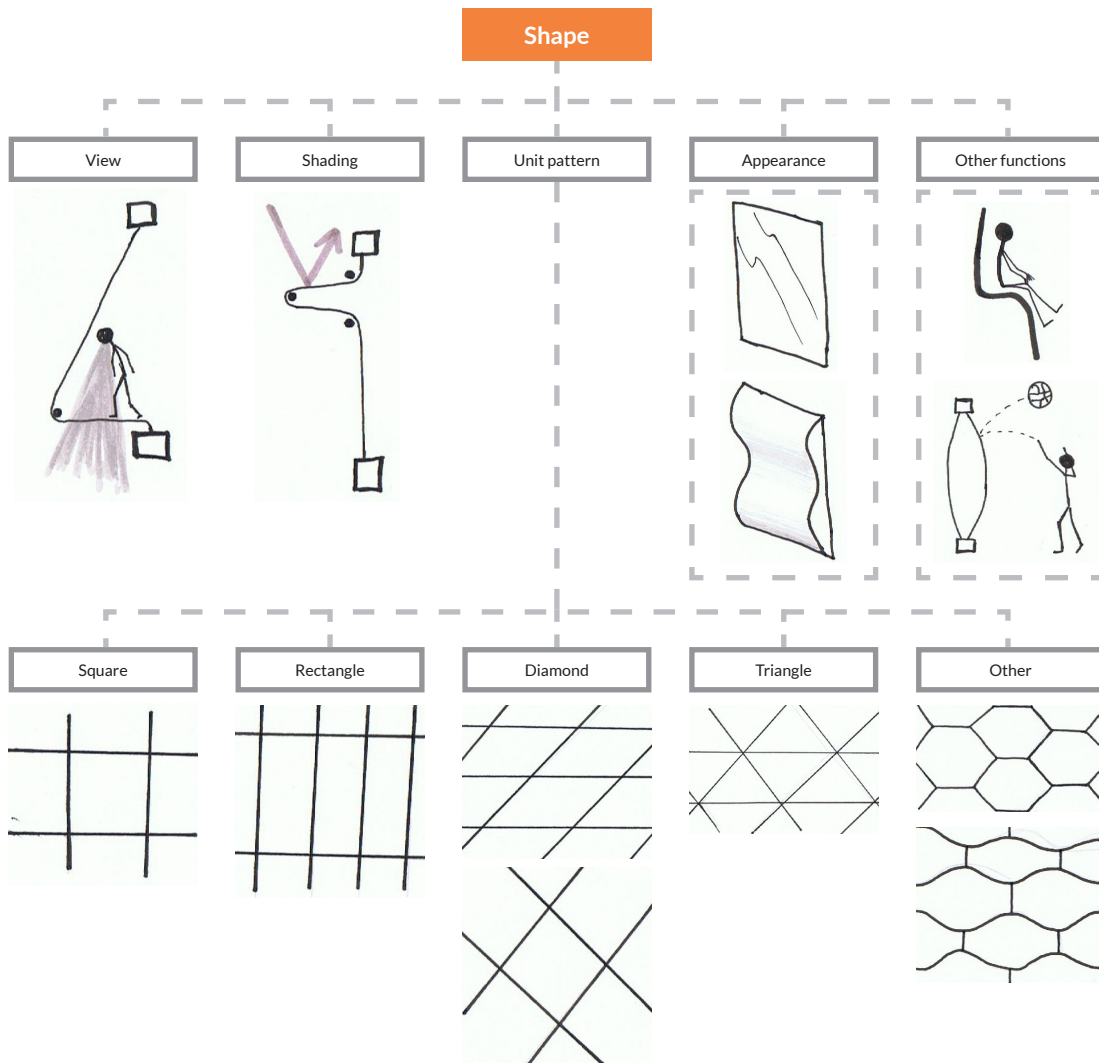
14. DEHUMIDIFICATION ZONE: (defined by and above Comfort Zone)

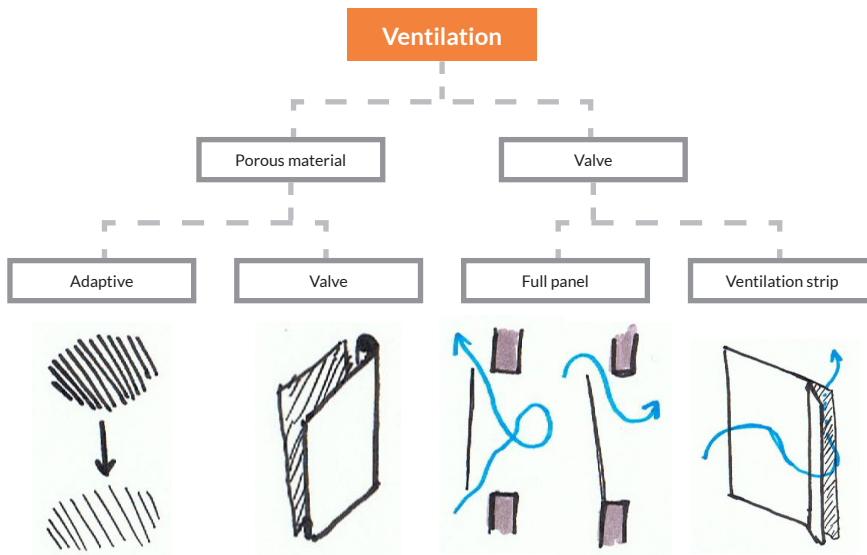
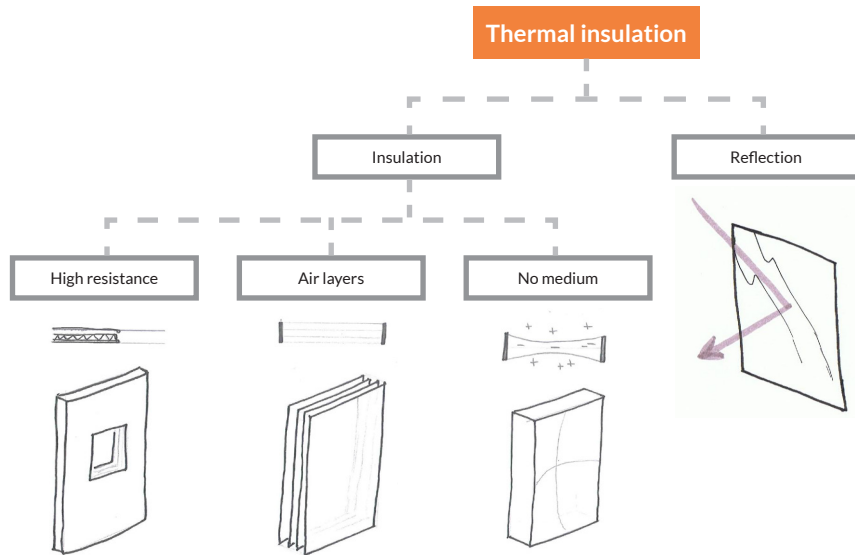
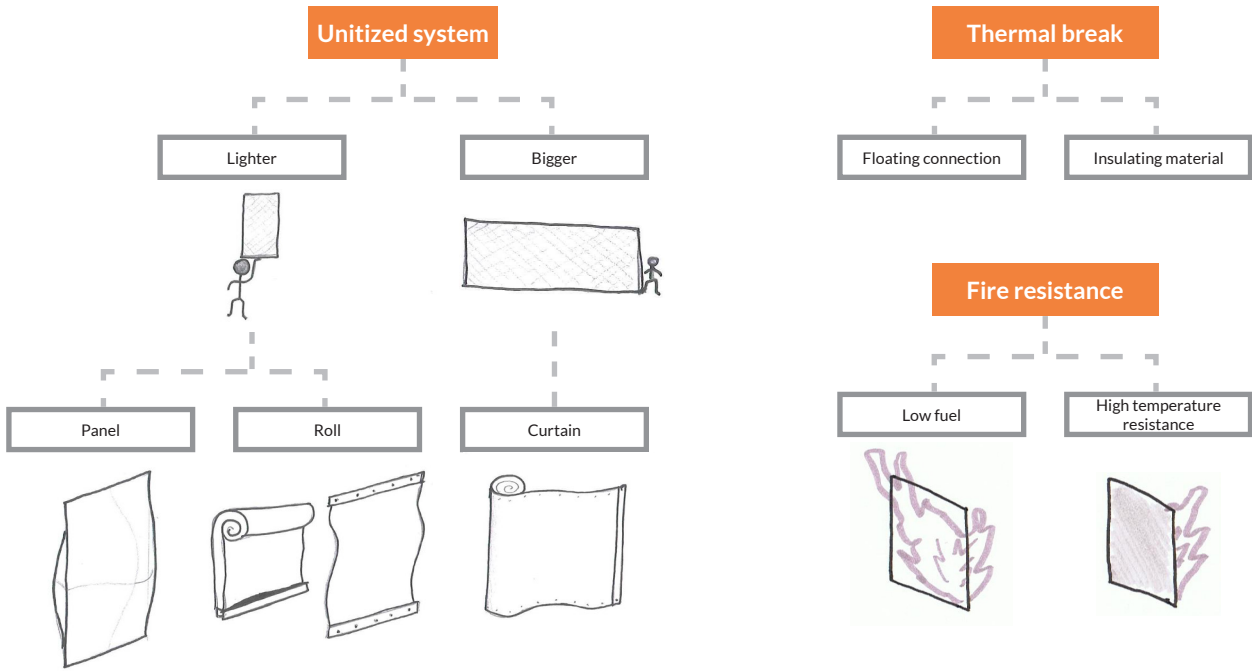
Design solution pathways

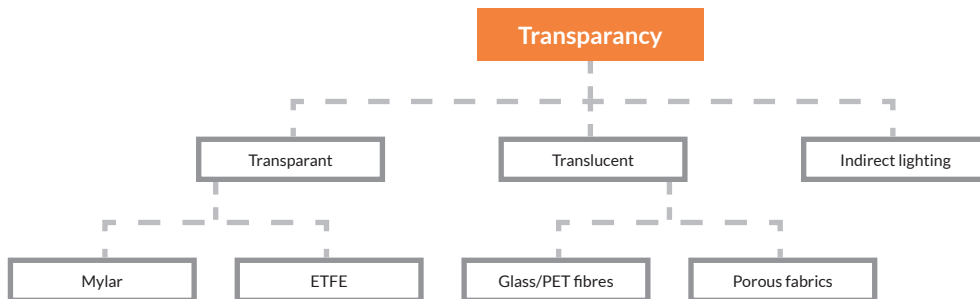
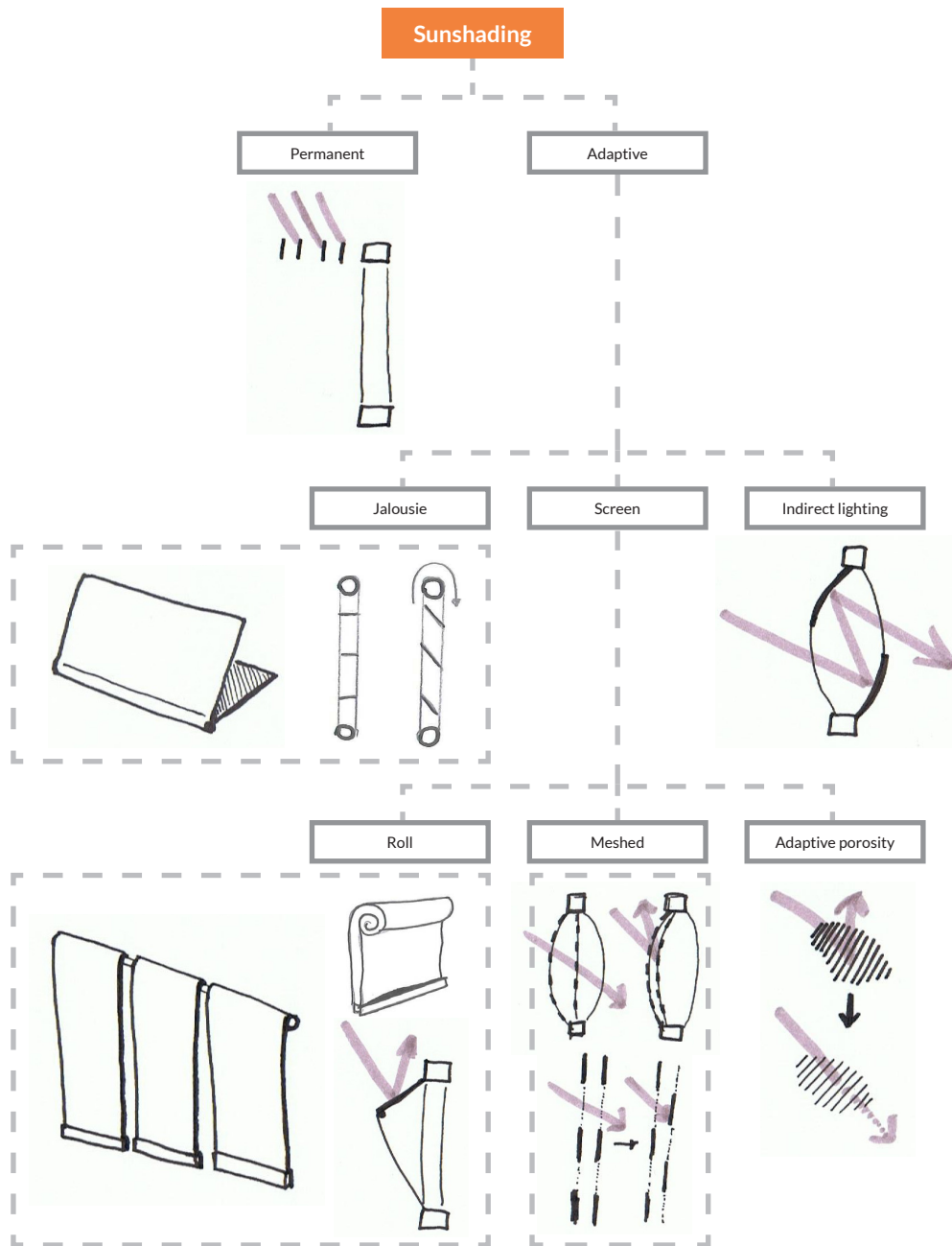


Connections

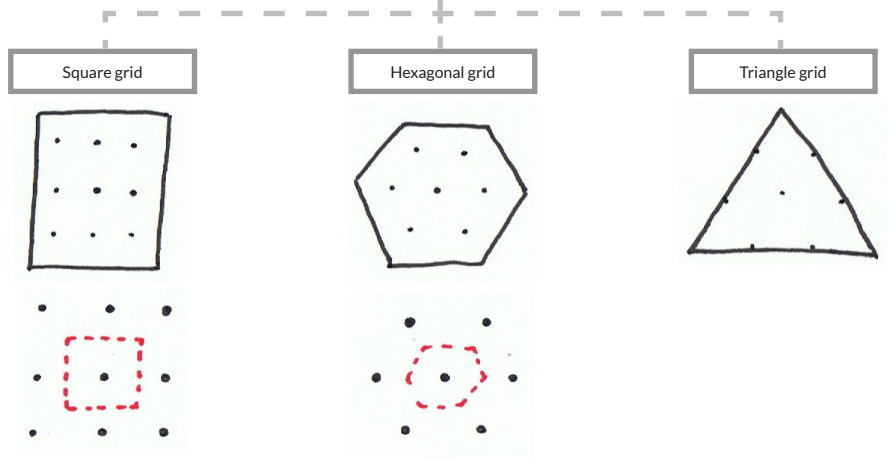




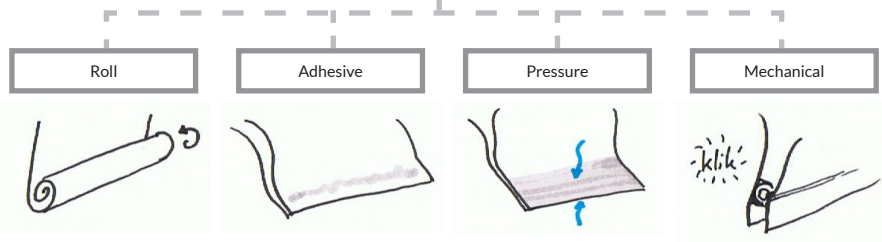




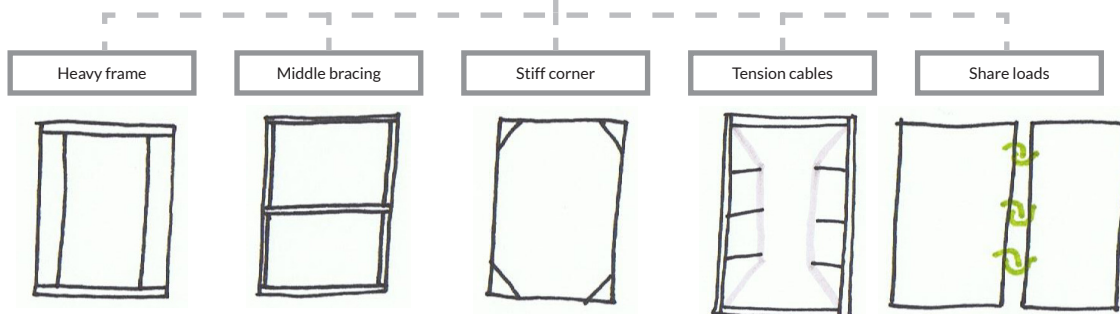
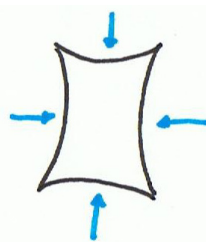
Shape



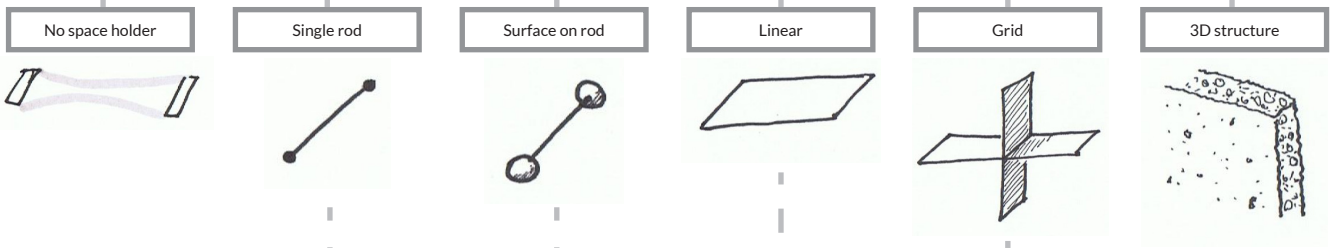
Pressure seal



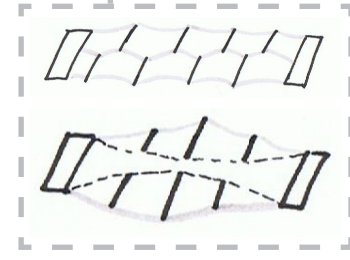
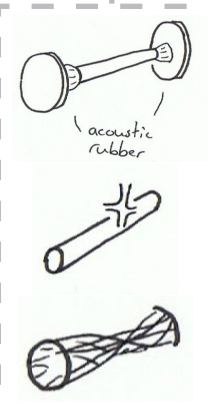
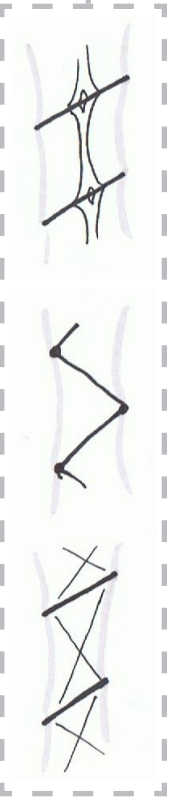
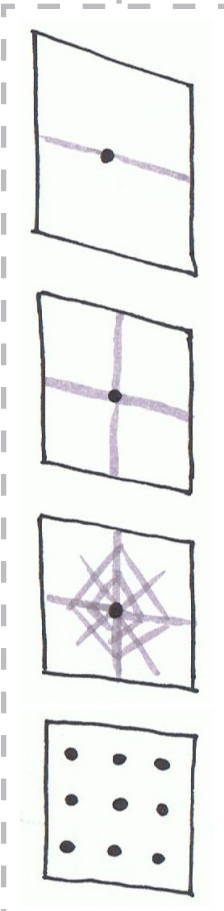
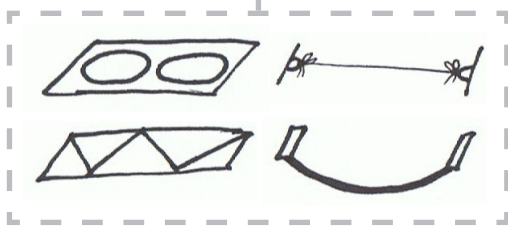
Pressure bracing



Vacuum space holder

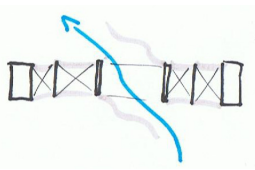


Line types

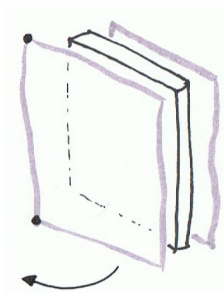


Facade openings

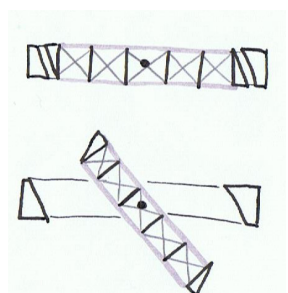
Tent flap



Membrane doors



Pivot window

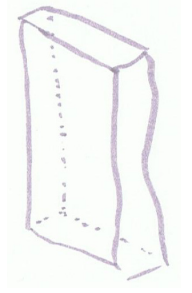
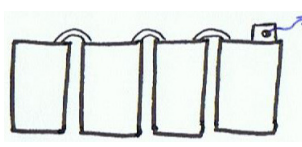


Vacuum pump

One per panel



Multiple panels per pump



Equations used in numerical evaluation

Equations thermal insulation

References: (Bokel, 2015) and (van der Linden, 2011)

r	Heat resistance	m ² K/W
d	Thickness	mm
λ _n	Heat conduction coefficient	W/mK

$$r = \frac{d}{\lambda}$$

λ _v /λ _n	Thermal conductivity ratio	
C	constant equal to 7.6x10 ⁻⁵	mK/N

$$\lambda_v \cdot \lambda_n = 1 / \left(1 + \frac{C}{PP} \right)$$

λ _v	Heat conduction vacuum	W/mK
----------------	------------------------	------

$$\lambda_v = \left(\frac{\lambda_v}{\lambda_n} \right) * \lambda_n$$

α	Heat conduction	W/m ² K
---	-----------------	--------------------

$$\alpha = \frac{1}{r}$$

PP	Pressure parameter	N/mK
P	Pressure	Pa
d	Plate distance	m
T	Absolute temperature	K

$$PP = P \times \frac{d}{T}$$

α _c	Heat convection	W/m ² K
----------------	-----------------	--------------------

ε _{res}	Resulting emission coefficient
ε ₁	Emission coefficient surface 1
ε ₂	Emission coefficient surface 2

$$\frac{1}{\epsilon_{res}} = \frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1$$

α _r	Heat radiation transfer	W/m ² K
σ	Stefan-boltzmann constant 5.67x10 ⁻⁸	W/m ² K ⁴
T ₁	Outside temperature	°K
T ₂	Indoor temperature	°K

$$\alpha_r = 4\epsilon_{res}\sigma \left(\frac{T_1 + T_2}{2} \right)^3$$

α_{cav}	Heat transfer cavity	W/m ² K
----------------	----------------------	--------------------

$$\alpha_{cav} = \alpha_e + \alpha_c + \alpha_r$$

r_i	Heat resistance inside	m ² K/W
r_o	Heat resistance outside	m ² K/W
R_{vac}	Heat resistance vacuum	m ² K/W
R_{spacer}	Heat resistance spacer	m ² K/W
R_{frame}	Heat resistance edge frame	m ² K/W

$$R_{vac} = r_i + r_{etfe} + r_{cav} + r_{etfe} + r_o$$

$$R_{spacer} = r_i + r_{etfe} + r_{spacer} + r_{etfe} + r_o$$

$$R_{frame} = r_i + r_{etfe} + r_{frame} + r_{etfe} + r_o$$

$R_{average}$	Heat resistance average	m ² K/W
S_1	Surface area panel	m ²
S_2	Surface area spacers	m ²
S_3	Surface area frame	m ²

$$R_{average} = R_{spacer} \times \frac{S_2}{S_1} + R_{frame} \times \frac{S_3}{S_1} + R_{vac} * \frac{(S_1 - S_2 - S_3)}{S_1}$$

Equations acoustical insulation

Reference: (Nederlof, et all, 2015)

d_1	Thickness material 1	m
d_2	Thickness material 2	m
ρ_1	Density material 1	Kg/m ³
ρ_2	Density material 2	Kg/m ³
m_1	Mass material 1	Kg/m ²
m_2	Mass material 2	Kg/m ²

$$m = d \times \rho$$

s	Stiffness	n/m ³
d_{cav}	Depth cavity	m
γ	Stiffness ratio	
P_{cav}	Pressure inside cavity	Pa

$$s = \frac{\gamma P_{cav}}{d_{cav}}$$

$f_{cav ms}$	Mass spring frequency	Hz
--------------	-----------------------	----

$$f_{cav ms} = \frac{1}{2\pi \cos\theta} \sqrt{s \left(\frac{1}{m_1} + \frac{1}{m_2} \right)}$$

$R_{cav ms}$	Sound insulation at mass spring resonance	dB
--------------	---	----

$$R_{cav ms} = 20 \log \left(\frac{m_1}{2m_2} + \frac{m_2}{2m_1} \right)$$

ρ_{air}	Density air at atmospheric pressure	Kg/m ³
ρ_{cav}	Density cavity air	Kg/m ³
P	Pressure relative to atmospheric	atm

$$\rho_{cav} = \rho_{air} \times P$$

ω	Angular frequency of the acoustic wave	Rad/s
f	Sound frequency	Hz

$$\omega = 2\pi f$$

$R_{cav bms n}$	Sound insulation below mass spring frequency at normal incidence	dB
c_{air}	Speed of sound through material	m/s
θ	Angle of impedance	0

$$R_{cav bms n} = 10 \log \left(1 + \frac{\omega(m_1 + m_2) \cos\theta^2}{2\rho_{cav} c_{air}} \right)$$

$R_{cav bms r}$	Sound insulation below mass spring frequency at random incidence	dB
-----------------	--	----

$$R_{cav bms r} = R_{cav bms n} - 5$$

$R_{cav ams n}$	Sound insulation after mass spring frequency at normal incidence	dB
-----------------	--	----

$$R_{cav ams n} = 20 \log \left(\frac{\omega m_1 \cos\theta}{2\rho_{cav} c_{air}} \right) + 20 \log \left(\frac{\omega m_2 \cos\theta}{2\rho_{cav} c_{air}} \right) + 20 \log \left(\frac{2\omega d_{cav} \cos\theta}{c_{air}} \right)$$

$R_{cav\ ams\ r}$ Sound insulation after mass spring frequency at random incidence dB

$$R_{cav\ ams\ r} = R_{cav\ ams\ n} - 8.5$$

$f_{cav\ t}$ Transition frequency Hz

$$f_{cav\ t} = \frac{c_{air}}{2\pi d_{cav} \cos\theta}$$

R_{m1} Sound insulation single leaf mass 1 at random incidence dB

R_{m2} Sound insulation single leaf mass 2 at random incidence dB

$$R_{m1/2} = 20 \log\left(\frac{\omega m}{2\rho c}\right) - 5$$

$R_{cav\ t}$ Sound insulation after transition frequency dB

$$R_{cav\ t} = R_{m1} + R_{m2} + 6$$

$f_{cav\ r}$ Cavity resonance frequency Hz
 n frequency mode integer

$$f_{cav\ r} = \frac{n c_{air}}{2 d_{cav}}$$

C Propagation speed of wave through the membrane material m/s
 E Youngs modulus etfe Pa

$$C = \sqrt{\frac{E}{\rho_{m1}}}$$

f_g Threshold frequency

$$f_g = \frac{64000}{C d_1}$$

S_{eff} Effective area of sound which is coupled by the spacer m²

$$S_{eff} = \frac{c_{air}^2}{3f_g^2}$$

m_s Mass spacer Kg

R_{spacer} Sound insulation spacer dB

$$R_{spacer} = 20 \log\left(\frac{\omega(m_1 + m_{spacer} + m_2)}{2\rho c}\right) - 5$$

$R_{composite}$ Average sound insulation of façade dB

S_{tot} Total surface area m²

S_{spacer} Spacer surface area m²

$$R_{composite} = -10 \log\left(\frac{S_{tot} - S_{spacer}}{S_{tot}} 10^{-\frac{R_{cav}}{10}} + \frac{S_{spacer}}{S_{tot}} 10^{-\frac{R_{spacer}}{10}}\right)$$

Equations structural performance

References: (Welleman, 2006) and (Charbonneau, 2011)

σ_{etfe}	Yield strength ETFE	N/mm ²
n	Safety factor	
$\sigma_{etfe\ eff}$	Yield strength ETFE with safety	N/mm ²
$\sigma_{etfe} = n * \sigma_{etfe\ eff}$		
C	Circumferencespacer head	mm
d_{spacer}	Diameter spacer head	mm
$C = \pi d_{spacer}$		
S_{spacer}	Surface area spacer head	mm ²
$S_{spacer} = \pi(d_{spacer}/2)^2$		
P	Atmospheric pressure	N/mm ²
P_{vac}	Vacuum pressure	N/mm ²
ΔP_{vac}	Pressure difference	N/mm ²
$\Delta P = P - P_{vac}$		
V	Wind speed	mm/s
P_{wind}	Wind pressure	N/mm ²
$P_{wind} = 0.631V^2$		
C_d	Surface drag coefficient	
$P_{wind\ eff}$	Effective wind pressure	N/mm ²
$P_{wind\ eff} = P_{wind} * C_d$		
L	Distance between spacers	mm
S_{load}	Load area per spacer	mm ²
$S_{load} = L^2$		
$\sigma_{outside}$	Tension on outside membrane	N/mm
$F_{outside} = (\Delta P_{vac} + P_{wind\ eff}) \times L$		
σ_{inside}	Tension on inside membrane	N/mm
$F_{inside} = \Delta P_{vac} \times L$		
$F_{outside}$	Force on spacer from outside	N
h	Sag depth of ETFE span	mm
$F_{outside} = \sigma_{outside}(L^2 + 4h)/8h$		
F_{inside}	Force on spacer from inside	N
$F_{inside} = \sigma_{inside}(L^2 + 4h)/8h$		

E_{etfe} ΔL	Youngs modulus ETFE Elongation during stress	N/mm ² mm
	$\Delta L = \sigma_{max}/E_{etfe}$	
F_{spacer}	Pressure on spacer	N/mm ²
	$F_{spacer} = F_{outside} + F_{inside}$	
d_{rod} I_{spacer}	Diameter spacer rod moment of inertia of spacer	mm mm ⁴
	$I_{spacer} = \frac{\pi(d_{rod}/2)^4}{4}$	
I_{buckle}	Moment of inertia radius	mm ²
	$I_{buckle} = \sqrt{\frac{I_{spacer}}{S_{spacer}}}$	
λ_{buckle} d_{cav}	Slimness Depth cavity	mm mm
	$\lambda_{buckle} = d_{cav}/I_{buckle}$	
E_{spacer} $\sigma_{max buckling}$	Youngs modulus spacer Buckling pressure	N/mm ² N/mm ²
	$\sigma_{max buckling} = \frac{\pi^2 E_{spacer}}{\lambda_{buckle}^2}$	
F_{pull}	Forces puling in frame per spacer	N
	$F_{pull} = \frac{F_{outside}L}{8h} + \frac{F_{inside}L}{8h}$	
F_{side} N	Force per side Number of spacers on that side	N #
	$F_{side} = \frac{F_{pull}}{4} \times N$	
W H q_{frame}	Panel width Panel height Linear force on frame	mm mm N/mm
	$q_{frame} = F_{side}/H$	
M	Maximum moment in frame	Nmm
	$M = \frac{q_{frame}H^2}{8}$	

I_{frame}	Moment of inertia of frame	mm^4
w	Width square frame profile	mm
h	Height square frame profile	mm
t	Thickness square frame profile	mm
	$I_{frame} = \frac{wh^3 - (b - 2t)(h - 2t)^3}{12}$	
D	Maximum deflection	mm
E_{frame}	Youngs modulus frame material	N/mm^2
	$D = \frac{5q_{frame}H^4}{384E_{frame}I_{frame}}$	
W_{frame}	Resistance moment of frame	mm^3
	$W_{frame} = \frac{wh^3 - (b - 2t)(h - 2t)^3}{6h}$	
σ_{frame}	Maximum tension in frame	N/mm^2
	$\sigma_{frame} = M/W_{frame}$	
ΔP_{vac}	Pressure difference	atm
S_{panel}	Panel surface area	m^2
G_{O_2}	Oxygen permeability	$cm^3/(m^2.day.atm)$
G_{CO_2}	Carbon dioxide permeability	$cm^3/(m^2.day.atm)$
G_N	Nitrogen permeability	$cm^3/(m^2.day.atm)$
G_{eff}	Air infiltration through permeation	cm^3/day

$$G_{eff} = (G_{O_2} + G_{CO_2} + G_N) \times (\Delta P_{vac} S_{panel})$$

Sound insulation test equations

Reference: (Nederlof, et al, 2015)

L_{ea}	Energetic average sound pressure level
t_{total}	total measurement time
L_s	Single measurement sound pressure level
t_s	Single measurement time interval

$$L_{ea} = 10 \log \left(\left(\frac{1}{t_{total}} \right) * \sum \left(10^{\frac{L_s}{10}} * t_s \right) \right)$$

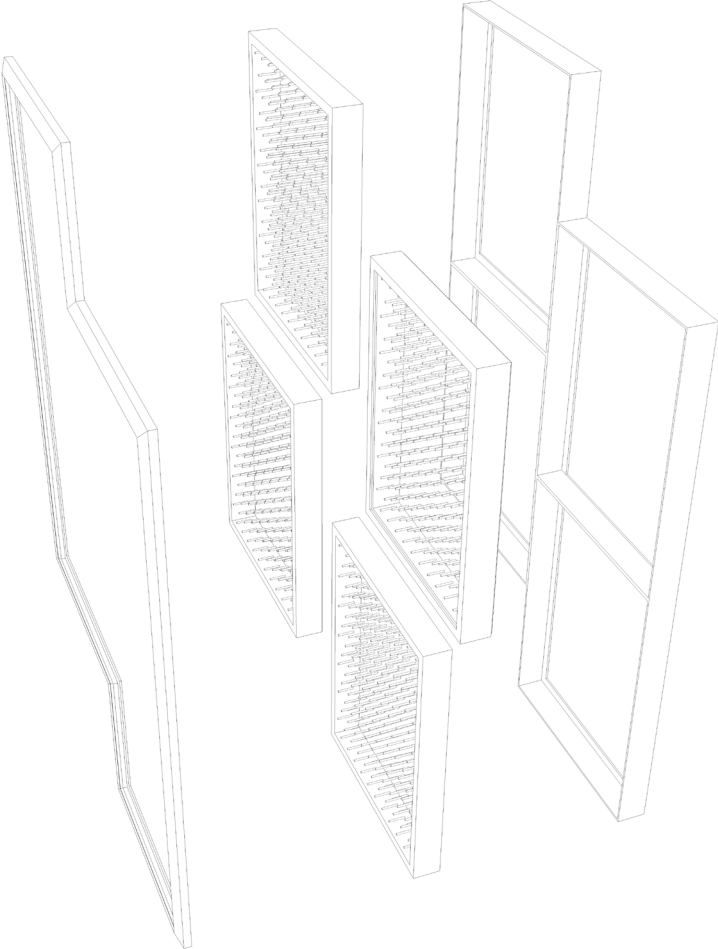
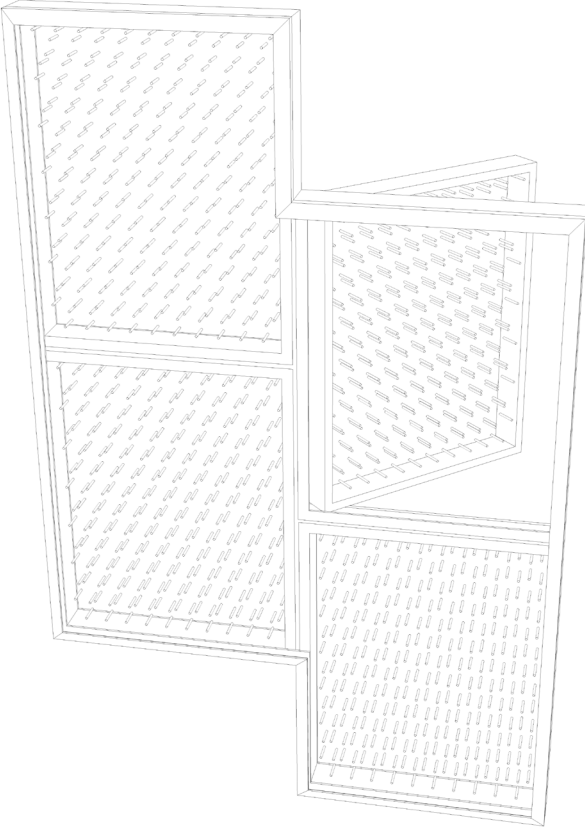
A_{room}	Sound absorption of the room
S_{room}	Inner surface area of the room
V_{room}	Volume of the room
v_{sound}	velocity of sound through air
R_{room}	measured reverberation time in the room

$$A_{room} = \frac{S_{room} * v_{sound}}{R_{room}}$$

$L_{material}$	Sound insulation of the tested material
L_{inside}	Measured sound pressure level inside the testbox
$L_{outside}$	Measured sound pressure level inside the room
$S_{material}$	Surface area tested material

$$L_{material} = L_{inside} - L_{outside} + 10 \log(S_{material}/A_{room})$$

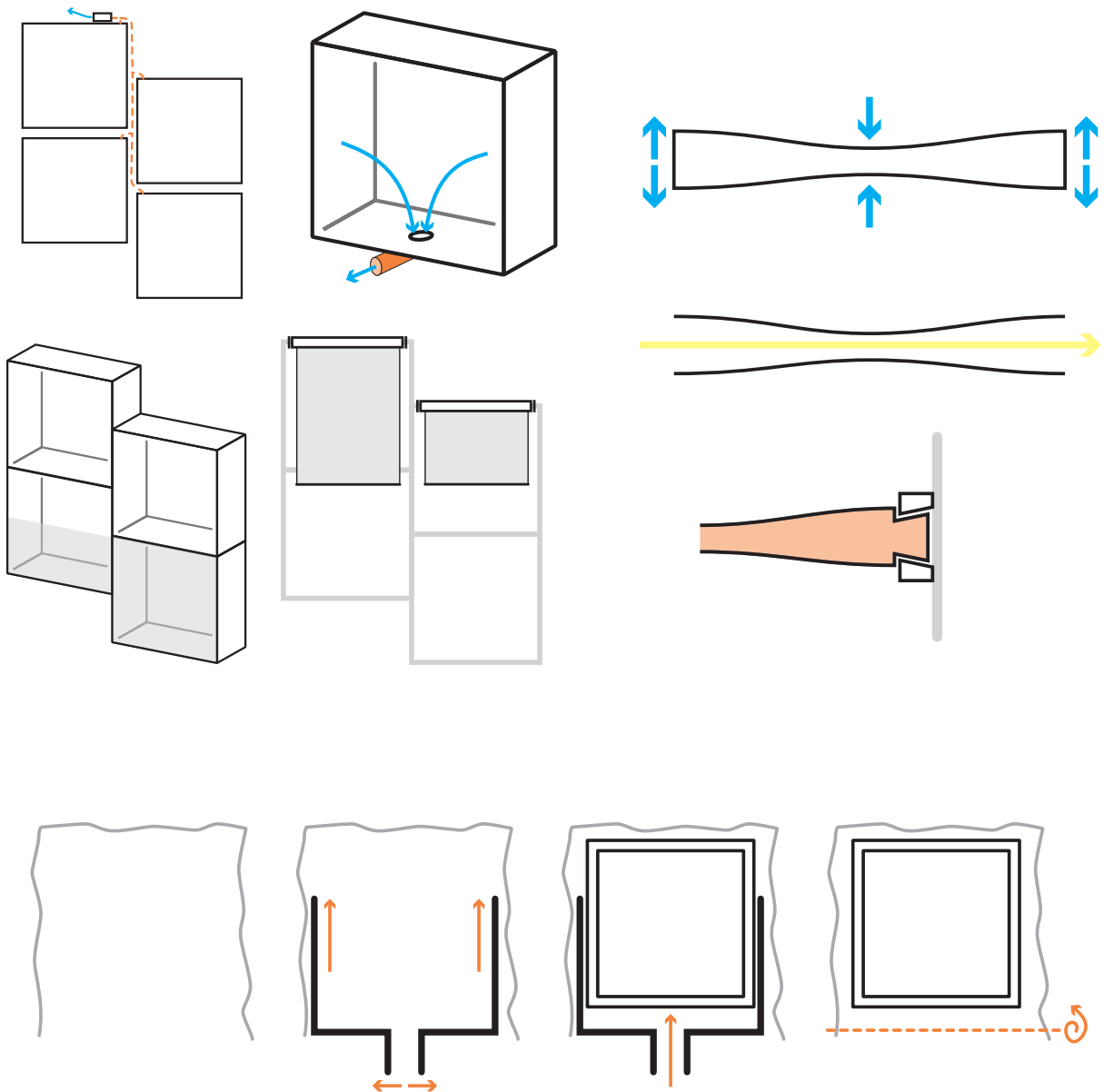
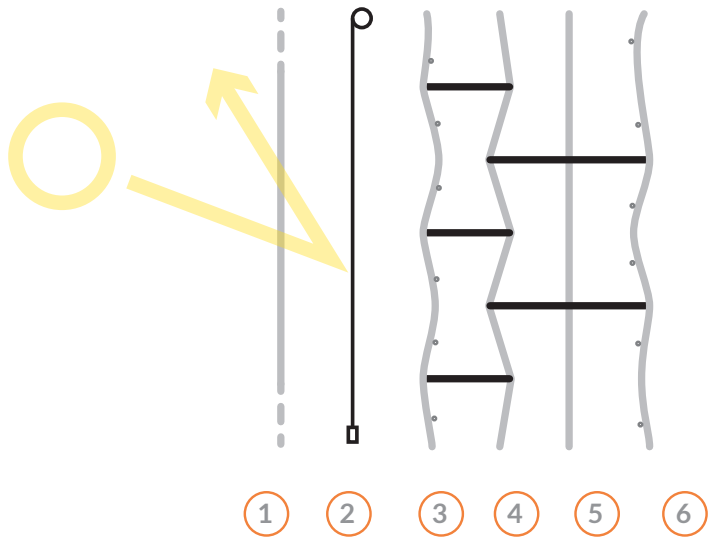
Final concept un-applied designs



Sunshine

Windforce

Convection



KOMO[®]

attest-met-productcertificaat



Nummer	K92424/01	Vervangt	-
Uitgegeven	2016-06-21	d.d.	-
Geldig tot	Onbepaald	Pagina	1 van 14

Verankeringen voor betonnen sandwichconstructies Schöck Nederland b.v.

VERKLARING VAN KIWA

Dit attest-met-productcertificaat is op basis van BRL 0511 "Verankeringen voor betonnen sandwichconstructies" d.d. 2016-05-09 afgegeven conform het Kiwa-Reglement voor Productcertificatie.

Het kwaliteitssysteem en de productkenmerken behorende bij verankeringen voor betonnen sandwichconstructies worden periodiek gecontroleerd.

Op basis daarvan verklaart Kiwa dat:

- Het gerechtvaardigd vertrouwen bestaat, dat de door de certificaathouder geleverde Verankeringen voor betonnen sandwichconstructies bij aflevering voldoen aan:
 - De in dit attest-met-productcertificaat vastgelegde technische specificaties,
 - De in de BRL en dit attest-met-productcertificaat vastgelegde eisen mits de verankeringen voor betonnen sandwichconstructies voorzien zijn van het KOMO[®]-merk op een wijze zoals aangegeven in dit attest-met-productcertificaat.
- De met deze verankeringen samengestelde betonnen sandwichconstructies de prestaties leveren zoals in dit attest-met-productcertificaat zijn omschreven, mits:
 - Wordt voldaan aan de in dit attest-met-productcertificaat omschreven toepassingsvoorwaarden
 - De verwerking geschiedt overeenkomstig de in dit attest-met-productcertificaat vastgelegde voorschriften en/of verwerkingsmethoden

In het kader van dit attest-met-productcertificaat vindt geen controle plaats op de productie van de overige onderdelen van betonnen sandwichconstructies of op de verwerking van verankeringen in betonnen sandwichconstructies

Luc Leroy
Kiwa

Het attest-met-productcertificaat is voorts opgenomen in het overzicht op de website van Stichting KOMO: www.komo.nl.

Gebruikers van dit attest-met-productcertificaat worden geadviseerd om te controleren of deze nog geldig is, raadpleeg hiertoe de website van Kiwa op www.kiwa.nl

Kiwa Nederland B.V.
Sir Winston Churchilllaan 273
Postbus 70
2280 AB RIJSWIJK

Tel. 088 998 44 00
Fax 088 998 44 20
info@kiwa.nl
www.kiwa.nl

Certificaathouder
Schöck Nederland b.v.
Amersfoortseweg15A
7313 AB APELDOORN
Tel. 055 526 88 20
Fax 055 526 88 22
info@schock.nl
www.schock.nl

Productielocatie
Fiberline Compositon A/S
Barmstedt Allé 5
5500 Middelfart - Denmark



Verankerings voor betonnen sandwichconstructies

1 TECHNISCHE SPECIFICATIE

1.1 Algemeen (onderwerp)

Onderwerp van certificatie zijn de verankeringsproducten van betonnen sandwichconstructies. Een betonnen sandwichconstructie bestaat uit een betonnen buitenwand die gekoppeld wordt aan de (dragende) betonnen binnenwand. Tussen de buitenwand en de binnenwand bevindt zich een spouw, waarbij een isolatielaag en/of een luchtlaag aanwezig is. De koppeling tussen de betonnen buitenwand en (dragende) betonnen binnenwand vindt plaats d.m.v. verankeringsproducten. De verankeringsproducten worden toegepast onder condities tot en met exposure class C4 van NEN-EN-ISO 12994-2.

Betonnen sandwichconstructies worden toegepast in gevels van gebouwen. De verankeringsproducten kunnen normaal-, dwarskrachten of momenten opnemen of combinaties daarvan, afhankelijk van het type.

De verankeringsproducten verzorgen een constructieve verbinding tussen de beide te verbinden betondelen van de sandwichconstructie. De belasting van het niet-dragende deel wordt met behulp van het verankeringsproduct overgedragen naar het dragende deel.

Binnen het systeem levert ieder soort anker een specifieke prestatie, daarom zal doorgaans een combinatie van verschillende typen voor de constructieve verbinding zorgdragen.

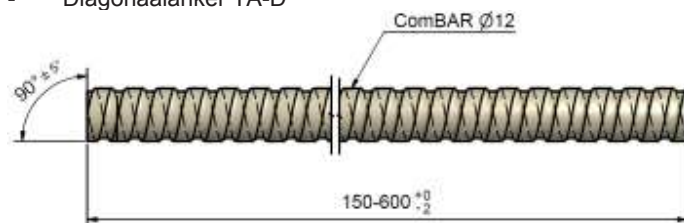
De volgende functies kunnen worden onderscheiden:

- Draaganker: Het Diagonaalanker draagt het eigen gewicht van het buitenblad en eventueel andere lasten evenwijdig aan het buitenspouwblad. Er worden altijd minimaal 2 draagankers toegepast.
- Koppelanker: Het Horizontaalanker neemt normaalkrachten op die ontstaan door eigen gewicht, windkracht, thermische uitzetting en hechting aan de bekisting bij het lossen van de elementen.

1.2 Productspecificatie

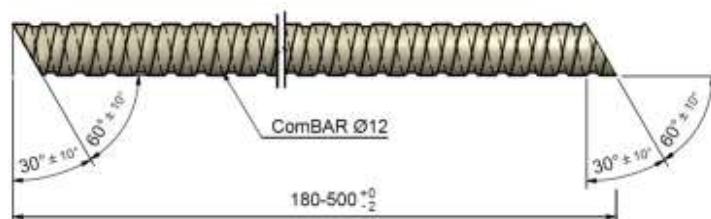
De volgende ankertypen kunnen worden onderscheiden, zie onderstaand figuren:

- Diagonaalanker TA-D



Figuur 1

- Horizontaalanker TA-H



Figuur 2

Diagonaalankers TA-D

Diagonaalankers TA-D zijn ankers vervaardigd uit glasvezelstaven Ø12 voorzien van een uitwendige profilering ten behoeve van een goede aanhechting. De ankers worden ingezet als draaganker en om eventueel andere lasten evenwijdig aan het buitenspouwblad over te dragen aan het binnenspouwblad.

Verankeringen voor betonnen sandwichconstructies

1.3 Onderdelen die in dit certificatiesysteem zijn opgenomen

1.3.1 Producten vervaardigd uit glasvezelversterkte kunststof

ComBAR[®] glasvezelstaven met volgens BRL0513 vastgestelde eigenschappen:

- representatieve treksterkte langeduur $f_{gtk} = 513 \text{ N/mm}^2$
- representatieve E-modulus $E_{gl} = 60000 \text{ N/mm}^2$
- verankeringsfactor $k_{verank} = 1,0$
- lambda-waarde = $0,708 \text{ W/(m}\cdot\text{K)}$

2 Merken en aanduidingen op de producten / verpakkingen / afleverdocumenten

De verpakkingen worden gemerkt met:

- Het KOMO[®]-merk gevolgd door het certificaatnummer. De uitvoering van het merk is als volgt:




- Naam van de certificaathouder
- Productiecode / typeaanduiding en productiedatum

De afleverdocumenten bevatten in ieder geval het volgende:

- Het KOMO[®]-merk gevolgd door het certificaatnummer
- Naam van de certificaathouder
- De productielocatie
- Productiecode / typeaanduiding en productiedatum



Values for global analyses, MD Plank

Geometric Properties	Unit	Value	Module
Moment of inertia, I_{yy}	mm ⁴ /m	1.390.000	
Shear area, A_{yshear}	mm ² /m	2.200	
Total area, A_{ytotal}	mm ² /m	7300	
Material Properties (average)	Unit	Value	
Elastic modulus, E_{ff}	N/mm ²	23.000	
Poisson's ratio, axial, ν_{yx}	-	0,230	
Poisson's ratio, transverse, ν_{xy}	-	0,090	
Temperature expansion, axial, α_{tx}	1/K	11·10 ⁶	
Temperature expansion, transverse, α_{ty}	1/K	19·10 ⁶	

Areal under the edge of the load

Load area [mm]	A ₁ [mm ²]	A ₂ [mm ²]	A ₃ [mm ²]	A ₄ [mm ²]	Total [mm ²]
100x100	676	676	450	450	2.252

Material Properties	Unit	Characteristic value
Full section modulus, E_{eff}	N/mm ²	23000
Tensile strength, axial, f_{tx}	N/mm ²	240
Tensile strength, transverse f_{ty} for - Resin "P2600" or "P2607"	N/mm ²	50
- Resin "P4506"	N/mm ²	35
Compression strength, axial, f_{cx}	N/mm ²	240
Compression strength, transverse, f_{cy}	N/mm ²	90
Flexural strength, axial, f_{fx}	N/mm ²	240
Flexural strength, transverse, f_{fy}	N/mm ²	60
Shear strength, τ_c	N/mm ²	60

Tefzel™ ETFE

Fluoroplastic Film

Properties Bulletin

Description

Tefzel™ ETFE film is a transparent, thermoplastic film that can be heat sealed, thermoformed, vacuum formed, heat bonded, welded, metallized, laminated (combined with dozens of other materials), and used as an excellent hot-melt adhesive. This wide variety of fabrication possibilities combines with the following important properties to offer a unique balance of capabilities not available in other plastic films.

Chemical Compatibility

Tefzel™ ETFE film is chemically inert and solvent resistant to virtually all chemicals, except molten alkali metals, gaseous fluorine, and certain complex halogenated compounds, such as chlorine trifluoride at elevated temperatures and pressures. It also has low permeability to liquids, gases, moisture, and organic vapors.

Electrical Reliability

- Superior reliability and retention of properties over large areas of film
- High dielectric strength, over 160 kV/mm for 0.025-mm film (4000 V/mil for 1-mil film)
- No electric tracking, non-wettable, and non-charring
- Very low power factor and dielectric constant

Wide Thermal Range

- Continuous service temperature: -100 to 150 °C (-150 to 300 °F)
- Melting range: 260 to 280 °C (500 to 536 °F)
- Heat sealable

Mechanical Toughness

- Superior anti-stick and low frictional properties
- High resistance to impact and tearing

Long Time Weatherability*

- Inert to outdoor exposure
- High transmittance of ultraviolet and all but far infrared

Reliability

- Tefzel™ ETFE film contains no plasticizers or other foreign materials.
- Conventional equipment and techniques can be used for processing; basic composition and properties will not be influenced.
- Rigid quality control by Chemours ensures uniform gauge, void-free film.

Tefzel™ ETFE Film

The convenience of Tefzel™ ETFE fluoroplastic in easy-to-use film facilitates the design and fabrication of this low friction thermoplastic for all sorts of high performance jobs. It is transparent and can be heat sealed, thermoformed, welded, and heat bonded. Superior anti-stick properties make it an ideal release film for many applications. A cementable type with an invisible surface treatment is available for bonding to one or both sides with adhesives. This versatility is augmented by the superior properties of a true melt-processible fluoroplastic and the wide choice of product dimensions available from Chemours.

* Type C film not recommended for outdoor use.



Table 1: Typical Properties of Tefzel™ ETFE Fluoroplastic Film

Property	Test Method*	Typical Value**	
		SI Units	English Units
Mechanical			
Tensile Strength at Break	D882	41 MPa	6000 psi
Elongation at Break	D882	300%	
Flex Modulus	D882	830 MPa	120,000 psi
Folding Endurance (MIT)	D2176	50,000 cycles	
Tear Strength—Initial (Graves)	D1004	4.90 N	500 g
Tear Strength—Propagating (Elmendorf)	D1922	0.74 N	75 g
Thermal			
Melt Point	D3418	260–280 °C	500–536 °F
Thermal Conductivity	Cenco-Fitch	0.24 W/(m·K)	1.65 Btu·in/(hr·ft ² ·°F)
Specific Heat	—	1172 J/(kg·K)	0.28 Btu/(lb·°F)
Dimensional Stability	30 min at 150 °C (302 °F)	MD= 1% shrinkage TD= 5% shrinkage	
Oxygen Index	D2863	30%	
Electrical			
Dielectric Strength, short-time, in air at 23 °C (73 °F), 6.35 mm (1/4 in) diameter electrode, 0.79 mm (1/32 in) radius, 60 Hz, 500 V/s rate of rise: 0.025 mm (1 mil) film	D149 Method A	160 kV/mm	4000 V/mil
Dielectric Constant, 25 °C (77 °F), 1 KHz	D150	2.6	
Dissipation Factor, 25 °C (77 °F), 1 KHz	D150	0.0007	
Volume Resistivity, 170 °C (338 °F)	D257	>1 x 10 ¹⁷ ohm·cm	
Chemical			
Moisture Absorption	—	<0.02%	
Permeability, Gas:	D1434	cm ³ /(m ² ·24 hr·atm)***	
Carbon Dioxide		3.9 x 10 ³	
Nitrogen		0.5 x 10 ³	
Oxygen		1.6 x 10 ³	
Permeability, Vapor:	E96	g/(m ² ·d)	g/(100 in ² ·24 hr)
Water		7.8	0.5
General			
Density	D1505	1700 kg/m ³	106 lb/ft ³
Coefficient of Friction Kinetic (Film-to-Steel)	D1894	0.2–0.3	
Refractive Index	D542	1.4	
Solar Transmission	E424	90%	

*ASTM method, unless otherwise specified

**For 0.050-mm (2-mil) film at 25 °C (77 °F), unless otherwise specified

***To convert to cm³/(100 in²·24 hr·atm), multiply by 0.0645

Table 2: Types and Gauges of Tefzel™ ETFE Fluoroplastic Film

Gauge	50	100	200	500
Thickness, mil	0.5	1	2	5
Thickness, µm	12.5	25	50	125
Approx. area factor, ft ² /lb	200	100	50	20
Approx. area factor, m ² /kg	40	20	10	4
Availability				
Type LZ – ETFE, general-purpose	X	X	X	X
Type CLZ – ETFE, one side cementable	—	X	X	X
Type CLZ-20 – ETFE, both sides cementable	—	X	X	—

Note: Each roll of Chemours film is clearly identified as to resin type, film thickness, and film type.

ETFE	200	CLZ
Resin type	Film thickness, 200 gauge, 2 mil	Film type, cementable one side

HOW TO USE THE TEFZEL™ BRAND NAME WITH YOUR PRODUCT

Tefzel™ is a registered trademark of Chemours for its brand of ETFE fluoroplastic resins. The Tefzel™ brand name is licensed by Chemours in association with approved applications. Without a trademark license, customers may not identify their product with the Tefzel™ brand name as Chemours does not sell such offerings with the Tefzel™ trademark. Unlicensed customers may refer to the Chemours product offering with only the Chemours name and product code number descriptor as Chemours sells its product offerings. There are no fair use rights or exhaustion of rights to use the Tefzel™ trademark from buying from Chemours, a Chemours customer or a distributor without a trademark license from Chemours.

If you are interested in applying for a trademark licensing agreement for the Tefzel™ brand, please visit teflon.com/license

CAUTION: Do not use Chemours materials in medical applications involving permanent implantation in the human body or contact with bodily fluids or tissues, unless the material has been provided from Chemours under a written contract that is consistent with Chemours policy regarding medical applications and expressly acknowledges the contemplated use. For further information, please contact your Chemours representative. For medical emergencies, spills, or other critical situations, call (866) 595-1473 within the United States. For those outside of the United States, call (302) 773-2000.

The information set forth herein is furnished free of charge and based on technical data that Chemours believes to be reliable. It is intended for use by persons having technical skill, at their own discretion and risk. The handling precaution information contained herein is given with the understanding that those using it will satisfy themselves that their particular conditions of use present no health or safety hazards. Because conditions of product use are outside our control, Chemours makes no warranties, express or implied, and assumes no liability in connection with any use of this information. As with any material, evaluation of any compound under end-use conditions prior to specification is essential. Nothing herein is to be taken as a license to operate under or a recommendation to infringe any patents.

NO PART OF THIS MATERIAL MAY BE REPRODUCED, STORED IN A RETRIEVAL SYSTEM OR TRANSMITTED IN ANY FORM OR BY ANY MEANS ELECTRONIC, MECHANICAL, PHOTOCOPYING, RECORDING OR OTHERWISE WITHOUT THE PRIOR WRITTEN PERMISSION OF CHEMOURS.

For more information, visit teflon.com/tefel

For sales and technical support contacts, visit teflon.com/industrialglobalsupport

© 2016 The Chemours Company FC, LLC. Teflon™, Tefzel™ and any associated logos are trademarks or copyrights of The Chemours Company FC, LLC. Chemours™ and the Chemours Logo are trademarks of The Chemours Company.

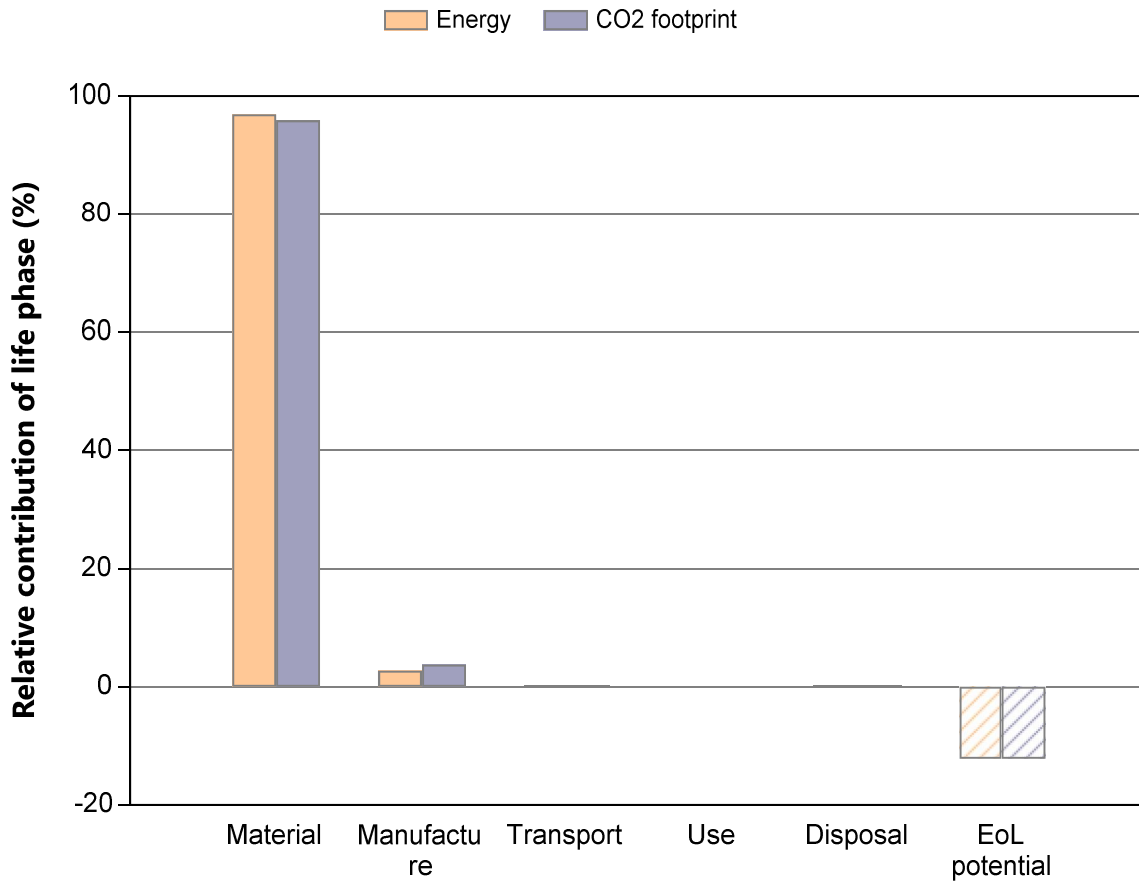
Replaces: K-26943

C-10201 (3/16)

Eco Audit Report

Product name: Membrane facade panel
 Country of use: Asia (excl.China)
 Product life (years): 25

Summary:



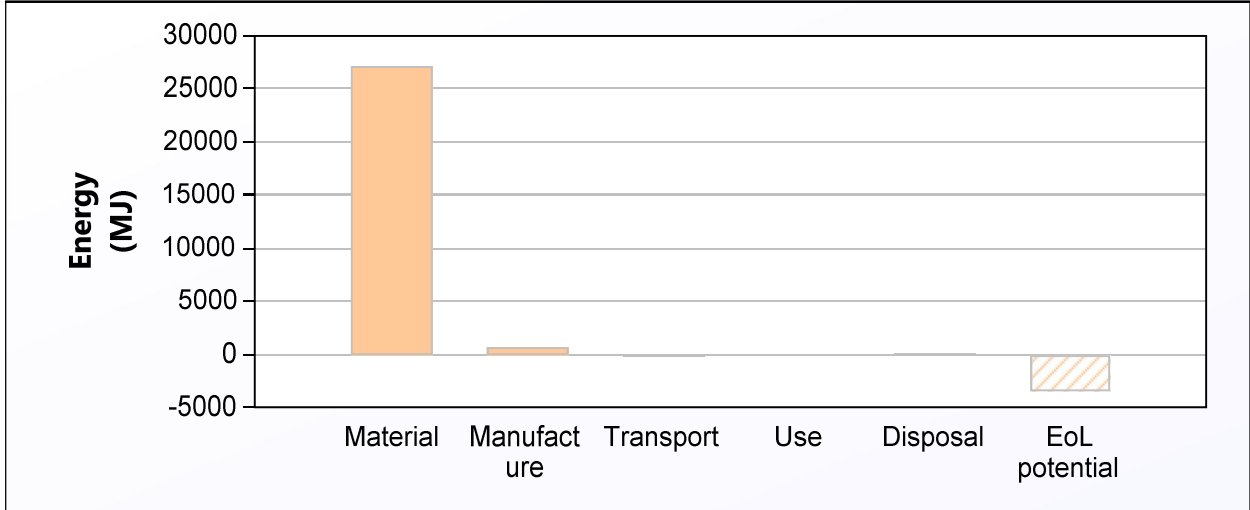
[Energy details](#)

[CO2 footprint details](#)

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	2,72e+04	97,0	1,5e+03	95,8
Manufacture	714	2,5	56,9	3,6
Transport	25,8	0,1	1,83	0,1
Use	0	0,0	0	0,0
Disposal	107	0,4	7,46	0,5
Total (for first life)	2,8e+04	100	1,57e+03	100
End of life potential	-3,47e+03		-190	

Energy Analysis

[Summary](#)



	Energy (MJ/year)
Equivalent annual environmental burden (averaged over 25 year product life):	1,12e+03

Detailed breakdown of individual life phases

Material:

[Summary](#)

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	Energy (MJ)	%
Membrane	ETFE (unfilled)	Virgin (0%)	22	1	23	5,3e+03	19,6
Frame	Epoxy/E-glass fiber, UD prepreg, UD lay-up	Virgin (0%)	1,7e+02	1	1,7e+02	2e+04	72,9
Spacers	Epoxy/E-glass fiber, UD prepreg, UD lay-up	Virgin (0%)	17	1	17	2e+03	7,5
Total				3	2,1e+02	2,7e+04	100

*Typical: Includes 'recycle fraction in current supply'

**Where applicable, includes material mass removed by secondary processes

Manufacture:[Summary](#)

Component	Process	% Removed	Amount processed	Energy (MJ)	%
Membrane	Polymer extrusion	-	23 kg	1,4e+02	20,0
Membrane	Cutting and trimming	5	1,2 kg	0,35	0,0
Frame	Pultrusion	-	1,7e+02 kg	5,1e+02	71,8
Frame	Cutting and trimming	-	0 kg	0	0,0
Spacers	Pultrusion	-	17 kg	53	7,4
Spacers	Cutting and trimming	-	0 kg	0	0,0
Adhering membrane	Adhesives, heat curing	-	0,2 m ²	5,4	0,8
Total				7,1e+02	100

Transport:[Summary](#)**Breakdown by transport stage**

Stage name	Transport type	Distance (km)	Energy (MJ)	%
Random delivery truck	32 tonne truck	1e+02	9,4	36,5
Random delivery boat	Sea freight	5e+02	16	63,5
Total		6e+02	26	100

Breakdown by components

Component	Mass (kg)	Energy (MJ)	%
Membrane	22	2,8	10,7
Frame	1,7e+02	21	80,9
Spacers	17	2,2	8,4
Total	2e+02	26	100

Use:[Summary](#)**Relative contribution of static and mobile modes**

Mode	Energy (MJ)	%
Static	0	
Mobile	0	
Total	0	100

Disposal:[Summary](#)

Component	End of life option	% recovered	Energy (MJ)	%
Membrane	Recycle	100,0	15	14,4
Frame	Downcycle	100,0	83	77,6
Spacers	Downcycle	100,0	8,5	8,0
Total			1,1e+02	100

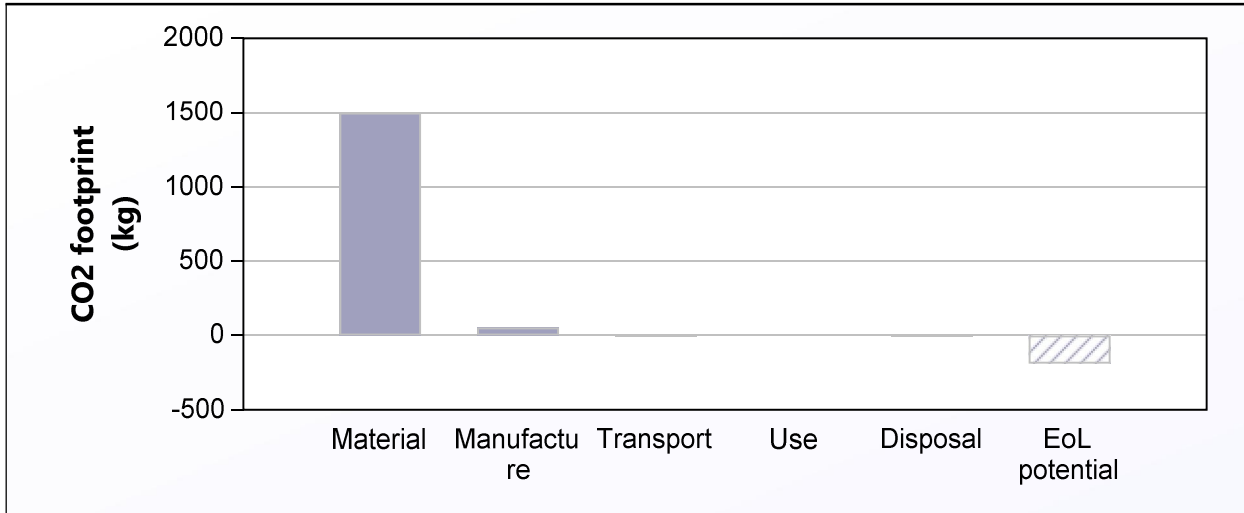
EoL potential:

Component	End of life option	% recovered	Energy (MJ)	%
Membrane	Recycle	100,0	-3,5e+03	99,5
Frame	Downcycle	100,0	-17	0,5
Spacers	Downcycle	100,0	-1,7	0,0
Total			-3,5e+03	100

Notes:[Summary](#)

CO2 Footprint Analysis

[Summary](#)



	CO2 (kg/year)
Equivalent annual environmental burden (averaged over 25 year product life):	62,8

Detailed breakdown of individual life phases

Material:

[Summary](#)

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	CO2 footprint (kg)	%
Membrane	ETFE (unfilled)	Virgin (0%)	22	1	23	2,9e+02	19,3
Frame	Epoxy/E-glass fiber, UD prepreg, UD lay-up	Virgin (0%)	1,7e+02	1	1,7e+02	1,1e+03	73,1
Spacers	Epoxy/E-glass fiber, UD prepreg, UD lay-up	Virgin (0%)	17	1	17	1,1e+02	7,5
Total				3	2,1e+02	1,5e+03	100

*Typical: Includes 'recycle fraction in current supply'

**Where applicable, includes material mass removed by secondary processes

Manufacture:[Summary](#)

Component	Process	% Removed	Amount processed	CO2 footprint (kg)	%
Membrane	Polymer extrusion	-	23 kg	11	18,8
Membrane	Cutting and trimming	5	1,2 kg	0,027	0,0
Frame	Pultrusion	-	1,7e+02 kg	41	72,1
Frame	Cutting and trimming	-	0 kg	0	0,0
Spacers	Pultrusion	-	17 kg	4,2	7,4
Spacers	Cutting and trimming	-	0 kg	0	0,0
Adhering membrane	Adhesives, heat curing	-	0,2 m^2	0,94	1,7
Total				57	100

Transport:[Summary](#)**Breakdown by transport stage**

Stage name	Transport type	Distance (km)	CO2 footprint (kg)	%
Random delivery truck	32 tonne truck	1e+02	0,67	36,5
Random delivery boat	Sea freight	5e+02	1,2	63,5
Total		6e+02	1,8	100

Breakdown by components

Component	Mass (kg)	CO2 footprint (kg)	%
Membrane	22	0,2	10,7
Frame	1,7e+02	1,5	80,9
Spacers	17	0,15	8,4
Total	2e+02	1,8	100

Use:[Summary](#)**Relative contribution of static and mobile modes**

Mode	CO2 footprint (kg)	%
Static	0	
Mobile	0	
Total	0	100

Disposal:[Summary](#)

Component	End of life option	% recovered	CO2 footprint (kg)	%
Membrane	Recycle	100,0	1,1	14,4
Frame	Downcycle	100,0	5,8	77,6
Spacers	Downcycle	100,0	0,6	8,0
Total			7,5	100

EoL potential:

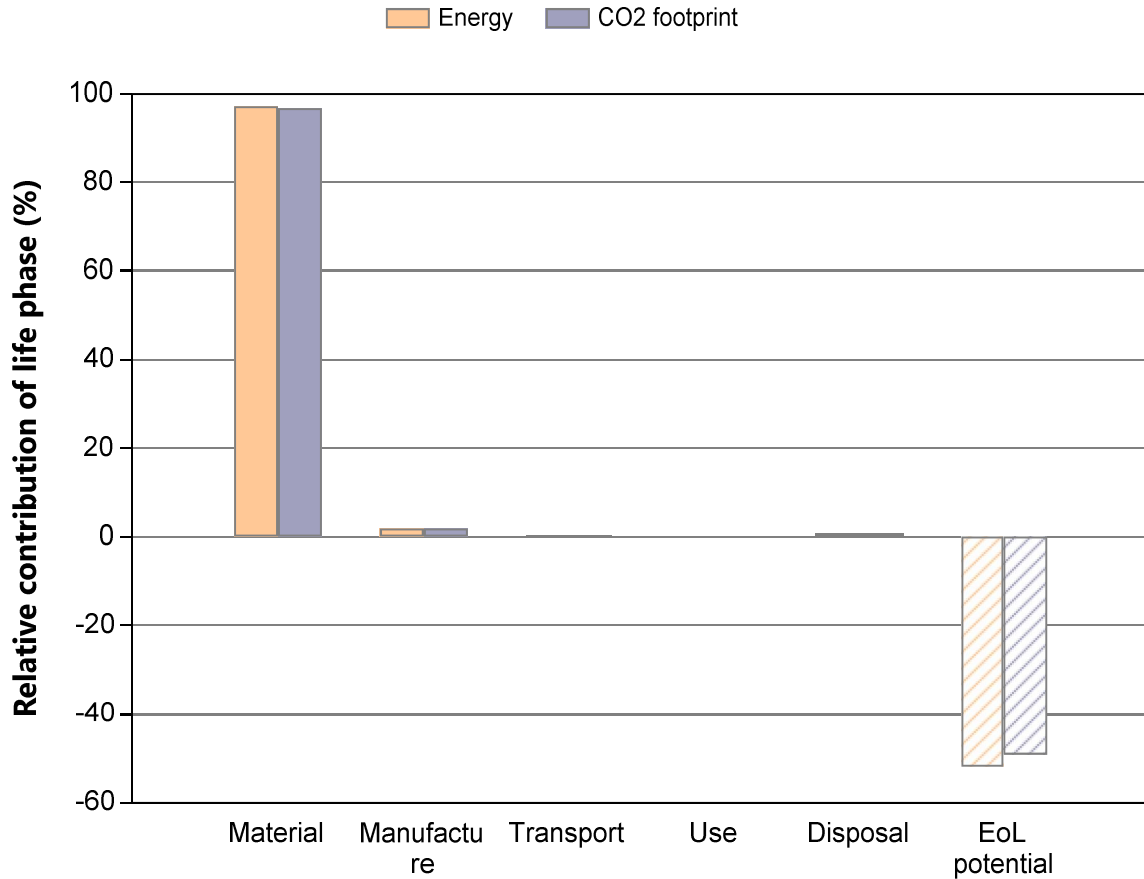
Component	End of life option	% recovered	CO2 footprint (kg)	%
Membrane	Recycle	100,0	-1,9e+02	99,3
Frame	Downcycle	100,0	-1,2	0,6
Spacers	Downcycle	100,0	-0,12	0,1
Total			-1,9e+02	100

Notes:[Summary](#)

Eco Audit Report

Product name: Common facade panel
 Country of use: Asia (excl.China)
 Product life (years): 25

Summary:



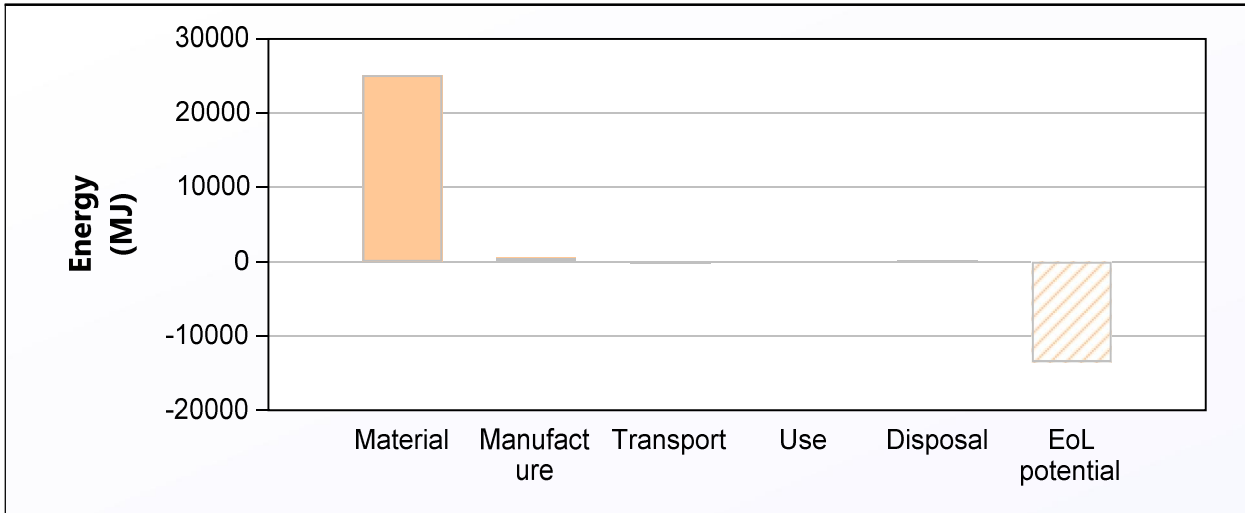
[Energy details](#)

[CO2 footprint details](#)

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	2,52e+04	97,2	1,68e+03	96,9
Manufacture	446	1,7	33,6	1,9
Transport	52,9	0,2	3,76	0,2
Use	0	0,0	0	0,0
Disposal	234	0,9	16,3	0,9
Total (for first life)	2,6e+04	100	1,74e+03	100
End of life potential	-1,35e+04		-853	

Energy Analysis

[Summary](#)



	Energy (MJ/year)
Equivalent annual environmental burden (averaged over 25 year product life):	1,04e+03

Detailed breakdown of individual life phases

Material:

[Summary](#)

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	Energy (MJ)	%
Window	Low-e glass	Virgin (0%)	1,3e+02	2	2,6e+02	4,7e+03	18,7
Frame	Aluminum, 6063, O	Typical %	79	2	1,6e+02	2,1e+04	81,3
Total				4	4,2e+02	2,5e+04	100

*Typical: Includes 'recycle fraction in current supply'

**Where applicable, includes material mass removed by secondary processes

Manufacture:

[Summary](#)

Component	Process	% Removed	Amount processed	Energy (MJ)	%
Frame	Extrusion, foil rolling	-	1,6e+02 kg	4,3e+02	97,3
Frame	Fine machining	3	4,9 kg	11	2,5
Adhering glass	Adhesives, cold curing	-	0,1 m^2	0,99	0,2
Total				4,5e+02	100

Transport:[Summary](#)**Breakdown by transport stage**

Stage name	Transport type	Distance (km)	Energy (MJ)	%
Random delivery truck	32 tonne truck	1e+02	19	36,5
Random delivery boat	Sea freight	5e+02	34	63,5
Total		6e+02	53	100

Breakdown by components

Component	Mass (kg)	Energy (MJ)	%
Window	2,6e+02	33	62,5
Frame	1,6e+02	20	37,5
Total	4,2e+02	53	100

Use:[Summary](#)**Relative contribution of static and mobile modes**

Mode	Energy (MJ)	%
Static	0	
Mobile	0	
Total	0	100

Disposal:[Summary](#)

Component	End of life option	% recovered	Energy (MJ)	%
Window	Downcycle	100,0	1,3e+02	56,2
Frame	Recycle	90,0	1e+02	43,8
Total			2,3e+02	100

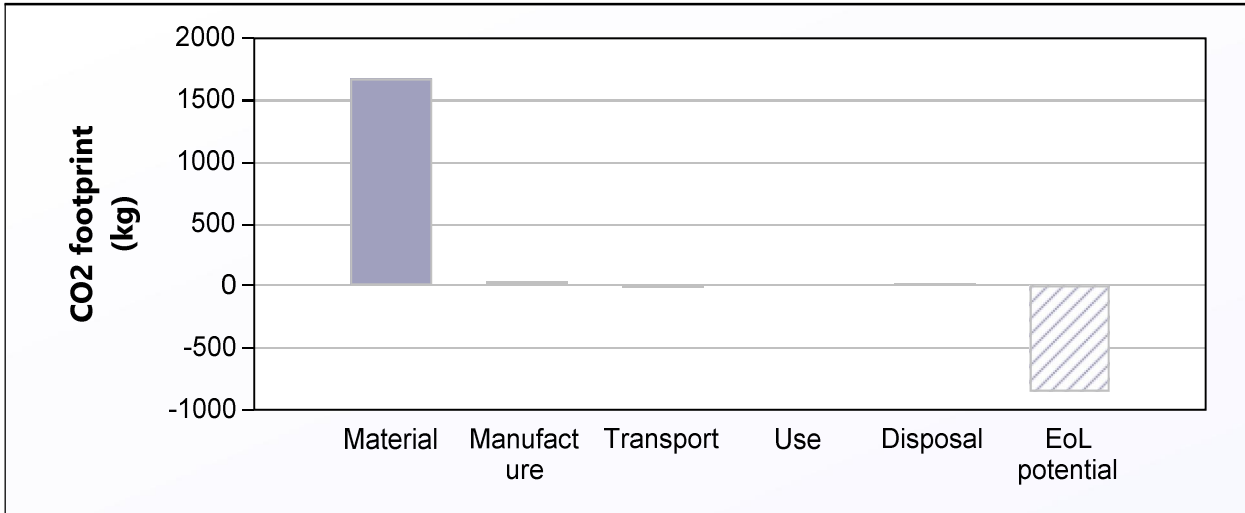
EoL potential:

Component	End of life option	% recovered	Energy (MJ)	%
Window	Downcycle	100,0	-26	0,2
Frame	Recycle	90,0	-1,3e+04	99,8
Total			-1,4e+04	100

Notes:[Summary](#)

CO2 Footprint Analysis

[Summary](#)



	CO2 (kg/year)
Equivalent annual environmental burden (averaged over 25 year product life):	69,4

Detailed breakdown of individual life phases

Material:

[Summary](#)

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	CO2 footprint (kg)	%
Window	Low-e glass	Virgin (0%)	1,3e+02	2	2,6e+02	3e+02	18,0
Frame	Aluminum, 6063, O	Typical %	79	2	1,6e+02	1,4e+03	82,0
Total				4	4,2e+02	1,7e+03	100

*Typical: Includes 'recycle fraction in current supply'

**Where applicable, includes material mass removed by secondary processes

Manufacture:

[Summary](#)

Component	Process	% Removed	Amount processed	CO2 footprint (kg)	%
Frame	Extrusion, foil rolling	-	1,6e+02 kg	33	97,0
Frame	Fine machining	3	4,9 kg	0,83	2,5
Adhering glass	Adhesives, cold curing	-	0,1 m^2	0,19	0,6
Total				34	100

Transport:

[Summary](#)

Breakdown by transport stage

Stage name	Transport type	Distance (km)	CO2 footprint (kg)	%
Random delivery truck	32 tonne truck	1e+02	1,4	36,5
Random delivery boat	Sea freight	5e+02	2,4	63,5
Total		6e+02	3,8	100

Breakdown by components

Component	Mass (kg)	CO2 footprint (kg)	%
Window	2,6e+02	2,3	62,5
Frame	1,6e+02	1,4	37,5
Total	4,2e+02	3,8	100

Use:

[Summary](#)

Relative contribution of static and mobile modes

Mode	CO2 footprint (kg)	%
Static	0	
Mobile	0	
Total	0	100

Disposal:

[Summary](#)

Component	End of life option	% recovered	CO2 footprint (kg)	%
Window	Downcycle	100,0	9,2	56,2
Frame	Recycle	90,0	7,2	43,8
Total			16	100

EoL potential:

Component	End of life option	% recovered	CO2 footprint (kg)	%
Window	Downcycle	100,0	-1,8	0,2
Frame	Recycle	90,0	-8,5e+02	99,8
Total			-8,5e+02	100

Notes:

[Summary](#)

