$COA_{eff} T^4 HoUsing$

$air\ permeability_{flexible} + sun\ shading_{flexible} = \text{Full\ control}$
Abstract

This report answers a research question. This main research question of this report is: How can an extra shell of fabric improve the gallery flat, Bosboom-Toussaintplein in Delft, on both its comfort and its energy performance? A design is made using an extra fabric shell for the gallery flat.

The methodology chosen for this project is ‘research by design’ system. This method is used to structure the research leading into the design. Normally research by design starts of by analyzing a real world problem. In this case it started of with a fascination, a fascination for fabric. This fascination led to the initial research on fabric, how fabric played its role in architecture, what fabric is, and what fabric can do. Later, due to the case study, fabric is combined with a double skin facade. The research question splits up in two main parts, the energy part and the comfort part. Both these parts determine what is needed from the extra layer. The main problems are stated, criteria are looked at, possible solutions come into play. This leads to a list of requirements. Once this list of requirements is finished, conceptual designs are made, and quickly tested on whether these design can pass these requirements. The first concept that meets the requirements is the ‘full control’ concept. This concept is a roll that combined PVC sheets and PTFE open woven fabric. The idea is to create an extra frame as a new facade, but this frame could hold two types of cladding. Design parameters are defined, by using equations on air- and heat flow. The design ‘COAT4Housing’ starts to take shape. The design is evaluated using the list of requirements.

Fabric offers great possibilities, it can shade the sun, it can take care of draft, it can reduce maintenance, it can create a comfortable space and above all I think it can improve the gallery flat, Bosboom-Toussaintplein in Delft, on both its comfort and its energy performance. Most requirements are met by the design. The full control it promises should be able to be realized. Yes, an extra shell of fabric can improve the gallery flat, Bosboom-Toussaintplein in Delft, on both its comfort and its energy performance.
1. Introduction

Case study and graduation plan

1 Introduction .............................................................. 2
1.1 Fascinating Fabric .................................................. 2
1.2 Graduation Plan ..................................................... 2
1.2.1 Case study: Gallery Flat ................................. 2
1.2.2 Graduation Plan, Goal & Research Question ...... 4
1.2.3 Conclusion ......................................................... 4
1.3 Why an Extra Layer of Fabric ................................. 4
1.4 Bosboom-Toussaintplein, Delft ............................ 5
1.5 Summary: Introduction ........................................... 6
1 Introduction

Case study and graduation plan

This is the introduction of P4 report. In this introduction I will explain why fabric fascinates me, on what grounds the case study building was picked, what my graduation plan is and why I think refurbishing a gallery flat with a new fabric facade is a good idea.

1.1 Fascinating Fabric

Fabric has been a great fascination of mine because of the powerful character it provides. Fabric is a very honest material. The way how fabric shows the tensile forces going through the material gives it a very natural, or even a biological, look. It is never boring to watch, it feels like there is always movement, or even a struggle, in and around the material. This honesty and natural look can come in many shapes and forms due to the flexibility of fabric, which makes it all the more interesting to look into.

1.2 Graduation Plan

Introduction

This subchapter will explain the current problems with gallery flats across the Netherlands. Then it will show why the gallery flat in Delft at the Bosboom-Toussaint-plein is chosen as a case study to represent a great portion of gallery flats across the Netherlands. And finally it will describe the graduation plan and why the combination of fabric and refurbishment has been chosen.

1.2.1 Case study: Gallery Flat

During the 60's and 70's a new era of architecture/urbanism was dawning in the Netherlands. People should live in one place, work in another and have their gardens in yet another place. A lot of areas were therefore developed as 'garden cities'. Due to this ideology many high-rise apartment buildings were built. Most of these high-rise apartment buildings were constructed as social housing. The cheapest and most effective way of constructing high-rise apartment buildings was to build the so called gallery flat. Gallery flats have been a problem when it comes to maintenance, comfort and energy performance since the early 1990's.

Most of these problems are directly linked to the flat's bad performance when it comes to its energy and comfort. The big windows add to the high solar heat gain, because there usually is no air conditioning, or any other way of cooling, making the high indoor temperatures a nuisance in these apartments. Fabric has a lot of potential and to make clear use of them I decided a case study is needed to connect this potential to certain existing problems. Two of the biggest problems are the flat's energy performance and its comfort, making these the main issues to focus on.

Combining a Gallery Flat with a Fabric Facade

The focus of the project, as mentioned before, will be on the flat's energy performance and its comfort. The main problems in these two fields are listed below, divided in comfort and energy consumption, including the benefits a layer of fabric can provide to solve the problems. Of course new problems always emerge when adding something new and these problems have to be solved accordingly.

Problems in the flat

Problems with these gallery flats are:

- High solar heat gain.
- Balconies are used for storage or laundry only.
- Windows can be opened but create heavy draft inside the apartment (and noise)
- Badly designed balconies aren't used as a place to stay due to acoustical problems.
- The gallery gets slippery due to rainfall. Specially combined with temperatures below zero.
- Like most buildings that are built pre oil crisis they have bad insulation properties. (thermal bridges, poor or no insulation, single glazing, etc)
- Also caused by the Dutch desire of big windows, and therefore high solar gain.
- Sunscreens are added individually giving the flats a chaotic appearance.
- Housing associations sold most rental housing right before the maintenance got out of hand.
1. Introduction

Image 1: Nirwana flat in Den Haag, example of a flat build for the expensive housing sector (source: Denhaagzaalhetwas, 2016)

Image 2: Example of social housing pre 1960's (source: Amsterdam museum, 2015)


Image 4: The gallery flat, Bosboom Toussaintplein in Delft, view on the balcony side. (source: own image)

Solutions fabric can offer:

Comfort

High solar heat gain:
The extra coat of fabric will act as a sunscreen, causing the heat to either stay outside or inside the created cavity.

Uncomfortable balconies:
The fabric layer will shelter the balcony area against the elements. This will give the balconies more days of use.

Opening windows causing draft:
The enclosed fabric layer will provide a varying air permeability, therefore it will shelter the dwelling from draft, and work as a wind buffer, slowing down the wind velocity inside the opened windows.

Slippery floors due to rainfall:
Rain will no longer be able to enter the gallery area.

Energy consumption

Poor or no insulation, Thermal bridges, Single glazing:
The extra shell added to the building will also form a new shield against heat loss, especially with a low-E coating added to the material the difference in U-value can be up to a 100%.
1. Introduction

**Gallery Flats in the Netherlands**

Till the 1960’s 8+ storey-flats were only built for the more expensive housing sector. Flats for social housing did exist, but were around 4 storeys of apartments on top of a storage floor. (M. Liebregts, 2009) During the second half of the 1960’s central heating became common knowledge and elevators were introduced in social housing. This led to the development of the gallery flat.

**Gallery Flat: Bosboom-Toussaint plein**

Gallery flats were mostly built in the late 1960’s till the early 1990’s, most of them sharing identical problems. The case study chosen will be a representation of a standard 1960’s gallery flat. I live in one of these gallery flats which is located in Delft at the Bosboom-Toussaintplein. Looking at different gallery flats all across the Netherlands, this flat shows a lot of similarities and could therefore be used as a good representation for a lot of gallery flats across the Netherlands.

### 1.2.2 Graduation Plan, Goal & Research Question

**Defining the Research Question**

The goal is to design a second skin for the case-study gallery flat, Bosboom Toussaintplein in Delft, that contributes to a better energy performance and comfort within the flat. The main research question of this graduation plan is:

**How can an extra shell of fabric improve the gallery flat, Bosboom-Toussaintplein in Delft, on both its comfort and its energy performance?**

By focussing on improving the comfort and the energy performance, indirectly this leads to the design having an environmental and economic impact as well. The design should pay itself back within 20 years, by lowering the heat demand and the maintenance costs of the building, increasing its comfort and energy label and therefore increasing the worth of the property, as well as lowering the periodic costs.

A design will be made of a fabric second skin façade for an existing building. This case study will be a representation of a standard 60’s arcade flat. I live in one of these arcade flats which is located in Delft at the Bosboom-Toussaintplein. Looking at different gallery flats all across the Netherlands this flat shows a lot of similarities and could therefore be used as a good representation for a lot of gallery flats across the Netherlands. Fabric has a lot of potential when it comes to what is needed in a façade. Since the case study is an existing building the lightweight property of fabric suits it perfectly, because not much or even no extra construction has to be added to support the lightweight shell. Fabric can be air tight or air open, depending on its structure, weave and coating, giving flexibility in how the space behind it can ventilate. This flexibility repeats itself, when it comes to water tightness, vapour tightness and strength, all these properties can be a built in feature within the material itself. While doing research on fabric it seems possible to construct a very specific material for various specific purposes. Thus fabric should be a suitable material for this case study, and this case study should be a valuable addition to showcase the possibilities of fabric.

### 1.2.3 Conclusion

Gallery flats have several problems, to illustrate these problems I will use my own flat as a case study. For this case study a fabric facade will be designed, with the purpose of increasing its energy performance and comfort.

### 1.3 Why an Extra Layer of Fabric

Since the goal is to add an extra layer on an existing façade a lightweight structure is preferred to prevent the use of extra construction to be added. Several lightweight façade types already exist. ETFE cushions and other types of foils are very lightweight structures that can be easily added to an existing façade due to their low weight. Fabric shares this low weight property however it can do more. Looking at the several double skin facades the second shell around the building should be able to do more than just be light weight. At several points or strips in the façade, outside air should be able to enter the newly formed cavity. Fabric can be flexible in its air tightness, due to its structure and weave, while foils are usually thin solid materials that do not allow this. Especially when combining fabric with this double skin façade principle fabric shines in its possibilities. Fabric meets all criteria given. It is lightweight, has visibility and performance features, thermal control, water and dirt repellency, light transmission, acoustical absorption and sustainability. I cannot think of any other lightweight material that has so much potential, and therefore think fabric is the perfect material to solve the issues and problems in the case study building.

"Fabric is being used as a building 'skin,' blending visible and performance features, such as thermal control, water and dirt repellency, light transmission, acoustical absorption, sustainability and disaster protection. Architects want light and air
1. Introduction

transmission, but control of moisture. They’re also looking at the potential for renewable energy with fabric, the ability to integrate thin film photovoltaic into a fabric skin.” (Ernster, 2010)

Decades of experimentation about how best to use fabric in building design and construction has garnered a lot more interest and growing potential for what fabric can do, driven by a desire for greener, cleaner, lighter, higher performing and sustainable structures. (Ernster, 2010)

1.4 Bosboom-Toussaintplein, Delft

In this chapter some images and drawings of the case study flat will be shown. (Image 3-8)

**Image 5:** The gallery flat, Bosboom Toussaintplein in Delft, view on the balcony side. (source: own image)

**Image 6:** The gallery flat, Bosboom Toussaintplein in Delft, position here in the middle, it is one of the many gallery flats in the Voorhof, Delft. (source: own image)
Fabric is fascinating because of its honesty, flexibility and (light) weight. Gallery flats have several problems, to illustrate these problems I will use my own flat as a case study. For this case study a fabric facade will be designed, with the purpose of increasing its energy performance and comfort. Fabric has many assets going for it. It is lightweight, has visibility and performance features, thermal control, water and dirt repellency, light transmission, acoustical absorption and sustainability. I cannot think of any other lightweight material that has so much potential, and therefore think fabric is the perfect material to solve the issues and problems in the case study building.
2. Methods

Methods

Research by design

2 Methods ................................................................. 8
  2.1 Methodology: Research by design ....................... 8
    2.1.1 Fascination Phase ....................................... 8
    2.1.2 Analyze Phase ........................................... 8
    2.1.3 Strategize Phase ......................................... 8
    2.1.4 Experiment Phase ....................................... 9
    2.1.5 Reflection Phase ....................................... 9
  2.3 Summary: Methods .......................................... 10
  2.2 Tools Used .................................................... 10
2 Methods

Research by design

This chapter includes the methodology, research by design, that is used during this project. Explains how research by design works and how it should be implemented. Furthermore it lists the tools that were used for realising this project's design and its report.

2.1 Methodology: Research by design

The methodology chosen for this project is 'research by design' system. Normally research by design starts of by analyzing a real world problem. In this case I started of with a fascination, a fascination for fabric. Therefore an extra phase is added to the 'research by design' methodology, the fascination phase.

"Design-based research defined as a systematic but flexible methodology aimed to improve educational practices through iterative analysis, design, development, and implementation, based on collaboration among researchers and practitioners in real-world settings, and leading to contextually-sensitive design principles and theories." (Wang and Hannafin, 2005).

This is known as the ASER (analyze, strategize, experiment, reflect) system. By including the now called 'fascination phase' the following scheme can be presented; Starting with the new fascination phase:

The five main stages are now described one by one starting with the fascination phase and ending with the reflection phase.

2.1.1 Fascination Phase

For my graduation project I picked 'Fabric Facades' because of my fascination for fabric and my interest in façades. At the start of the graduation project I started familiarizing myself with fabric in architecture. A broad scala of fabric use in architecture was observed and arranged into multiple types of roof and façade systems. Further knowledge of fabric was obtained by reading about fabric, its origin, history, properties, weaving and knitting patterns. Basically this first phase is the start of the literature study, without having a clear research question yet. I used it to familiarize myself with the possibilities and potentials fabric has, so some knowledge about the material is acquired before a problem is chosen which could potentially be solved with this material.

2.1.2 Analyze Phase

After familiarizing myself with fabric and its possibilities, some problems that could potentially be solved with fabrics were analyzed. Influenced by a building in Utrecht called Westraven (Rijkswaterstaat) which was refurbished by the Dutch architectural office CePeZed. This refurbishment was meant to cure the buildings 'sick building syndrome' by focusing on the ability of fresh air being able to enter the building. For the sole purpose of being able to open windows manually in a high rise building, a fabric shell was designed around the building to buffer air pressure and lower wind speeds around the windows, so that these windows could be opened without creating heavy draft inside the building. I found myself wondering about a similar system on my own flat. I decided to use my own gallery flat as a case study to show some of the great potentials that fabric has to offer.

"In the analyze phase the researcher performs a detailed analysis of a real-world problem. When analyzing the problem, the researcher ensures that scope of the problem is general enough to warrant design research, and that the problem is indeed a design problem. This phase requires crafting a research question." (Hogue, 2011)

In the analyze phase the problems of the case study has been identified and analyzed. The main problems are the focus of the research, the gallery flats comfort and energy performance. With these two main problems, the case study and the fascination of fabric combined the research question is crafted.

2.1.3 Strategize Phase

"The strategize phase requires the development of strategies to support the design research project." (Hogue, 2011)

The strategize phase is mainly the preparation of the experiment phase. Since a lot of the literature study has been done in the fascination phase, the strategize phase lays out more focus on the literature study. Where the fascination phase purely focused on fabric in architecture and fabric itself; the strategize phase concluded this literature study and combined it with the problem and the goal. The problem and goal are, of course, defined in the analyze phase. Since the goal is a combination of fabric, a double skin façade and the case study (the gallery flat), all research done on these three aspects has to be combined in the strategize phase.
2. Methods

“The researcher performs detailed literature reviews and chooses or develops frameworks based upon current theories.” (Hogue, 2011)

Once the literature study has been completed and combined, the next step in the strategize phase is to develop a framework in which the research can be done. This framework once again is a combination of fabric, a double skin façade and the case study, together with the goal of increasing the comfort of the gallery flat and increasing its energy efficiency. The strategy so far is to make possible design solutions based on calculations; a calculation of draft inside the building when windows are opened and a calculation on how the extra shell can increase or decrease (whichever one is needed) the temperature in the generated buffer zone (the space between the existing façade and the added shell).

“The researcher defines the strategies for the experiment phase, including identifying research methods and data collection methods, and identifying specific goals for each experiment cycle.” (Hogue, 2011)

The collected data will be a number of designs that should improve over time, and are calculated on each aspect individually. The boundaries are investment costs, addition in comfort and decrease of heating demand costs, which will be calculated for a lifespan of 10 years. The goal is to have a cost efficient solution for this same investment period of 10 years.

“In the strategy, the researcher defines the specific boundaries for the beginning and ending of cycles and the project as a whole. These boundaries provide the necessary scope.” (Hogue, 2011)

2.1.4 Experiment Phase

“The experiment phase is the iterative phase in the ASER approach. The researcher uses iterative cycles of design, develop, instructional experiment, and evaluate, with the evaluate step providing input to the next design stage and the first iteration acting as the feasibility test for the project. The four cycles align directly with the design, develop, implement, and evaluate phases.” (Hogue, 2011)

As mentioned in the strategize phase, and like Hogue explains here, each design will be developed, experimented with by using calculations and evaluated based on the return of investment on a lifespan of 10 years. By constantly gathering information on which designs work and which designs only increase the price, the evaluation step will provide the next input for the next design. Of course price is not the only important value of the design, the design will be optimized on three aspects: Price, comfort quality and energy performance. These aspects can be seen as a triangle, and all varieties of designs can fit in this triangle, giving an easy overview of the designs focus and performance. The last evaluation stage in the experiment phase will conclude the last design(s), chosen on their performance.

2.1.5 Reflection Phase

The final phase is the reflection phase. In this phase the data collected throughout the iterative cycles is analyzed as a whole. (Hogue, 2011) The theme of this phase is based on extracting design principles out of the collected data from the experiment phase.

“In addition to the analysis of the research results, an evaluation of the overall research process is performed and learnings are shared.” (Hogue, 2011)
2. Methods

The final outcome is a reflection on the research project, which gives design principles, which could be used to speed up the next similar design. How to increase the speed (of the design phase) and creating a better design in the future are the learnings that should be shared in this final reflection.

2.3 Summary: Methods

The chosen methodology for this project is research by design. This will be implemented in this by using the ASER (analyze, strategize, experiment, reflect) system, but preliminary to this the fascination phase was included before beginning with the A, S, E and R phases, therefore forming the newly acquired FASER (fascination, analyze, strategize, experiment, reflect) system. The tools that are used for this project so far are all computer programs as listed in chapter 2.2.

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2.2 Tools Used

**Rhinoceros 5 (64-bit)**
Rhinoceros 5 is a commercial 3D computer graphics and computer-aided design (CAD) application software developed by Robert McNeel & Associates.

**Grasshopper**
Grasshopper™ is a graphical algorithm editor tightly integrated with Rhino’s 3-D modeling tools. Unlike RhinoScript, Grasshopper requires no knowledge of programming or scripting, but still allows designers to build form generators from the simple to the awe-inspiring.

**Ladybug & Honeybee**
Ladybug and Honeybee are two open source environmental plugins for Grasshopper to help designers and engineers create an environmentally-conscious building design.

**Autodesk AutoCAD 2017**
AutoCAD is a commercial computer-aided design (CAD) and drafting software application. Developed and marketed by Autodesk.

**Microsoft Excel**
Microsoft Excel is a spreadsheet developed by Microsoft

**Google Docs, Google Sheets and Google Slides**
Google Docs, Google Sheets and Google Slides are a word processor, a spreadsheet and a presentation program respectively, all part of a free, web-based software office suite offered by Google within its Google Drive service.

**GeoGebra 5.0**
GeoGebra is an interactive geometry, algebra, statistics and calculus application, intended for learning and teaching mathematics and science from primary school to university level.

**Adobe Illustrator**
Adobe Illustrator is a vector graphics editor developed and marketed by Adobe Systems. Adobe Photoshop
Adobe Photoshop is a raster graphics editor developed and published by Adobe Systems. Adobe InDesign
Adobe InDesign is a desktop publishing software application produced by Adobe Systems.

**Contam W 3.2**
CONTAM is a multizone indoor air quality and ventilation analysis program designed to help you determine airflow, contaminant concentrations, and personal exposure in buildings.

**CES Edupack 2016**
CES EduPack is a unique set of teaching resources that support Materials Education across Engineering, Design, Science and Sustainable Development. Developed and published by GRANTA design.
3. Analysis & Research

Fabric and double skin facades

3.1 Fabric
  3.1.1 Fabric Research
  3.1.2 Mounting Techniques
  3.1.3 Case Studies

3.2 Double Skin Facades
  3.2.1 Double Skin Façade Research

3.3 Comfort
  3.3.1 Visual Comfort
  3.3.2 Air Quality
  3.3.3 Acoustical Comfort
  3.3.4 Thermal Comfort

3.4 Energy Consumption

3.5 Summary: Analysis & Research
3 Analysis & Research

Fabric and double skin facades

As explained in the methodology, this project started with a fascination for fabric and this fascination led to this first part of the research. This first part is all about fabric and how it is, has been and will be used in architecture. After researching fabric, the analyze phase slowly came into being. Analyzing possibilities of design questions. Since the chosen focus of the project is aimed towards creating a second skin made out of fabric on an existing façade the research follows these two directions. Therefore the research is split into two main aspects fabric and façade.

3.1 Fabric

The current fabric research answers the following questions:

- What is fabric?
- What is the history of fabrics in architecture and how did they come into being?
- How are fabrics currently being used in architecture?
- What types of fabric exist?
- Which fabric types are currently being used for exterior architectural purposes? (and what are their properties?)
- Which fabric types are most suited for exterior architectural purposes?

3.1.1 Fabric Research

What is Fabric?

“A textile or cloth is a flexible woven material consisting of a network of natural or artificial fibres (yarn or thread). Yarn is produced by spinning raw fibres of wool, flax, cotton, or other material to produce long strands. Textiles are formed by weaving, knitting, crocheting, knotting, or felting. “ (Wikipedia, 2015)

Fabric is a material created by knitting or weaving yarns. Yarns are produced by spinning natural or artificial fibres. Fabric derives from Latin, or more recent from French fabrique meaning build or made. (Wikipedia, 2015) In Latin it comes from fabrica meaning: trade, art or skill. Maybe referring to their trade with more eastern countries which made beautiful and art worthy types of fabric, such as: silk and carpets.

What is the History of Fabrics in Architecture and How did They Come into Being?

“The remains of tent-like structures that utilized animal hides have been identified from as early as 150,000 years ago.” (R. Kronenburg, 2015)

Most fabric structures were used, created and developed by nomad tribes, due to their relatively easy way to transport these structures, and to their flexibility in general. (R. Kronenburg, 2015) Tents have, over thousands of years, been evolving nearly to perfection.

Image 11: Reconstruction of a 10,000 year old tent structure. From remains found at, Princevent, Northern France. (Source: R. Kronenburg, 2014)

Later on fabrics were also used in non-temporary buildings. A good example is the roman colosseum. The roman colosseum in Rome, of which the construction started in 70 AD, had a textile roof providing the spectators some form of shading from the sun and protection against other elements like rainwater. This tent like structure was highly inspired by the quick evolving shipping industry. Fabric in the shipping industry evolved for thousands of years before the sails were replaced by steam engines. Architectural use of these new techniques was not very common, but every building that somehow relied on fabric as its construction material closely looked at the maritime techniques.

Another example of the phenomenon lies 1500 years later in time and is called: Camp du Drap d’Or (Field of Cloth of Gold). A series of multiple tent structures, the greatest of which spanning a total of 22 meters, and was said to be quite impressive. This Camp du Drap d’Or looks like it is the first of many flexible and movable big scale tent projects, later followed, amongst others, by circustent structures like the Barnum & Bailey ‘Greatest show on earth’.
“Fabrics represent some of the lightest artifacts made by humanity, and yet, buildings represent some of the heaviest. Because of their lightweight nature, fabrics are also flexible and mobile, whilst buildings, at least in their traditional sense, are solid and permanent.” (R. Kronenburg, 2015)

The main purpose of fabrics throughout history is its lightweight which makes it easy to transport and its flexibility. Early tent structures evolved over the years by nomad tribes, and later structures were highly dependent on the quick evolving maritime knowledge of how to use fabric.

How are Fabrics Currently Being Used in Architecture?

Since fabrics are being used in roofs and in facades, this question will be split up into two subquestions.

How are Fabrics Currently Being Used in Roofs?

Roof structures

As roofs four main types:

- Saddle roof
- Mast supported
- Arch supported
- Point supported

See Image 11
3. Analysis & Research

The saddle roof is supported either on two sides or all around the fabric. The mast and arch supported structure much like they already narrate are supported by a mast or arch. A mast usually supports the structure all around it, creating a circular hanging point for the fabric to be attached to. A point supported structure can also be supported by a mast but then only in a single direction. Of course combination of these types are commonly used.

**How are Fabrics Currently Being Used in Facades?**

Facades tend to copy these types while adding a frame supported system and curtain system. Adding these two types while removing the saddle roof, ending up with:

As roofs four (five) main types:

- Frame supported
- Mast supported
- Arch supported
- Point supported
- (Curtain)

See Image 12 - 16
3. Analysis & Research


Image 19: Mast supported fabric facade system. (source: Fabricarchitect, 2016)

Image 20: Curtain fabric facade system. (source: Dornob, 2016)
One could argue that the frame supported façade system replaces the saddle roof since it also supports the fabric all around it using the frame. The mast, arch and point supported systems are exact copies of the roof types. Adding one extra system, although only seen in one example, is the curtain system. Most currently used façade fabric systems, with exception to the curtain system, seem to be a copy of the roof fabric systems which are simply mounted onto the façade.

Only a couple of façade fabric system types exist. There seems to be very little innovation in these currently used systems, since they are (with few exceptions) a copy of existing fabric roof systems. Most of the examples given seem to be a standard façade with the fabric mounted on to them, therefore very little integration in these façade types seem to exist.

What Types of Fabric Exist?

The creation of fabric starts off with fibers with which the yarn is spun. (J. McLoughlin and S. Hayes, 2015) The yarn is then woven or knitted into a fabric. Therefore the types of fabric that exist are derived from which fibers can potentially form a yarn and how this yarn is woven or knitted.

Which Types of Fibers are Suitable for Creating Yarns?

Fibres are either natural or synthetic. Natural fibres come from plants or animals. Synthetic fibres derive from altered plant materials or from processed fossil fuels. See image 17.

Fabric is created by spinning fibres into a yarn. This yarn is then woven or knitted into fabric. When asking what type of fabrics exist? The answer is found looking at which fibres are suitable for spinning yarns. The main two groups of fibres are natural and synthetic, where some of the synthetic fibres are derived from natural ones.

Image 21: Types of fibres (source: McLoughlin & Sayes, 2013)
3. Analysis & Research

Which Types of Weaving and Knitting Exist?

Weaving

Two main types of weaving exist (McLoughin & Sayes, 2013):

- Plain weave
- Twill weave

Plain weave

Properties of a plain-woven fabric are:

- The fabric is the simplest and tightest of interlacing warp and weft yarns.
- Opposite sides of the fabrics are the same.
- These fabrics have high abrasion and are resistant to yarn slippage.
- Types of fabrics produced include batiste, cambric, Donegal, fresco, and voile.

Twill weave

Properties of the twill-woven fabric are:

- These lines can either run in the Z direction or the S direction.
- Warp-faced twills show a predominance of warp yarns on the face of the fabric.
- Weft-faced twills show a predominance of weft yarns on the face of the fabric.

Twill weaves are more complex weaving patterns. A lot of twill weave types exist, a.o. here are the most used types of twill weave patterns:

- Welt-faced twill weave
- Satin twill weave
- Sateen twill weave

The strongest of all weaving patterns is the simplest of all and is the plain weave since it has the most interaction between the warp yarns and the weft yarns. Twill weaves have less and less interaction between the warp and the weft yarn and are therefore weaker but softer to the touch, materials that need strength use the plain weave, materials that need to be soft to the touch often use more complex twill weaves.
Knitting

Knitted elements are sometimes called ‘smart fabric’ due to their complexity. Most knitted products perform similar functions to their woven cousins, mainly in how they look and both are products of the automotive industry. Two main types of knitting exist:

- **Plain knitting (one hooked)** (NL: haken)
- **Rib knitting (two hooked)** (NL: breien)

Rib knitting is an interesting pattern, due to its complex structure it is more extensible, flexible and has the ability to capture air, giving it thermal properties. Wool is commonly rib knitted into sweaters, its thermal properties make it a nice material for cold winter days.

**Image 24:** Plain knitting pattern and structure, the simplest way of knitting. (source: McLoughin & Sayes, 2013)

**Image 25:** Rib knitting pattern and structure, a more complex way of knitting. Interesting about this structure is its ability to capture air, giving it thermal properties. The complex structure also makes it a very extensible material. (source: McLoughin & Sayes, 2013)
Which Fabric Types are Currently Being Used for Exterior Architectural Purposes? (and What are Their Properties?)

"Several fibres have the material properties to be potentially applied; however, the high costs may prevent a widespread utilization. Most of the commonly used fibres are chemical fibres, particularly nonorganic polymer fibres." (R. Houtman, 2015)

A grand variation of fabric types are used in architecture. What follows is a list of common fabric types and an explanation of why they are used, or why they are not used.

Cotton
This organic fibre was used in fabric architecture mostly in the beginning of its development. (R. Houtman, 2015) Frei Otto has commonly used cotton in his early work with fabric architecture. The problem with cotton however is its short expected lifetime of about four to five years. Due to the organic nature of the material it is subject to fungi and moisture. It does however have a very high resistance against ultraviolet waves (UV-light).

Polymer Polyamide (PA or nylon)
Polyamide fibres are also known as nylon fibres. (R. Houtman, 2015) The material has a high strength, stiffness and tenacity. When the fibres get wet the material elongates itself, this makes it difficult to use this material in architecture. Nylon also has a poor resistance to ultraviolet light and stretches considerably. Nylon is mainly used in the sailing industry because of its low weight and high strength, but not in architecture.

Polymer Polyethylene (PE)
Polyethylene fibres have a low self-weight and are able to float on water. (R. Houtman, 2015) Like other polymer fibres, they can only take tension and, therefore, are used solely for tensile applications like ropes and weaves. When the density of the PE is enlarged, strong fibres originate like PE-HD UHMPE (Dyneema). Dyneema, commonly used in the kiting industry as a replacement for the more expensive Kevlar, is 15 times stronger than steel wire (weight to weight ratio). PE materials have a low surface adhesion; therefore it is difficult to coat PE. When treated with a special recoating, it is possible. As it is a thermoplastic material, it can be recycled well.

Polymer Polyester
Polyester, together with fibreglass, is the most common fibre in textile architecture and regarded as a standard product. (R. Houtman, 2015) The fibre has good tensile strength and elasticity. Because of its considerable elongation before yield, the material is forgiving. It enables small corrections during installation. However, the mechanical properties of the material decrease with UV light, and it is subject to aging.

Polymer Fluor Polymer Fibres
Fluor polymer fibres are known under several trade names including Teflon, Hostaflon, Polyflon and Toyoflon and are normally made as monofil fibres or extruded to foil (ETFE). (R. Houtman, 2015) Amongst others, fibres are made from PTFE and PVDF. Compared to the non-fluor polymers, the strength and stiffness of the fibres are less. Also, the material has a tendency to creep. Due to its high flexibility and bending capacity, as well as the self-cleaning properties of the material, it is frequently used as an uncoated weave in retractable roof applications.

Polymer Aramid Fibre (Kevlar)
Aramid fibre is an artificially made organic polymer (an aromatic polyamide) produced by spinning a solid fibre from a liquid chemical blend. (R. Houtman, 2015) The bright golden yellow filaments produced can have a range of properties, but all have high strength and low density. All grades have good resistance to impact; lower modulus grades are used extensively in anti-ballistic applications. Compressive strength, however, is only similar to that of E glass. Although most commonly known under its Dupont trade name Kevlar, there are now a number of suppliers of the fibre, most notably Akzo Nobel with Twaron. Each supplier offers several grades of aramid with various combinations of modulus and surface finish to suit various applications. As well as the high-strength properties, the fibres offer good resistance to abrasion and chemical and thermal degradation. However, the fibre can degrade slowly when exposed to UV-light.

Polymer Vectran Fibre
A second aromatic polymer that is being applied gradually in textile membranes is the so-called Vectran fibre, a polyester fibre with aromatic rings. (R. Houtman, 2015) It has a very high strength and is not sensible to creep (like Dyneema). It can be used as fabric reinforcement. However using big quantities of this material might be costly.
Non-Organic Fibreglass

Obviously, the material from which fibreglass is made is glass. (R. Houtman, 2015) Threads are spun from glass that have a certain bending capacity. The fibreglass has high tensile strength but brittle behaviour and low elastic strain. Because of the brittleness, the material needs to be handled carefully and needs very accurate manufacturing. Ageing exerts little influence on the material, which has a tremendous impact on the expected lifetime of the structure. The tensile strength of the material decreases, however, when it is subjected to moisture.

Image 26: Differences between materials on various aspects. (source: own image)
3. Analysis & Research

What Coatings are Used on These Fabrics?

“To create durable and watertight cloths, most of the fibres need a coating on both sides. Moreover, a coating is often used to create a smooth surface and, thereby, reduce the potential pollution area. There are several coatings available. The most common ones are PVC coatings and fluor polymer coatings. Silicone coatings have made a comeback, due to their flexibility. The coating is often used to weld the different parts of the membrane together. Therefore the adhesion of the coating to the fabric is an indication of the strength of the seams.” (R. Houtman, 2015)

Silicone coatings are making a comeback, due to their flexibility they can move along with the fabric, increasing the lifespan of the material. Wind tightness, watertightness, cleanability, dirt repellency, UV-resistance, durability, fungi repellency, strength and stiffness can all be gained by coating the material on one or two sides.

By looking at the current use of fabrics in architecture some interesting combinations were found. Some due to their long term use, and therefore being a standardized product, others are interesting due to their structure and flexibility. So far I determined three interesting combinations: PTFE coating on fiberglass weave, stretch fabrics and fabrics with a low-E coating.

PTFE Coating on Fibreglass Weave

Teflon-coated fibreglass fabric is the most permanent of the coated architectural fabrics. (R. Houtman, 2015) First employed in 1973 for a roof at the La Verne College Student Centre in California, it has a lifetime of over 30 years. It can be used only for permanent applications and cannot be relocated or retracted. The fabric is noncombustible and, as such, meets the most stringent building codes worldwide. Off the roll, it has an oatmeal appearance, which bleaches out to white after a couple of months in the sun. With translucency up to 25%, it has been used in projects such as the Millennium Dome in London.

Stretch Fabrics

The origin of stretch fabrics can be found in South Africa. (R. Houtman, 2015) To protect from the hot sun, sun shades were made out of non-coated knitted weaves. Soon, the step was made to have them coated, at first on one side and shortly after that on both sides. Basically, two types of coating are used: PVC coating and PU coating. Depending on the coating, the seams have to be stitched and sealed for watertightness or welded. Different weights and accompanying strengths are available. The amount of flexibility determines the shape possibilities and the span of the structure. The nature of the structure makes it suitable for temporary applications.

Fabrics with a low-E Coating

Low-emissivity (low-E) coatings are used in situations where radiation takes an important role in heat loss or gain. (R. Houtman, 2015) When building materials have a high specific mass, the heat loss or gain is determined predominantly by convection and conduction. Radiation, then, is less of a problem. Membrane structures have a very low specific mass, and therefore radiation plays an important role in the thermal behaviour of a structure. Comparable to low-E coatings on glass, this type of coating can be applied on membranes and foils as well. The benefit of low-E coatings can be illustrated by means of the following pictures.
3. Analysis & Research

Table 1: Commonly used fabrics in architecture, with the exception of nylon. The table shows the density, tensile strength, strain and elasticity of the materials. There is not much difference in density, but a lot of difference in elasticity and tensile strength. Note that a higher tensile strength usually gives less tensile strain. The remarks as listed are interesting because it gives a sense to the use in architecture of the material. (source: R. Houtman, 2015)

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/cm³)</th>
<th>Tensile strength (N/mm²)</th>
<th>Tensile strain (%)</th>
<th>Elasticity (N/mm²)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton</td>
<td>1.5–1.54</td>
<td>350–700</td>
<td>6–15</td>
<td>4500–9000</td>
<td>For temporary, demountable structures</td>
</tr>
<tr>
<td>Polyamid 6,6 (nylon)</td>
<td>1.14</td>
<td>Up to 1000</td>
<td>15–20</td>
<td>5000–6000</td>
<td>• When exposed to light, only average resistance to ageing</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Swelling when exposed to moisture</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Only of little importance in fabric structures</td>
</tr>
<tr>
<td>Polyester fibre</td>
<td>1.38–1.41</td>
<td>1000–1300</td>
<td>10–18</td>
<td>10,000–15,000</td>
<td>• Widely spread, together with fibre-glass, a standard product in fabric structures</td>
</tr>
<tr>
<td>Fibreglass</td>
<td>2.55</td>
<td>Up to 3500</td>
<td>2.0–3.5</td>
<td>70,000–90,000</td>
<td>• When exposed to moisture, reduction of breaking strength</td>
</tr>
<tr>
<td>Aramid fibre (Kevlar, Twaron)</td>
<td>1.45</td>
<td>Up to 2700</td>
<td>2–4</td>
<td>130,000–150,000</td>
<td>• Brittle fibres, therefore is spun into filaments of 3 μm diameter</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Together with polyester, widely spread in fabric structures</td>
</tr>
<tr>
<td>Polytetrafluorethylene (Tenara, Hostaflon, Polyflon, Toydon)</td>
<td>2.1–2.3</td>
<td>160–380</td>
<td>13–32</td>
<td>700–4000</td>
<td>Special fibre for high-tech products</td>
</tr>
<tr>
<td>Carbon fibres (Celion, Carbolon, Sigrafil, Thomel)</td>
<td>1.7–2.0</td>
<td>2000–3000</td>
<td>&lt;1</td>
<td>200,000–500,000</td>
<td>Special fibre for high-tech products</td>
</tr>
</tbody>
</table>

Table 2: Commonly used combination of fabrics and coating. A very interesting table since it tells a lot about the properties needed in a façade system, such as transparency, fire behavior and expected lifetime. (source: R. Houtman, 2015)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Top coating</td>
<td>PVC Weldable PVDF</td>
<td>PVC Non-weldable PVDF</td>
<td>PVDF PTFE</td>
</tr>
<tr>
<td>Expected lifetime</td>
<td>15 years</td>
<td>&gt;20 years</td>
<td>&gt;25 years</td>
</tr>
<tr>
<td>Soiling protection</td>
<td>Average</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Transparency</td>
<td>5–15%</td>
<td>8–14%</td>
<td>Flame retardant</td>
</tr>
<tr>
<td>Fire behaviour</td>
<td>Flame retardant</td>
<td>Flame retardant</td>
<td>Flame retardant</td>
</tr>
<tr>
<td>Tolerance to folding</td>
<td>Very good</td>
<td>Good</td>
<td>n.a.</td>
</tr>
</tbody>
</table>

(source: R. Houtman, 2015)
3. Analysis & Research

<table>
<thead>
<tr>
<th>Fabric/coating</th>
<th>Weight g/m² DIN 53552</th>
<th>Tensile strength Warp/WofN 50N mm² DIN 53344</th>
<th>Tensile strain Warp/WofN 650N % DIN 53345</th>
<th>Tear strength N DIN 53363</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton-polyester</td>
<td>350</td>
<td>1700/1000</td>
<td>35/18</td>
<td>60</td>
</tr>
<tr>
<td>Polyester/PVC</td>
<td>520</td>
<td>2500/2000</td>
<td>38/20</td>
<td>80</td>
</tr>
<tr>
<td>Type I</td>
<td>750</td>
<td>3000/5000</td>
<td>15/20</td>
<td>300/5000</td>
</tr>
<tr>
<td>Type II</td>
<td>800</td>
<td>4200/4000</td>
<td>15/20</td>
<td>500/5000</td>
</tr>
<tr>
<td>Type III</td>
<td>1100</td>
<td>5800/5400</td>
<td>15/25</td>
<td>1200/1200</td>
</tr>
<tr>
<td>Type IV</td>
<td>1300</td>
<td>8000/6500</td>
<td>15/30</td>
<td>300/3000</td>
</tr>
<tr>
<td>Type V</td>
<td>1450</td>
<td>10,000/9000</td>
<td>20/50</td>
<td>1500/1800</td>
</tr>
<tr>
<td>Fiberglass/PTFE</td>
<td>800</td>
<td>3500/1500</td>
<td>30/50</td>
<td>350/5000</td>
</tr>
<tr>
<td>PTFE</td>
<td>900</td>
<td>5000/4500</td>
<td>35/50</td>
<td>500/5000</td>
</tr>
<tr>
<td>PTFE/PVDF</td>
<td>1200</td>
<td>7000/6000</td>
<td>50/50</td>
<td>500/5000</td>
</tr>
<tr>
<td>PTFE/PVDF</td>
<td>1500</td>
<td>8000/7000</td>
<td>50/50</td>
<td>500/5000</td>
</tr>
<tr>
<td>Fiberglass/Si</td>
<td>150</td>
<td>2500/7000</td>
<td>56</td>
<td>600/600</td>
</tr>
<tr>
<td>Aminit/PVC</td>
<td>750</td>
<td>7500/7500</td>
<td>56</td>
<td>600/600</td>
</tr>
<tr>
<td>1050</td>
<td>8000/8500</td>
<td>56</td>
<td>600/600</td>
<td></td>
</tr>
<tr>
<td>1150</td>
<td>2000/2450</td>
<td>56</td>
<td>450/4450</td>
<td></td>
</tr>
<tr>
<td>PTFE/PVDF</td>
<td>320</td>
<td>2000/2500</td>
<td>365/530</td>
<td></td>
</tr>
<tr>
<td>PTFE/PVDF</td>
<td>530</td>
<td>4000/5300</td>
<td>669/550</td>
<td></td>
</tr>
<tr>
<td>PVDF/PVDF</td>
<td>800</td>
<td>4000/4000</td>
<td>798/730</td>
<td></td>
</tr>
<tr>
<td>PVDF/PVDF</td>
<td>1000</td>
<td>1400/1300</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PVDF/PVDF</td>
<td>260</td>
<td>1600/1500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ETPE foil</td>
<td>87.5</td>
<td>365/0500</td>
<td>450/450</td>
<td></td>
</tr>
<tr>
<td>Thickness</td>
<td>58/55</td>
<td>500/600</td>
<td>450/450</td>
<td></td>
</tr>
<tr>
<td>100 µm</td>
<td>175</td>
<td>58/57</td>
<td>550/600</td>
<td>400/400</td>
</tr>
<tr>
<td>150 µm</td>
<td>250</td>
<td>58/57</td>
<td>550/600</td>
<td>400/400</td>
</tr>
<tr>
<td>200 µm</td>
<td>350</td>
<td>52/52</td>
<td>600/600</td>
<td>400/400</td>
</tr>
<tr>
<td>250 µm</td>
<td>437.5</td>
<td>40-40</td>
<td>&gt;3000/300</td>
<td>&gt;300/300</td>
</tr>
<tr>
<td>300 µm</td>
<td>450</td>
<td>40-40</td>
<td>&gt;3000/300</td>
<td>&gt;300/300</td>
</tr>
<tr>
<td>150 µm</td>
<td>525</td>
<td>40-40</td>
<td>&gt;3000/300</td>
<td>&gt;300/300</td>
</tr>
</tbody>
</table>

Table 3: Mechanical properties of commonly used fabrics. A higher weight usually suggest a higher tensile strength. Tear strength of the fibre is usually around 1/10th to 1/5th of the tensile strength. (source: R. Houtman, 2015)

Which Fabric Types are Most Suited for Exterior Architectural Purposes?

Three options really stand out: Stretch fabrics, Fabrics with low-E coatings and PTFE coated fiberglass. All three options are highlighted on this page.

Stretch Fabrics

Because of their rib knitted nature, these fabrics are flexible and have the ability to encapsulate air, giving the material thermal properties (think of a woolen sweater). Together with a flexible (silicon) coating, the ability to create a material which has still air in between both coating layers is very interesting, it could be seen as double glazing made out of fabrics. The downside of this is that this solution would have very low to no transparency.

Low-E Coatings

Commonly used in double glazing, Low-E coating can do their job equally well on a layer of fabric. Increasing the potential U-value of the construction by 100%, low-E coatings can be a great solution to lower the heat and cool demand of the building.

Non-organic Fiberglass and Polymer Polyester

Due to their long time use a lot of information is available on fiberglass and polymer polyester. These two fibre types are the most commonly used ones in architecture for a good reason. Due to their low cost, good strength and good UV resistance the materials have a long lifespan, which might guarantee a good return of investment.
3. Analysis & Research

Image 28: Stretch fabric, here seen as a tent structure (Source: RHI tents)

Image 29: Low-E coating, here seen applied on a combination of PTFE woven fabric and ETFE sheets (Source: ArchiExpo)

Image 30: Non-organic fiberglass with a PTFE coating (Source: ArchiExpo)
3.1.2 Mounting Techniques

Mounting techniques in fabric systems vary a lot depending on the support system, the size of the fabric and the type of the fabric.

All these mounting techniques have one thing in common, all of them spread the tensile forces in the textile over an as big as possible area to reduce the amount of point loads on the fabric to a minimum.

Image 31: Shows several mounting techniques for fabric facades and roofs. Note how every connection attempts to keep the number of point loads as low as possible to spread the forces equally throughout the fabric. (source: J. Llorens, 2013)
3.1.3 Case Studies

During the literature research on fabrics a lot of projects came by, since the focus of this project is refurbishing an old facade some projects stood out. What follows is a short description of two case studies. The first one is the refurbished building of Rijkswaterstaat in Utrecht 'Westraven'. The second one is a product by Serge Ferrari called the bioclimatic facade.

Westraven
First I thought the fabric layer on the Westraven project did two things. It blocks the sun as a permanent sunscreen and it reduces peak wind pressure so that windows can be opened behind it, without creating too much draft in the building. This second part however is barely true, and can be neglected. What the facade does however is reducing the amount of airflow through the window by reducing the wind speed and not the wind pressure.

Serge Ferrari
shows us that a double skin facade can be created with just a thin layer of fabric in front of the existing or newly built facade.

Image 32: Shows the facade of the westraven project by cepezed. (Cepezed.nl, 2016)

Image 33: Shows the studied Serge Ferrari product, Bioclimatic facade. (source: Serge Ferrari, 2016)
3. Analysis & Research

3.2 Double Skin Facades

Since the chosen focus of the project is aimed towards creating a second skin made out of fabric on an existing façade, the research follows these two directions. Therefore the research is split into two main aspects: fabric and façade.

3.2.1 Double Skin Façade Research

The double skin façade research answers the following questions.

- What is a double skin façade?
- What kind of double skin facades exist?
- What is the purpose of the first and second skin in these existing double skin façade systems?

What is a Double Skin Façade?

The Double-skin façade is a system of building consisting of two skins placed in such a way that air flows in the intermediate cavity. The ventilation of the cavity can be natural, fan supported or mechanical. Apart from the type of the ventilation inside the cavity, the origin and destination of the air can differ depending mostly on climatic conditions, the use, the location, the occupational hours of the building and the HVAC strategy.

Image 27 shows several types of double skin facades. The box window type is basically a separate box (usually made of glass and aluminum) around every window. A corridor type is a continuous box in horizontal direction, stretching from floor to floor. The shaft box type is a series of shafts stretching vertically over the building. The multi-storey variant is a corridor type which covers multiple floors.

The ventilation of a double skin façade comes in three forms: natural and mechanical, where the third form is a combination of both. The type of air flows that can be achieved with double skin facades vary a lot, and can be best explained with some sketches that are stated below.

What is the Purpose of the First and Second Skin in These Existing Double Skin Façade Systems?

The main purpose of the first and second skins in double skin facades is the variation in airflow they can offer. Heating up air in winter times and ventilating the hot air away in summer times is their most common practice.

Image 35: This is the most common way a double skin façade is used, the façade preheats the air in winter times, and ventilates the hot air away during the summer. (source: Harvard.edu, 2015)

Image 34: Classification of double skin facades. Sorted by their type, ventilation mode and air flow type. In red the most logical options are shown for the case study flat. Since the flat has long corridors spanning on both sides, the corridor type or box window are interesting types. There is plenty of wind and air pressure different, so natural ventilation should be sufficient. The air flow type used can used as a static air buffer. (source: Perkins&Will, 2013)
For a gallery flat with existing galleries and balconies it makes sense to use the double skin façade as a separate system for each floor; therefore making use of a corridor type. Since the apartments inside the gallery flat make use of radiators, preheating the air inside the double skin façade should be sufficient (as shown in image 30). To prevent the use of more energy the preference goes towards a natural ventilating system, although calculation should prove this as sufficient. Both the inside and the outside layer of the façade should be openable on top and bottom facilitating the ability to preheat the air in the winter, and to exhaust the warm air during the summer.

Image 36: A double skin façade used as an exhaust duct, cold air is supplied by the HVAC system and warm air is exported out via the façade. (source: Harvard.edu, 2015)

Image 37: Double skin facades can be used to heat up the air which can directly be poured into the building, either a separate system per floor or one shaft for multiple floors. (source: Harvard.edu, 2015)

Image 38: The warm air inside the building can be mixed with fresh air colder air inside the façade to preheat the fresh air. (source: Harvard.edu, 2015)
3.3 Comfort

A definition for comfort is: A human that can do his/her daily activities without being hindered by his surrounding conditions is comfortable (Vakgroep Bouwphysica TU Delft, 1990). In building physics comfort lies within four groups: Thermal comfort, visual comfort, air quality and acoustical comfort. Some examples of the most important requirements when it comes to comfort are:

- Protection against cold and heat (Thermal)
- Prevention of draft (Air quality)
- Shelter from bothersome sound created by neighbours or outside noises (such as traffic) (Acoustical comfort)
- Preventing surface condensation on walls, ceilings, floors and windows (Air quality)
- Fostering good ventilation with fresh and clean air; this should also take care of odors and potential air pollution (Air quality)
- Fostering efficient and comfortable lighting (Visual comfort)
- Preventing glare (Visual comfort)
3.3.1 Visual Comfort

Important to visual comfort is a well divided lighting across the space, all surfaces within a space should not vary too much in brightness to avoid glare. A daylight factor is the ratio of the light level inside a structure to the light level outside the structure. The daylight factor of a space is a good indication of how much daylight can enter the space. One of the greatest benefits of living in an apartment building is the great view. Having a great view is not only good for the price of the property, nor for having a greater experience inside the apartment, but it also ensures that your eyes get enough training throughout the time spent in your home. The view might be the most valuable thing people have in these apartments. If some of the view is blocked in any way due to the new construction this might be fatal to the owner’s perception of the project.

3.3.2 Air Quality

In the bathroom and kitchen a mechanical exhaust sucks the air out of the apartment. This is done to ensure enough fresh air enters the apartment and, by having a negative pressure inside both the bathroom and the kitchen, the odors created in these spaces are less likely to flow into the rest of the apartment. But this mechanical system is just the bare minimum needed, most of the fresh air comes into the apartment naturally through the windows. Wind speed increases by increasing the altitude, so especially on the higher floors opening a window creates a massive airflow through the apartment. This airflow can be quite severe and therefore qualifies as draft often. In summer this draft is usually a good thing, because it ventilates the hot air away quite effectively and a breeze is always welcome when it is hot. But in winter opening a window can cool down the entire apartment within seconds.

3.3.3 Acoustical Comfort

Adding an extra layer of fabric might create other routes for air and moving air might cause howling sounds. The extra layer itself also might start to flutter, which is unwanted since this can also create extra sound. Also noises from neighbours and other sources of sound from inside the building might be reflected back inside. Outside noises will either stay on the same level or will even be reduced a little by adding the extra layer of fabric. Reducing the draft throughout the building will also reduce the noise level created by draft.

3.3.4 Thermal Comfort

Thermal comfort can be divided into heat and cold. Thermal comfort is sometimes described as a state where you neither shiver (from the cold) or sweat (from the heat).

Heat
Most of the heat that enters the living spaces is due to the big windows of the flat and therefore its high solar heat gain. Since the extra shell of fabric will disturb some of the heat from going into the building, the solar heat gain will be lessened. The airflow that is created by opening windows is very pleasant during hot summer days, the new facade will also disturb this pleasant airflow; during hot summer days the facade needs to be able to block out most of the sun’s radiance while still being open enough to ventilate the heat away (and/or maintain the pleasant airflow).

Cold
The current radiators in the apartment are more than sufficient to deal even with the coldest of days. The cold winter days are not a problem when it comes to comfort, they are a problem however when it comes to the buildings energy consumption.

3.4 Energy Consumption
As said in chapter 3.3.4 the radiators of the apartment are sufficient to deal with even the coldest of days, but because of the poor insulation of the building they are needed and turned on very frequently, not only in winter. By increasing the insulation value of the facade, the energy consumption can go down.
3.5 Summary: Analysis & Research

Fabric Research
The main purpose of fabrics throughout history is its flexibility and its lightweight which makes it easy to transport. Early tent structures evolved over the years by nomad tribes, and later structures were highly dependent on the quick evolving maritime knowledge of how to use fabric. Fabric is created by spinning fibres into a yarn. This yarn is then woven or knitted into fabric. When asking what type of fabrics exist? The answer is found looking at which fibres are suitable for spinning yarns. The main two groups of fibres are natural and synthetic, where some of the synthetic fibres are derived from natural ones.

The strongest of all weaving patterns is the simplest of all and is the plain weave since it has the most interaction between the warp yarns and the weft yarns. Twill weaves have less and less interaction between the warp and the weft yarn and are therefore weaker but softer to the touch, materials that need strength use the plain weave, materials that need to be soft to the touch often use more complex twill weaves. Rib knitting is an interesting pattern, due to its complex structure it is more extensible, flexible and has the ability to capture air, giving it thermal properties. Wool is commonly rib knitted into sweaters, its thermal properties makes it a nice material for cold winter days.

By looking at the current use of fabrics in architecture I found some interesting combinations. Some due to their long term use, and therefore being a standardized product, others are interesting due to their structure and flexibility. So far I determined three interesting combinations: PTFE coating on fiberglass weave, stretch fabrics and fabrics with a low-E coating.

Stretch fabrics: Because of their rib knitted nature, these fabrics are flexible and have the ability to encapsulate air, giving the material thermal properties (think of a woolen sweater). Together with a flexible (silicon) coating, the ability to create a material which has still air in between both coating layers is very interesting, it could be seen as double glazing made out of fabrics. The downside of this is that this solution would have very low to no transparency.

Low-E coatings: Commonly used in double glazing, Low-E coating can do their job equally well on a layer of fabric. Increasing the potential U-value of the construction by 100%, low-E coatings can be a great solution to lower the heat and cool demand of the building.

Non-organic fiberglass and polymer polyester: Due to their long term use a lot of information is available on fiberglass and polymer polyester. These two fibre types are the most commonly used ones in architecture for a good reason. Due to their low cost, good strength and good UV resistance the materials have a long lifespan, which might guarantee a good return of investment.

All mounting techniques have one thing in common, all of them spread the tensile forces in the textile over an as big as possible area to reduce the amount of point loads on the fabric to a minimum. Consequently whether using a frame, point, arch or any other type of support, the toolkit for fabrics always tends to spread out the forces going through the material. The facade of the 'Westraven project' shows us how to reduce wind speeds, so that windows can be opened even on higher floors. Serge Ferrari shows us that a double skin facade can be created with just a thin layer of fabric in front of the existing or newly built facade.
Double Skin Facades Research
For a gallery flat with existing galleries and balconies it makes sense to use the double skin façade as a separate system for each floor, therefore making use of a corridor type. Since the apartments inside the gallery flat make use of radiators preheating the air inside the double skin façade should be sufficient. To prevent the use of more energy the preference goes towards a natural ventilation system, although calculation should prove this as sufficient. Both the inside and the outside layer of the façade should be openable on top and bottom facilitating the ability to preheat the air in the winter, and to exhaust the warm air during the summer.

Comfort Research
Some examples of the most important requirements when it comes to comfort are:

- Protection against cold and heat (Thermal)
- Prevention of draft (Air quality)
- Shelter from bothersome sound created by neighbours or outside noises (such as traffic) (Acoustical comfort)
- Preventing surface condensation on walls, ceilings, floors and windows (Air quality)
- Fostering good ventilation with fresh and clean air, this should also take care of odors and potential air pollution (Air quality)
- Fostering efficient and comfortable lighting (Visual comfort)
- Preventing glare (Visual comfort)

A well divided lighting across the space is important and can be determined by measuring the daylight factor. For the inhabitants of the flat one of the main assets the flat gives is the view, especially for the higher lying apartments.

Although there is a mechanical exhaust in the kitchen and bathroom, most ventilation is natural. This natural flow of ventilation can create draft, especially on the higher floors where the wind velocity is higher. Acoustically the extra layer of fabric might protect the building more, but internal sources of sound might be reflected.

Thermal comfort can be divided into heat and cold. Thermal comfort is sometimes described as a state where you neither shiver (from the cold) or sweat (from the heat). The extra shell of fabric will disturb some of the heat from going into the building, the solar heat gain will be lessened. The airflow that is created by opening windows is very pleasant during hot summer days, the new facade will also disturb this pleasant airflow, during hot summer days the facade needs to be able to block out most of the sun's radiance while still being open enough to ventilate the heat away (and/or maintain the pleasant airflow). The current radiators in the apartment are more than sufficient to deal even with the coldest of days.

Energy Consumption
By increasing the insulation value of the facade, the energy consumption can go down.
Requirements & Design

Problems, solutions, design requirements, concept & design.

4 Requirements & Design ........................................ 34
4.1 Problems and Solutions of the Case Study Flat. 34
4.2 Design Requirements ........................................ 35
4.4 Design: Coa4Housing ...................................... 38
4.5 Material Selection ............................................ 49
  4.5.1 Transparent flexible material ....................... 49
  4.5.2 Woven Air Open Material ......................... 57
  4.5.3 Technical Solutions .................................. 57
4 Requirements & Design

Problems, solutions, design requirements, concept & design

This chapter focuses on listing all the criteria, requirements, problems and solutions for the design. Appendix 1 forms the basis of this chapter, showing the full list of criteria and requirements. Once all the criteria and requirements were listed they were organized from most important to least important in the hierarchy subchapter. Chapter 4.2 concludes the requirements and criteria by listing the most important. This final list will function as a checklist for the design. The lists in subchapters 4.1 and 4.2 led to the initial concept of the design, described in subchapter 4.3. In subchapter 4.4 the design is shown, and 4.5 describes the materialization as well as some of the technical solutions.

4.1 Problems and Solutions of the Case Study Flat

This subchapter lists the problems in four categories: Energy, comfort, technical and costs. After stating all the problems solutions can be given, later on these solutions will be tested with calculations. What follows is a list of problems and possible solutions in italic:

**Energy**

- High solar heat gain. *By adding sunscreens outside of the current facade the solar heat gain can be brought down almost completely.*
- Also caused by the Dutch desire of big windows, and therefore high solar gain. Sunscreens are added individually giving the flats a chaotic appearance. *By adding sunscreens on each apartment of the flat as a whole, instead of each apartment or even room individually, the appearance will be a whole too.*
- Like most buildings that are build pre oil crisis they have bad insulation properties. (thermal bridges, poor or no insulation, single glazing, etc) *Adding an extra layer of fabric gives the facade a lower U-value, with which less heat can escape.*

**Comfort**

- High solar heat gain. *By adding sunscreens outside of the current facade the solar heat gain can be brought down almost completely.*
- Windows can be opened but create heavy draft inside the apartment (and noise). *Just like in 'project Westraven' the fabric can buffer the wind speeds and therefore less draft will be created.*
- The gallery gets slippery due to rainfall. Specialy combined with temperatures below freezing point. *If an extra facade is added on the gallery side of the flat, the temperatures will rarely drop below freezing point, and the gallery walkways will be protected from rain.*

**Technical**

- Balconies are used for storage or laundry only. *Because of the extra facade, the climate on the balconies will become more pleasant throughout the year; this will make it a place to stay more often, therefore it will be more flexible for usage.*
- Maintenance is high. *If the new facade is well designed, its maintenance can be low, while it protects the old facade, this will lead to lower maintenance in general.*
- Mounting the facade. *Solution will be shown in chapter 4.4*
- Creating (flexible) air tightness of the current and new facade. *Solution will be shown in chapter 4.4*
- Creating flexible sunscreen. *Solution will be shown in chapter 4.3-4.4*

**Costs**

- Return of investment, *it is hard to assess the price of comfort.*
- Maintenance is high. *If the new facade is well designed, its maintenance can be low, while it protects the old facade, this will lead to lower maintenance in general.*
4.2 Design Requirements

This requirements subchapter summarises everything that is mentioned in appendix 1 a strict list of requirements. The hierarchy in the requirements is important, the hierarchy chosen is the one used in the Dutch building code. The Dutch building code starts with safety, then health, then usability, then energy and environment, then installations, then usage and finally the building process and demolition.

List of requirements

Safety
- The construction should be able to handle the wind load.
- The construction needs to meet the criteria of the safety factors of the safety class CC2.
- The facade on the gallery side needs to be able to ventilate the smoke away.
- If the gallery side of the flat is closed off by a facade, and since the gallery is the fire escape route, the gallery will need to be compartmentalised.

Health
- The facade should reduce draft when windows are opened.
- Air permeability needs to be reduced (when needed) to an EPC class 2.
- The minimum ventilation is $0.7 \text{ dm}^3/\text{s} \text{ per m}^2$.
- The new facade needs flexible sun shading, so that the solar heat gain can be reduced when needed.
- Glare has to be prevented.

Usability
- One person should be able to operate the facade.
- The openable windows will keep their function.

Energy and environment
- The U-value of the entire facade should be lowered by 50% to prevent heat from escaping during cold days and nights.
- Recyclable materials should be used as building materials for the facade.
- The facade should be durable, and parts should be easily replaced.
- The maintenance of the new facade should be low, coatings and materials should be dirt repellent.
- The maintenance of the old facade should be brought down.

Building process and demolition
- The facade should be built up in elements, so that if something breaks or does not function a single element can be easily replaced, while the replaced element can be repaired elsewhere.
- The total of maintenance costs should go down by adding this new facade.
- The total of energy costs should be halved.
4.3 Concept: Full Control
The concept created works like a roll that combines transparent sheets and PTFE open woven fabric. The idea is to create an extra frame as a new facade, but this frame could hold two types of cladding. The two types of cladding will be:

The transparent sheets, which can let up to 95% of sunlight through, while being completely airtight. And the PTFE open plain woven fabric, which can block 70% of sunlight in each layer; but would be 40% air open.

The concept for coat4housing is an equation:

Full control = adjustable sun shading + adjustable air permeability

With two different types of materials on a roll, hanging on the outside of the balconies and galleries inside its frame, full control is given over the newly created space between old and new facade. This newly created space can be used as a buffer zone for sun radiance, airflow and wind speeds. With these two materials it is possible to vary air permeability from approx. 35% to 1%, and vary the solar radiance infiltration from 90% to 10%. This way the facade is either air open and the sun almost fully shaded (summer scenario) or air tight while the sun radiance can enter the building (winter scenario). Both these scenarios seem perfect for the warmest and the coldest seasons.
Image 42: Concept of the new facade. Air tight and sun open vs. air open and sun tight. Because it is a roll, more than two options are available. This image shows the facade being half open, and therefore letting both a higher percentage of sun radiance through as well as letting more air through the facade. (source: own image)

Image 43: Conceptual render showing what the facade could look like. Since it is possible to print on woven PTFE before coating it, the facade can have any colour. (source: own image)

Image 44: Conceptual render showing what the gallery could look like. (source: own image)
4.4 Design: Coat4Housing

The width of the apartments is 7000 mm, the height of the apartments is 3000 mm. This area can be covered by three elements of 2300 x 2970 mm. The initial design, after the concept was formed, puts three of these elements on the balcony side of each apartment, the gaps between the balconies will be filled to prevent too much air exchange between the apartment’s balconies, striving for a closed system for each individual apartment. Closing off the balconies in this way also adds to the acoustical comfort. For now the gallery side of the apartment is left open since both gallery sides of the L-shaped flat point to the north-west and the north-east the needs for sun shading on these sides is almost non existing.

The floorplan shows where the three elements will be hung on the facade. Each apartment will have its own air flowing to and from its own balcony; this is to prevent indoor air going from 1 apartment to the next.

The balconies are constructed out of an extruded L-shaped concrete horizontal element. The facade elements will be hung on these L-shaped balconies from center to center.

Image 45: Floorplan of two apartments with the new facade. Showing 2 options, on the left the option with 3 panels per apartment and on the right the option with 2 panels per apartment (source: own image)
4. Requirements & Design

**Image 46:** Axonometric view/Elevation of the new facade on the old balcony structure. (Source: own image)

**Image 47:** Axonometric view of the apartment building, with a highlighted facade piece. (Source: own image)
4. Requirements & Design

**Horizontal Profile Aluminium**
Aluminium square extruded profiles, for stiffness

**Aluminium Box**
Aluminium box to keep most dirt and rain out of the system.

**Sheet Material**
Transparent PVC or Woven fiberglass with PTFE coating
The sheets that roll across the system. Made from transparent PVC or woven fiberglass.

**Tube Engine**
Automates the system, can be up to 4000mm long.

**Existing Construction**
Concrete existing balcony element
4. Requirements & Design

**Horizontal Profile Aluminium**
Aluminium square extruded profiles, for stiffness

**Vertical Profile Aluminium**
Aluminium profile with PVC holders to keep the sheet materials in place. Zip lock system

**Mounting System**
Rust free stainless steel mounting systems with four anchors inside the existing construction

**Sheet material**
Transparent PVC or Woven fiberglass with PTFE coating
The sheets that roll across the system. Made from transparent PVC or woven fiberglass.

**Tube engine**
Automates the system, can be up to 4000mm long

**Existing construction**
Concrete existing balcony element

*Image 49: Axonometric view of the highlighted facade piece (Source: own image)*
4. Requirements & Design

**Horizontal Profile Aluminium**
Aluminium square extruded profiles, for stiffness

**Vertical Profile Aluminium**
Main constructive element of the facade system, spans from top to bottom and is held in place directly by the mounting system

**Mounting System**
Rust free stainless steel mounting systems with four anchors inside the existing construction

*Image 50: Axonometric view of the highlighted facade piece (Source: own image)*
4. Requirements & Design

**Image 51:** Exploded view of one facade element. (Source: own image)
**4. Requirements & Design**

**Detail A, horizontal connection between two facade elements**

- **Anchors**
  - Holding the system

- **Zipper edge**
  - Fits and stays in the zipscreen profile

- **PVC sheet**
  - Transparent sheet

- **PVC Zipscreen profile**
  - To guide the zipper edge

- **Aluminum Profiles**
  - Structural frame holding everything in place

- **PTFE shading**
  - Woven fiberglass with PTFE coating
  - Sun shading material

- **Filament**
  - For airtightness, as adjusting space and flexible to let the material expand & shrink

*Image S2: Detail A, horizontal connection between two facade elements*
4. Requirements & Design

**Image 53:** Detail B1, vertical connection between the new facade and the existing construction, option 1: contains PVC brizzle holders with brizzles to control air permeability.

- **Filament**
  - For airtightness, as adjusting space and flexible to let the material expand & shrink

- **PVC Brizzle Holder & Brizzles**
  - For airtightness

- **PVC sheet**
  - Transparent sheet

- **Aluminum Profiles**
  - Structural frame holding everything in place

- **PTFE shading**
  - Woven fiberglass with PTFE coating
  - Sun shading material

**Image 54:** Detail B2, vertical connection between the new facade and the existing construction, option 2: contains rubber tape and PVC profiles to control air permeability.

- **Filament**
  - For airtightness, as adjusting space and flexible to let the material expand & shrink

- **PVC sheet**
  - Transparent sheet

- **Aluminum Profiles**
  - Structural frame holding everything in place

- **Rubber tape & PVC Profile**
  - For airtightness

- **PTFE shading**
  - Woven fiberglass with PTFE coating
  - Sun shading material
4. Requirements & Design

Image 55: Impression of the balcony with the system closed. (Source: own image)

Image 56: Impression of the balcony with the system almost completely open. (Source: own image)

Image 57: Impression of the balcony with the system open. (Source: own image)

Image 58: Impression of the flat with the new facade on it. 3 panels per apartment (Source: own image)

Image 59: Impression of the flat with the new facade on it. 2 panels per apartment (Source: own image)

Image 60: Impression of the flat with the new facade on it. 3 panels per apartment (Source: own image)
4. Requirements & Design

Image 61: Outside view of model made from wood, pvc and woven fiberglass of one facade element. Stance 1 of 4 (Source: own image)

Image 62: Outside view of model made from wood, pvc and woven fiberglass of one facade element. Stance 2 of 4 (Source: own image)

Image 63: Outside view of model made from wood, pvc and woven fiberglass of one facade element. Stance 3 of 4 (Source: own image)

Image 64: Outside view of model made from wood, pvc and woven fiberglass of one facade element. Stance 4 of 4 (Source: own image)
4. Requirements & Design

Image 65: Inside view of model made from wood, pvc and woven fiberglass of one facade element. Stance 1 of 4 (Source: own image)

Image 66: Inside view of model made from wood, pvc and woven fiberglass of one facade element. Stance 2 of 4 (Source: own image)

Image 67: Inside view of model made from wood, pvc and woven fiberglass of one facade element. Stance 3 of 4 (Source: own image)

Image 68: Inside view of model made from wood, pvc and woven fiberglass of one facade element. Stance 4 of 4 (Source: own image)
4.5 Material Selection

This paragraph explains why the materials have been selected for the design.

4.5.1 Transparent flexible material

ETFE was expected to be the best option for this material, since ETFE has been used in the building industry in various forms, therefore it has been tested on both the long term and in various applications. Since the material will move on a daily basis, and needs to be thicker than in usual ETFE applications, the transparency of the material will suffer. Taking a look at different materials that are up for the task seemed necessary. In the CES Edupack 2016, a material database for education, four main filters were made. Firstly, the material has to be transparent, making the first filter transparency, the material needs to be UV-resistant. The third filter is a so-called ‘material family’ picking 6 out of 13 families to filter out the glasses, ceramics and metals. The fourth and final main filter applied asks for the materials processing property: Polymer extrusion, since this excludes materials that cannot be made into sheets. After doing this 35 materials were left, taking a closer look at these materials 1 by 1, looking at their usual applications, a list of 10 potential materials was made:

- ETFE
- FEP
- PCTFE
- PEI
- PEN
- PET
- PETG
- PMMA
- PVC
- PVDF

After some investigation, mostly calling suppliers, materials like PCTFE, PEI, PEN, PMMA and PVDF were either too expensive or completely unsuitable for the job. According to Vink Kunststoffen, anything is possible in the world of plastics, PVC and PET are two logical choices. Properties like UV-resistance and flexibility as well as certain coatings (like a Low-E coating) can be given to almost every plastic, so why would you pick an expensive one. A revised list of 5 potential materials was made:

- ETFE
- FEP
- PET
- PETG
- PVC

1 ETFE

ETFE is the number one most used clear plastic roofing and facade material. ETFE (Ethylene Tetrafluoroethylene) film is durable and very lightweight in comparison to glass structures. (birdair, 2017) ETFE is being considered the material of choice for traditional skylight applications to long span structures and building facades. Few building materials can match ETFE for its impact or presence when you want a structure that stands out from the crowd. According to Birdair the benefits of ETFE, while trying to sell the material, are the following:
4. Requirements & Design

• “Exceptional Light Transmission – ETFE films can be highly transparent (from 90% to 95%) and allow for the passing of UVs which are responsible for the promotion of photosynthesis thus facilitating plant growth.
• Solar Control/Shading – ETFE film systems can incorporate a number of frit patterns on one or multiple layers to alter their solar performance. The foil is printed with various standard or custom patterns. Colors can be introduced in a variety of ways whether it’s applied during the film extrusion process providing a consistent tint in various tones from red to violet or adding lighting with unlimited color options.
• Elasticity – While ETFE films are very elastic (up to 600% at breaking point), they are still structurally resistant. The tensile strength at the limit of elasticity/plasticity is 21-23 N/mm² but tensile strength to breaking point is 52/Nmm². For structural calculation a limit of 15 N/mm² is conservatively usually taken.
• Long Lasting/Longevity – Under exposure to environmental pollution, UV light, harsh chemicals or extreme temperature variations, ETFE does not degrade.
• Acoustics – ETFE film has approximately 70% acoustic transmission.
• Sustainable/Energy Efficient – From extruding of the film to transportation to site, compared to other similar cladding material, little energy will be consumed thus reducing the overall carbon footprint. In addition to this, the nature of the product enhances the building physics through insulation and daylighting, therefore contributing to the global low energy aspect of the building.
• Cost Effective – Due to the lightweight nature of ETFE, substructure support systems and concrete foundations can be designed more efficiently. ETFE systems also provide ample natural daylighting, thus minimizing energy costs by lowering the demand for indoor lighting.
• Recyclable – Easily recyclable, waste from the manufacturing process or even old ETFE elements can be remolded into new ETFE products such as tubing components, wires or castings.” (birdair, 2017)

This wide variety of fabrication possibilities combines with important properties to offer a unique balance of capabilities not available in any other plastic film.

3 PET

PET is short for polyethylene terephthalate - the chemical name for polyester. PET is used frequently as a food or drink container. PET can acquire a hazing effect, when bend a lot. This hazing effect comes from the crystallization of the product. This can be dealt with by using plasticizers before extruding the material, or by adding glycol, thereby creating PETG.

4 PETG

PETG is used a lot on the faculty of architecture, it is mostly known by its brand name VIVAK. It is used in application that require deep draws, complex cuts or precisely molded in details. It is more expensive than PET by quite a margin.

“PET, or ‘polyethylene terephthalate,’ is a combination of two monomers. PETG is of the same chemical composition as PET but with the addition of glycol. The addition of glycol to create PETG removes the hazing effect seen during heating and also prevents an undesirable crystallization effect that causes standard PET to become brittle.” (Petrosh, 2017)

5 PVC

Palram is a supplier in PVC sheets, one of their products is called ‘PALCLEAR’, according to Palram:

“PALCLEAR transparent sheets provide solutions to various applications in populated indoor areas. PALCLEAR combines excellent mechanical properties and impact strength, water-clear transparency, excellent resistance to chemicals and fire resistance. It withstands many chemical agents and can be easily formed using various fabrication techniques. Optional characteristics range from high clarity and anti-glare surface to increased impact resistance.

• Excellent resistance to chemicals
• High fire rating: Suitable for populated areas
• High light transmission
• “Water Clear” transparency
• Optional high-impact and UV resistance
• Formable: can be thermoformed, vacuum formed, bent hot or cold, fabricated” (Palram, 2017)

Samples were gathered of these five remaining materials. The samples were made into little sketch models, to see what the materials would look like.

These are all quite bold claims. And we will take these claims to the test.

2 FEP

Teflon FEP film is a transparent, thermoplastic film that can be heat sealed, thermoformed, vacuum formed, heat bonded, welded, metalized, laminated-combined with dozens of other materials, and can also be used as an excellent hot-melt adhesive. (The Chemours Company, 2016)
Image 70: ETFE sample, thickness approx. 0.25-0.3 mm, note how the material looks quite milky, especially compared to the other materials. (Source: own image)

Image 71: FEP sample, blow extruded, thickness approx. 0.1 mm, blow extruded FEP is very transparent, unlike tube extruded FEP, the milkyness in the tube extruded version can also come from the slightly higher thickness. (Source: own image)
4. Requirements & Design

Image 72: FEP sample, tube extruded, thickness approx. 0.25 mm, still quite transparent, but a milkier appearance than its thinner brother. (Source: own image)

Image 73: PET sample, thickness approx. 0.3 mm, PET is very transparent, besides PETG and PVC it is the most transparent material. (Source: own image)
Image 74: PETG sample, AKA Vivak, thickness approx. 0.5 mm, PETG is the most transparent material out of the 5 selected ones. (Source: own image)

Image 75: PVC sample, thickness approx. 0.3-0.4 mm, PVC is very transparent, besides PETG it is the most transparent material. For the transparency of the material the thickness does not seem to matter much, since the thicker samples seem to share a similar transparency. (Source: own image)
At this point, graphs can be made, showing the starting 10 materials and their properties.

**Image 76:** Shows the transparency of the 10 selected materials on the x axis, while showing the price/kg on the y axis. (source: own image)

**Image 77:** Price/kg on y axis vs UV radiation resistance on the x axis. Note that PEI and PVDF are the only two materials selected with an excellent UV radiation resistance. An excellent score on UV-resistance = tens of years +, while a good score represents years without wear. (source: own image)
Image 78: Price/m3 on y axis vs flexural strength on the x axis. Note that once again PET and PVC are doing well on flexural strength for their low price. (source: own image)

Image 79: The CO2 footprint of the 10 selected materials. Even though ETFE is sold as one of the most environment friendly materials, in this list it is located at the top. (source: own image)
Image 80: Not all selected materials perform well against strong acids. PET and PVC do very well in all aspects, however, PVC has a way higher resistance to chemicals and especially to acidic chemicals. (source: own image)

PVC seems to be the best material for its strength, resistance, transparency, CO2 recycling footprint and price.
4.5.2 Woven Air Open Material

**PTFE**

As seen earlier in chapter 3, PTFE is a good option, with good durability, self cleaning properties and great UV-resistance. It is a strong material, and can be woven in numerous ways.

“PTFE, or polytetrafluoroethylene, is a Teflon®-coated woven fiberglass membrane that is extremely durable and weather resistant. PTFE fiberglass membranes can be installed in climates ranging from the frigid arctic to the scorching desert heat with an expected project life exceeding 30 years.” (Birdair, 2017)

**TiO2 - Coated PTFE**

TiO2 coating takes PTFE’s self cleansing abilities to the next level. (Birdair, 2017) The name is self explanatory, it is PTFE coated with TiO2, Titanium Oxide Nanopowder / Nanoparticles that form a non-toxic and flame resistant photocatalytic membrane. This membrane acts similar to a green facade, actively neutralizing airborne pollutants and odors.

“TiO2 – coated PTFE is a popular choice with designers and architects in sustainable commercial roofing market sectors throughout Asia and is now beginning to find its niche in custom tensile systems in North America. The unique self-cleaning benefits of TiO2 allow the material to break down dirt and other organic materials through a chemical reaction with the sun’s UV rays, oxygen and water vapor, present in the air.”(Birdair, 2017)

Priced around 15 euro per kilogram, that is without taking the coating process into account, it is quite an expensive material. But in areas where pollutants are a problem, it could definitely be a good option.

4.5.3 Technical Solutions

**Zip screen**

One of the problem areas in the design concept are the edges where the fabric and sheet meet the frame. In sunscreens this problem is well known, and the current solution for this problem is called a zip screen. It basically consists of a glued or stitched on side guidance zipper that runs through a PVC profile.

Image 81: PTFE woven mesh (source: chinapasia)  

Image 82: An example of a closed zip screen system (source: Sunrise Zonwering)  

Image 83: Example of a zip screen, the PVC profile inside the aluminium profile guides the fabric (Source: Sunrise Zonwering)
A Ladybug and two models
5 Climate Analysis & Calculation

A Ladybug and two models

In this chapter the climate is analyzed, and the designs heat flows are calculated by using two models: the one-node-model and a Honeybee model. Finally the design is evaluated using the list of requirements given in subchapter 4.2.

5.1 Climate Analysis

Ladybug is used for early climate analysis, by using a weather file of Amsterdam (nearest available one, closest to Delft), the climate data is used to make graphs. First a few graphs are made showing the wind speed, and the influence it has on the percentage of comfort hours. Then the potential internal heat gain is graphed, and its influence on the percentage of comfort hours. As a final step in Ladybug the annual solar radiation on the case study flat is checked and graphed on a model of the flat itself.

![Image 84: Ladybug climate results, comfort by windspeed, temperature and internal heat gain. Lowering the windspeed (shown as the top graph) can increase the comfortable outdoor hours from +/- 2% to +/- 5%. While using internal heat gain (shown as the bottom graph) has a potential of increasing this number to +/- 35%. (source: own image)]

5.2 Calculation model 1: One-node model of an atrium

The one-node model of an atrium is used to calculate the temperatures on the balcony, when it functions as a sun space. The internal temperature \( T_i \) can be calculated using the following equation:

\[
T_i = T_e + \frac{W}{H_e} \left( 1 - e^{-\frac{H_e}{M} t} \right)
\]

where:

- \( T_i \): Internal temperature [K]
- \( T_e \): Outside temperature [K]
- \( t \): Time in second [s]
- \( W \): Solar load per m² [W/m²]
- \( H_e \): Solar energy transmittance coefficient
- \( M \): Overall heat transfer coefficient [W/(m²K)]

\[
W = Q_{sun} = g A q_{sun}
\]

Here the solar energy transmittance coefficient determines how much of the solar load penetrates into the building, therefore the \( g \) is one of the design parameters.

\[
H_e = U A + \rho cv V_{air}
\]

where:

- \( U \): Overall heat transfer coefficient [W/(m²K)]
- \( A \): Area of the facade [m²]
- \( \rho \): Air density [kg/m³]
- \( c \): Specific heat capacity [J/kgK]
- \( V \): Volume of the balcony [m³]

![Image 85: Ladybug climate results, radiation on the case study flat in kWh/m2 viewed from the south-east side. These are the balcony sides of the flat, the south-south-east facade receives the most radiation, about 700 kWh/m2. (source: own image)]
The two values that can be influenced with the design here are the overall heat transfer coefficient \([U]\) and the ventilation rate per second \([n]\). But since the building is mostly naturally ventilated the ventilation rate per second \([n]\) relies purely on the airflow through the building which in its turn depends on the effective area of the openings \([A_{\text{eff}}]\). Therefore the only new design parameter in this equation is the \(U\)-value of the new facade.

\[
M = \sum_n (m_n c_n)
\]

where:

<table>
<thead>
<tr>
<th>m</th>
<th>Mass [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>c</td>
<td>Specific heat capacity [J/kgK]</td>
</tr>
</tbody>
</table>

Although increasing or decreasing the thermal mass of the balcony or the interior of the building could have a big effect on the temperatures inside the balcony or the building, adding or removing concrete or any other type of heavy material is of course nonsense. Therefore these values are very relevant to the calculation but cannot be changed, and are excluded from the design parameters.

\[
q_{\text{sun}} = 200 \text{ W/m}^2
\]

\[
q_{\text{sun}} = 600 \text{ W/m}^2
\]

\[
T_e = 30 \degree C
\]

\[
T_{\text{balcony}}
\]

\[
T_{\text{inside}}
\]

\[
\text{Air density [kg/m}^3\text{]}
\]

\[
\text{Solar load per m}\text{² [W/m}^2\text{]}
\]

\[
\text{Outside temperature [K]}
\]

\[
\text{Internal temperature [K]}
\]

So far 3 main design parameters have been established:

- \(A_{\text{eff}}\): Effective area
- \(g\)-value: Solar energy transmittance coefficient
- \(U\)-value: Overall heat transfer coefficient

These three design parameters have an impact on the heat balance of the concept design. Now these design parameters will be linked to summer and winter scenario’s to see their impact. In summer the \(g\)-value will be set to 0.1, and the \(A_{\text{eff}}\) can be made as high as possible, 0.24 m². Here we see 4 summer scenario’s, the outside temperature \((T_e)\) is 30 °C. The scenario’s have two different wind velocities \((v_{\text{wind}})\) of 2 m/s and 8 m/s, and two different solar loads \((q_{\text{sun}})\).

<table>
<thead>
<tr>
<th>Summer</th>
<th>Wind 2 m/s</th>
<th>Wind 8 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>(T_e = 30 \degree C)</td>
<td>(T_{\text{balcony}})</td>
<td>(T_{\text{inside}})</td>
</tr>
<tr>
<td>(q_{\text{sun}} = 600 \text{ W/m}^2)</td>
<td>30,1 °C</td>
<td>30,35 °C</td>
</tr>
<tr>
<td>(q_{\text{sun}} = 200 \text{ W/m}^2)</td>
<td>30,1 °C</td>
<td>30,1 °C</td>
</tr>
</tbody>
</table>

Table 4: Summer scenario’s, \(g\)-value = 0,1, \(A_{\text{eff}}\) = 0,24 m² and \(U_{\text{new facade}} = 3\) (source: own image)

Due to the low \(g\)-value the temperature on the balcony \((T_{\text{balcony}})\) warms up very little, even with a high amount of solar load \((q_{\text{sun}})\) of 600 W/m². The high \(A_{\text{eff}}\) makes sure there is plenty of ventilation throughout the apartment which ventilates all the incoming energy away. Due to the flexibility of the \(A_{\text{eff}}\) and the \(g\)-value the inside temperatures will barely become higher than the outside temperatures. Note that in these summer scenario’s the two \(U\)-values of the facades do next to nothing. Making the \(A_{\text{eff}}\) and the \(g\)-value the most important design parameters for summer (warm and sunny) scenario’s.

In winter however the facade strives for the complete opposite. All windows are closed which makes the \(A_{\text{eff}}\) of the apartment approximately 0,015 m². Now the impact of the new facade’s \(A_{\text{eff}}\) can be seen in temperature differences in four winter scenario’s. For the winter scenario’s the outside temperature \((T_e)\) is -5 °C. The wind speeds remain the same, 2 m/s and 8 m/s. The solar load will be lowered in these winter scenario’s to 400 W/m² and 100 W/m². The new facades \(A_{\text{eff}} = 0,26\) which leaves the \(A_{\text{eff}}\) of the total apartment on 0,015.
Table 5: Winter scenario’s, g-value = 0,9, A eff = 0,015 and U new facade = 3 (source: own image)

With a U-value of 2 on the old facade and a U-value of 3 on the new facade, an outside temperature of -5 °C and an inside temperature of 20 °C, the temperature on the balcony at would be around 5 °C, without any sun. With little sun the temperature on the balcony warms up just a little 2,7 °C with little wind, while if the wind speed is higher most generated heat is ventilated away and the Tbalcony only warms up 1,6 °C. If the solar load in winter is higher the temperatures rise 13,8 °C with low wind and with 9,4 °C with a higher wind speed.

The new facades A eff = 0,013 which makes the A eff of the total apartment 0,008.

Table 6: Winter scenario’s, g-value = 0,9, A eff = 0,008 and U new facade = 3 (source: own image)

Once the A eff is decreased we can see the highest differences when the wind is stronger. The temperature rise with a high solar load and high wind speed went from 9,4 °C to 11,7 °C, while with low wind it went from 13,8 °C to 14,7 °C still an increase but lower. It can be concluded that the A eff has more effect on the design when the wind speed is higher; and of course if there is any heat generated that could potentially be ventilated away. Note that if barely any heat is generated due to a low solar load, the impact of a lower A eff on the ventilation is barely noticeable.

A low-E coating is added to the outside facade decreasing the U-value from 3 to 1.

Table 7: Winter scenario’s, g-value = 0,9, A eff = 0,008 and U new facade = 1 (source: own image)
5.2.2 Calculations: Night Situation
At night and similarly on cold days with little or without any sun the U-value of the total facade package becomes the most important design parameter. In this overview we can see various U-values of different types of fabric facade layouts. (See image 89)

The current concept has two layers and the effect a low-E coating has, even if only applied on one of the two layers, is quite high. The difference in lost energy with these R and U-values can be seen with this formula, (to get the outcome in kWh it is divided by 36):

\[ Q = AU \times 238/36 \]

Where:

<table>
<thead>
<tr>
<th>U</th>
<th>Area of the facade [m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>overall heat transfer coefficient [W/(m²K)]</td>
</tr>
</tbody>
</table>

(In this case 21 m²)

Graphing this formula gives the following graph: (see image 88)

Image 88: Showing the amount of energy lost in kWh, for the current situation, a double layered system and a doubled system layer with a Low-E coating. (source: own image)

Image 89: R- and U-values of different fabric facade layouts, notice how much effect a low-E coating can have. (source: own image)
5.3 Calculation model 2: Honeybee

EnergyPlus uses zones to calculate. These 5 zones represent one apartment on the 16th floor. This is the model used for upcoming calculation results (see image 90).

The heating load nearly halves, while the solar heat gain, when needed, has the potential to quadruple.

![Model view with its 5 zones](Image 90: Honeybee model in rhino, with its urban masses in red and the zones in grey. (source: own image))

The model without the system shows some strange behaviour; the temperature on the balcony sometimes goes up to 25 degrees Celsius while the outside temperature is around zero degrees Celsius. Even though the balcony zone has been materialized accordingly, the results that the model currently gives might be too mild compared to the actual heating requirements of the current building.

![Model view inside of building mass](Image 91: Livingroom without the system (top) compared to the livingroom with the system (bottom). The heating demand drastically decreases because of the new facade. (source: own image))

![Model view of urban masses](Image 92: Kitchen-zone without the system (top) compared to the kitchen-zone with the system (bottom). The heating demand decreases less, but still decreases. (source: own image))
The temperature of the balcony with the system turned on here has a tendency to overheat. That is because the system in the honeybee model is the air-closed/sun-open system, but as seen in the calculations of the one node model (as shown in Table 6), when the system is set to its air-open/sun-closed position, the sufficient ventilation and lowered g-value of the system makes sure that the temperatures on the balcony barely exceed the outdoor temperature.
5.4 Conclusion Evaluation of the Design

What follows is the list from chapter 4.2 the design requirements. The list has been filled in with one of three symbols:

O = Not yet calculated
V = The design meets the requirement
X = Does not apply

Thus far most requirements have been met. Some of them should still be determined. Since this report focusses on energy and comfort, most of the requirements on costs and strength have not been confirmed yet.

List of requirements

**Safety**

O The construction should be able to handle the wind load.
O The construction needs to meet the criteria of the safety factors of the safety class CC2.
X The facade on the gallery side needs to be able to ventilate the smoke away.
X If the gallery side of the flat is closed off by a facade, and since the gallery is the fire escape route, the gallery will need to be compartmentalised.

**Health**

V The facade should reduce draft when windows are opened.
V Air permeability needs to be reduced (when needed) to an EPC class 2.
V The minimum ventilation is 0,7 dm³/s per m².
V The new facade needs flexible sun shading, so that the solar heat gain can be reduced when needed.
V Glare has to be prevented.

**Usability**

V One person should be able to operate the facade.
V The openable windows will keep their function.

**Energy and environment**

V The U-value of the entire facade should be lowered by 50% to prevent heat from escaping during cold days and nights.
V Recyclable materials should be used as building materials for the facade.
V The facade should be durable, and parts should be easily replaced.
V The maintenance of the new facade should be low, coatings and materials should be dirt repellent.
V The maintenance of the old facade should be brought down.

**Building process and demolition**

V The facade should be built up in elements, so that if something breaks or does not function a single element can be easily replaced, while the replaced element can be repaired elsewhere.
O The total of maintenance costs should go down by adding this new facade.
O The total of energy costs should be halved.
Conclusion

A summary and discussion

6. Conclusion .............................................. 68
6.1 Introduction ........................................... 68
6.2 Methods ............................................... 68
6.3 Analysis and Research ............................. 68
6.4 Strategize ............................................. 69
6.5 Evaluation of the Design ......................... 70
6.6 Discussion ........................................... 71
6.7 Cost Estimate ......................................... 72
6. Conclusion

A summary and discussion

In this chapter the conclusions of each previous chapter will be listed.

6.1 Introduction

Fabric is fascinating because of its honesty, flexibility and (light) weight. Gallery flats have several problems, to illustrate these problems a case study flat is picked, the gallery flat in Delft at the Bosboom-Toussaintplein. For this case study a fabric facade will be designed, with the purpose of increasing its energy performance and comfort. Fabric has many assets going for it. It is lightweight, has visibility and performance features, thermal control, water and dirt repellency, light transmission, acoustical absorption and sustainability. It is hard to think of any other lightweight material that has so much potential, and therefore fabric can be the perfect material to solve the issues and problems in the case study building.

6.2 Methods

The chosen methodology for this project is research by design. This will be implemented in this by using the ASER (analyze, strategize, experiment, reflect) system, but preliminary to this the fascination phase was included before beginning with the A, S, E and R phases, therefore forming the newly acquired FASER (fascination, analyze, strategize, experiment, reflect) system. The tools that are used for this project so far are all computer programs as listed in chapter 2.2.

6.3 Analysis and Research

Fabric Research

The main purpose of fabrics throughout history is its lightweight which makes it easy to transport and its flexibility. Early tent structures evolved over the years by nomad tribes, and later structures were highly dependent on the quick evolving maritime knowledge of how to use fabric. Fabric is created by spinning fibres into a yarn. This yarn is then woven or knitted into fabric. When asking what type of fabrics exist? The answer is found looking at which fibres are suitable for spinning yarns. The main two groups of fibres are natural and synthetic, where some of the synthetic fibres are derived from natural ones.

The strongest of all weaving patterns is the simplest of all and is the plain weave since it has the most interaction between the warp yarns and the weft yarns. Twill weaves have less and less interaction between the warp and the weft yarn and are therefore weaker but softer to the touch, materials that need strength use the plain weave, materials that need to be soft to the touch often use more complex twill weaves. Rib knitting is an interesting pattern, due to its complex structure it is more extensible, flexible and has the ability to capture air, giving it thermal properties. Wool is commonly rib knitted into sweaters, its thermal properties makes it a nice material for cold winter days.

By looking at the current use of fabrics in architecture I found some interesting combinations. Some due to their long term use, and therefore being a standardized product, others are interesting due to their structure and flexibility. So far I determined three interesting combinations: PTFE coating on fiberglass weave, stretch fabrics and fabrics with a low-E coating.

Stretch fabrics: Because of their rib knitted nature, these fabrics are flexible and have the ability to encapsulate air, giving the material thermal properties (think of a woolen sweater). Together with a flexible (silicon) coating, the ability to create a material which has still air in between both coating layers is very interesting, it could be seen as double glazing made out of fabrics. The downside of this is that this solution would have very low to no transparency.

Low-E coatings: Commonly used in double glazing, Low-E coating can do their job equally well on a layer of fabric. Increasing the potential U-value of the construction by 100%, low-E coatings can be a great solution to lower the heat and cool demand of the building.

Non-organic fiberglass and polymer polyester: Due to their longtime use a lot of information is available on fiberglass and polymer polyester. These two fibre types are the most commonly used ones in architecture for a good reason. Due to their low cost, good strength and good UV resistance the materials have a long lifespan, which might guarantee a good return of investment.

All mounting techniques have one thing in common, all of them spread the tensile forces in the textile over an as big as possible area to reduce the amount of point loads on the fabric to a minimum. Consequently whether using a frame, point, arch or any other type of support, the toolkit for fabrics always tends to spread out the forces going through the material.

The facade of the ‘Westraven project’ shows us how to reduce wind speeds, so that windows can be opened even on higher floors. Serge Ferrari shows us that a double skin facade can be created with just a thin layer
Conclusion

of fabric in front of the existing or newly built facade.

Double Skin Facades Research

For a gallery flat with existing galleries and balconies it makes sense to use the double skin façade as a separate system for each floor; therefore making use of a corridor type. Since the apartments inside the gallery flat make use of radiators preheating the air inside the double skin façade should be sufficient. To prevent the use of more energy the preference goes towards a natural ventilation system, although calculation should prove this as sufficient. Both the inside and the outside layer of the façade should be openable on top and bottom facilitating the ability to preheat the air in the winter, and to exhaust the warm air during the summer.

Comfort Research

Some examples of the most important requirements when it comes to comfort are:

- Protection against cold and heat (Thermal)
- Prevention of draft (Air quality)
- Shelter from bothersome sound created by neighbours or outside noises (such as traffic) (Acoustical comfort)
- Preventing surface condensation on walls, ceilings, floors and windows (Air quality)
- Fostering good ventilation with fresh and clean air; this should also take care of odors and potential air pollution (Air quality)
- Fostering efficient and comfortable lighting (Visual comfort)
- Preventing glare (Visual comfort)

A well divided lighting across the space is important for visual comfort. Also the amount of light that comes into a space is important and can be determined by measuring the daylight factor. For the inhabitants of the flat one of the main assets the flat gives is the view, especially for the higher lying apartments. Although there is a mechanical exhaust in the kitchen and bathroom, most ventilation is natural. This natural flow of ventilation can create draft, especially on the higher floors where the wind velocity is bigger. Acoustically the extra layer of fabric might protect the building more, but internal sources of sound might be reflected.

Thermal comfort can be divided into heat and cold. Thermal comfort is sometimes described as a state where you neither shiver (from the cold) or sweat (from the heat). The extra shell of fabric will disturb some of the heat from going into the building, the solar heat gain will be lessened. The airflow that is created by opening windows is very pleasant during hot summer days, the new facade will also disturb this pleasant airflow during hot summer days the facade needs to be able to block out most of the sun’s radiance while still being open enough to ventilate the heat away (and/or maintain the pleasant airflow). The current radiators in the apartment are more than sufficient to deal even with the coldest of days.

Energy Consumption

By increasing the insulation value of the facade, the energy consumption can go down.

6.4 Strategize

The created list of requirements is the conclusion of the strategize phase. In the order of the Dutch building code, the requirements list is as follows:

Safety
- The construction should be able to handle the wind load.
- The construction needs to meet the criteria of the safety factors of the safety class CC2.
- The facade on the gallery side needs to be able to ventilate the smoke away.
- If the gallery side of the flat is closed off by a facade, and since the gallery is the fire escape route, the gallery will need to be compartmentalised.

Health
- The facade should reduce draft when windows are opened.
- Air permeability needs to be reduced (when needed) to an EPC class 2.
- The minimum ventilation is 0,7 dm³/s per m².
- The new facade needs flexible sun shading, so that the solar heat gain can be reduced when needed.
- Glare has to be prevented.

Usability
- One person should be able to operate the facade.
- The openable windows will keep their function.

Energy and environment
- The U-value of the entire facade should be lowered by 50% to prevent heat from escaping during cold days and nights.
- Recyclable materials should be used as building materials for the facade.
- The facade should be durable, and parts should be easily replaced.
- The maintenance of the new facade should be low, coatings and materials should be dirt repellent.
- The maintenance of the old facade should be brought down.
Building process and demolition

- The facade should be built up in elements, so that if something breaks or does not function a single element can be easily replaced, while the replaced element can be repaired elsewhere.
- The total of maintenance costs should go down by adding this new facade.
- The total of energy costs should be halved.

6.5 Evaluation of the Design

List of requirements

<table>
<thead>
<tr>
<th>O</th>
<th>V</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not yet calculated</td>
<td>The design meets the requirement</td>
<td>Does not apply</td>
</tr>
</tbody>
</table>

Safety

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X The facade on the gallery side needs to be able to vent the smoke away.
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O The total of maintenance costs should go down by adding this new facade.
V The total of energy costs should be halved.

Thus far most requirements have been met. Some of them should still be determined. Since this report focuses on energy and comfort, most of the requirements on costs and strength have not been confirmed yet.
6.6 Discussion

How can an extra shell of fabric improve the gallery flat, Bosboom-Toussaintplein in Delft, on both its comfort and its energy performance?

6.6.1 Fabric offers great possibilities, it can shade the sun, it can take care of draft, it can reduce maintenance, it can create a comfortable space and above all it can improve the gallery flat, Bosboom-Toussaintplein in Delft, on both its comfort and its energy performance.

<table>
<thead>
<tr>
<th>Draft</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar heat gain</td>
<td>V</td>
</tr>
<tr>
<td>Insulation</td>
<td>V</td>
</tr>
<tr>
<td>Thermal bridges</td>
<td>V</td>
</tr>
<tr>
<td>Energy performance</td>
<td>V</td>
</tr>
</tbody>
</table>

Wind speeds are lowered, the design allows for a very little air permeability, so draft will be reduced
The facade can block up to 90% of solar radiation
The extra shell increase the R-value of the facade, and since the shell is outside the current structure, thermal bridges will have less effect.
40% less heating. If the sunspace is used well this might even be less

<table>
<thead>
<tr>
<th>Visual comfort</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condensation</td>
<td>0</td>
</tr>
<tr>
<td>Gallery side</td>
<td>0</td>
</tr>
<tr>
<td>Cleaning the facade</td>
<td>0</td>
</tr>
<tr>
<td>Plasticizers</td>
<td>!</td>
</tr>
<tr>
<td>Usage Design</td>
<td>!</td>
</tr>
</tbody>
</table>

Visual comfort
Although a very transparent material is found, vision will be blocked, the view is one of the most important things for people living in this flat.
Condensation
Like in a double glass pane with an airleak, tiny water drops blur the view.
Gallery side
The Gallery side will barely benefit from this current system. Therefore the system is not implemented there on the current design, either another system needs to be designed, or alternatives should be looked at.

Cleaning the facade
The current design has some downsides, like its own cleaning and maintenance, specially the inside.
Plasticizers
As well as increasing the UV-resistance, plasticizers increase the PVC’s (or any other plastics) plasticity, this also makes it more vulnerable for scratches. I noticed this while cutting the materials that were send to me.

Usage of the design
How the design is used can both have a positive and negative effect. However I do believe that a good usage of the design can improve comfort tremendously and could decrease the heating load even more.
## 6.7 Cost Estimate

<table>
<thead>
<tr>
<th>Item</th>
<th>Quantity</th>
<th>Cost (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabric and Plastic sheets 30 €/m2</td>
<td>x21</td>
<td>1260</td>
</tr>
<tr>
<td>Tube engines 100 €/m</td>
<td>x7</td>
<td>700</td>
</tr>
<tr>
<td>Aluminium profiles and tube 1-2 €/m</td>
<td>x85</td>
<td>85-190</td>
</tr>
<tr>
<td>Aluminium containers 5 €/m</td>
<td>x14</td>
<td>70</td>
</tr>
<tr>
<td>Fabrication personal 40 €/h</td>
<td>x4</td>
<td>160</td>
</tr>
<tr>
<td>Mounting personal 40 €/h</td>
<td>x3</td>
<td>120</td>
</tr>
<tr>
<td>Crane 285 €/h</td>
<td>x2</td>
<td>570</td>
</tr>
<tr>
<td>Profit margin 500 €/company</td>
<td>x2</td>
<td>1000</td>
</tr>
<tr>
<td><strong>Total: euro per apartment</strong></td>
<td></td>
<td>~ 4000</td>
</tr>
<tr>
<td><strong>Durability 10-15 years</strong></td>
<td></td>
<td>~ 400-250</td>
</tr>
<tr>
<td><strong>Gas price 0.7 €/m3 for 5-7 kWh</strong></td>
<td></td>
<td>0.14 - 0.10</td>
</tr>
<tr>
<td><strong>Heating reduction halved 2000 kWh</strong></td>
<td></td>
<td>280 - 200</td>
</tr>
<tr>
<td><strong>Comfort &amp; maintenance costs</strong></td>
<td></td>
<td>120 - 50</td>
</tr>
</tbody>
</table>

**Cost Estimate**

The estimated costs of the new facade is about 4000 euro per apartment. With a durability of about 10-15 year the annual cost of the facade would be 400-250 euro. Reducing the heating load by 2000 kWh a year; around 200-280 will be saved annually. This leaves about 100 euro per year; which is the cost for the extra comfort, the rise of the apartments value and the possibly lowered maintenance costs.
Recommandations
7. Recommandations

7.1 Case Study Design

On the balcony sides of the apartment building the proposed design does everything it should do, and due to its great control over the design parameters it makes the building more energy efficient and more comfortable. With an eye on the changing climate this system can be highly beneficial, weather will become more extreme, colder winters and warmer summers. The extra insulation and buffer zone to acquire heat with are a good solution for cold winters. Once summers get warmer; one could say that the building would be in need of cooling, because once temperatures reach a certain level just ventilation is not going to do the trick anymore. But what the design does do is it brings this potential cooling load down, therefore when cooling is needed, it will be the minimum amount, which in the end can save a lot of energy.

On the gallery side the current design might do more than it should do. Of course the gallery side will benefit from this extra facade, but does not need the sun shading the facade gives. A more open material could therefore be picked, a material that does not focus on shading the sun, but which focusses on buffering wind speeds.

Another option for the gallery side of the flat, is replacing all single paned glass with double glazing and insulating the cavity between the two layers of brick. This way the gallery is not closed of, and all the complications caused by fire escape routes, smoke clear rate and compartmentalisation are already solved, while the benefits of a lower U-value will be there.

7.2 Flexibility

The current product as a facade system for refurbishment of gallery flats could be used not just on the case study flat. It could greatly reduce energy use and increase comfort in multiple similar buildings (there are a lot of gallery flats in the Netherlands after all), making it a very interesting product especially when it comes to increasing comfort and energy performance.

7.3 Comfort and energy performance

By reducing the wind speeds on the balcony, and therefore throughout the whole flat, once windows are opened, the system reduces draft and increases the comfort on the balcony as well as inside the apartment. By generating heat on the balcony when needed and by decreasing the U-value of the facade, the current heating demands are almost halved.

7.4 Design Materials

Flexible transparent material
PVC seems to be the best material for its strength, resistance, transparency, CO2 recycling footprint and price. Also the vision through the material seems really good. The low cost of PVC allows for a thicker film to be used, even if this is not needed structurally, a thicker film of 2-3 mm thick will flutter less due to high wind speeds.

A low-E coating on PVC is possible, and would decrease the total U-value of the facade, but it’s shininess inside the material might not give a pleasant view through the system.

Woven material
PTFE is a good option, with good durability, self cleaning properties and great UV-resistance. It is a strong material, and can be woven in numerous ways.

TiO2 coated PTFE is more expensive, but could be used in areas where the flat is located next to a highway or another source of pollution.

7.5 Further Research

Building a mock-up on 1 to 1 scale for testing. This mock-up can be used to test the design on every aspect. How does it function under heavy wind loads? Will the current design make a lot of noise when the wind blows through it from various angles? How clear is the vision through the design, when the PVC layer is moving because of the wind? Will coatings stay on the materials, even through 1000’s of cycles? If a low-E coating is applied, what happens to the visibility through the system? And if this reflective coating is moved by the wind, what does this look like?

Designing a system where sun shading is not needed, but a flexible air permeability is.

Structural calculations, thus far there have been very little structural calculations done.

Installation of the system, what is the easiest way to install this system on gallery flats across the netherlands?
8. Reflection

This reflection describes the process first, then it looks at what could have gone better, what a better strategy could have been, and which steps should have been taken sooner or later.

8.1 Process

This part describes the process of how the project went. The image below shows the order in time from top to bottom, as well as which blocks formed the foundation for the next one shown by the arrows.

This project started off with a fascination for fabric. What followed was a research on what fabric is, how it was and is used, and what possibilities it has. Because there was no clear goal yet of what the fabric was going to do, the research became very broad. After deciding to use the gallery flat I live in as a case study, things got a little more clear; the fabric would be used as a coat for this flat. Requirements could be made, a double skin facade would be formed so research could be done on that and calculations could be made of what the effect of such a coat would be on the building.
Since the first concepts of possible coats like breathing facades were not really based on anything, these concepts became pointless ideas and were put away.

Instead the focus was set upon creating a detailed requirement list, since there was no design yet, the requirements just kept coming, and the list got bigger and bigger.

Once the requirement list and the first calculations were done, finally a concept came across that made sense, it focussed on the problems, the requirements and took the initial calculations into account. It felt like an exit out of an endless tunnel.

This design concept gave directions to new calculations which led to design parameters that gave the concept shape and brought it to the first design. The first drawings were made, and these could be discussed, leading to more problems and in return more discussion and solutions.

Fabrics had been researched, double skin facades had been researched, but the design also has a flexible, transparent, air-tight material. Till this point ETFE was considered as the only option, and that seemed very short sighted, especially after two ETFE specimens came in. They were milky, not as transparent as was hoped for. New research had to be done, the search for a transparent flexible material that fit the requirements.

In the meantime a second design was drawn that took care of some the problems the first design had. Together with the newly acquired knowledge on flexible transparent materials, a third design was made.

Ladybug allows quick analysis of .epw files, this climate analysis was done really quickly and gave a lot of solid and strong information. With the knowledge of Ladybug software, the next stage of energy modelling could be made in the form of Honeybee. Unlike Ladybug, Honeybee is very time consuming, it uses EnergyPlus, DaySIM and Radiance to calculate all energy flowing through a model made up out of zones.

A third and final design is made, and tested using the list of requirements. Using both calculation models to proof this conceptual design.

8.2 A Better Process

A better process would not start with a blind fascination, but with a clear goal or a clear problem. Once the problem was defined the process started smoothing out, and the aim and scope of the project became clearer. Some ideas were made into concepts that were not based on anything, these ideas/concept quickly faded away, and in the end these little side trips were a waste of time.

Instead of trying to design something after doing some broad research on a type of material. Once the requirements for the to be designed object started taking shape, the problems and their possible solutions got clearer; an idea came to mind that was based on something. Mainly if there is control over the air permeability and the solar radiation permeability, then the newly created zone between the two facades can be fully controlled. This idea became the first concept that made a lot of sense, and that is because it was based on the research that was done before, combined with the case study flat.

After this concept was created, everything went really smooth, and the experiment phase became a circular process.

Analyzing the dutch coastal climate, using Ladybug, took about one day. Including everything, learning Ladybug, making graphs, showing the climate's potential and weakness. I should have done this as soon as I knew the project would be in the Netherlands. This small step gave so much insight, even to someone who lived his entire life in this climate, I learned a lot about it.

Pictures and text that were used in the report or for meetings with my tutors, should have been saved with their source and date instantly. A lot of time was spent googling for certain images to locate their source once again, or doing the same for texts. Being more organized with the sources used can really help.
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Appendices

Appendix 1: Criteria

1.1 Stability
a. Strength
i. TGB: A window or frame on the outside construction of the building is also a construction, since it has to withstand wind load during its life. (Overveld et. al)

If for example the window frame is painted to prevent corrosion which could lead to less strength, the paint job is also part of this construction. Also a construction that is connected to the building which is not necessarily part of the building is a construction by law. This means that this addition to the building should also be able to withstand the wind load.

ii. Safety factors:
If the building would be more than 70 meters high, it would be considered high rise, and therefore have a safety class CC3. Safety class CC3 is the highest and most strict safety class, when it comes to strength, within the Netherlands. The building is 54 meters high at its highest point, and is a residential building, which puts it in safety class CC2. (Overveld et. al)

The forces on the building can be categorized in three types:
- Permanent forces (G), such as the own weight of the structure, installations, indirect forces (crimp, uneven settlement or a deformation).
- Changeable forces (Q) like wind- or snow load, load on floors due to people, furniture or goods and thermal load.
- Extraordinary forces (A) like an explosion or a crash due to a vehicle.

1.2 Fire Safety
b. Spread of fire
i. NEN standards
c. Spread of fire through walls and floors

i. Fire department requirements
: The dutch fire department requirements are all written down in either NEN-standards or in the dutch building code. All regulations and requirements within the Netherlands are done on a national scale.

ii. Signalling:
Signalling can be done through a fire alarm system, smoke detectors or similar solutions.

d. Flame spread
i. Combustibility:
Combustibility is a measure of how easily a substance will set on fire, through fire or combustion. This is an important property to consider when a substance is used for construction or is being stored.

ii. Smoke density:
The Smoke Density Chamber is used to measure propensity of building materials to generate smoke when exposed to a heat source. The

Appendices
Appendices .......................................................... 79
Appendix 1: Criteria .................................................. 79
Appendix 2: Calculation and finding the design parameters .................................................. 87
Appendix 1: Criteria

In this subchapter a list of all the criteria is given, where needed extra information is provided. Later on in this chapter this list will be refined and reduced to a list that states the most important criteria.

1.1 Stability

a. Strength
   i. TGB: A window or frame on the outside construction of the building is also a construction, since it has to withstand wind load during its lifetime. (Overveld et. al) If for example the window frame is painted to prevent corrosion which could lead to less strength, the paintjob is also part of this construction. Also a construction that is connected to the building which is not necessarily part of the building is a construction by law. This means that this addition to the building should also be able to withstand the wind load.
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d. Flame spread
   i. Combustibility: Combustibility is a measure of how easily a substance will set on fire, through fire or combustion. This is an important property to consider when a substance is used for construction or is being stored.
   ii. Smoke density: The Smoke Density Chamber is used to measure propensity of building materials to generate smoke when exposed to a heat source. The
smoke propensity is quantified by measuring the obscuration of a light beam traveling through the smoke generated within the chamber.

iii. **Escape routes**: The gallery is used as the escape route.

iv. **Compartmentalisation**: For the gallery to be called an open smoke free escape, minimum dimensions apply, these dimensions are a minimum width of 850 mm and a minimum height of 2300 mm. The minimum ventilation rate of an open smoke free escape should be six times its volume per minute, for this to happen about 15% of the facade should be permanently open, if this does not apply for the gallery it is a closed smoke free escape and other rules apply. If the gallery is closed, and still remains a smoke free escape route, every 30 meters there should be a door, with a minimum of 30 minutes of smoke prevention (to ensure smoke does not pass the door for at least 30 minutes) and the door should be self closing or a suitable alternative should be made. The maximum distance from each dwelling to a safe space or (emergency) staircase is 45 meters.

1.3 User Safety

e. **Passive safety**
   i. **Screening**
   ii. **Burglary prevention**: Doors, windows and window frames and similar constructions must have a minimal anti burglary class of at least 2 according to article 2.130, if these elements are within a reachable part of the construction according to NEN 5087. A reachable element is located till 5,5 meters above the a place-to-stand-on, this place-to-stand-on also has to be reachable.

Burglary prevention class 2:
Doors, windows and window frames and similar reachable constructions of the dwelling must be at least within anti burglary class which says:

- window frames, window and door parts do not deform easily with a crowbar
- secure doors and windows should be applied

iii. **Window security bars**: If an openable window has a windowsill, this should be at least 0,7 meters high, to prevent it from being climbed, or lower than 0,2 meters. If it is lower than 0,85 meters one or more extra bars have to be applied to prevent people from falling out of the window. (Overveld et al., 2012) If the parapet of a window should not be climbed, this also applies to the radiator in front of the parapet (or any other forms of installations).

f. **Active safety**
   i. **Door and window locks:**
   ii. **Signalling**
1.4 Wind and Watertightness (1st, 2nd line)

g. **Air permeability**: Air permeability is the ability of a façade element to let air through if there is a difference in air pressure between the two sides. (Tapper, 2014). Air leakage is the uncontrolled flow of air through the gaps and cracks in the fabric of a building. Air leakage is measured as either:
- air leakage index
- air permeability

The leakage of air (m³/hour) in or out of the building, per square meter of building envelope at a pressure differential of 50 Pascals (m³.h⁻¹.m⁻²@50Pa) between the inside and outside of the building.

i. **Standards**: A maximum of 0,6 dm³/s per m² is given as the official standard in the dutch building code. The Dutch building code makes a demand on the air permeability: not more than 200 dm³/s at 10 Pascal. This is a very large amount of air, say a quantity of milk 200 packs per second of air that goes through the facade with only a little bit of wind. However, this large amount of air is undesirable for the sake of energy efficiency. Therefore the value for air-tightness in the EPC calculations is lower, and so more strict than the Dutch building code. The EPC classes are as follows:

<table>
<thead>
<tr>
<th>Class</th>
<th>Basic</th>
<th>qv;10 &gt; 0,6 dm³/s.m² = passes the Dutch building code, no special criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 2</td>
<td>Good</td>
<td>qv;10 between 0,3 and 0,6 dm³/s.m² = building energy efficient</td>
</tr>
<tr>
<td>Class 3</td>
<td>Excellent</td>
<td>qv;10 &lt; circa 0,15 dm³/s.m² = passive houses, or other types of very energy efficient buildings.</td>
</tr>
</tbody>
</table>

Table 4: showing the EPC classes (source: Tapper, 2014)

ii. **Draught**: One of the major issues currently in the case study building is the amount of air spewing through the dwelling when windows are opened on both sides. By creating an extra coat around the building, the draught will be lessened, but it has to be lessened to an extent where it is not an uncomfortable phenomenon anymore. The Dutch building code gives a maximum air speed inside a building of 0,2 m/s due to ventilation, however with high wind speeds in the higher dwellings in the flat, this goal might be unreachable.

iii. **Chinks and seams**: One of the ideas behind the second skin is to reduce the effect of currently existing chinks and seams in the construction.

h. **Watertightness**: Watertightness is the ability of a closed façade filling to withstand the entry of water. (Tapper, 2014) Water leakage is the continual or repeated entry of water that then comes into contact with elements that should not get wet. Water leakage can occur in six different ways:
Image 30: Shows multiple ways of water entry into or through the facade. (Source: Tapper, 2014)

1. By kinetic energy pushing the water through a hole.
2. Gravity pulling the water in.
3. Capillarity with a pressure difference pushing the water in.
4. Capillarity itself sucking the water in.
5. Surface tension of the water spreading it out over a horizontal element, which transfers it inside the construction.
6. Pressure difference itself pushing the water into the construction.

1.5 Hygrothermal Comfort

Olgyay defines comfort as “a sensation of physical and psychological well-being” (Olgyay, 1963) and the thermal comfort as a “point to which the individual spends the least quantity of energy to adapt to its environment” (Olgyay, 1963). On the latter, we know that the well-being sensation refers to the temperature and relative humidity of the surrounding air: Hygrothermal comfort.

i. **Air temperature**
   - **Standards**

ii. **Thermal insulation**: Thermal insulation refers simply to the reduction of heat transfer. Since the average temperature in Delft is approximately 11 degrees, this means that on the average day the dwelling has to be heated by 8 to 9 degrees. The current facade of the case study building has a lot of thermal bridges, and a low thermal insulation value: with a U-value of 2.04. By adding an extra layer to the facade a U-value of 1.00 for the new total facade package should be reached.

iii. **Heat accumulation**: Balconies have a less strict comfort temperature, also due to the sun the radiant temperature could be higher here. If there is no wind but there is sun, it acts like a wintergarden, and therefore should be comfortable throughout the year, even in winter due to heat accumulation. In summer however the accumulated heat will be more of a nuisance,
therefore the balcony and the gallery side must be able to ventilate the heat away as much as possible.

j. **Radiant temperature**: Radiant temperature rises when heat energy is transmitted by electromagnetic waves in contrast to heat transmitted by conduction or convection. The mean radiant temperature (MRT) is defined as the uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body is equal to the radiant heat transfer in the actual non-uniform enclosure. (Wikipedia, 2015)
   
i. **Sun protection**: Refers to the protection of the sun, and therein protection against radiance and glare. This is important, especially in summer, and should at least prevent 90% of solar heat coming into the building. The biggest source in the MRT is usually the sun, that is why blocking the sun would normally result in a lower MRT.

ii. **Glass/openness for light percentage**: Should be as open as possible, in its minimal stance the construction should block less than 25% of the visual light entering the building, and less than 15% of the view should be blocked (from both a standing and a sitting position in the living room and bedroom)

k. **Humidity**
   
i. **Ventilation**: On the gallery side of the flat, a new method for “spui ventilatie” should be made possible, on the balcony side, each balcony should be ventilated separately to or the exchange of odors and used air should be avoided in yet another way.

ii. **Vapour-resistant layer**

iii. **Thermal bridges**: Existing thermal bridges will remain, but the extra layer of the facade places these thermal bridges inside an extra envelope, preventing current heat loss through these thermal bridges.

iv. **Condensation**: Due to the extra layer condensation should not take place within the buildings second facade.

1.6 Ventilation
   
i. **Ventilation rate**: The minimum ventilation rate is 0,7 dm³/s per m² for a residence area, and a minimum of 0,9 dm³/s per m² for a residence room. However this would mean that a small room of less than 5 m² might not get enough fresh air for one person to properly breath, this is why a minimum per room is set to 25 m³/h.
   
i. **Natural ventilation**: Natural ventilation will be present in the form of openable windows, just like in the current situation.

ii. **Mechanical ventilation**: Currently mechanical ventilation is used to ventilate the dwelling, and to keep the bathroom and kitchen in underpressure. This underpressure is created to prevent odors from escaping the bathroom, toilet or kitchen.

m. **Air change**
   
i. **Openable windows**: Openable windows are currently present, and will be part of the final design.

1.7 Acoustic Comfort
   
n. **Noise insulation**
Appendices

i. **Standards**: Should at least be 20 dB, maximum sound level of noises from outside to the inside should be 33 dB if it comes from trains and traffic or 35 dB if it comes from industry.

ii. **Noise level**: Max 33 dB (traffic) to 35 dB (for industry, but no industry is near the case study building.)

iii. **Noise reduction**: At least 20 dB for any facade.

iv. **Flanking transmission**: Balconies should be closed individually, right between both balconies, to prevent flanking transmissions.

v. **Noise output**: The noise output level of the facade system itself, due to mechanical systems or the wind ‘playing’ with the facade. This noise output should of course be kept as low as possible.

As important as acoustics are this list is quite irrelevant since the existing building already meets all the requirements that are given for acoustics.

1.8 Visual Perception

o. **Artificial lighting**

i. **Glass percentage**: At least 85% vision of the current vision should remain, both in sitting and in standing position in the living room and bedrooms.

ii. **Daylight penetration factor**: Also known as the daylight factor, and shows the percentage of daylight falling on the rooms surface, usually measured at a height of 80 cm, compared to the full 100% of the outside dome.

“In architecture, a daylight factor is the ratio of the light level inside a structure to the light level outside the structure. It is defined as:

\[ DF = \frac{E_i}{E_o} \times 100\% \]

where, \( E_i \) = illuminance due to daylight at a point on the indoors working plane, \( E_o \) = simultaneous outdoor illuminance on a horizontal plane from an unobstructed hemisphere of overcast sky.”

(Wikipedia, 2015)

p. **Light reflection**

i. **Glare**: DGP or DGPs (Daylight Glare Probability formulas)

A simplified version of the DGP, that shows that the only parameter that is highly affecting the DGP is the vertical luminance on eyesight level:

\[ \text{DGPs} = 6.22 \times 10^{-5} E_v + 0.184 \]

Where:

\( E_v \) is the vertical luminance on eyesight level [lux]

DGPs is the probability is percentage that a person will be bothered by glare [%]

If the design can lessen the \( E_v \) then glare problems can not happen.
1.9 Tactile Comfort

q. Static electricity
   i. Materials: Tactile comfort is important, especially in fabrics, but it is hard to say which level of softness is required or which level of hardness should be avoided.
   ii. Facade earthing: If due to movement of the facade due to the wind, or other forces, the facade gets statically loaded with electricity this static load should be able to go somewhere, therefore the facade should might have to be earthed.

1.10 Operating Comfort

r. Ease of operation
   i. Type of window: will stay the same
   ii. Window furniture: should be easy to operate
   iii. Driving gear: One person should be able to operate the facade.

1.11 Flexibility

s. Possibilities of partitioning
   i. Facade module: Facade should be modulair, preferably in at least 2 pieces per dwelling.
   ii. Elements that can be opened

t. Replaceability
   i. Order of facade parts: Parts should be replaceable in any order, without taking out more than one dwellings facade.
   ii. Paintability

1.12 Durability

u. Functional durability
   i. Materials: Recyclable or environmentally safe materials.
   ii. Surface treatment: Surfaces should be dirt and dust repellent.

v. Maintenance
   i. Cleaning: One of the main purposes of the extra facade is to reduce maintenance of the existing facade. The wooden window frames of the existing facade are currently being painted once every 5 years.

1.13 Economy

w. Investment
   i. Building cost estimate: The investment should be returned within 10 years of use. By increasing comfort the price of each apartment should go up, and by lowering maintenance and energy usage the cost in terms should go down.

x. Operation
Appendix 2: Calculations & Finding the Design Parameters

In this subchapter the design parameters are defined using calculations. The most relevant design parameters are the effective area of the openings in the facade ($A_{\text{eff}}$) and the solar energy transmittance coefficient ($g$). A closer look is taken on equations on air and heat flow.

2.1 Air Density

In most calculations used in this report, be it in heat transfer or airflow calculation, the density of the air $\rho$ plays a big factor. Usually the density of air is around 1.294 $\text{kg/m}^3$, but pressure and temperature can have an impact on this number.

"The density, or more precisely, the volumetric mass density, of a substance is its mass per unit of volume." (Wikipedia, 2017)

Mathematically, density is defined as mass divided by volume:

$$\rho = \frac{m}{V},$$

For gases however the density relies strongly on the pressure:

$$\rho = \frac{PM}{RT}$$

<table>
<thead>
<tr>
<th>$\rho$ = luchtdichtheid [kg/m³]</th>
<th>$P$ = luchtdruk [Pa]</th>
<th>$M$ = de molaire massa [g/mol]</th>
<th>$R = 8,314472$ [J mol⁻¹ K⁻¹] (de gasconstante)</th>
<th>$T$ = de absolute temperatuur in kelvin [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>0.2095</td>
<td>32.00</td>
<td>6.704</td>
<td></td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.7809</td>
<td>28.02</td>
<td>21.88</td>
<td></td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>0.0003</td>
<td>44.01</td>
<td>0.013</td>
<td></td>
</tr>
<tr>
<td>Hydrogen</td>
<td>0.00000005</td>
<td>2.02</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Argon</td>
<td>0.00933</td>
<td>39.94</td>
<td>0.373</td>
<td></td>
</tr>
</tbody>
</table>

Since air is a mixture of gases the total molar mass ‘$M$’ is the sum of the molar mass per volume ratio, for dry air the total molar mass is 28.97 [g/mol] (Engineering toolbox, 2017)
<table>
<thead>
<tr>
<th>Gas</th>
<th>Concentration</th>
<th>Molecular Mass</th>
<th>Pressure Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neon</td>
<td>0.000018</td>
<td>20.18</td>
<td>0</td>
</tr>
<tr>
<td>Helium</td>
<td>0.000005</td>
<td>4.00</td>
<td>0</td>
</tr>
<tr>
<td>Krypton</td>
<td>0.000001</td>
<td>83.8</td>
<td>0</td>
</tr>
<tr>
<td>Xenon</td>
<td>0.09 $10^{-6}$</td>
<td>131.29</td>
<td>0</td>
</tr>
<tr>
<td>Total Molecular Mass of Air</td>
<td>28.97</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5: Air is a mixture of gases and the total mass can be estimated by adding the weight of all major components as shown here. (source: Engineering toolbox, 2017)

R is the gas constant and is given as: 
$$R = 8.314472 \text{ [J mol}^{-1}\text{ K}^{-1}]$$

P is the pressure in Pascal and T is the absolute temperature in Kelvin.

The air density $\rho$ varies mostly by pressure and temperature, but since the pressure differences are mostly really small, the main parameter $\rho$ varies by is the temperature.

Image 37: air density by temperature with a pressure of 1013 hPa. Between -10 °C and 30 °C the $\rho$ value for the air is between 1350 and 1170 g/m³. (source: own image)

2.2 Wind Pressure

Wind on a building varies the pressure in and around the building. (Reader bouwfysica CT 3221, 2005) The wind pressure on a certain point in the building can be derived from the wind speed 'v' and the wind pressure coefficient ‘$C_p$’ as follows:

$$P_w = C_p \times \frac{1}{2} \rho v^2$$

$P_w$ = wind pressure in pascal [Pa]
\[ C_p = \text{wind pressure coefficient} \ [-] \]
\[ \rho = \text{air density} \ [\text{kg/m}^3] \]
\[ v = \text{wind velocity} \ [\text{m/s}] \]

The total pressure in Pascal is the sum of the wind pressure ‘\( P_w \)’ and the general air pressure \( P_o \).

\[ P_{wp} = P_o + P_w \]

Air pressure in point ‘\( p \)’ in pascal [Pa]

Most equations use the pressure difference [\( \Delta P \)] between two points, so on both sides of the building the \( P_o \) is added which for most equations does not make a difference.
2.3 Wind Velocity

Before the wind pressure can be calculated the wind velocity on a specific height needs to be derived out of the following equation:

\[ v_h = v_o K h^a \]

<table>
<thead>
<tr>
<th>( v_h = v_o K h^a )</th>
<th>( v_h ) is the windspeed on height ( h ) in meters per second [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( v_o ) (or ( V10 ))</td>
<td>( v_o ) or ( V10 ) is the wind speed on a height of 10 meters in meters per second [m/s]</td>
</tr>
<tr>
<td>( K )</td>
<td>constante vrije veld: 0,68; 0,52; 0,35; 0,21</td>
</tr>
<tr>
<td>( a )</td>
<td>constante vrije veld: 0,17; 0,20; 0,25; 0,33</td>
</tr>
<tr>
<td>( h )</td>
<td>height</td>
</tr>
</tbody>
</table>

The \( K \) and \( a \) values can be taken out of this table.

<table>
<thead>
<tr>
<th>omgeving</th>
<th>( K )</th>
<th>( a )</th>
<th>( h_g ) in m</th>
</tr>
</thead>
<tbody>
<tr>
<td>vrije veld</td>
<td>0,68</td>
<td>0,17</td>
<td>250</td>
</tr>
<tr>
<td>landschap met bomen en struiken</td>
<td>0,52</td>
<td>0,20</td>
<td>300</td>
</tr>
<tr>
<td>bebouwde omgeving, dorp</td>
<td>0,35</td>
<td>0,25</td>
<td>400</td>
</tr>
<tr>
<td>stedelijk centrum</td>
<td>0,21</td>
<td>0,33</td>
<td>500</td>
</tr>
</tbody>
</table>

Table 6: Shows coefficients \( K \) and \( a \) in four scenario’s: Open field, landscape with trees and bushes, built environment (village) and build environment (city). The \( h_g \) is the height where the maximum wind speed is. (source: Reader bouwphysica CT 3221, 2005)

Image 39: Showing the relationship between wind and landscape type. (source: Reader bouwphysica CT 3221, 2005)
Image 40: example where the $v_0 = 10\text{m/s}$ and the $K$ and $a$ values are given as in the four scenario’s. Y-axis shows the wind speed, x-axis shows the building height. The case study building is 50 meters high, so it falls in the zone between 0 and 50 meters. Note that $v_0 = 10\text{m/s}$ in the open field. (source: own image)

\[ \Delta P = \frac{1}{2} \xi_i \rho v_i^2 + \left( \mu \frac{L}{D} + \xi_a \right) \rho v_a^2 \]

<table>
<thead>
<tr>
<th>$\Delta P$</th>
<th>Pressure difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\xi_i$</td>
<td>Weerstandscoëfficiënt toevoersopening</td>
</tr>
<tr>
<td>$\xi_a$</td>
<td>Weerstandscoëfficiënt afvoersopening</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Luchtdichtheid in kg/m$^3$</td>
</tr>
<tr>
<td>$\mu$</td>
<td>weerstandcoëfficiënt van de koker</td>
</tr>
<tr>
<td>$L$</td>
<td>Lengte koker</td>
</tr>
<tr>
<td>$D$</td>
<td>diameter koker</td>
</tr>
<tr>
<td>$v_i$</td>
<td>snelheid ingang lucht</td>
</tr>
<tr>
<td>$v_a$</td>
<td>snelheid uitgang lucht</td>
</tr>
</tbody>
</table>
2.4 Air Flow Through the Building

The amount of air going through the building can be determined using the following equation:

\[ Q = A_{\text{eff}} \sqrt{2 \frac{\Delta P}{\rho}} \]

(source: H. Awbi, 2010)

Where:

| \( Q \) | Airflow [m³/s] |
| \( A_{\text{eff}} \) | effective area [m²] |
| \( \Delta P \) | Pressure difference [Pa] |
| \( \rho \) | Air density [kg/m³] |

Since the pressure difference and air density are given by the wind and the temperature, the only design parameter in this equation is the effective area (\( A_{\text{eff}} \)). Also \( 2.\Delta P/\rho \) is rooted, which means when this value has less impact to the Airflow (Q) than the \( A_{\text{eff}} \). To determine the effective area (\( A_{\text{eff}} \)) the discharge coefficient is needed, and multiplied by the area, like so:

\[ A_{\text{eff}} = C_d A \]

(source: H. Awbi, 2010)

Where:

| \( A_{\text{eff}} \) | Effective area [m²] |
| \( C_d \) | Discharge coefficient between 0.6 - 1 |
| \( A \) | Area of opening [m²] |

The discharge coefficient depends on the area of the opening and the pressure difference. For small openings (\( A < 0.2 \) m²) the discharge coefficient lies between 0.8 and 1. Because of this the influence on the discharge coefficient is low, making the area of the opening (A) the main design parameter in this equation.
When openings are bigger, the discharge coefficient gets lower, which means one big opening with the same area as several smaller openings will sum up to have a smaller $A_{eff}$.

Openings can be combined in two ways, either in a parallel circuit or in a series circuit. Both of these are calculated differently:

For parallel:

$$\frac{1}{A_{eff}^2} = \frac{1}{(A_1 C_{d1})^2} + \frac{1}{(A_2 C_{d2})^2} + \ldots$$
For serie:

\[ A_{\text{eff}} = C_d A = C_{d1} A_1 + C_{d2} A_2 + \ldots \]

The entire air flow through the dwelling can be calculated by determining a single Aeff value for one apartment. This single value is derived from a scheme which includes some series of openings and some parallel openings.

Image 43: Scheme of air openings in the apartment. When all windows and doors are closed the A_{eff} value for the apartment is approximately 0.015 m².

The new facade can bring this A_{eff} value of 0.015 m² down, the next graph shows the influence of the airtightness of the new facade on the airtightness of the entire apartment.
Since the building relies heavily on natural ventilation, the $A_{\text{eff}}$ should not be too small when there is low wind. Of course because of the concept the $A_{\text{eff}}$ can always be made bigger due to the flexibility of the facade, but this still means that when the wind drops down the residents still need to open the facade slightly. This can be compared to the use of a ventilation grille.

2.5 Heat balance

The sum of the total heat balance is 0 (R. Bokel, 2014):

$$Q_{\text{transmission}} + Q_{\text{ventilation}} + Q_{\text{sun}} + Q_{\text{intern}} = 0$$

Heat travels through transmission:

$$Q_{\text{transmission}} = U A \Delta T$$

Heat travels through ventilation:

$$Q_{\text{ventilation}} = \rho c n V \Delta T$$

Heat travels through radiation (sun):

$$Q_{\text{sun}} = g A q_{\text{sun}}$$

Heat comes from internal sources:

$$Q_{\text{intern}} = \text{radiator or 0}$$