Adaptive ETFE Façade

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Contents

1.Introduction

Pneumatic ETFE facades as an alternative constructional system to glazing, have defined a potential market in commercial buildings. There has always been a need for renovation of existing buildings and adapting the behavior of new buildings to market demands.

When it comes to the construction of new buildings, the German “Energiewende” began in 1990 with the development of highly efficient passive houses. Unfortunately, although many buildings can now be renovated to fulfill very ambitious standards close to the Passive House Standard, a lot of progress still needs to be made towards increasing the energy efficiency of renovated buildings (Morris & Pehnt, 2012) for example Steinbach (Möwe project, 2016) demonstrates the lack of ETFE cushion’s impact on building physics characteristics, which doesn’t make perceptible change or insulation against outdoor temperature. This is while in Germany, roughly 40 percent of all energy is consumed in buildings, most of it for heating (Morris & Pehnt, 2012). Therefore for this segment of market improvement is crucial to reduce ecological footprint.

German Strategy for Adaptation to Climate Change (Deutsche AnpassungsStrategie, DAS) declares about more rain in winter and extended summer waves in future (2008, p.19). This report states that there will be a need for greater adaptation to higher mean summer temperatures and longer periods of heat. DAS defines proper thermal insulation and shading elements as a basic need of buildings (DAS, 2008).

Environmental condition and possibilities of both now and future depicts that, it is beneficial to invest on kinds of façades which can adapt to different conditions and use them as its benefit. Improvements seen in following categories of constructional ETFE market contribute to the abovementioned vision:

Technological Objectives

- Upgrading ETFE cushions and make them able to actively and passively change their function, to reach occupant’s comfort and preference
- Suggesting a new experience for living in space
- Collecting Heat and Solar Radiation energy from ETFE Cushion

Scientific Objectives:

- Reducing U-value of ETFE cushions
- Controlling solar spectrum transmittance, reflectance and absorbance

1.1 Research question

Based on the German Strategy for Adaptation to Climate Change, longer periods of heat in future summers is inevitable. Already existing and new buildings must have the ability of adaptation into overheating and wind-driven rain problems. This fact shapes the main question of this research:

Are existing applications and methods of ETFE construction able to adapt themselves into climatic challenges and client’s desires?

1.2 Approach

To design a responsive and smart façade, there are four main domains to be taken into consideration. **Thermal**, **Optical**, **Airflow** and **Electrical** domains are basic criterias which can directly affect the comfort zone and energy efficiency of a building (Loonen, 2010).

Figure 1.1 The four physical domains and overlap zones (Loonen, 2010, cited in Marysse, 2016)

In cases that achieving control over each or a combination of aforementioned domains is desired, a specific zone could be chosen as a target. Shading systems are the most popular applications among adaptive façades because of their efficiency in preventing overheating. Shading systems also bring the ability of controlling thermal and optical domains and also create a possibility to manage airflow inside a building. **In this thesis, *Zone H* is chosen as a target for designing an adaptive ETFE façade.**

To enrich both User Experience(UX) and building physics characteristics of an ETFE cushion, **integration of an Electro tropic film** (with high transparency in On mode and decent radiation blockage in Off mode) **into ETFE cushion** is proposed (Figure 1.2 and 1.3).

Figure 1.2: Solar control demonstration in Adaptive ETFE, On and Off mode

Figure 1.3: IR-radiation control demonstration in Adaptive ETFE, Off mode

1.3 Management plan

For having a proper approach to this topic, a simple management plan is defined as following:

Why?

- To further develop ETFE cushions to contribute to energy saving
- Upgrading its aesthetics.
- Partially solve problems of cushion systems with harsh climate conditions (improving U&R-Values)
- Hypothetically using ETFE for wider climate conditions.

Who?

Master student in membrane structures at IMS, with supervision of Institute for Lightweight Structures and Conceptual Design (ILEK), and building physics experts.

Where ?

- Anhalt University of Applied Sciences, Institute for Membrane Structures and Shell Technologies (IMS), Dessau, Germany
- Institute for Lightweight Structures and Conceptual Design (ILEK), Stuttgart,Germany

How?

- Experimenting integration of Electrochromic/-optic films into ETFE cushions.
- Logging all spectrum and temperature data.
- Classifying data in its relevant charts and tables for statistical analyzing.

What?

Independent variables :

- Suggested middle layer prototypes
- Electrochromic/-optic films
- Climatic simulation of planned scenarios

Dependent variables :

- Transmitted, absorbed and reflected radiation Data Logs, U-Value of whole system

When?

- March 2017 till September 2017

Literature Review

What we find changes who we become
-Peter Morville-

2.Pneumatic structures

In case you hadn't figured out a reason or excuse, why to build inflatables, it becomes obvious as soon as you get people inside.

-Ant Farm-

2.1 Introduction

Our society has drastically changed since the 1960's. Not only did sociological concepts and issues in the field of politics and social life change drastically, also a handful of technical innovations have improved the overall quality of life. Televisions were introduced in our living rooms; communication via telephone was made available to anyone; and popular rock music got introduced to the masses (Niels Wouters,2009).

In the field of architecture, innovative materials and new knowledge allow for more intensive formal and structural experimenting. Building upon the foundations from the 1950's towards formal experiments and freeform thinking that Richard Buckminster Fuller based, a new generation of engineers and architects introduce the population to an architecture for the new era. An overwhelming embrace of bubbles in their numerous connotations (**lightness**, **transparency**, **embrace**, **equality**, **difference**) characterizes the period of the 60's.

Figure 2.1: A study of foam by Frei Otto; Photo: © IL Uni Stuttgart, courtesy of Kunsthaus Kaufbeure

An environment in which free thinking was allowed and stimulated, resulted in the use of airy constructions for shaping enclosures. Nevertheless, due to budget restrictions and technical obstacles, the whole subculture of pneumatic constructions silently died out. Of those exploring inflatable architecture in the sixties and seventies, Ant Farm was the most prolific, gearing a number of projects around air and plastic, and even creating an Inflatocookbook. Fellow Americans like Jersey Devil also explored what they called Inflatables in the early seventies, created as "happenings" that stood out in their urban contexts, such as alien crafts landed amongst the stone, glass and grass. In Austria renowned artists like Coop Himmelb(l)au and Haus-Rucker-Co explored the possibilities of pneumatic dwelling units. Yet without clients or sites they failed to get beyond the prototype stage. Even critic Reyner Banham got in on the act, combining the ideas of Buckminster Fuller and Marshall McLuhan in a transparent igloo he designed with Francois Dallegret (Niels Wouters,2009).

Figure 2.2: Inflatable Suit-Home, David Greene, 1968; Photograph by Dennis Crompton, © Archigram

2.2 Definition of Pneumatic structures

The term pneumatic structures includes all the lightweight structures in which the load bearing capacity is achieved by means of air under pressure. They are mainly subdivided into two categories: the buildings characterised by a single layer, stabilised by a slight difference in pressure between the inside and the outside of the structures, and the building envelopes stabilised by air under pressure enclosed between two or more membrane layers.(P. Beccarelli, 2015)

The basic idea of single layer pneumatic structures is quite simple, an internal volume delimited by the thin membrane is maintained under pressure by means of fans, a low level of pressure leads to a distributed force on the membrane surface, which receives the support necessary to compensate for the self-weight and the external loads, assuming the classical synclastic curvature. This type of structure is generally designed to maintain an internal pressure between 0.2 and 0.55 kN/m2 , which assures the necessary stability for wind loads but can be inadequate for heavy snow falls. The snow loads, which can reach a value on plan from 0.2 to 2.4 kN/m2 , represent a critical aspect of these structures which can be overcome heating the internal air space. If the stabilising forces do not exceed the external loads, due to overloading or dysfunctions in the internal control system, dimpling occurs in the membrane and the reversion of the surface curvature can lead to the collapse of the structure, with consequent damages to the structure and its occupants. Air-supported structures provide a cost effective alternative for seasonal wide span coverings, nevertheless, the reduced resistance under bad weather conditions combined with high costs due to great pressure losses, reduced insulation, maintenance and the seasonal mounting and dismounting costs can progressively reduce the initial convenience over the entire lifespan (Shaffer, 2013, cited in Beccarelli, 2015).

Membrane structure that is stabilized by the pressure of compressed air. Air-supported structures are supported by internal air pressure. A network of cables stiffens the fabric, and the assembly is supported by a rigid ring at the edge. The air pressure within this bubble is increased slightly above normal atmospheric pressure and maintained by compressors or fans. Air-inflated structures are supported by pressurized air within inflated building elements that are shaped to carry loads in a traditional manner. Pneumatic structures are perhaps the most cost-effective type of building for very long spans (Gloria Lotha, 2016).

Figure 2.3: The Allianz Arena in Munich (2005) by Herzog & de Meuron / Photography: Hans Heigenhauser

In pneumatic constructions, pressure differences between the enclosed space and the exterior are responsible for giving the building its shape and also for stabilizing the hull. Fabric is pretensioned by an internal overpressure of the air. While this might seem at first to be uncomfortable to the occupants of the structure, the pressure differential is no greater than that of ordinary barometric fluctuations.

Pneumatic structures are a combination of two components with very different properties: **an airtight membrane** and **compressed air**. Air is a gas, essentially composed of nitrogen, oxygen and carbon dioxide, and its properties are merely defined by its composition, the temperature, the pressure and the volume. The membrane is in a solid state and its properties are defined by the material properties and geometry of the constituents, as well as by the way materials are used for its construction, such as the chemical composition and the elastic modulus of the yarn, the mass density of the coating, the type of weaving and so on.

The compressed air pretensions the membrane and forms the volume of the structure defined by the membrane-cutting pattern. Such a pre-stressed membrane can support both tension and compression and thus can withstand bending moments. Obviously, the pre-stress in the membrane is a function of the air pressure. The membrane s minimal weight and small size when deflated allow for easy manipulation and transport, hence offer a lot of perspectives towards repeated use at different locations. However, proper attention should be paid to deflating the construction. Depending on the materials used for constructing the skin, there is a danger that folds damage the skin when improperly stowed. Should any cracks and leaks appear, a prompt repair is necessary although a damaged inflated structure will most likely maintain its form because of the minimal difference between inner and outer air pressure. One of the main disadvantages of pure pneumatic constructions however is that a constant high air pressure is required to keep the elements in shape. This leads to higher energy costs, a parameter which cannot be relentlessly denied in a century of energy awareness. Innovations in this field have led to a new structural concept, Tensairity. It counters the major energy-related disadvantage, by combining the classic pneumatic structure with an internal cable strut structure. The main function of the pneumatic structure is to stabilize the cable-strut structure. Tensairity structures have a multitude of very interesting properties. Not only is the beam very light, but it can also keep its shape under very low pressure. Compact transport and compact storage is possible, as well as fast and easy deployment on site. Furthermore, new lighting possibilities and special forms can be realized with Tensairity. One of the most outstanding properties of Tensairity is that the structure is adaptable to changing load conditions. However, because of the specifics of Tensairity structures an explanation of which would fall beyond the scope of this research it is likely that focus will remain on classic pneumatic structures(Niels Wouters,2009).

2.3 Form

Pneumatic structures follow strict physical rules, which influence their form-finding and their design process. The form of a pneumatic structure can always be derived from the boiler formula: $P = Fk / rk + Fs / rs$, where ‘P’ stands for inner pressure, ‘F’ for forces in axial directions, and ‘r’ as radius of curves. Based on the results of this formula, a classification of three different types of constructions can be drafted. A first group of constructions are the air-supported halls, which are fixed circumferentially to a foundation and have a great synclastic curvature. The external loads like forces of nature and weight of the skin itself, are supported by the air residing inside the hall. Internal loads pointing outwards are carried by the membrane and have a tension-increasing effect. Secondly, cushion structures are pneumatic structures in two layers. They are attached to an internal structure coupling high lateral forces of the border in the cushion. Another option is to implement them as a cover on a primary structure and allowing them to guide horizontal forces into the main structure. Compression load is carried by an increase in pressure on the other side of the cushion (Niels Wouters,2009).

Figure 2.4: Kinds of pneumatic pre-stressed constructions (Moritz 2007)

Figure 2.5: Different air management of cushions (Moritz,2007)
Note* OL: Outer Layer, ML: Middle Layer, IL: Inner Layer

Figure 2.6: Classification of cushions due to number of layers(Moritz, 2007)

2.4 Technical background

2.4.1 Boiler formula

“Relation between curved geometry and stresses

Boiler formula demand:
- Cable forces or membrane forces F

Assumption:
- Circular geometry of deformation given:
- Radius r [m] and
- Loads

→ Boiler formula: line loads [kN/m] area load[kN/m2]

F = p x r F [kN] = p [kN/m] x r [m] F1 [kN/m] = 1/2 p x r
F2 [kN/m] = 1/2 p x r

(Moritz and Schiemann, 2015)

2.4.2 Sag in Pneumatic cushions

General relation between radius of curvature,
foil sag ‘f’ and chord length of a segment of a circle: → $R = l^2 / 8f + 1/2 f$

Note* : ‘l’ represents the length of cushion
‘R’ represents the radius of curve on outer surface

curved cushion
→ big foil sag
→ less radius of curvature
→ less membrane forces

less curved cushion
→ less foil sag
→ bigger radius of curvature
→ bigger membrane forces

(Moritz and Schiemann, 2015)

Table 2.1 Applicable Max. span of ETFE modules(Moritz and Schiemann, 2015)

Geometry and the structural system of ETFE modules	**Max. Span(m)**
mechanically prestressed, 1-layer system	1.5
pneumatically prestressed (rectangular form, elongated elements, sag 10% of the length):	4.7
pneumatically prestressed (circular form / polygonal elementsΦ sag 10% of the length)	7/5

* Note:
- For structural analysing aspects the length of rectangular geometries is not decisive. (e.g. cushion of Masoala rainforest hall, Zürich: length = 106 m)
- By using cables or cable nets: the span of the ETFE films structure depends on the cable structures”

2.4.3 Load-bearing behaviour of a cushion

Three typical load cases of cushions:

1.) Inner pressure (pre-stress)
2.) Wind loads and inner pressure
3.) Snow Loads and inner pressure

Figure 2.7: Cushion - action: inner pressure (pre-stress)(Moritz and Schiemann, 2015)

If do = du , fo = fu , g ≅ 0 ⇒ Fo = Fu = F
If R ≅ constant ⇒ F = const. (boiler formula: F [kN/m] = pi [kN/m2] x R [m])
⇒ vertical loads: Vres = Vu – Vo = 0 ; horizontal loads: H res = Hu + Ho ≠0
⇒ resulting support reactions of two adjacent cushions:
⇒ SV = Vl + Vr = 0 ; SH = Hl – Hr = 0 (if Hl = Hr)

Figure 2.8: Cushion - action: wind uplift (wind suction)(Moritz and Schiemann, 2015)

In this case εo and Fo are increasing, εu, Fu and pi are decreasing. (ε = strain)
Vertical load: V = Vu – Vo = - 0.5 Ws x l (l = span, Ws = wind suction (uplift) = const., Ws ≅ Ws, vertical)
Horizontal load: H = Hu + Ho ≠0
⇒ resulting support reactions of two adjacent cushions: **Σ**V = Vl + Vr ≠0 ;
ΣH = Hl – Hr = 0 (if Hl = Hr)

Figure 2.9: Cushion - action: snow load(Moritz and Schiemann, 2015)

Under snow load εo and Fo are decreasing, εu, Fu and pi are increasing.
Vertical load: $V = Vu – Vo = - 0.5s \times l$ (l = span, s =snow load= const.)
Horizontal load: $H = Hu + Ho \neq 0$
⇒ resulting support reactions of two adjacent cushions: $\Sigma V = Vl + Vr \neq 0$;
$\Sigma H = Hl – Hr = 0$ (if $Hl = Hr$)

(Moritz and Schiemann, 2015)

2.5 Materials

Made from laminated membranes such as fiberglass, nylon, or polyester, coated with polyvinyl chloride (PVC), silicon rubber or Teflon for weather protection, the electronically welded components are tailored to define the building shape. The durability and heat and light-filtering properties of the membrane are determined by the careful choice of surface finishes and inner lining. Because of its lightness, the air-supported structure is among the most efficient structural forms, combining high-tensile strength materials with the shell form. The fabric is not made and shipped in one piece. It is made in sheets, usually about 3,6m wide and with varying length. The easiest and most common method of joining the fabric together is the standard lap joint. The two pieces of fabric are overlapped by approximately 8 cm and Teflon FEP (fluorinated ethylene-propylene) film is inserted between them. The joint is then heat welded together. When completed, the joint is stronger than the fabric, and completely water- and airtight. In structures where cables are necessary to maintain the form, mostly steel cabling is used. Although Kevlar and glass fiber cables are stiffer and stronger, they are not widely used because of a high cost and degradation issues when exposed to ultraviolet light (Wouters,2009).

Figure 2.10: Classification of membrane materials based on isotropic properties(Moritz and Schiemann, 2015)

2.5.1 Materials mainly used for textile architecture

PVC coated Polyester fabrics, Type IV

PTFE coated glass fibre fabrics

PTFE laminated glass fibre fabrics

Fluorpolymer coated glass fibre fabric

PTFE coated PTFE fabric

ETFE films

Figure 2.11: Samples of popular membrane materials (Bögner-Balz, 2016)

2.5.2 Foils

2.5.2.1 ETFE Foil

Ethylene tetrafluoroethylene (ETFE) is one of the most stable chemical compounds and its films are largely employed in the building industry due to the very good long-term stability, resistance to soiling and high light transmittance. The mechanical strength is relatively good, especially considering that the material is not reinforced by a woven support, and make ETFE foils suitable for load bearing envelopes characterised by small spans or supported by cables. The best known ETFE façade is the Beijing Aquatics Centre, however, the material has been recently used for single layer projects such as the Unilever building in Hamburg (Beccarelli, 2015).

2.5.2.2 PVC Foil

polyvinylchloride (PVC) foils are characterised by an extremely poor mechanical resistance, long-term stability and resistance to soiling. The optical properties, which deteriorate quickly despite the initial transparent and clear aspect, are inferior if compared with ETFE, especially considering specific wavelengths. However, the flexibility of the material and the extremely low cost, make PVC foils a valid alternative for indoor or temporary applications. One of the most relevant projects is the façade for the Finmeccanica Pavilion designed for the Farnborough International Air Show (Beccarelli, 2015).

2.5.2.3 PE Foil

Polyethylene or polythene (PE) foils do not present any relevant properties for the building sector except for the extremely low price, which compensates for its very poor UV and soiling resistance. For this reason its use is mainly confined to greenhouses and the agricultural field with no relevant permanent projects in architecture. However the film has been successfully used for temporary pavilions and installations such as the Mobile Action Space in Berlin (Beccarelli, 2015).

2.5.2.4 THV Foil

Tetrahydrocannabivarin (THV) foils offer a good flex cracking resistance and long-term stability comparable with those provided by ETFE foils. However its optical properties and resistance to soiling are considerably lower than ETFE. Although it can be easily welded with high frequency welding machines, its use in architecture is quite sporadic due to the lower mechanical and tearing resistance which reduce its use over medium and large spans (Beccarelli, 2015).

2.5.2.5 PU Foil

Thermoplastic polyurethane (TPU) foils are flexible in cold weather, resistant to abrasion and air tightness. Due to the relatively high price, the low elastic modulus (elongation at break up to 800 %) the progressive yellowing and the poor performance at high temperatures clear PVC films are preferable for architectural applications. One of the few exceptions is represented by airtight bladders for inflated structures. Polyurethane comes in two variations: polyester-based and polyether-based. Polyester-based material is subject to early hydrolysis and degradation in many environments that the polyether-based material is not. Heat, oxidation, and certain chemicals will accelerate this degradation. Polyurethane can be recycled easily and does not release hazardous compounds when being processed or recycled (Beccarelli, 2015).

Figure 2.12: Classification of plastics,(Schiemann and Moritz, 2010)

Figure 2.13: Plastic-pyramide (Schiemann 2009)

2.5.3 Material selection

In order to have a good membrane structure, the building should be lightweight, safe, efficient and suitable. Sobek believes that “A construction is called light structure, if it transfers a load over a long distance or over a big surface to it‘s support.” (Sobek, cited in Moritz and Schiemann, 2015)

In material selection process for a buildings facade we have several variables to take into consideration, like: material performance, manufacturing, experience and context. Beside these principles, we should always add time,money and designer’s intentions too (Lisa and WOUTERS, 2009).

Figure 2.14: Refined framework of material selection considerations in architectural design, (Lisa and WOUTERS, 2009)

Beside the common procedure of choosing materials for a facade, there are other clarifications and guidelines specifically for choosing the right material in membrane structures.

Figure 2.15: a simple comparison between popular membrane materials (web.1)

Table 2.2 : Right Choice of Membrane Material,(Moritz,2011)

	Load bearing capacity (Tensile strength)	Fire classification according to DIN 4102	Resistance to environmental exposures, dirt,..	Light transmittance	Resistance to cross-breaking (Flexibility, Folding)	Transparency
	[kN/m]	[Class]	[High/Medium/Low]	[%]	[High/Medium/Low]	[Yes/No]
PVC/PES-fabric(Type v)	High(190/166)	B3	Medium	Up to 10	Medium	No
Silicon/fibre glass (Type G VII)	High(170/158)	A2	Medium	Up to 25	Medium	No
PTFE/Fibre-Glass-fabric (Type G VII)	High(170/158)	B1	High	Up to 14	Low	No
PTFE-fabric (Fluoropolymer fabrics)	Medium (80/80)	B1	High	Up t0 40-85	High	No
ETFE-foil 250 µm	Low (13/13)	B1	High	Up to 90	Low	Yes
Conclusion	PVC/PES and Fibre-glass fabric	Silicone-Fibre-glass fabric if the material has	PTFE-Fibre-glass fabrics, Fluoropolym	Fluorpolymer fabrics and	PTFE-fabrics for retractable or mobile constructions	ETFE -foils for the requirement of

	were used for high loaded constructions and/or for big span widths	to be incombustible	er fabrics and ETFE foils for the requirement of a high lifetime and durable clean surface	ETFE-foils for the requirement of a high light_or UV. transmittance	which has to be assembled many times	transparency

2.6 Design

Niels(2009) believes that “A sustainable design philosophy should definitely be combined with an aesthetic sensibility and a constructively critical approach to the production of art”, and in a very similar perspective Beccarelli(2015) defines the design process as :”The design of traditional rigid structures follows a linear sequence in which the initial architectural shape is transmitted to the engineering office in charge of the structural design; subsequently once the architectural shape has been upgraded in accordance with the structural requirements, the definitive project is transmitted to the builder for the realisation of the construction. The correlation between the several subjects is generally reduced to the correct information transfer between two consecutive phases. Only masterpieces of modern architecture and engineering are an exception to this procedure” (P. Beccarelli, 2015).

The architectural and the structural idea should converge to a solution which is both aesthetically pleasing and structurally efficient and feasible. The design process cannot leave out of consideration the issues related to the material chosen, the manufacturing and the erection. It is therefore desirable that manufacturers and material producers are involved in the project development at the earlier phases of the projects, when the type of membrane material is selected, with consequent repercussion on the joints realisation and assembling procedure.(P. Beccarelli, 2015)

Figure 2.16: Flowchart illustrating the general approach to tensile membrane structures design and engineering. Modified from (Campbell,1991)

3.Building façades

Façades are subjected to numerous structural and
technical challenges, while at the same time
they are required to offer maximum
visual and thermal comfort.

-Werner Sobek-

3.1 Introduction

Human has always been trying to better his living condition according to the location and the season he is living in. The world's population is increasing significantly and the global warming and climate change form a challenge for our planet. We are facing a trend in designing and building higher buildings on a smaller surface which enables people to live more concentrated. To obtain a good performance in combination with an efficient energy use for mid/high-rise buildings, new building methods are developed (Marysse, 2016).

Façades of commercial buildings and high-rise buildings are commonly built with steel frames and glass. Such façade configurations can result in significant heat losses or heat gains depending on the season. The creation of highly glazed façades with an excellent performance is a complex challenge for which still a lot of tools, technologies, processes and databases are missing. Using a second layer that accommodates the first one can contribute to an improved performance. When a façade is built, some functional requirements need to be fulfilled. First of all, some essential requirements are important such as the tightness, fire safety, maintenance and repair. In addition, the design of an advanced façade tries to achieve improved indoor air quality, energy efficiency, thermal performance and keep occupant in a comfort zone by concepts such as ventilation systems, shading systems for sun control, and acoustic insulation. This optimisation of the building façade decreases the heating, cooling and lighting load of the building. The most difficult aspect for the design is to combine several strategies together (Marysse, 2016).

3.2 Functional requirements

Advanced façades need to focus on different functions to improve the performance of the building. An efficient façade has to fulfil different functional requirements (Figure 3-1). The most important building functions to achieve a good internal comfort are the enhancing of the daylight and the protection from the sun combined with the avoidance of overheating problems.

Figure 3.1: Functional requirements façade (Steinbach, 2013)

3.2.1 Essential requirements

The essential requirements are the aspects that are absolutely necessary and form the basic features for a good façade design.

3.2.1.1 Tightness

In a good Façade both air and water tightness should be considered as basic design and installation principles, it should be well sealed to avoid the penetration of rain and wind from outside. If we can’t make the Façade waterproof, it is important to provide measures to enable the ventilation or drainage of the entered water to the outside. It is crucial to keep our Façade water and air tightened so we can decrease the potential of mold growth and deterioration.

3.2.1.2 Other essential requirements

Apart from the tightness, **ventilation** is another essential requirement. Smoke ventilation and comfort ventilation are the two basic types of ventilation for a room. Opening windows are the basic features that are used for ventilation. Next to ventilation, **moisture** regulation is another important aspect. It can result in an uncomfortable feeling for people if a low relative humidity (below 30%) is combined with a low room temperature (lower than 18°C). Also a high relative humidity (higher than 70%) in combination with a room temperature of 24°C or higher results in an uncomfortable feeling. The façade should furthermore be designed in a way that prevents the **fire propagation** and provides a good fire resistance. Fire partitions can serve for this. In addition, the use of incombustible materials in the façade is crucial. The materials of a façade must have a limit flame spread. The compartmentation of façades results often in a gap between the façade and the building. To avoid fire spread between rooms, perimeter firestopping (sealing of the gap) is extremely important.(Marysse, 2016).

3.2.2 Comfort zone in buildings

Just like Sobek group, (2017) defines a facade as “Facades are subjected to numerous structural and technical challenges, while at the same time they are required to offer maximum visual and thermal comfort”, we can possibly extract this point as a basic principle for designing our facade, and it is, trying to keep the interior in comfort zone for occupants beside keeping our building suitable and functional.

3.2.2.1 Temperature

Thermal comfort is a condition of mind that expresses satisfaction with the thermal environment. Due to its subjectivity, thermal comfort is different for every individual. It is maintained when the heat generated by the human metabolism is allowed to dissipate at a rate that maintains thermal equilibrium in the body. Any heat gain or loss beyond this generates substantial discomfort. Essentially, to maintain Thermal comfort, heat produced must equal heat lost (Raish, 2009)

Figure 3.2 Definition of a comfortable temperature based on air and surface temperature(Steinbach, 2013)

3.2.2.2 Relative humidity

The amount of humidity in the air has a direct impact on Thermal Comfort which in turn impacts upon the health and wellbeing of building occupants. Maintaining the level of indoor humidity between 30-70 %rh is essential in spaces that human beings occupy as it allows them to function optimally. (HEVAC Humidity Group, 2016)

Figure 3.3 comfort for relative humidity (Steinbach, 2013)

3.2.2.3 Acoustic comfort

Noise pollution is a major environmental problem affecting millions of people around the world. According to the World Health Organisation (WHO), noise induced hearing impairment is the most prevalent irreversible occupational hazard and it is estimated that 120 million people worldwide have disabling hearing problems (Rockwool co., 2012)

Table 3.1 acoustic comfort for different types of buildings (Steinbach, 2013)

Room	Noise Level [db] (A)	Reverberation time [s]
Living/Sleeping room	35/30	0,5
Theater/Opera	30/25	1
Cinema,Lecture room	35	1

Church	35	3
Small office	35	0,5
Plan office	45	0,5
Restaurant	40-55	1
Museum	40	1,5
Gym/Swimming pool	45/50	1,5/2

Note* :
- for noise level ; 30-40 dB(A)
- for reverberation time ; 0,5 - 1 s

3.2.2.4 Required illuminance

Light Level or Illuminance is the total luminous flux incident on a surface per unit area. The area - the work plane - is where the most important tasks in the room or space are performed. Illuminance is measured in *foot candles (ftcd, fc, fcd)* in the Imperial system or *lux* in the metric SI system (Web 2).

Table 3.2 : Needed illuminance in internal spaces (Steinbach, 2013)

Representative activity	**Standard maintained illuminance (lux)**
Cable tunnels,nighttime sidewald, parking lots	50
Corridors, changing rooms, loading bay	100-150
Foyers and entrances, dining rooms, warehouses, restrooms	200
Libraries, sports and assemble halls, teaching spaces, lecture theaters	300
Computer work, reading & writing, general offices, retail shops, kitchens	500
Drawing offices, chain stores, general electronics work	750
Detailed electronics assembly, drafting,cabinet making, supermarkets	1000
Hand tailoring, precision assembly, detailed drafting, assembly of minute mechanisms	1500-2000+

3.2.2.5 Air quality

Air quality has several aspects such as air humidity , CO2 , odorous substances, and air pollutants which each of them has a great impact on the comfortability of occupants in a closed or open space (S. Steinbach, 2013).

Figure 3.4: air quality based on Pettenkofer benchmark (Steinbach, 2013)

3.2.2.6 Solar control

Solar radiation is a factor which has its direct impact on most of the comfort requirements in a building. There are different solar control systems and the important ones are explained in following.

Figure 3.5: Solar control systems: a) exterior, b) spectrally selective, c) angular selective, d) solar filter

Exterior solar control

The general concept is to intercept direct sun before it enters the building. Once direct sun enters the building, the only way it can get back out is through reflection (only the visible and near-infrared wavelengths of solar radiation can be reflected back out) or indirectly by convection and long-wave radiation. In contrast to fixed systems, they can control thermal gain, reduce glare and redirect sunlight and are far more flexible and efficient. Louvers and blinds are examples of these systems performance. These are composed of horizontal or/and vertical slats. Their most important function is to serve as shading system, but they are able to redirect light as well (Lee et al., 2002).

Spectrally selective solar control

Spectrally selective glazings are glass systems that in contrast to the common glazings screen out, absorb or reflect the ultraviolet and infrared radiation which arrives at the building surface. By blocking this portion of the solar spectrum, the generation of heat diminishes. In general, absorption can still result in some of the heat that transfers to the interior of the building, which makes reflection more efficient than the principle of absorption (C. Marysse, 2016).

The spectrally selective glazings have a proper thermal functionality based on seasonal aspects as they can deal with overheating problems during summer and heat loss during winter. Another valuable characteristic of such spectrally selective systems is that they transmit a big range of visible spectrums, resulting in efficient use of natural daylight as well (Lee et al., 2002).

Angular selective solar control

Another possibility to allow the entering of daylight in combination with blocking or reflecting of sunlight are angular selective façades. These façades control the solar radiation by a system based on the angle of the sun. To adjust the blockage angle to the changing position of the sun during the year, automated control systems can be used (C. Marysse, 2016).

Besides the traditional systems, another promising idea is to develop coatings that result in angular solar control (Lee et al., 2002).

Solar filters

Solar filters, made with an opaque or transparent base material, absorb or reflect a portion of both direct and diffuse solar radiation. Solar filters are mostly classified by their thickness, opacity and reflectance/absorbance properties with play an important role in the effectiveness of the solar control. Solar filters are usable both in interior and exterior installations (Lee et al., 2002).

3.3 Façade structures

The construction of an advanced façade can roughly be distinguished in two important groups: the curtain wall façades and the double façades. A curtain wall system can be defined as a covering of the building that is a non-structural independent frame and that acts like a kind of curtain that keeps the weather out. The curtain wall can have different functions. Double façades consist of two skins with an intermediate air cavity.

Figure 3.6: Types of façades: a) curtain wall façade and b) double façade (Knaack et al., 2007)

Both groups use a concept of layering to improve the performance of the façade and the global building performance. Compared to curtain wall systems, the double façade uses the layering strategy on the level of the 'building parts'. The curtain wall systems use the layering principle on the 'element' level (Klein, 2013, cited in C. Marysse, 2016).

3.3.1 Curtain walls

In general, a curtain wall is a system in which the outer walls are not contributing to the structural stability but have the purpose to keep the weather out. In Dutch, the meaning of curtain wall façade is 'vliesgevel', a membrane façade. This term refers to the fact that the wall is often characterised by a permeable, textile-like structure. However, rigid elements are also commonly applied. This system offers the opportunity to go from a massive exterior wall to a more transparent construction (Klein, 2013) .

There are other similar definitions of a curtain wall in architectural parlance, which defines a "curtain wall" as any non-load-bearing exterior wall that hangs (like a curtain) from the face of floor slabs, regardless of construction or cladding material. However, in common usage, the term curtain wall usually refers to aluminum framed systems carrying glass, panels, louvers, or occasionally, granite or marble (Wausau group, 2010).

Generally, when considering the structural concept of a façade, there are three main types of structures that need to be considered (Knaack et al., 2007). The most important one is the primary structure, which forms the main load-bearing structure of the building. This structure is responsible for taking the loads of the entire building and also for transferring the loads to the foundation.

The second group is the secondary structure, which is the load-bearing structure for the façade. This is in essence the curtain wall that transfers the loads (dead load of the curtain wall and life loads) to the primary structure through connections, typically at the floor line. For this force transfer, a properly designed wall, that allows differential movements, is essential. At last, there are the infill panels that are mounted on the secondary structure (Klein, 2013).

3.3.1.1 Different types of curtain walls

Storefront

“Storefronts” are non-load-bearing glazed systems that occur on the ground floor, which typically include commercial aluminum entrances. They are installed between floor slabs, or between a floor slab and building structure above (Wausau group, 2010).

Stick wall

“Stick” curtain wall systems are shipped in pieces for field-fabrication and/or assembly. These systems can be furnished by the manufacturer as “stock lengths” to be cut, machined, assembled, and sealed in the field, or “knocked down” parts pre-machined in the factory, for field-assembly and -sealing only (Wausau group, 2010).

Pressure walls

Many stick curtain walls are called “pressure walls,” because exterior extruded aluminum plates are screwed applied to compress glass between interior and exterior bedding gaskets. A snap-on cover or “beauty cap” is then used to conceal pressure plate fasteners (Wausau group, 2010).

Unitized walls

To accomplish as many critical seals as possible in controlled factory conditions, and minimize dependence on field labor, “unitized” curtainwall systems have been developed. Unitized curtain walls are factory assembled and -glazed, then shipped to the job site in units that are typically one lite wide by one floor tall (Wausau group, 2010).

Window wall

“Window wall” systems span from the top of one floor slab to the underside of the slab above. Window wall employs large, side stacking window units, contained in head and sill receptors, also called “starters,” which accommodate movement and drainage, but require field-applied perimeter sealants (Wausau group, 2010).

Conclusion

The most popular curtain walls are **stick** and **unitized** walls and each system would be chosen based on designer’s intention and buildings type and height.

Table 3.3: Stick system vs Unitised system (Marysse, 2016)

Stick system	Unitised system
+ Cheap construction	- Little bit more expensive
+ Great flexibility	
+ More economic (lower volume, lower complexity)	
+ Site modification possible	- No site modification possible
- Quality control difficult	+ Quality control in factory
- Heavy site workmanship	+ Minimises site operations
- Difficult to accommodate building movements	+ Accommodate building movements
- External access required	+ Usually no external access required
- More storage space and longer storage on site	+ Shortens construction duration
- Difficult water drainage control	+ Better water drainage control
- High maintenance costs	+ Easier maintenance
Mostly low- to mid-rise building	Cost efficient for high-rise buildings

Table 3.4 Advantages and disadvantages of curtain wall façades(Marysse, 2016)

Advantages	Disadvantages
Huge daylighting benefits	Solar control difficult with glazing panels
Lightweight construction possible	Regular maintenance (sealants …)
Recycling of material is possible	Installation cost and time
Reduced energy use	

Resistance to condensation	
Improved internal comfort, view and light	
Sound control	
Prevents air and moisture penetration	
Can act as fire stop	

3.3.2 Double façades

The Double Skin Façade is a European architectural trend driven mostly by:

- the aesthetic desire for an all glass façade that leads to increased transparency
- the practical need for improved indoor environment
- the need for improving the acoustics in buildings located in noise polluted areas
- the reduction of energy use during the occupation stage of a building

Although that the concept of Double Skin Facades is not new, there is a growing tendency by architects and engineers to use them.

Harrison and Boake, (2003) in the Tectonics of the Environmental Skin, described the Double Skin Facade system as “essentially a pair of glass “skins” separated by an air corridor. The main layer of glass is usually insulating. The air space between the layers of glass acts as insulation against temperature extremes, winds, and sound. Sun-shading devices are often located between the two skins. All elements can be arranged differently into numbers of permutations and combinations of both solid and diaphanous membranes”.

Figure 3.7: Double façade types: a) second-skin, b) box-window, c) corridor, d) shaft-box (Knaack et al., 2007)

Table 3.5: Advantages and disadvantages of double façades(Marysse, 2016)

Advantages	Disadvantages
Thermal insulation during the winter	Higher construction cost
Thermal insulation during the summer	Fire protection
Night-time ventilation	Reduction of useful building space
Natural ventilation	Additional maintenance and operational costs
Mixed ventilation	Overheating problem
Energy savings and reduced environmental impacts	Reduced daylight quality
Better protection of the shading devices	Sometimes acoustic problems
Reduction of wind pressure effects	

3.3.3 Classification of Pneumatic façades

Design-build projects or a subcontracted portion of a design-build project (delegated design) due to the unique characteristics of the system and the need for highly specialized and experienced designers. Throughout the design-build process, coordination is critical to the system's overall aesthetics and performance. In general, the basic enclosure performance of the ETFE system is much like a curtain wall glazing system.

Figure 3.8: ETFE double curtain wall from "Media-TIC" south west façade (Web 3)

In general, the basic enclosure performance of the **ETFE system** is much like a **curtain wall** glazing system. From a building science perspective, technical performance of materials, assemblies, and systems is mainly concerned with the control of four elements: 1) heat, 2) air, 3) moisture liquid, and 4) moisture vapor (known within the building science community as HAMM), which these are all influenced by the performance of current facade system. The curtain wall system with its defined specifications could make a proper guideline for evaluation of a facade while 2 or 3 layer cushions are installed as external skin. With today's typical ETFE cushion and rail systems, much like a curtain wall glazed system, the main strategy for management of liquid moisture and air is a pressure seal created by the extruded cap plate and silicone gasket placed between ETFE cushions (L. Durston, & S. Robinson 2016).

Since the air circulation in inflated cushions has a constant stream, it is also possible to use the warmed up/cooled down air in the cushions for energy saving purposes, such as ventilation or reduction of conductive heat exchange in cushions. Therefore it is assumable that pneumatic structures could also have functional similarities with **double skin** facades.

3.4 Pneumatic and glazing systems as façade

Rudorf-Witrin (2006) believes that glass architecture is quite common and It provides light, gives the feeling of brightness inside and also shows a sort of lightness of a structure.the advantages of glass in comparison with other building materials are arguable, but there are disadvantages as well. One point of importance is the weight of glass. Not only the weight of glass needs a proper structure to carry its load and other potential loads, but also the size of a single glass pane is limited which again requires an additional secondary structure. The result is, that glass structures are not cheap. Beside that don't forget the maintenance cost for cleaning on one hand and the necessary safety precautions (Rudorf-Witrin, 2006).

'ETFE facades offer innumerable opportunities for architectural expression, with complex geometries being structurally achievable and economically attractive(Castejón, 2017).

3.4.1 Structural characteristics

ETFE-foil structures provide interesting alternatives to push the limitations we would face in using glass, like size or cost. Different shapes, additional features like low-maintenance cost, UV-permeability and not to forget good U-Values roundup the design resources for an architect. Another interesting aspect of this system is its statical behaviour of ETFE-foil cushions, where the behaviour of the material allows to optimize supporting structures (e.g. to rope supported systems) since distortions by statical loads can be taken due to the elasticity of the foil (Rudorf-Witrin, 2006).

Cushions as long as 25m by 3.5m can be made as a single panel [there are references which believe the span of an ETFE cushion could be increased as long as the width is kept in range of 3.5m(Web), and it contrasts with glass where the dimensions should be governed by such factors as weight, handleability, toughening over restrictions.. etc. The commonly sizes of glass panels are 4m by 2m, even though larger dimensions are possible to be made but less common (Tanno, 2000).

Another major difference between glass and such inflated cushions is the way these two systems accommodate the tolerances and movements. In glass structures these movements are absorbed by the structural joints but in ETFE cushions, tolerances are absorbed by their well elastical behaviour (Tanno, 2000).

3.4.2 Life time

Concerning the life time expectation of ETFE-foil structures and glass roofs. Glass itself has exceptional long lifetime expectancy, but the lifetime of such structures should be considered as a system . The components like frames, sealing etc. determine the overall lifetime of a glass structure. Corrosion, water tightness etc. are not a question of the glass itself. The same arguments are valid for ETFE-foil cushions. The ETFE-foil has been tested within existing structures as well as under laboratory conditions for more than 25 years. So far there is almost no drop of technical data or the translucency visible. That underlines that a structural lifetime depends on the overall system (Rudorf-Witrin, 2006).

3.4.3 Thermal characteristics

The main thermal characteristic of facades is the U-value, which in ETFE cushions it is improvable based on number of layers used and also specific coatings on foils.

Table 3.6 comparison between U-value of ETFE cushion and Glass(Moritz and Schiemann, 2015; Salz and Schepers, 2006),

Different layering systems for ETFE cushions & Glass	u-value (heat transfer coefficient [W/(m²K)	g-value
1-layer foil	7.0	-
2-layer cushion	3.5	0.71
3-layer cushion	2.0	0.71
4-layer cushion	1.5	0.71
5-layer cushion	1.2	-
Glass 6mm	1.1 – 1.4	0.95

Note*

- The u-value is assumed to be measured based on DIN EN 675: 2011-09 for glass.
- The u-value for ETFE in single and multiple layers differs significantly in different sources.
- In g-value 1 represents the maximum and 0 the minimum amount of solar energy passing through object

Table 3.7 comparison between G-value of ETFE foil and Glass (Moritz, Schiemann, 2015)

Type of foil or cushion	g-value (energy transfer [%], approx. values
1-layer foil 200 μm transp	90
3-layer cushion transpar	80
1-layer foil 200 μm printed	60
3 layer cushion outer layer printed	50

3.4.4 Energy consumption

The energy consumption used by inflation units is minimal, because the blower units only need to maintain pressure in cushions, and do not need to create air flow. Each inflation unit can cover up to 1000m^2 and the blower is f=working approximately 50 % of the time, thus a 100 watt blower just has a half power usage of a normal light bulb (Tanno, 2000).

3.4.5 Safety/Explosion risk

Tanno, (2000) claims that "*ETFE is a flexible material which can take extremely high short term loading. This makes it an ideal material for use where there is a risk of explosion. It is able to absorb shock loading without risk of fracture, breakage or structural overload /collapse. Glass on the other hand , being a brittle material represents, a major concern in a bomb blast or similar shock load situations".*

Figure 3.9 Test Mockup, bursting tests on a 1:1 (3m x3m) ETFE-foil cushion with two layers, (seele cover GmbH ,2007).

3.4.6 Replacement/ Repair

In case an ETFE cushion is damaged and it should be replaced with new foils, the panel can be easily accessed from roof with no internal access required. Small repairs are also possible to be done on site.

3.4.7 Fire

ETFE is a self extinguishing material with low flammability properties. The hot air causes the foils to shrink back from the source of fire and let the fire to vent into the atmosphere. The material doesn't make any molten drips and also the quantity of material in terms of weight is also low. In comparison with glass, ETFE foil allows for minimal fire emergency measures and eliminates the need for smoke extraction in case of fire(Tanno, 2000).

3.4.8 Acoustics

Transparent pneumatic roofs and facades are mostly believed to show less acoustic insulation than other opaque materials. ETFE cushions are even considered to have less external noise reduction than glazing systems.ETFE film has approximately 70% acoustic transmission (adapted from Taiyo europe website). The foils in cushions are the main noise absorber in such systems.

ETFE transmits more sound than glass, and can be too noisy for some places. For a roof subject to raindrops, the workaround is to add another layer of film, thus decreasing the deafening drumbeats of rain but increasing the construction price (Web 6)

Table 3.8 Comparison in Acoustic insulation of ETFE and Glass(Moritz and Schiemann, 2015)

Different layering systems for ETFE cushions and films & Glass	Acoustic insulation R'w [dB], approx. values
3-layer cushion	8
2-layer cushion	5
1-layer foil	3
Glass	35

3.4.9 Cleaning

Unlike traditional fabric structures, ETFE Foil is an extruded material and therefore has a smooth surface. Therefore the cleaning and maintenance of ETFE is also small, the majority of the time water will wash off any dirt, this is due to the smoothness and anti adhesive properties of the material. If cleaning is needed then only light PH neutral detergents are used making the environmental impact minimal. It is recommended for cushions to be cleaned both externally, every 2-3 years and internally every 5-10 years, but this will vary from site to site.

3.4.10 weight and cost

The inflated cushions are approximately 1% the weight of glass. This significantly reduces amount of structural framework is required which in turn has a substantial cost benefit.The overall cost estimation of an ETFE foil roof is roughly as half of a conventional glass roof. The installation of an ETFE roof costs 24% to 70% less than a glass roof.(Tanno, 2000 & Web.6)

Table 3.9 Comparison in weight of ETFE and Glasses (Web 5)

Different layering systems for ETFE cushions and films & Glass	Weight [kg/m^2]
3-layer cushion	1.05
2-layer cushion	.7
1-layer foil	.35
Single layer Glass(FL16)	15
Double glazed (FL16)	30

3.4.11 Conclusion

Rudorf-Witrin (2006) has an optimistic perspective about future of inflated cushions, as he claims that "*Yes, ETFE-foil cushions are a good alternative to glass roofs. They never will substitute glass structures but they provide a big additional variety of solutions to those architects and clients who try to gamble with different forms and larger free spans and who ask for economical solutions.*"

Working with ETFE cushions for small residential buildings is complex and also there are several reports of damages into ETFE roofs in case of hail storms. The annoying sound of rain drumbeats is also another down point of these structures. Such current disadvantages of ETFE cushions should be improved to make it a superior system than glazing systems.

3.5 Climate zone of a building and orientation of its façade

There are different variables surrounding a building, which have significant impacts on building's ambient and its physics. They could be named as the **climate zone** which the building is located in, the **sun path** which differs by building's coordinates, and finally the **orientation of building's façade**.

3.5.1 Orientation of the façade

Orientation of the façade can affect the interior comfort, because the different adaptation to physical functions is a main task of a good façade. The following table gives an overview of the differences between the different orientations and is reflected in plusses and minuses to give the level of adaption.

Table 3.10 Comparison of the different orientations (Van Dijk, 2009)

Absolute	**North**		**South**		**East**		**West**		**Level of adaptation**
	Min.	Max	Min	Max	Min.	Max.	Min.	Max.	
Thermal insulation	--	++	--	++	--	++	--	++	Similar for every orientation
Heat storage	--	+	--	++	--	++	--	++	North facade is different
Dehumidif -ication	--	++	--	++	--	++	--	++	Similar for every orientation
Natural Ventilatio n	--	--	--	++	--	+	-	+	North facade is different
Daylight	--	o	--	++	--	+	--	+	North facade is different
Overheati ng control	--	-	--	++	--	+	--	+	North facade is different

This table show how effectively a facade can adapt itself to its ambient and impact the comfort zone of the building. The term ‘absolute’ refers to the fact that the absolute differences that occur during all seasons are showed and not for every season separately. In following we can extract some useful information from aforementioned table:

- The largest level of adaption for daylight and overheating control is necessary for the south façade.
- For the east and west façade, this level also has to be significant.
- Daylight and overheating control are most effective during summer.
- The blinding effect of the sun is higher in winter due to the lower position of the sun.
- Heat storage can be done during spring/autumn and summer.
- Moisture does not necessary needs adaption.
- The effect of adaptation is lower than for e.g. thermal insulation.

- Natural ventilation is especially necessary during summer while in winter, closure is necessary.

The needed level of adaptation directly depends on the orientation of the façade. Therefore the functionality of a facade should be investigated regarding the direction it is facing. For example west and east façades can be problematic due to the lower solar angles (Van Dijk, 2009, cited in Marysse, 2016)

3.5.2 Climate zones

For the design of a building and its façade, it is important to know the climate conditions of the region. Because the problems a building would face are specific in each zone. The world can be split up in different climate zones. The most widely used system is the Köppen(-Geiger) Climate Classification System. This classification system is based on the concept that the vegetation of a region is the best expression of its climate.The classification system divides the world into five main groups of climates : the Polar, Cold, Moderate, Subtropical and Tropical climate (Web 7).

Figure 3.10 The five climate zones (Web 7)

Temperature fluctuations and precipitation rates(rain and snow) of a climate zone, should also be taken into consideration for designing the facade.

Table 3.11 Temperature and precipitation of the climate zones (Van Dijk, 2009)

Climate zone (Example)	T average (°C)			precipitation
	Year	Hottest month	Coldest month	mm/year
warm and humid (Paramaribo)	26	27	25	2800
warm and dry (Cairo)	19.5	24	15	80
moderate (Netherlands)	13	23	4	800
boreal(siberia)	1.3	20	-14	500
Ice climate(Greenland)	-8	4	-20	580

Each climate zone with its specific conditions, needs several elements and solutions to protect the building's interior comfort form being significantly impacted by its surrounding climate zone. In following the recommended solutions for each climate zone is suggested.

3.5.2.1 Humid-warm climate / Tropical rain / Equatorial

The tropical climate is characterised by a high relative air humidity (60-100%), constantly high average temperatures around 30°C, large precipitation amounts and low day/night temperature fluctuation. The high direct solar radiation is mostly tempered by a high frequency of cloud cover due to the relative humidity, which results in diffuse radiation (Marysse, 2016).

The recommended elements for this climate zones are **sun protection** and **ventilation elements**. For heat dissipation we would need a continuous air circulation and to protect the building from direct sun, shading systems are helpful. For cooling the houses, adiabatic cooling can be used (Barbosa et al., 2015) (Bilow, 2012).

3.5.2.2 Dry climate / Arid / Subtropics

The typical characteristics of a dry climate are the high solar radiation, a very low relative air humidity (10-50%) and a low amount of precipitation (short strong rain falls). In a dry climate with low humidity and intense direct sunlight, the **sun protection** systems are essential for making a comfort internal ambient. The large daily temperature fluctuations can be used in an effective way to protect the building from overheating during the day and avoid high energy exchanges in night. For the cooling needs, the air exchanging principle can be applied. **Natural ventilation** can also be extracted from large temperature fluctuations between day and night, especially in desert regions (Bilow, 2012).

3.5.2.3 Warm moderate rain climate / warm temperate

The annual temperature differences can be large and the intensity of the solar radiation can differ a lot. The air humidity is situated in the mid to high range (typical of 60-80%). The bordering areas with the tropical climate are characterised by a long, warm summer and a short, rainy winter. Contrarily, the bordering areas to the cold climates are dominated by a long, cold winter and a short, warm period. Continental climates can have extreme temperature differences between the seasons. In these zones, protection against cold during winter and overheating during summer is necessary. Often **naturally generated temperature flow** can be used to heat surface areas. **Large windows** can create sufficient daylight. However, a **balance** should be found between the light incidence and the heat loss in winter (Bilow, 2012, cited in Marysse, 2016).

3.5.2.4 Boreal or snow forest climate / Cold

A **good covering and mass of the houses** is necessary to keep them warm and insulated by acting as a temperature buffer. In such climate zones the highest energy lost can occur due to conductive heat exchange, therefor a proper insulation, preferably with large mass could decrease the energy exchange. A summer-warm climate is characterised by fluctuations in temperature between -10°C and 30°C. The **orientation of the building towards the south** is important to reduce the heating load. Secondary functions in the building should be directed towards the cold north (Bilow, 2012).

3.5.5 Snow climate / Polar

A snow climate is characterised by extreme temperatures often far below the freezing point. The climate has polar days and polar nights and a low relative humidity. During polar days the sun is positioned at a very flat angle towards the ground. During polar nights, the sun is under the horizon. We need, in essence, a “perfect” **air barrier** and a “perfect” **vapor barrier,** which these demands could also be integrated into an **insulation with low conduction losses** (Billow, 2012) (Web, 8).

3.5.3 Sun path

Regarding the climate zone that the building is constructed in, sun protection or sunlight absorption are influential elements of facade and need to be designed based on the sun path of construction site.

Figure 3.11 Sunshade analysis (Web 9)

By studying the **sun path diagram for each climatic zone**, the shaded areas represent the periods of overheating, related to undesirable solar gain. This means that tropical areas receive high sun radiation which makes overheating a usual phenomena to deal with. In zones with a higher latitude, overheating only occurs during the summer months (cold and moderate zones). Based on the **sunshade strategy**, the efficiency of a horizontal or vertical sunshade element depends on the situation. Tropical regions need both vertical and horizontal shading throughout the year, Shielding the building from low sun angles in the morning and evening, and also horizontal sun shading blocking against the high midday sun. In higher latitudes, horizontal and vertical shading is only needed during the summer on the south-facing sides of buildings. **The sun requirements for each climate zone** shows that solar heating is important for the higher latitudes and solar shading is more important for the lower latitudes and also by beginning at the equator and moving north, the need for solar heating increases while the need for solar shading diminishes (Web 9).

3.5.4 Overview

Based on what was discussed previously on protection and gaining systems of a facade based on different variables, the following table shows an overview of the recommended methods and solutions to know how to deal with aforementioned variables, especially **climate zone**.

Table 3.12: Characteristics for each climate zone (Adapted from (Bilow, 2012),cited in Marysse, 2016)

Climate zone > **Principle ˅**	Polar zone	Cold zone	Moderate zone	Subtropical zone	Tropical zone
Sunscreen	Not necessary Sun irradiation used	Variable Blocking or gaining sun energy	Variable Blocking or gaining sun energy	Shading required	Shading required
Insulation	Maximise insulation Use buffer zones	Insulation required Thermal mass Multilayer walls (fast heating)	Insulation required Multilayer walls Prevent overheating	No insulation required Thermal mass is buffer	Insulation required Lower temperature peaks by thermal mass
Natural ventilation	Minimise ventilation Air intake via buffer zone	Air outtake on highest point Support of distribution of heat	Seasonally Winter as low as possible	Maximise natural ventilation	Maximise natural ventilation
Heating	Necessary	Necessary Air or wall heating	Required in cold season	Not necessary	Sometimes required during night Thermal mass temperature storage
Cooling	Not necessary	Not necessary	Not totally necessary Natural ventilation, use thermal mass	Required Good natural ventilation, adiabatic cooling	Required Good natural ventilation, adiabatic cooling, use thermal mass

Sun orientation	Gain sun energy Maximise orientation towards south	Gain sun energy Maximise orientation towards south	Gain sun energy Cover north side (insulation) Open south side (maximise gain)	Minimise solar heating Blocking direct sun	Minimise solar heating Blocking direct sun
Sun path	Flat angle towards the ground	Small angle towards the ground	(Small) angle towards the ground	Almost vertical angle at noon	Vertically at noon almost the entire year

3.5.5 The dominant climate zone and façade's orientation of ETFE structures

First application of ETFE foils in the building industry took place in the early 1980s in Europe. Then this constructional material gained recognition with three major projects, the **Eden Zoo Project** in 1998, the **Allianz Arena** for the 2006 Soccer World Cup and the "**Water Cube**" at the 2008 Beijing Olympics (Web 10)

Figure 3.12: Dispersion of Vector-foiltec company projects in worldwide (Web 11)

ETFE constructional applications are mostly known as single layer or multi-layer cushions. Both systems are applicable for specific demands or purposes, but the cushion system has more popularity than single layer ones.

Figure 3.13: Methods of ETFE foil constructions (Moritz, 2007)

As it is also obvious in the dispersion of ETFE applications in Vector-foiltec company, the main concentration of such systems is in europe. By taking constructional ETFE projects, done by Vector-foiltec and Taiyo-europe companie as a decent Statistical population, The following charts could be extracted.

Figure 3.14: Dispersion of ETFE constructions based on their climate zone(adapted from vector-foiltec and Taiyo-europe ETFE projects)

Figure 3.15: Constructional ETFE projects based on types of application(adapted from vector-foiltec and Taiyo-europe ETFE projects)

By knowing the number of applications, installed as **façades**, **roofs** or **canopies** we can have a proper overview on how potentially further researches on improvement of ETFE systems can affect the market.

More than 80%of already installed ETFE systems are in moderate zones, and less than 20% of them are in cold, tropical and subtropical zones. The conclusion could be made that such systems didn't gain popularity among clients and architects in these climate zones because of their characteristics.

3.5.6 Potential markets for ETFE façades

ETFE systems with their specific building physics characteristics should be investigated regarding the **climate zones** they are working properly and the regions that ETFE couldn't gain its popularity as a building element. Based on latest world **population** density and **income** dispersion, the potential markets for ETFE systems could be mostly concentrated in temperate(oceanic) and coastlines such as **western and eastern asia**, **oceania** and **northern america.**

Figure 3.16: world dispersion of income and population(Web 12)

It is known that ETFE and pneumatic systems didn’t gain popularity in these regions because of their disadvantages in temperate or cold regions. Building physics characteristics of aforementioned systems are mostly criticized to be inefficient in comparison with the possible alternatives such as glazing systems.

3.6 Report on an ETFE cushion roof

A report done by Steinbach, (2016), on the behaviour of ETFE cushions in building physics aspects of **Möwe project (**designed by Robert Off), contains various temperature measurements in summer and winter days.

Figure 3.17: Covers the 195 m² courtyard of the state representation Consists of 5 membrane cushions(R. Off, cited in Steinbach,2016)

Figure 3.18: Measurement points in cushions, indoor and outdoor (Steinbach,2016)

The sensors in cushions measure all top, middle and bottom section temperatures. The bottom layer mostly had the highest temperature among all. In following graphs the cushion’s temperature represents the average of all 3 measurements.

Figure 3.19: Temperature development on a winter day(Steinbach,2016)

The maximum difference in temperature of cushions and atrium can reach up to 6 degrees. This fact is based on the absorbance of ETFE films and lack of inner air convection in cushions.

Figure 3.20: Temperature development on a summer day(Steinbach,2016)

This case report demonstrates the lack of ETFE cushion's impact on building physics characteristics, which doesn't make perceptible change or insulation against outdoor temperature.

But there could be an option in winter time. In case the cushions have a constant warmer air, this air could massively help the ventilation of a building, for a more decent air quality. In general this notable difference could lower the overall energy consumption of a building in winter time.

Beside the temperature measurements in this report, the loud sound effect of raindrops in cushions is also mentioned(Steinbach,2016).

4.Adaptive Façade

“To enhance
environmental
performance and
create dramatic
visual effects,
architects devise
façades that adapt to
changing conditions”

-Russell Fortmeyer-

4.1 Introduction

The raising climate challenge is undeniable. Since buildings are responsible for a large part of the global energy consumption, the popularity of low-energy buildings has enormously increased. The building industry needs to focus more on sustainable designs to lower the negative climate impact. Low-energy buildings can roughly be distinguished in two groups: **active technology** and **passive design strategies**. Active technology is currently the most popular approach. Active technologies in low-energy buildings have two major criterias. Innovative technical devices that enhance the efficiency of the conversion of resources or make use of renewable sources to supply energy are the two basic types. In contrast, passive design strategies focus on the design of the building and its construction to capture, store and distribute solar and wind energy (Loonen et al., 2013)

In recent years adaptive systems, smart structures and “intelligent” building envelopes achieved great attention and these developments promise new prospects for architectural and civil engineering projects (Sobek et al., 2006)

Traditional, static buildings make use of fixed systems that possess no flexibility, which results in robust building designs. Such robust buildings are typically equipped with a lot of HVAC systems that increase the cost of energy consumption. But in contrast, flexible, adaptive systems have the opportunity to maintain good performance during their lifetime by anticipation and reaction in the façade without the need for oversizing(Loonen et al., 2013). The adaptive system or strategies lower the need for HVAC systems and consequently the total energy cost of the building (Loonen, 2010).

Driven by the climate problem, adaption came to the front in the design of buildings. Adaptive structures - and adaptive architecture in general in terms of buildings - refer to continuously changing the configuration of buildings to perform better. Adaptive buildings are more efficient by the clever use of light and space. Due to the changed approach in the design of buildings, the façade is no longer seen as just a static barrier separating the interior building environment from the external one. The façades possess the ability to adapt to climate changes. To design a façade that responds to changing climate conditions, multiple objectives are important, such as the building environment and the objectives of the building occupants. The interaction between these multiple perspectives makes a good design a complex affair (Kirkegaard, 2011; Loonen, 2010, cited in Marysse, 2016)

4.2 Definition

The definition of ‘Adaptive’ as a term is not univocal and therefore a literature review is needed to reach a proper understanding of this term, which could be used in rest of this thesis.

Loonen, Knaak and Kirkegaard have done several researches on adaptive façades and each of them have their own definition of adaptation in façade. We can take them as a proper reference for getting an idea about the term of ‘adaptive’ in this text.

Loonen (2013) as one of the superior researchers in adaptive buildings, defines such buildings as: ‘A climate adaptive building shell has the ability to repeatedly and reversibly change some of its functions, features or behaviour over time in response to changing performance requirements and variable boundary conditions. This is done with the aim of improving overall building performance in terms of primary energy consumption while maintaining acceptable thermal and visual comfort conditions. These façades can seize the opportunity to save energy by adapting to prevailing weather conditions, and support comfort levels by immediately responding to occupants’ wishes.’ (Loonen et al., 2013).

Knaack (2007) prefers to use the term ‘Adaptive’ as: ‘Buildings able to adapt to changing climatic conditions are called intelligent buildings. Since the term intelligent can be misleading when used in the context of buildings or façades, we will use the term adaptive façade instead. Adaptation generally means that buildings and façades adapt to current weather conditions.’ (Knaack et al., 2007).

Kirkegaard (2011) says that adaptive buildings can ‘adapt their performance, in real time, to environmental changes and use less energy, offer more occupant comfort, and feature better overall space efficiency than static buildings do’ (Kirkegaard, 2011).

Three different states can be distinguished in such an adaptive system (Weilandt, Lemaitre, Sobek, 2006). The passive state is defined as the state where the system is without manipulation and burdened only with external loads. The activated state as the condition where only the actuators are active and the third state is the adaptive state which is defined as the superposition of the passive and the activated state.

Passive + activated = adaptive

Based on aforementioned definitions about the term of ‘Adaptive’, the following description would be used in this thesis.

An adaptive façade is able to actively and passively change its functions and behaviours, in order to reach occupant’s comfort or preference.

Adaptive façade has several alternatives in different literatures. Even Though they don’t have exact same meanings, but they are used as synonyms by professionals and researchers.

Figure 4.1: Alternatives for 'Adaptive' (Marysse, 2016)

There are several variables for regulation of the adaption to desired functions. Firstly, the **humidity** can be regulated by **absorbing**, **collecting** or **evaporating**. Secondly, the **temperature** can be regulated by **dissipating**, **gaining** or **conserving**. Thirdly, the **air quality** (related to the carbon dioxide level) can be regulated by **filtering** or **exchanging**. Finally, the **light** can be regulated by **absorbing**, **redirecting** or **diffusing**. Various mechanisms could be used in an adaptation process, but combination of the different mechanisms can make a design very complex (López et al., 2015).

Figure 4.2: Façade regulation mechanisms(Adapted from Marysse, 2016)

4.2.1 Dynamic interfaces

Adaptive façades belong to the category of ‘dynamic interfaces’ which they have the possibility to activate for a decent reaction to external environment. The building envelope is no longer seen as just a shield but as a surface that controls occupant’s comfort and energy balances. Dynamic buildings perform better and have a higher sustainability based on their time-based, responsive and dynamic performance. This evolution results today in two major solutions for dynamic interfaces on a building (Premier, 2015).

Green façades as one of the dynamic interface subcategories are mostly known as vertical gardens. It is based on natural climbing of plants on façades and is a passive approach to save energy (Premier, 2015). Some researchers believe that green façades shouldn’t be categorized as an adaption in façades as their growth is a part of their nature. But others mention that as long as plants react to their environment, it is necessary to keep them as a passive system with influences on occupant’s living.

On the other hand **Adaptive façades** have a one-way relationship with their environment. Artificial materials are replaced by natural growing plants. The most common type in this category are the sun shading systems, often in combination with smart materials and innovative technology (Premier, 2015).

The design of dynamic interfaces is often accompanied by innovative technologies. Application of these technologies is usually high in risk, investment and maintenance which could also result in failures. Computational tools and softwares can already predict the operational performance in the design stage. In addition, the performance of dynamic systems is cumulative and specific for every case, which makes it a complex job (Loonen et al., 2013).

4.2.2 Ecological footprint

Nowadays a new objective for designing low energy buildings is changing to a trend. The main goal of this designing process is to reduce the ecological footprint of buildings. Approximately one third of the world’s energy use takes place inside buildings. Statics show that a massive energy consumption is happening in HVAC systems (heating, ventilation and air conditioning). The energy use of HVAC systems is directly related to the internal thermal comfort. Not only the thermal comfort, but also the relative humidity needs to be of sufficient quality to satisfy the wishes of the people in the building. By implementing dynamic systems in the façade, energy savings between 10-50% are possible, which lowers the ecological footprint significantly. In addition, the reduction of lighting and HVAC use can decrease the operation costs of the buildings with 10-40% (Velasco et al., 2015).

Figure 4.3 : Heat dominates final energy consumption both of private households and non-residential buildings in Germany by 2012 (AGEB, 2013)

Based on the BMU targets (Figure 4.4) for reducing heat demands of buildings and their high energy consumption, especially in form of heat, there should be a great effort in increasing both insulation and energy efficiency of buildings.

Figure 4.4 : Long-term, comprehensive energy and climate targets set by the German government (BMU, adapted from Morris and Pehnt, 2012)

Marysse (2016) extracts the fact that, from an ecological point of view, the adaptive behaviour of the systems requires various elements and nearly all of them are in need of electricity for a desired functionality. Actuators, power sources, processors, sensors, and networks are mentionable elements of a commonly installed adaptive façade. However, the amount of energy that these elements require is mostly negligible compared to the lower energy use achieved by the adaptive behaviour of the façade (Kirkegaard, 2011; Loonen, 2010).

The **orientation, adaptation time scale** and **climate zone** of the façade with dynamic interfaces play a great role in decrement of HVAC and lighting costs.Both the magnitude of the energy saving achievable and the most effective range of variability of ideal states of the façade strongly depends on the climate context and orientation of the room/building (Favoino et al.,2014)

4.2.2.1 Climate zone

For instance an adaptive façade is more effective in decreasing cooling energy demand, which is more significant in hotter climates. Although the benefits of adaptive facades can still be significant in colder climates (Favoino et al.,2014).

4.2.2.2 Adaptation time scale

It is believed that a glazing façade with monthly adaptiveness can significantly reduce the energy consumption. Moreover a first quantification of the potential energy saving achievable with a daily adaptive glazing façade demonstrates that a shorter reaction time of the glazing façade could result in higher energy savings. Further researches show that saving up to 20% for monthly and 30% for daily-adaptive façade may be achievable (Favoino et al.,2014).

4.2.2.3 Orientation

In general, north exposed facades present lower energy saving potential by the employment of adaptive glazing, especially for façade with long response times. In general the highest decrease in energy consumption is achieved in the cooling primary energy demand of the building for all the orientation (80-90% reduction). This results represent an ideal limit of the performance achievable by means of an adaptive glazing façade (Favoino et al.,2014).

4.2.3 Environmental impacts

The surrounding environment of a building can change in different orders of time. **Short-term** fluctuations can be in order of **seconds**, like wind speed or wind direction. Other examples of short-term environmental impacts are categorized under **minutes** and **hours.** Cloud cover and daylight availability can change in minutes. Most of adaptive façades are designed to react as an dependent variables of changes in minutes. The angular movement of the sun through the sky results in fluctuations in the air temperature. The resulting changes are in the order of magnitude of hours.The availability of solar radiation is dependent to altitude of the sun and such **long-term** changes are known as the **seasonal** changes during winter, summer, spring and autumn.

Table 4.1 gives an example for the interaction of functions and the environmental changes in different orders of time. The example is based on the behaviour of a west façade.

Table 4.1 Level of adaption for a west façade (Van Dijk, 2009)

Function	Minute-to-Minute	Day/Night	Seasonal	Yearly (upgrade)
Thermal Insulation				
Heat storage				
(DE) Humidification				
Natural ventilation				
Daylight				
Overheating control				
Vision				
Wind & Water				
Acoustics				

This table helps us to pull some important conclusions out. **Thermal insulation** is mainly mentionable in seasonal changes. For Instance, during summer days the building needs less insulation than the same building in cold winter days. **Heat storage** systems could be also useful based on seasonal changes, even though in climates with a big difference in day and night temperature, heat storage systems could help the efficiency of building's physics.

Moisture and **natural ventilation** are mostly related to seasons. But in buildings with big changes in number of occupants during the day, the necessary demands for ventilation and humidity could also change in minute-to-minute scale.

Daylight is a dependent variable of sun and visible light, and sunlight can easily change in scale of minute-to-minute. **Overheating** usually occurs during daytime and shadings during intense sunlights can be very efficient to prevent it. **Vision**, **wind and water** barriers and **acoustics** have no clear seasonal relationship and depend only slightly on day and night cycles (Van Dijk, 2009).

4.3 Classification of adaptation systems

Based on a classification done by Velasco et al. (2015), **Movement** and **Control** systems are the main specifiers of an adaptive Façade. In previous classifications, movement has always been the main factor for adaptation. But since the type of control system is a fundamental aspect in the design and operation of dynamic façades, 'Control' is also taken into consideration of this classification.

Figure 4.5: New classification system (Adapted from (Velasco et al., 2015), Cited in Marysse, 2016)

4.3.1 Movement

The movement is divided into a category for **mechanical movement** and a category for **changing material** properties. The mechanical based deformation can be a **translation**, **rotation** or **hybrid movement**.

4.3.1.1 Mechanical based deformation

Installation of sensors and mechanical components are in the basic needs of a mechanical based deformation. Such systems are mostly driven by electricity or outsource powers like user's interaction. **Sun shading** systems are the most well known and oftenly used application of mechanical movements in adaptive façades. Three types of sun shading exist, the **external** ones, the **internal** ones and the **intermediate placed systems** between two glazing layers.

4.3.1.2 Material based deformation

Ritter, (2007), defines the components of a material based deformation as shape-changing materials. He believes that "**shape-changing smart materials** include materials and products that are able to reversibly change their shape and/or dimensions in response to one or more stimuli through external influences,the effect of light, temperature, pressure, an electric or magnetic field, or a chemical stimulus. Among these, there are materials and products that are able to change their shape without changing their dimensions, and other materials and products that retain their shape but change their dimensions. Some are also able to change both parameters at the same tim." (Ritter, 2007)

Active or shape-changing smart materials are classified under their triggering stimuli or their function.

Table 4.2 Smart materials and their triggering stimuli(Ritter, 2007)

Shape-changing material	Triggering stimuli
PHOTOSTRICTIVE SMART MATERIALS	Excited by the effect of light (electromagnetic energy).
THERMOSTRICTIVE SMART MATERIALS	Excited by the effect of temperature (thermal energy).
PIEZOELECTRIC SMART MATERIALS	Excited by the effect of pressure or tension (mechanical energy).
ELECTROACTIVE SMART MATERIALS	Excited by the effect of an electric field (electrical energy).
MAGNETOSTRICTIVE SMART MATERIALS	Excited by the effect of a magnetic field (magnetic energy).
CHEMOSTRICTIVE SMART MATERIALS	Excited by the effect of a chemical environment (chemical energy).

Table 4.3 Smart materials and their functions(Marysse, 2016)

Function	**Components**			
Heat storage	Phase change materials		Thermotropics	Light reactive materials
(DE) Humidification	Humidity reactive materials		Silica gel	
Natural ventilation	Carbon dioxide reactive materials			
Daylight	Chromics (thermo/photo/electro)	Thermotropics	Vegetation	Liquid crystals/ Suspended particles
Overheating control	Chromics (thermo/electro)	Tropics (thermo/photo)	Vegetation	Phase change materials
Vision	Electrochromics	Thermotropics	Vegetation	Liquid crystals
Wind & Water	Breathable fabrics		Vegetation	
Acoustics	Piezoelectrics			

4.3.1.2.1 Electrochromic/-optic materials (EC,EO)

To change the visible appearance of a material with specific characteristics and requirements, the electrical energy could be an external activation. During the charge insertion/ extraction or chemical reduction/oxidation processes, some materials change their colors accordingly, which can be clearly observed when they are fabricated on transparent current collectors. This phenomenon is called electrochromism. Electrochromic (EC) materials and as a great example, smart windows, are one of the most important types of electrochromic device (Monk et al., 2007 ; Granqvist, 2014).

Amundson et al.,(1996) defines the Liquid crystal as a major candidate for electro-optic materials in a variety of applications. Where thin films of nematics between conductive substrates are applied. Several new dispersions of liquid crystals and polymers have been developed. One of these is the polymer-dispersed liquid crystal (PDLC), where the liquid crystal is trapped as 1–3 μm diameter drops embedded within a polymeric matrix. PDLC applications are widely used for flat panel displays, switchable privacy windows, and switchable optical elements such as holographic films, because their scattering power can be modulated by an electric field. Typically, as the electric field aligns the liquid crystal in the drops, the scattering power of the film decreases substantially, bringing the film from a highly scattering state to transparency. While twisted- and super twisted-nematic displays gain their contrast through absorption at polarizers, PDLC films gain contrast through scattering (Amundson et al., 1996).

In general, chromogenic switchable transparent surfaces can help the performance of building physics requirements like **mitigate energy loss**, **unwanted energy gain** and **visual discomfort (glare)**. One of the best ways for achieving switchable shading is using liquid crystals. This system is based on the use of electricity to organise and align particles that are suspended between two treated surfaces, which results in an increased transparency. If no electricity is present, the random organised particles block the light that tries to enter the building (Van Dijk, 2009).

Figure 4.6 Electrochromic Material a)Off mode b) On mode (Ritter, 2007)

Figure 4.7 Electrochromic shading performance(Korgel, 2013)

4.3.1.2.2 Application of Switchable glazing as an adaptive façade

Electrooptic switchable systems are currently becoming more popular worldwide.Apart from dividing walls, doors etc. that have been manufactured and installed to provide temporary optical separation to parts of rooms, one of the world's largest contiguous switchable electro-optical surfaces was built for the Chanel fashion group, a facade in Tokyo in 2004. Its 910 square meter display facade, which allows the 56 m high building to take on different appearances throughout the day, consists of a laminate with several functional layers. By day the electro-optic glass and hence the whole facade is switched to the transparent state which brings the view into the building 1(Ritter, 2007).

Figure 4.8 Chanel group building, Tokyo

4.3.1.2.3 Electrochromic/-optic limitations and developments

The requirements for handling and processing the products depend on the technology and the EC or EO used. **Installation** and **shipment** of EC or EO materials are two major factors that can affect their desired performance. With all glass- and plastic-laminated transparent systems, the substrate must not be **overstressed,** e.g. by compression, which may arise from inadequately specified installation tolerances. **Moisture** must also not be allowed to penetrate the electrical connections. Some electrochromic and electro-optic glasses are not suitable for installation as **overhead roof lights**. In addition, the specified **voltages** must not be exceeded (Ritter, 2007).

Currently the available windows that can change its light transmission properties only work with an external power source. But Wang and his colleagues at Nanyang Technological University (NTU),(2014) report a **self-powered electrochromic window**, which can be used as a **self-rechargeable battery**. They use aluminium to reduce Prussian blue (PB, blue in colour) to Prussian white (PW, colourless) in potassium chloride electrolyte, realizing a device capable of self-bleaching. This electrochromic window is also a self-rechargeable transparent battery. Thus the PB/aluminium device they report is bifunctional, that is, it is a self-powered electrochromic window as well as a self-rechargeable transparent battery (Wang et al., 2014).

Figure 4.9:| Characterization of the self-powered PB/Al EC device. (a) Optical photo of the as-prepared EC device. (b) The bleached state by connecting the PB and Al electrodes (Wang et al., 2014)

Figure 4.10: Photos of the as-prepared two PB/Al devices connected in series acting as self-rechargeable batteries. (a) In coloured state with two electrodes disconnected, and (b) the connected circuit powering a LED.

4.4 Conclusion

Based on the German Adaptation Strategy (Deutsche AnpassungsStrategie, DAS), the framework for building new constructions and renovation of existing buildings is found on overcoming climatic and ecological footprint challenges.

ETFE and pneumatic constructions as a part of commercial real estate market, should have the ability of adaptation into current and future demands and standards.

In this research ETFE cushions as the majority of pneumatic construction market is aimed to gain adaptability. Developing the building physics characteristics of each inflated module, makes a notable improvement on the energy efficiency of the building.

The term of “adaptive” with its various definitions, is oriented into the main objectives of this thesis. “An adaptive façade is able to actively and passively change its functions and behaviours, in order to reach occupant’s comfort or preference”.

Among four main domains of building physics characteristics, Thermal, Optical and Airflow are chosen to be controlled by improving ETFE cushions as adaptive façade elements of a building. Therefore, Zone H (Figure 1.1) defines the target of this thesis to achieve.

Considering the target zone of this research, shading is the most reliable system in preventing overheating challenges. To make this shading system user friendly and also controllable at a center or locally, Electro-tropic films are selected as a proper approach to reach target zone.

By embedding an additional film into a two or 3 layer cushion, beside the active functionality of electrooptic film, the passive behaviours of switchable films should be investigated in both On and Off modes.

This research would be conducted by implementing PDLC films which are available in market scale, to increase the practical aspects of the project. Even though working on self-powered electrochromic devices or devices with higher energy efficiency characteristics would make a great impact on popularity of adaptive façades, there is still a distance between laboratory scale and building standards for their market introduction. Thus investigating the adaptation of current PDLC films into building façades is still a great representative for electro tropic materials.

5. Case studies of adaptation in ETFE cushions

ETFE has the potential in design of more adaptive buildings in the future.

-Stephen Tanno-

5.1 Cycle bowl ETFE wall

Table 5.1 Cycle bowl ETFE wall case definition

Location & date of construction	Hannover, 2000
Architect(s)	Atelier Brückner, Stuttgart
Façade type	Triple-layer cushion
Function	Thermal(Solar control)

The triple-layer ETFE cushion has two printed sheets and one transparent. In each cushion, one ETFE sheet is a positive print and one negative print. Under pneumatic control the printed middle sheet could be pressed against the reverse-printed outer sheet or against the unprinted inner sheet to change the shading and appearance of the façade. The internal space could also get sealed by help of transparent tubes applied in the roof (Ritter, 2007)

Figure 5.1: Mechanical based movement for shading, Cycle bowl, Hannover Expo(Ritter, 2007)

5.2 Media-TIC building, ETFE-MFM

Table 5.2 Media-TIC building, ETFE-MFM case definition

Location & date of construction	Barcelona, 2010
Architect(s)	Enric Ruiz Geli
Façade type	Double curtain wall ETFE
Function	Thermal(Solar control)

Triangular elements of southeast façade are made up of 3 separate layers, outer and middle layer are printed in positive and negative patterns. Middle layer can move manipulating the air pressure.

Figure 5.2: Cushions of “Media-TIC” south east façade and their changeable sunscreen system(ETFE-MFM, 2014 : Web 13)

In the southwest of the same project another innovative solution for controlling solar radiation and avoiding overheating is applied. A sensor system is used that detects the solar radiation and temperature and in case of need, activates a system with that injects in a fog made with vegetable oil between ETFE curtains, reducing the transparency and obtaining more shadow. With this innovative solution, the solar factor could be reduced from 0,55 (in normal conditions) to 0,1 (with fog in cushions) (ETFE-MFM, 2014).

Figure 5.3: Media-TIC south west façade, a) clear ETFE cushion , b) with vegetable oil injection into cushions(ETFE-MFM, 2014)

5.3 Cushion-integrated sunscreen

Various printings on ETFE films could be used as a constant element or movable by air pressure, but in both cases the visual sight of ETFE as a transparent material is highly influenced. Another method for providing sun shadings is integration of retractable membranes into ETFE cushions.

Figure 5.4: (Moritz et al., 2005, cited in Moritz & Schiemann, 2015)

Rotatable blinds

This type of solar control system in a single layer ETFE application, and was introduced in DBU conference pavilion as a project done by ‘Herzog + Partner’ ,Osnabrück, Germany (2002). In this approach rotatable blinds and a translucent insulation material together form a functional roof that is covered by a single ETFE layer as seen in Figure 18.

Figure 5.5: Rotatable blinds and ETFE,(Loonen, 2010)

5.4 Responsive ETFE façade

The study explores the tectonic integration of a distributed computer network and the façade of a high-rise tower through the use of ETFE cushions, exploiting the soft nature of this material to embed a sensor network to provide touch responsive changes of opacity in the façade (Daniel et al., 2009)

Figure 5.6: Main components of a responsive ETFE façade(Daniel et al., 2009)

This system is proposed to integrate the existing electrochromic systems into an ETFE cushion. To activate the electrochromism procedure, an air-pressure sensor is installed. The schematic information of first prototypes are shown in figure 4.13.

Figure 5.7: Schematic section of the façade, detail and front view of a sensor’s node(Daniel et al., 2009)

5.5 Tungsten Trioxid coating on ETFE

The Fraunhofer institute for solar energy systems (ISE) has also developed a specific coating for ETFE foils. This coating is able to change the light and heat permeability of an ETFE foil and correspondingly an inflated ETFE cushion. The coating is based on a Tungsten Trioxide substance and can be darkened in presence of hydrogen and back into clear while oxygen is pumped in the cushion (Schröder, 2011)

6. Prototyping

6.1 Case definition

Based on the conclusion made in section 4.4, for reaching the decided target zone(Zone H, see Figure 1.1) shading system is chosen to be applied in an ETFE cushion. Integration of Electro optic films into the inner space of a cushion, shapes the core of this research. To define the proposed solution for creating a solar radiation control system, the following table uses the Velasco et al. (2015) classification (Figure 4.5).

Table 6.1: Case definition

Case definition	
Building façade	• Roof; • Triple layer ETFE cushion.
Climate zone	• Moderate zone; • Oceanic climate(Cfb); • Stuttgart.
Movement system	• Material based; • External input; • Electricity.
Control system	• Local; • Direct.
Relative physics	• Daylight; • Solar control; • Energy gain.

The chosen climate zone for the tests is moderate climate zone which is an ideal environment for an adaptive façade. This climate is characterised by a seasonal variation between the need for solar heating and the avoiding of overheating, which creates an attractive situation. In this specific case of adaptation, solar protection and potentials of energy gain is aimed. Since the majority of ETFE applications in urban zones are commercial buildings, city of Stuttgart is a proper representative for the tests.

Having control over thermal and optical domains, is the most logical way of increasing building's performance and lower energy use. Achieving such adaptation, decreases the HVAC cost in all aspects of infrastructures, maintenance and annual energy consumption. Solar heat and daylight control are both dependent to radiation exchange rates(transmittance,reflectance and absorbance) of a façade. Therefore the most efficient approach is to define the influential spectrum ranges, and direct the design and material choosing process based on an efficient combination.

A good design has several factors to be taken into account. Following table demonstrates the key principles in design of the prototype.

Table 6.2: Design aspects

Design aspects	
Standardisation	● Easy to design for different buildings ● Expandable without fundamental changes
Functionality	● High energy efficiency and low ecological footprint ● Proper visual aspects for different architectural desires
Weather resistance	● Good durability against different weather conditions ● An acceptable lifetime
Economical	● To reduce the initial cost of fabrication and installation in comparison to available alternatives with same functionality ● To decrease the annual cost of energy consumption and maintenance
Simplicity	● User friendly systems ● Easy to maintain and repair
Comfort	● Minimal movement noise ● Uniform visual light transmittance
Maintain in target zone	● Provide comfort zone for inhabitants, both in active and passive functionality

6.2 Material selection

ETFE is the most popular material in pneumatic structure applications. ETFE has a proper lifetime and a superior transparency in comparison to other inflatable membranes. Even Though ETFE has been a great option for lightweight and transparent roofs/façades, a new alternative with specific improvements is worth to be considered.

Halar® ECTFE (Ethylene Chloro Trifluoro Ethylene) is a true thermoplastic resin and can therefore be welded by conventional techniques known for common plastics such as PVC and PE, such as hot air welding etc.(Tonioloa and Carellaa, 2016).

Halar® ECTFE has a minor improvement in visual light transmittance value in comparison to ETFE, but shows a perfect improvement in Haze value, which has a notable impact on visual sight of inhabitants.

Table 6.3: ETFE and Halar® ECTFE visual comparison(Toniolao and Carellaa, 2016)

Foil in 250(μm) thickness	TT(%) measure in air	Haze(%) measured in air
Halar® ECTFE High Clarity	95.0	0.9
ETFE	93.8	9.2

Halar® ECTFE shows a better tensile strength with a similar elastic modulus to ETFE film. The module obtained with the tensile test at room temperature (23 °C) are equivalent to those from the DMTA test:

Table 6.4: ETFE and Halar® ECTFE tensile strength test(Toniolao and Carellaa, 2016)

Foil in 250(μm) thickness	DMTA	Tensile test
Halar® ECTFE High Clarity	1500MPa	1410MPa
ETFE	1010MPa	950MPa

Beside the great water vapor barrier properties of Halar® ECTFE, it also shows similar QUV-B aging test to ETFE films.

Table 6.5: ETFE and Halar® ECTFE water vapor permeability(AT 38°C AND 90% R.H.) (Toniolao and Carellaa, 2016)

Foil in 250(μm) thickness	Water vapor permeability P [cm3(STP)·mm/m2·atm·d]
Halar® ECTFE High Clarity	1100
ETFE	6600

Figure 6.1: ETFE film 250 μm

Figure 6.2: ECTFE film 250 μm

Figure 6.3 Halar® High Clarity ECTFE is being used for a covered walkway at Solvay Specialty Polymers' headquarters in Bollate, Italy

Based on the refined framework of material selection (Figure 2.10) , the following table for evaluating Halar® ECTFE films would be used.

Table 6.6: Halar® ECTFE material evaluation

Halar® ECTFE	
Material performance	• Show better physical properties than ETFE
Manufacturing	• Available in industrial production scale by Solvay company • Weldable by conventional techniques known for common plastics such as PVC and PE
Experience	• Recently introduced to the market and not many applications are available
Context	• Based on similarity to ETFE, the applications would be the same.

6.2.1 Electrochromic/-optic film

Conducting polymer materials have long been in focus because of the **low cost**, **fast preparing** process and remarkable electrochemical properties such as **short response time** and **high transparency**. Other available electrochromic materials in market are Electrochromic metal oxides with drawbacks such as slow switching times and poor coloration efficiencies (Yang et al., 2016)

For this specific research a Polymer Dispersed Liquid Crystal (PDLC) films was selected, because this electrochromic device consume little power in producing transparency which, once formed, require little input of power. Also in principle, there is no limit to the size and cut of a PDLC film. Aforementioned advantages make this material a suitable choice for long span cushions in different formations.

Figure 6.4: a) PDLC film Off mode, b) PDLC film On mode, c) Halar® ECTFE, 250 μm

Table 6.7: Technical data of tested electrochromic film

Technical Data> Material˅	Visual light transmittance	Haze	IR-blocking	UV-Blocking	Power dissipation
Self-adhesive PDLC film (On)	78.80%	5.8%	14.7%	42.2%	6-9 W
Self-adhesive PDLC film (Off)	6%	90%	30.2%	97.6%	

6.2.2 Spectrum analyser report

The purpose of this measurement is to achieve a reliable data for analysing the integration of Electrochromic films into pneumatic cushions. In this report 6 different combination of ECTFE and Electrochromic films are tested, as single elements and in combinations, representing the vertical layout of Pneumatic cushions.

The spectrum analyser logged in the wavelength data in range of 200-2500 nm, covering “UV-B & UV-A”, “Visible Radiation”, “IR-A & IR-B”. Spectral Transmittance in wavelength (Tλ) and Spectral Reflectance in wavelength (R λ) were measured, and Spectral Absorbance in wavelength (Aλ) is calculated with approximation.

Figure 6.5 a) & b) PDLC electrochromic device at spectrum analyser test, ILEK

In following the graphs of all abovementioned variables are shown in particular charts for easy understanding of materials behaviour in different layouts and modes.

Figure 6.6 Spectral behaviour of a single layer Halar® ECTFE, 250 µm

Figure 6.7 Spectral behaviour of a double layer Halar® ECTFE, 250 µm

The spectral behaviour of a single layer Halar® ECTFE is close to the data sheets provided by Solvay company. The foils show a high transparency with a very low absorption rate in visual light range.

Figure 6.8 Spectral behaviour of a PDLC film, On mode

Figure 6.9 Spectral behaviour of PDLC film, Off mode

A single layer of tested PDLC film in On mode has a proper visual light transmittance of almost 82%. In contrast, the spectral behaviour of the same film in Off mode shows less than 4% visual light transmittance and a high blocking characteristic in all spectral ranges.

Figure 6.10: Spectral behaviour of integrated PDLC(On Mode) film into a double layer ECTFE film

Figure 6.11: Spectral behaviour of integrated PDLC(Off Mode) film into a double layer ECTFE film

To simulate the most common triple layer cushions, two Halar® ECTFE films and a PDLC film as the middle layer was also tested. The results show a high spectrum blockage performance in Off mode and an acceptable visual light transmittance in On mode.

5.3 Roof enclosure test preparation

A triple layer prototype of integrated electrooptic film in an ETFE cushion was designed to be tested in real conditions. The ‘Roof enclosure test simulates the installation of the prototype as an exposed roof (Figure 5.9). To investigate the functionality of prototype in detail, both U-value and Spectrum behaviour of the sample was analysed.

Figure 6.12: a) Roof enclosure test at ILEK, b) Triple layer ECTFE, Off mode, c) Triple layer ECTFE, On mode

The dimensions of roof enclosure test at ILEK make a size limitation for specimens. The height of specimens shouldn’t exceed 16.9 cm and both width and length are limited to 82.9 cm. Because of fixation and insulation challenges for fitting an inflatable cushion inside the roof enclosure test, the surface of ETFE foils was decided to be flat. To represent the sag of a pneumatic cushion with 72x72 cm dimension, 9% of the specimen’s length (6.5 cm) is considered as the gap between middle and outer layers of ETFE foil.

Figure 6.13: Specimen inside roof enclosure test box, Side section

On each layer 4 thermocouples are installed. Two on each side of their surface with a constant pattern (Figure 6.17)

Figure 6.14: fixing thermocouple sensors with help of guidelines

Figure 6.15: a) Outer ETFE frame b) Middle ETFE-PDLC frame c) Inner ETFE frame

For applying the middle electro-tropic layer, ETFE foil is decided to be the adhesive base of PDLC film, since PDLC films are not qualified as load-bearing elements in pneumatic cushions.

Figure 6.16: Applying PDLC film on ETFE foil

This specimen is able to turn On and Off with a 60v supplier which provides 6-13 W of electric power. The adaptor can cover up to 5 m^2 of PDLC films with a response time less than 0.2 s.

Figure 6.17: PDLC film supplier

Figure 6.18: a) Specimen turned Off, b) Specimen turned On

7. Conclusion and discussion

’’It is more fun to arrive a conclusion than to justify it.’’
-Malcolm Forbes-

We believe by utilizing controllable shading functionalities and using **Halar® ECTFE** we can improve this type of facade both in terms of building physics and User Experience. Building physics will be affected, while solar control system lowers U-Value and prevents radiation exchange. User Experience is improved because inhabitants are no longer exposed to direct sunlight and also they can have privacy and shading when desired. **Adaptive ETFE** is a responsive cushion which consists of an integrated Electro-troptic film layer that corresponds to its environment in benefit of insulation,solar control, comfort level and user experience for inhabitants. While these functions will be controlled by sensors and softwares that optimize building energy consumption, we also consider the ability of local control as means of overriding presettings and making privacy. For the future development we consider energy harvesting as a milestone In specific conditions such as Intense sunlight or a warm summer day (see figure 6.1).

Figure 7.1 concept of harvesting heat in Adaptive ETFE

There are already several adaptation systems for enhancing User Experience and energy efficiency of ETFE facades. Table 6.1 brings various aspects of these systems together, which makes comparison of existing adaptations with our suggested method easier.

Table 7.1: Adaptive ETFE and available adaptations in market

	Adaptive ETFE	Air Pressure-Print	Tungsten Trioxid coating on ETFE[1]
Transparency	High	Low	High
Activation	Electricity	Electricity & air pressure	Air pump, Oxygen & Hydrogen
Control	Local and Central	Central	Central
Energy Consumption	6W	Depends on cushion inner pressure	100W(without Oxygen and Hydrogen purifier)
Response time	<0.2s	20s	30s-1min.
Color Scheme	5	1(same as print)	1(dark blue)

In comparison to available adaptation systems in ETFE market, **Adaptive ETFE** is/has:

- **Low response time**
- **Expandable** without fundamental changes
- **Energy efficient** with low ecological footprint
- **Proper visual aspects** for different architectural desires
- **Easy to maintain** and repair

The current Liquid Crystal based EO devices used in **Adaptive ETFE** have 10 years of lifetime with the manufacturing price of 80 € /m^2 , also available in various cuts and colors. The ongoing researches on the lifetime of EO devices and possible reductions in their manufacturing cost would directly affect the potential of **Adaptive ETFE** in the market.

Another drawback of alternative adaptation systems which activate with air pressure is that more than 85% of the electrical energy input to an air compressor is lost as waste heat, leaving less than 15% of the electrical energy consumed to be converted to pneumatic compressed air energy (U.S. DOE-ITP EM, 2008).This makes compressed air an expensive energy carrier compared to other energy carriers. The technology used in **Adaptive ETFE** offers the opportunity of less energy loss and maintenance in comparison to air pressure.

[1] Fraunhofer institutional collaboration, 2011

8.Vision

"The best way to predict the future is to create it."
- Alan Kay-

Micro-algae production affects the future of economic viability and environmental sustainability, which lowers environmental impacts and production cost. It is worth to mention air purification characteristics of micro-algae's synthesis. Micro-algae can absorb an enclosed space carbon dioxide and provide refreshing oxygen instead. The algae pads – which are considered in the next generation of Adaptive ETFE concept (See figure 19) – have up to 40% solar gain efficiency which in comparison to current renewable energy systems are noteworthy(Arup Group,2013).

Figure 8.1: Concept of integrating Electro-Optic devices and Biomass production in pneumatic cushions.

Our next step is to develop a multi functional middle layer system for membrane cushions to selectively control a range of radiation transmission to keep building in its comfort-zone. We call these cushions: Adaptive Membrane Cushions (AMCs). In this step we focus on integrating Energy Harvesting systems within AMCs to enhance a facade's energy harvesting potential in form of Heat or Biomass. Besides Electro-optic materials, Micro-Algae pads will be embedded in AMCs. Micro-algae have received considerable interest as a potential feedstock for producing sustainable transport fuels (biofuels).

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