Structural Adaptive Façades

Chloë Marysse

Supervisor: Prof. dr. ir.-arch. Jan Belis
Counsellor: Bert Van Lancker

Master's dissertation submitted in order to obtain the academic degree of
Master of Science in Civil Engineering

Department of Structural Engineering
Chair: Prof. dr. ir. Luc Taerwe
Faculty of Engineering and Architecture
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Preface

The rapidly changing climate and the growing population present science and engineering major challenges to save energy. A direct result is the increasing popularity of low-energy buildings during the last decades. Buildings are responsible for a considerable part of the global energy consumption, which explains this growing popularity. More sustainable designs may contribute to lower the negative impact of buildings on the climate. Up till now, active technology was the most popular approach to save energy in buildings. However, passive design strategies possess also fundamental advantages to develop low-energy buildings. Efforts to lower the energy use by focusing on the construction and the shape of a building have already resulted and will further result in promising energy efficient and aesthetic applications.

By continuously changing their configuration, structural adaptive façades ensure a better building performance. The flexibility in the systems allows to maintain a good performance over time by anticipation and reaction. The façade is no longer seen as just a static barrier that separates the interior building environment from the external one. In contrast, the façade becomes a dynamic playground to optimise between energy objectives and occupants' wishes. Clever and creative thinking and designing allow to realise beautiful pieces of architecture that contribute to the lowering of the total energy use of the building.

Acknowledgements

During the year, I worked on the accomplishment of this thesis with a high interest and fascination for the subject. At the realisation of this thesis many people, both directly and indirectly, contributed. I would like to use this word of thanks for their support and dedication.

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Finally, I am very thankful to my dad, Ferdy Marysse, for his continuous support and creative ideas. He also took the time to read my thesis and to give helpful comments which had a final positive influence to the end-result.

Permission for usage

June 1, 2016

Chloë Marysse

Overview

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Summary

Structural adaptive façades are worldwide a rather unknown subject but in architectural surroundings a lot of knowledge and structures are already available. Notwithstanding, most of this knowledge is only applied on a small scale and for specific projects. A lot of opportunities exist to further broaden this subject to a larger application scale and to develop new potential prototypes. The main aim of this thesis is to provide insight in the application and design of structural adaptive façades, and to use this knowledge in the development of innovative prototypes.

In the first part of the thesis, an extensive literature research is done to understand the possibilities of combining transformable structures with façade applications. Research about the different types of transformable structures is followed by the studying of façade structures. In a third part, both aspects are integrated to obtain a clear view over the design of adaptive façades. During this research, several case studies were analysed to gather knowledge about which current applications already exist and which shortcomings offer opportunities for the design and improvement of future creations. These case studies also provide a better understanding of the working principles of structural adaptive façades.

The second part is focused on the design of new promising structural adaptive prototypes. A first prototype faces the current energy problem with the emphasis on the intelligent application of photovoltaic cells. The adaptability is used to provide both a higher energy efficiency and better shading control. The design is characterised by its simplicity and functionality. A second prototype approaches the balcony as a dynamic feature of a curtain wall façade. A double using principle arises from the complete transformation between a balcony and a perforated screen. The design decreases the primary energy use of the building by its positive influence on glare problems, overheating and ventilation. The prototype facilitates an improved aesthetical appearance and allows more architectural freedom. In addition, the prototype permits local control according to the users' wishes.

Keywords

Sustainable building, transformable structure, adaptive façade, photovoltaics, dynamic balcony

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Abstract – **This paper presents the implementation of structural adaptive façades as a clever and aesthetic solution to lower the energy footprint of a building. An overall review of the current knowledge and applications is given, followed by the design of two new adaptive prototypes.**

Keywords – **Sustainable building, transformable structure, adaptive façade, photovoltaics, dynamic balcony**

I. Introduction

The prevalent climate change faces science and engineering with increased challenges to save energy. Buildings are responsible for approximately one third of the world's energy use, which makes them an attractive area to concentrate on. More sustainable building designs may contribute to lower the negative impact of buildings' energy consumption on the vulnerable climate.

Triggered by the need for more low-energy buildings, structural adaptive façades win in recognition as they present aesthetic and economic solutions. These flexible systems break with the traditional use of the façade as a static barrier that separates the internal and external environment. In contrast, the façade becomes a dynamic playground to make a compromise between energy objectives and occupants' wishes.

The subject of structural adaptive façades is - apart from in architectural surroundings - not widely known. Most of the knowledge is applied on specific and unique projects. A lot of opportunities exist to improve future designs and to broaden this branch of architecture to a larger application scale.

II. Literature review

A good understanding of the current knowledge about structural adaptive façades is essential to understand the present shortcomings and/or opportunities to develop new innovative adaptive solutions. The literature review concentrates on the different types of transformable structures and the contemporary knowledge about advanced building façades. Both aspects are integrated to obtain a clear view on the design of adaptive façades.

A. *Transformable structures*

Adaption and reaction to changing circumstances are only possible with the application of transformable structures. Therefore, a clever designed deployment system, based on controlled movement, is necessary. A wide range of possibilities exists to create these structures. However, not all systems are suited for façades. For building purposes, lattice structures combined with flexible membranes or rigid plates can provide stable and lightweight solutions. A good consideration of the used actuators and locking systems is important to make a fluent deployment possible.

B. *Building façades*

More sustainable buildings originate from the use of advanced façades accommodated with a lower total life cycle cost, decreased environmental impact and increased internal comfort. The façade, as the envelope of the building, permits to lower the impact of environmental changes in an effective way.

Two major types of façades exist: curtain walls and double façades. Both can contribute to a more optimal thermal comfort. Curtain walls have high qualities in influencing daylight control and energy gain. The strong aspects of double façades are the capacity for natural ventilation and acoustic control. Double façades have the disadvantage of higher costs and a higher loss of useful building space. A curtain wall is better suited for the high position of the sun on the south façade, due to its potential for horizontal shading systems. In contrast, the double façade is more appropriate for the east and west façade, because the lower position of the sun requires vertical shading systems.

The higher initial cost, required for the construction of these façades, is compensated by the lower energy use of the building during its life cycle. A current shortcoming of most façade applications is the strict focus on only one (or two) comfort increasing parameters, mostly solar control. A higher influence on the energy balance may be achieved by concentrating on different building physics integrated in one clever design.

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Different geographical locations have different climate characteristics and other primary requirements. Adaptive systems are most suited for the moderate climate zone, as a consequence of the seasonal variation between the need for heating and the protection against overheating. In addition, adaptive systems can be efficient for (sub)tropical zones as well by providing solar shading and natural ventilation. In contrast, cold and polar zones require less adaptivity due to their primary need for solar heating.

C. *Adaptive façades*

An envelope that uses flexibility to actively regulate the indoor conditions, is one of the effective solutions to increase the energy efficiency of a building. In this line, adaptive systems with a mechanic based movement principle hold endless possibilities. Rotational, translational and even hybrid systems are possible. Extrinsic control of these adaptive systems possesses the quality to combine (central) automated strategies with local control and individual user needs.

The domain of adaptive façades is far from saturated and mature. Most current adaptive systems focus on thermal and/or optical aspects. The amount of applications that focus on the domain of energy gain is rather small. This offers considerable opportunities for the development of new promising photovoltaic building applications. The biggest challenge is to make the systems cost efficient and to combine creativity with simplicity and standardisation to facilitate their design.

III. Creating New Prototypes

Based on the knowledge acquired during the literature review, the noticed shortcomings and their opportunities are used to elaborate two designs of prototypes with a future potential.

A. *Prototype I: A photovoltaic solar shade system*

Structural adaptive façades that emphasise the smart application of photovoltaic cells in building façades are currently present to a lesser extent. However, these cells possess the quality to improve the overall building performance.

The first prototype, 'A photovoltaic solar shade system', couples the principle of solar shading and energy gain with the conservation of good exterior views. The design focuses on providing shadow during summer and the allowance of sun entering during winter, according to the seasonal variations in a moderate climate. A model of this prototype can be seen in Figure 1.

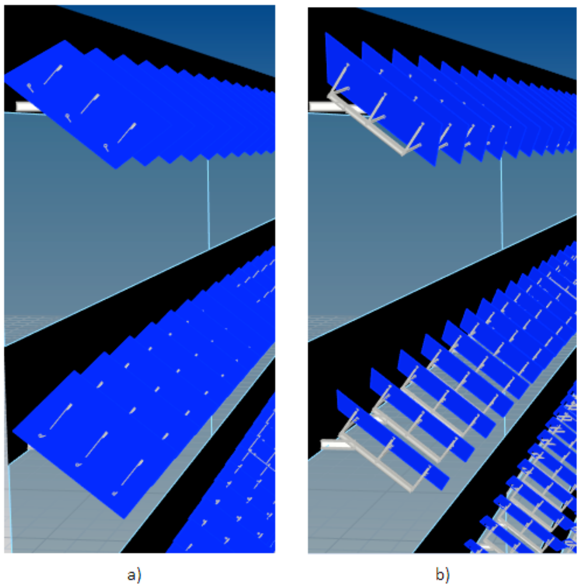

Figure 1: Panels: a) turning west, b) turning east

To gain energy, photovoltaic cells are necessary. The current photovoltaic market is already widely developed. Different cell types exist that make both rigid and flexible designs possible. The main difference is related to their energy efficiency. For building applications, space efficient cells are necessary which results in the choice for mono- and polycrystalline PV cells. Secondly, the use of rigid panels is preferred to flexible membranes to provide a good durability and resistance against weather conditions. Rigid panels are moreover easier to keep stable during deployment.

The adaptability of the prototype is presented by the tracking of the sun during the day. By making it possible for the panels to follow the path of the sun, the solar incidence angle on the cells is optimised. A thorough research resulted in a sustained choice for an east-west tracking system on the south façade of the building. The efficiency can further be improved by tilting the panels to a fixed angle from horizontal to capture the sun optimally during the whole year. In Belgium, this optimal tilt is 38 degrees.

The combination of east-west tracking with an optimal inclined rotation axis results in a considerable increase in power output of the photovoltaic panels. Depending on the power output of the implemented PV panels, the system - integrated on the south façade of every storey - may be able to generate about one fifth of the total energy consumption in office buildings in case of a ground surface equal to 100 square metres. By limiting the tracking of the panels to only one degree of freedom, the system is kept simple while the improved efficiency stays high.

A major problem of photovoltaic panels is the lowered energy output due to shadow problems of neighbouring panels. By limiting the tracking angle to 30 degrees east and west, and by making use of bypass diodes, the energy output can be kept high and the losses due to shadow negligible.

To make the adaptive prototype not only functional but also aesthetically attractive, frameless panels with glass sheets provided at both sides of the photovoltaic cells are used. This laminated module is combined with a lightweight aluminium carrier system at the back. Adhesive point fixings realise the connection between the photovoltaic module and the aluminium system.

The simultaneous movement from east to west (and backwards) of the panels can be achieved by a push-pull system with steel bars and a gearing wheel. This tracking system can be foreseen close to the wall of the building to maintain an elegant façade and to facilitate an easy placement.

B. *Prototype II: A perforated balcony screen*

The second prototype, 'A perforated balcony screen', approaches the balcony as a dynamic feature of a curtain wall façade. From the complete transformation of a perforated screen (in front of the transparent glazing) to a balcony, a double using principle arises. This multi-ability is illustrated in Figure 2. The dynamic balcony permits the inhabitants to use the flexibility of the system according to their individual needs. An aesthetically pleasing façade, both from an inside and outside viewpoint, originates from the creative implementation of a perforated curtain wall.

The design offers architectural freedom for original and creative aspects with a different appearance. This freedom is firstly present in the used patterns, colours and finishes for the perforated screen. Secondly, the mounting freedom of the structural placement of the curtain wall also creates different possibilities for the overall appearance. In addition, the dimensions of the balcony can be chosen within some ranges, taking functionality and safety in mind.

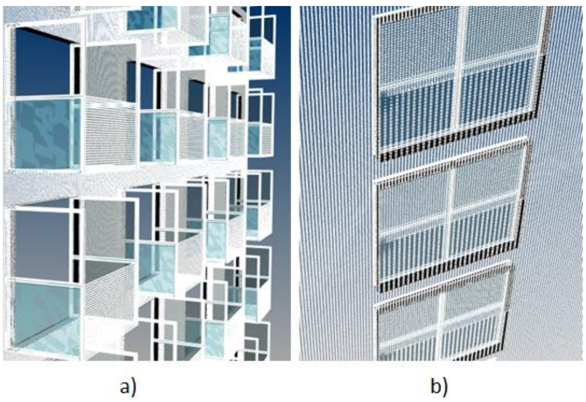

Figure 2: Double principle: a) balcony, b) perforated screen

The double principle decreases the primary energy use of the building by its positive influence on different aspects. Firstly, the perforated screen protects the internal environment against overheating by partially blocking the sun. Besides that, it lowers glare problems, reduces wind loads and offers more privacy. On the other side, the balcony creates extra useful building space and allows natural ventilation.

The folding balcony is most suited for moderate and (sub)tropical areas. These zones can highly profit from the protection against overheating and the maximum natural ventilation to lower the building's total energy use.

The transformation between the two functional options can be realised by the application of two moving principles. Firstly, the rotation of the lower part of the perforated screen in combination with the translation of the upper part. Secondly, the rotational movement of the two window wings along their side (Figure 3).

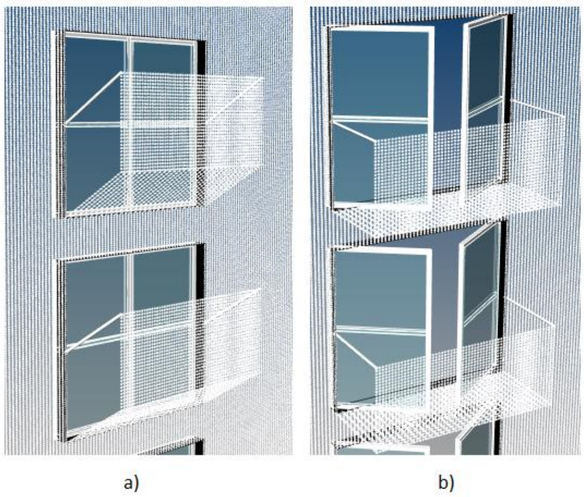

Figure 3: Transformation principle: a) unfolding screen, b) opening windows

For the screen, perforated steel is most suited to provide enough strength and stiffness for the balcony floor and the balcony parapet. The sides of the balcony are formed by the opened windows which exist of a strong steel frame connected to the glass panes with glued joints. Both the screen and window can be locked to each other in opened position. This connection makes the force transfer through the windows possible.

IV. CONCLUSION

The current changing climate triggers the increased interest to study the contribution of the building's façade in the design of low-energy buildings. Structural adaptive façades use flexibility to adapt and react to changing conditions. This with the purpose to enhance the quality of the building environment and to improve the energy balance. By focusing on several building physics and design aspects, new promising prototypes arise that may contribute to a more sustainable building.

Every design differs completely and has its own specific challenges that ask for an elegant solution. A careful, scientifically based analysis along with creative, gradually developing concepts and meticulous calculations may contribute to an improved building performance and internal comfort on the same time.

V. Future

A lot of applications already exist, but the domain of adaptive façades remains far from saturated. By considering different building physics, multiple opportunities are present to create new promising designs.

The two developed prototypes in this paper require application-specific and context-dependent calculations to further optimise their design.

Furthermore, there is a lack of monitoring and evaluating the performance of adaptive façades. New simulation tools and whole-life evaluation methods should be developed to judge the often challenging adaptive designs.

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Contents

List of abbreviations

a-Si	Amorphous silicon
BIPV	Building-integrated photovoltaic
CABS	Climate adaptive building shells
CC2	Consequence class 2
CdTe	Cadmium Telluride
CIGS	Copper Indium Gallium Selenide
CO_2	Carbon dioxide
DCMS	Deployable closed-membrane structure
DDC	Developable double corrugation
ETFE	Ethylene tetrafluoroethylene
EVA	Ethylene-vinyl acetate
GCR	Ground cover ratio
HVAC	Heating, ventilation, and air conditioning
IGU	Insulated glass unit
ISA	Instantaneous screw axis
LED	Light-emitting diode
LTR	Length-to-thickness ratio
Mono Si	Monocrystalline silicon
NURBS	Non-uniform rational basis spline
Poly Si	Polycrystalline silicon
PTFE	Polytetrafluoroethylene
PV	Photovoltaic
PVB	Polyvinyl butyral
PVC	Polyvinyl chloride
SLE	Scissor-like element
SLS	Serviceability limit state
ULS	Ultimate limit state
UV	Ultraviolet

List of Symbols

Remark: The units are listed below corresponding to the SI-units. In the text, the unit will often be switched to decimal multiples of the unit in question when these are more suitable for the order of magnitude of the results.

Greek Symbols	Description	Unit
α	Tilt angle from horizontal	[°]
β	Tracking angle (from south to east or west)	[°]
β_e	Effective porosity	[-]
γ_M	Material safety factor	[-]
$\gamma_{M;A}$	Material partial safety factor for annealed glass	[-]
$\gamma_{G,j}$	Material partial safety factor for permanent load j	[-]
$\gamma_{M;v}$	Material partial safety factor for surface prestress	[-]
$\gamma_{Q,i}$	Material partial safety factor for variable load i	[-]
λ	Sun's inclination from horizontal	[°]
μ	Snow load form coefficient	[-]
ρ	Air density	[kg/m³]
σ	Normal stress	[MPa]
σ_x	Normal stress in x-direction	[MPa]
σ_y	Normal stress in y-direction	[MPa]
τ	Shear stress	[MPa]
τ_y	Shear stress in y-direction	[MPa]
τ_z	Shear stress in z-direction	[MPa]
ψ_s	Shelter factor	[-]
ψ	Load combination factor	[-]
ω	Coefficient for interlayer contribution to laminate stiffness	[-]

Lower-case Latin Symbols

b	Width of the PV panel	[m]
c_{dir}	Directional factor	[-]
c_f	Wind pressure coefficient	[-]
$c_{p,net}$	Netto wind pressure coefficient	[-]
c_{prob}	Probability factor	[-]

c_r	Roughness factor	[-]
c_{season}	Seasonal factor	[-]
c_0	Orography factor	[-]
d	Distance between turning tube and PV panel	[m]
$d_{m,i}$	Distance between centre of gravity of layer i and median plane of laminate	[m]
$f_{b;k}$	Characteristic bending strength	[MPa]
$f_{g;d}$	Design strength of glass	[MPa]
$f_{g;k}$	Characteristic strength of glass	[MPa]
f_{yd}	Design yield strength	[MPa]
f_{yk}	Characteristic yield strength	[MPa]
g	Self-weight/m²	[N/m²]
h_{eff}	Effective thickness	[m]
$h_{eff,\sigma}$	Effective thickness for stress checks	[m]
$h_{eff,v}$	Effective thickness for deformation checks	[m]
h_i	Thickness of layer i	[m]
k_{mod}	Modification factor for the load duration	[-]
k_v	Modification factor for the manufacturing process	[-]
l	Height of the panel	[m]
m_real	Distance needed over ceiling to floor area	[m]
p	Wind load	[N/m²]
q_p	Peak velocity pressure	[Pa]
q_k	Characteristic value of the load	[kN/m²]
s	Snow load	[N/m²]
s_k	Characteristic value of the snow load on the ground	[kPa]
$v_{b,0}$	Fundamental value of the basic wind velocity	[m/s]
v_b	Basic wind velocity	[m/s]
v_m	Mean wind velocity	[m/s]
x_real	Length cantilever arm	[m]
z_e	Reference peak height	[m]

Upper-case Latin Symbols

A	Profile area	[m²]
C_e	Exposure coefficient	[-]
C_t	Warmth coefficient	[-]
C_D	Drag force coefficient	[-]
E	Young's modulus	[MPa]
F_d	Design value load	[N]
$F_{tensile}$	Tensile force adhesive point fixing	[N]
G	Self-weight load acting on one adhesive point fixing	[N]
$G_{k,j}$	Characteristic permanent load j	[N]
H_1	Horizontal reaction force clamp 1	[N]
H_2	Horizontal reaction force clamp 2	[N]
I_v	Turbulence intensity	[-]
K_{FI}	Coefficient of class of consequence	[-]
M	Moment	[Nm]
M_1	Reaction moment clamp 1	[Nm]
M_2	Reaction moment clamp 2	[Nm]
N	Normal force	[N]
N_x	Normal force in x-direction	[N]
P	Wind load acting on one adhesive point fixing	[N]
$Q_{k,i}$	Characteristic variable load i	[N]
S	Snow load acting on one adhesive point fixing	[N]
S_{shear}	Shear force adhesive point fixing	[N]
V	Shear force	[N]
V_y	Shear force in y-direction	[N]
V_z	Shear force in z-direction	[N]
V_1	Vertical reaction force clamp 1	[N]
V_2	Vertical reaction force clamp 2	[N]
W	Resistance moment	[m³]

1 Introduction

The prevalent climate change triggers the growing need for measures with a positive impact on the global energy use. Buildings, both residential and commercial, are responsible for about one third of this total energy consumption. This explains that a focus on this research area is of great importance.

The façade is the envelope of the building that forms the interface between the indoor and outdoor climate. The total energy consumption of a building is mainly dictated by this interface. That is the reason why concentrating on this design aspect is important for the development of a sustainable building.

From an architectural point of view, the façade is the place where the architects can implement their creative ideas that will determine the aesthetic appearance of the building. From the engineering point of view, the façade is in the first place important for the influence of the design on the energy efficiency of the building. The combination of both the architectural and the engineering input will be the guidance for this thesis.

The conventional envelope is based on static designs that do not possess the flexibility to adapt and react to changing conditions. However, both the building's environment and the occupants' wishes are changing over time. This insight explains the growing interest towards adaptive façades. The building envelope is no longer seen as just a shield but as a surface that can control efficiently the energy balances. Adaptive façades add the fourth dimension of time - by implementing dynamic features - which is an underestimated aspect that receives up till now not enough attention in the building industry. To better understand the current state of adaptive applications, case studies are analysed. The investigated examples can be found in Appendix A. A large part of these examples are still quite complex and more research and experience is necessary to facilitate and improve future economic designs.

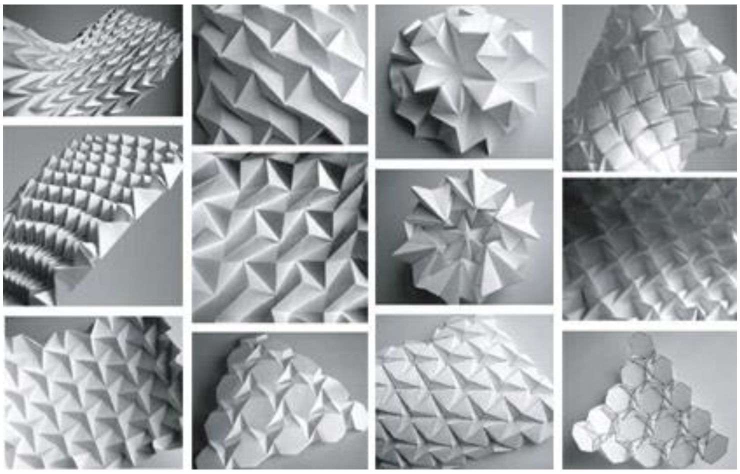
To create adaptive façades, transformable structures are needed. These structures are characterised by controlled movement during transformation, but result in static structures once the mechanism is locked in place. A good understanding of this type of structures is necessary to be able to develop smart and creative adaptive façades.

From this viewpoint, the following important research questions can be formulated for the literature study:

- What is the state of the art of transformable structures/building façades/adaptive façades?
- How can an adaptive façade be made with a transformable structure?
- Which type of transformable structure is best suited for an adaptive façade?
- Which type of façade is best suited for an adaptive façade?

The domain of designing adaptive façades possesses a wider range of solutions than only structural adaptability. The literature research will shortly mention the other possibilities but will focus on the structural domain in the issue of adaptive façades. In this line, the accomplishment of the literature study about transformable structures, building façades and adaptive façades will be followed by a second part that will focus on the design of some structural adaptive prototypes. These prototypes investigate current shortcomings in existing applications with the purpose of a more sustainable building in mind.

PART I. Literature review



'Our design medium is behaviour itself. Elegance and economy remain the pre-eminent values of good design. An elegant mechanism translates a simple push or pull into rich and complex behaviour.'

- Chuck Hoberman -

TRANSFORMABLE STRUCTURES

2 Transformable structures

2.1 Introduction

Transformable and deployable architecture possesses unique opportunities. This kind of architecture aims for structures that are efficient, economic and elegant. The elegance of the structure is related to the transformation of the structure and its resulting behaviour. Changing behaviour due to transformations creates possibilities to design structures that are more aesthetically pleasing because of their exciting dynamics. The changing behaviour is often regulated by dynamic feedback from the environment or other types of smart technology. Control systems based on feedback are intelligent ways to change the physical properties of structures in an effective manner.

The dynamic behaviour makes it possible to improve the sustainability of structures. Transformable design is multidisciplinary. It contributes to create not only structures but also products and environments that change their size and shape. This adaptive, interactive approach is needed to deal with the current climate change. Transformable architecture may contribute in a creative way in the design of buildings to save energy and enhance the quality of the building environment.

The integration of adaptive elements in the design process requires mathematics, mechanics and structural engineering. Chuck Hoberman states that a process of transformation needs to respect three requirements to come to fluid responsiveness, adaptability and ease of use. These three aspects are a *complete and fully three-dimensional transformation* that is *smooth and continuous* and on the same time *reversible and repeatable*.

2.2 Definition

In literature, many different definitions are given for adaptive structures. There is often a lot of confusion to make a clear distinction between **adaptable, transformable and deployable** architecture (Figure 2-1).

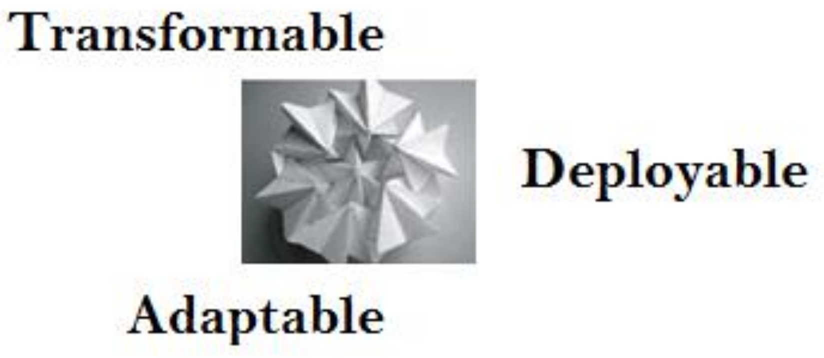


Figure 2-1: Adaptive structures

Adaptable architecture is described by Frei (2015) as a change of shape, change of location, change of utilisation or change of spaciousness. By change of location, he wants to indicate that the structure is mobile, easy to be transported and fast to be constructed and deconstructed. The basic principle that is used for the construction of adaptable architecture is the 'Lightweight Principle'. This principle relies on the optimal use of material and built mass (Möller & Nungesser, 2015). At present, it becomes more important to make optimal use of materials because of the increasing problem of running out of raw materials. De Marco Werner (2013) characterises adaptable architecture for buildings in her master's thesis as structures planned to be easily altered or modified to fit changing social functions (De Marco Werner, 2013).

In 1970, Zuk and Clark described kinetic architecture as follows: 'the architectural form could be inherently being displaceable, deformable, expandable or capable of kinetic movement' (De Marco Werner, 2013). The response of **transformable structures** or kinetic architecture in general needs to be efficiently tuned to boundary conditions such as climatic conditions, different locations, varying functional requirements or emergency situations. For this response an actuation force is needed that generates the movement. The type of transformation mechanism has a wide range of possibilities (from hinging, rolling till inflating). The transformation process goes from a compact to an expanded configuration or backwards. The transformation phase needs to consist of controlled, stable movements and results in a rigid and secure structure, once it is locked in place.

For **transformable structures** four dimensions are of importance. First of all, the three dimensional space is important. In addition to static structures, *time* is a determining design parameter because the structures are transformable over time (Bouten, 2015) (Temmerman et al., 2013). In most applications the transformable structure makes part of reversible and repeated architecture, which is characterised by a transformation in a non-destructible manner.

There exists no clear definition for a **deployable structure**. Deployable is a name that implies the transformation from a closed compact state to a final functional state, which is a predetermined expanded form (Hanaor & Levy, 2001). The main difference between transformable and deployable structures is associated to prefabrication. Deployable or prefabricated structures stand more or less for the pre-assembly of the entire structure in a factory and the deploying of the structure on site (De Marco Werner, 2013).

Although the differences between adaptable, transformable and deployable structures are not always clear, there is no doubt about their useful applications. Adaptive structures can be efficiently used for purposes as temporary spaces, climatic response in buildings and buildings with change of use.

2.3 Classification

To create a clear overview and to gain insight, making a classification in transformable architecture is necessary. In literature, a lot of classifications have been made. The choice of the classification system depends on which parameters are of predominant importance for the specific study. A very useful one, is the classification by Hanaor and Levy (2001) (Figure 2-2).

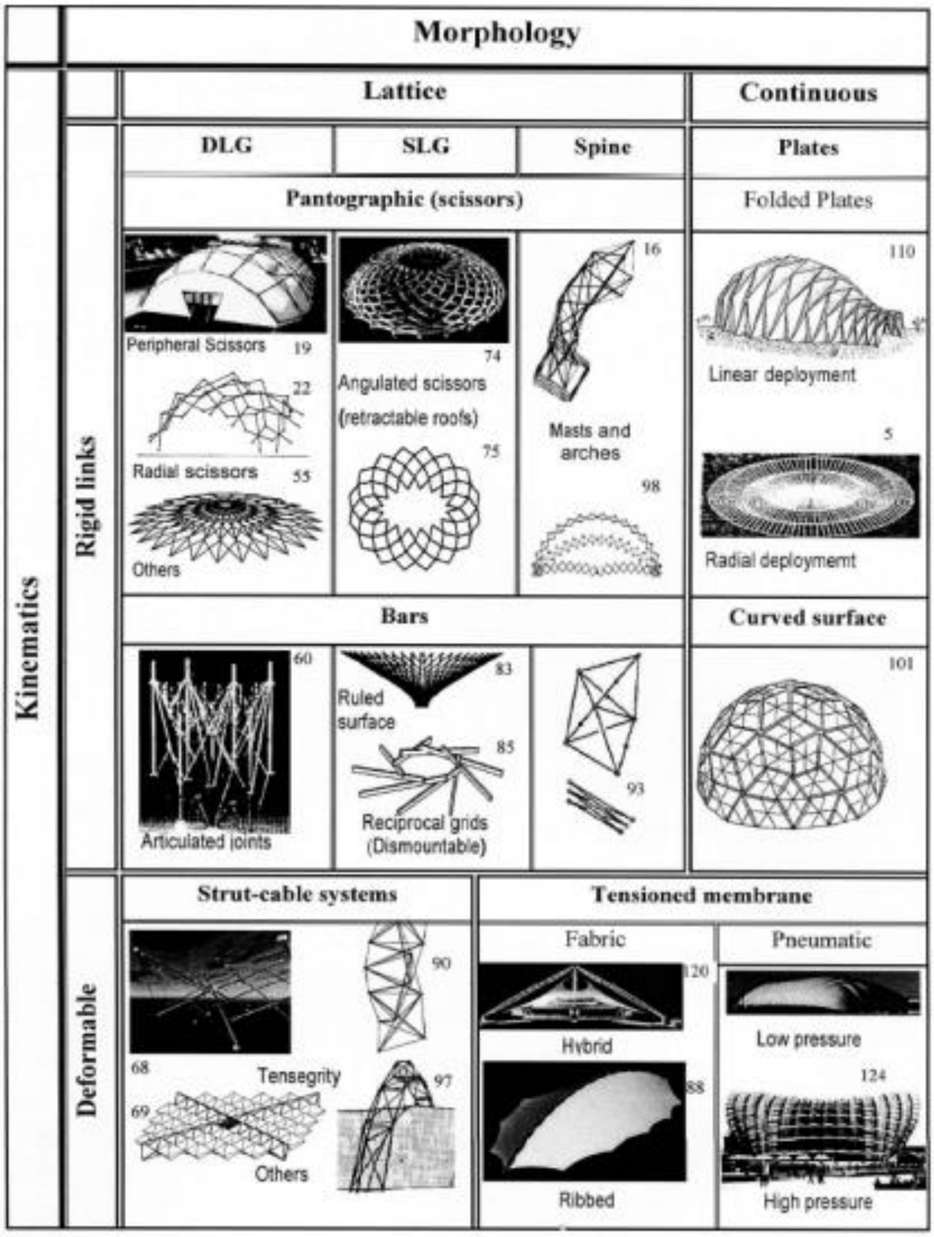


Figure 2-2: Hanaor classification system (Hanaor & Levy, 2001)

This classification is based on two main parameters: **kinematics and morphology** (structural-morphological properties). For transformable structures, morphological aspects are most important. They describe the way of deployment of the structure. In the master's thesis of Bouten (2015), a third parameter, *mobility*, is added to this classification. Mobility represents the degrees of freedom of the structure in case it is constructed of rigid link mechanisms. Considering the first parameter, the *kinematic* degrees of freedom that characterise a mechanism, two types of release are possible. A hinge, which results in a rotational degree of freedom, and a slide, resulting in a translational degree of freedom. The secondary parameter, *morphological* aspects, makes a difference in the elements that form the transformable parts of the structure. Each of the parameters is further subdivided into substructures. The kinematic subdivision is between **rigid links and deformable** components. The morphologic subdivision makes a distinction between **lattice (bar structures)** and stressed-skin structures, which are **continuous surfaces**. In lattice structures, the load-bearing structures are discrete members (bar elements), while in the continuous surfaces, the surface covering itself carries out the load-bearing function. A third possible class is the combination of both, resulting in **hybrid** structures.

Structures often need auxiliary permanent or non-permanent **supports** for their stability. If structures are stable without the use of a support, they are called dynamic, **self-erecting** structures. These structures are most interesting to apply in adaptive façades. Mostly, structures that have more degrees of freedom are more flexible and need to be stabilised to be able to carry loads. Curved surfaces are more resistant than planar structures. They can be subdivided in three important groups, the single curvature structures, double curvature structures and freeform structures. The single curvature structures are characterised by a zero Gaussian curve. Double curvature structures can be synclastic (positive Gaussian curve) or anticlastic (negative Gaussian curve). Freeform curved structures have much more flexibility compared to the previous two types. Typical known freeform curves are Bézier curves, B-spline curves or NURBS (Non-uniform rational basis spline) curves. The first ones are structural most easy and therefore most applied. The NURBS curves are the most complex of the three given examples (Susam, 2013).

Table 2-1 gives an overview of the different transformable structures that are explained in the following part.

Table 2-1: Overview transformable structures

Morphology **Kinematics**	Bar structures		Continuous surfaces
Rigid links	Pantographics Jitterbug-like linkages Bennett linkages Bricard linkages	Goldberg linkage Myard linkage Sarrus linkage Wren platform	Rigid origami
Deformable links	Foldable strut-cable systems Tensegrity		Curved origami Tensioned membrane structures

2.3.1 Rigid links – Bar elements

2.3.1.1 SLE's (Scissor-Like Elements) - Pantographic structures

Lattice bar structures (also called SLE's) are divided into three major types in the chart of Hanaor: the double-layer grids, single-layer grids and linear grids (masts or spines). Most scissor-like elements are foreseen of a cover layer. The grid, composed of bar elements, forms the primary load-bearing structure; contrarily to the covering, which forms the non-load-bearing surface. The interaction between the grid and the covering, both in deployed and undeployed state, is crucial. Scissor elements are often combined with flexible cladding components such as membranes as covering.

Scissor units, also called **pantographs,** are pivot-hinge structures. These mobile, deployable structures consist of hinged bars (Temmerman et al., 2013). A basic scissor unit is composed of two bars, interconnected by a revolute joint at the intermediate hinge point. This allows a free rotation of the bars around the axis perpendicular to the plane of the pantograph. Planar and spatial grids can be created by linking these units together. Scissor elements are subdivided into three groups (three basic unit types): *translational, polar and angulated* units (Figure 2-3). The subgroups are based on the shape and the placement of the intermediate hinges.

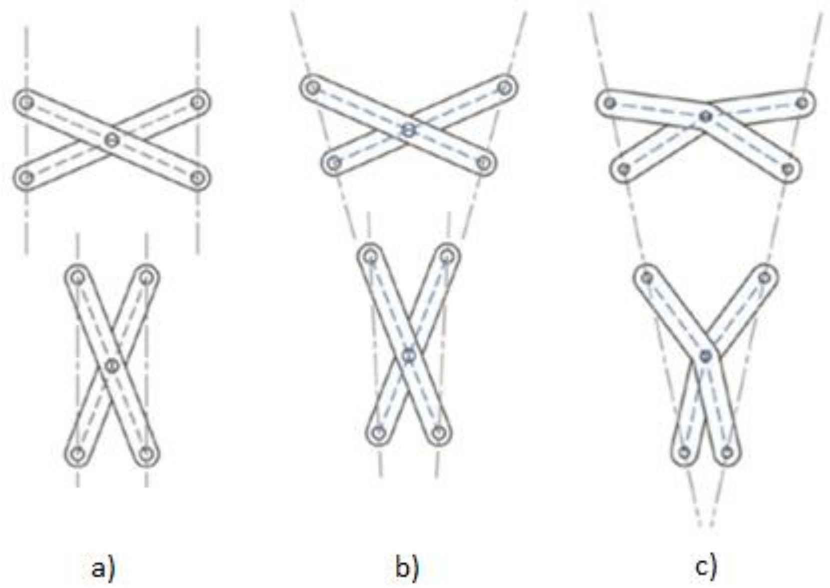


Figure 2-3: Basic scissor units: a) translational, b) polar and c) angulated (Web 2-01)

Scissor-like elements can deploy easily into space frameworks from compact bundles. The scissor units can be combined to form a polygon unit (triangle, square, hexagon) and these polygon units can be expanded to a connection network (Jung et al., 2015). When realising scissor-like elements, the position of the crossing of the bars often varies. Due to this variation, the homogeneity of the structure is lost and the internal transformation becomes heterogeneous.

With the use of many angulated and polar units, synclastic and anticlastic deployable structures can be made. When each side face of the base prism is formed by a pair of scissors, it is called a prismatic element. When pairs of scissors intersect at the centroid of the prism, it is called an anti-prismatic element. Peripheral scissors are composed of prismatic moduli. In contrast, radial scissors are composed of anti-prismatic structures and are less common (Hanaor & Levy, 2001).

The grid of scissor structures has in architecture the popular trend to form the network of the principal curvature lines. This creates a more efficient way of translating the forces that act on the structure (Bouten, 2015). Pantographs are in architecture often used in combination with a movable supporting structure, like struts, arches or frames. These are substructures which are permanent and can act as supporting system for the transformable structure (Susam, 2013).

For a successful deployment and folding, issues like the shape of elements, the type of material, the deployment behaviour, joint connections should be carefully considered. For the total performance, not only the structural performance in deployed and undeployed state is important but also the dynamic performance during transformation plays a major role (Umweni & Ianakiev, 2015).

2.3.1.2 Jitterbug-like linkages

Mechanisms that possess only one degree of freedom are called **Jitterbug-like linkages**. These mechanisms can transform from one polyhedron into a different one by using only one single process. Fuller was the first person who invented and created a Jitterbug mechanism. The polyhedron structure that he used was an octahedron. The Jitterbug transformation is not only applicable for an octahedron but can be applied to the different polyhedron groups. Most often, polyhedrons from the Platonic and Archimedean solids are used (Bouten, 2015).

The Jitterbug mechanism (Figure 2-4) is based on the screwing of the elements of the polyhedron along their ISA (instantaneous screw axis), normal to the plane of the elements. This screwing results in a closed spatial loop. Special care has to be taken to design the joints that link the facets of the structure together in a proper way. These joints remain the dihedral angle between the facets and may only allow a rotation of the facets in their plane. The rotation of each facet is opposed to the rotation of the adjacent facet (Bouten, 2015).

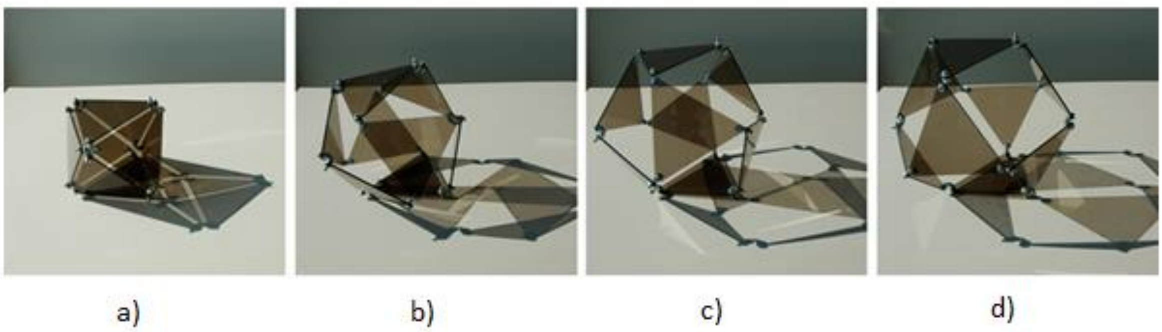


Figure 2-4: Deployment phases of a Jitterbug mechanism (Web 2-02)

There exists a wide range of variations of the Jitterbug mechanism. Important for the existence and applicability of these variations is the mobility. The linkages can only be mobile when the base polyhedron has an even amount of facets coming together at a vertex. A well-known variation originates from the use of double facets, resulting in so-called dipolygonids. The original idea of this structure was from a student of Fuller, Clinton. The double facets are connected in an alternate manner and result in more stable Jitterbug mechanisms. Another possibility is to subdivide the facets of the base polyhedron into smaller subfacets. Furthermore, offset elements are possible between the vertices of the facets. These offset elements eliminate the need for an even amount of facets at a vertex because the amount of elements around each vertex is doubled.

2.3.1.3 Linkages and platforms

Next to SLE's and Jitterbug mechanisms, **overconstrained linkages** are another application of rigid bar elements. These linkages all possess one degree of freedom and are connected by only revolute joints. The term overconstrained is related to the prediction of less degrees of freedom according to the Grübler criterion. Different types of these linkages are treated below.

Bennett linkage

This type of overconstrained linkage was invented by Bennett in the early 1900s. It consists of a closed loop of four elements that are connected to a mobile '4R linkage', resulting in a spherical mechanism. The four elements are connected by four revolute joints (Figure 2-5). To make the structure mobile, some geometrical conditions need to be satisfied between the axes of the bars and the revolute joints. Bennett linkages have some drawbacks: the placement of the joints is complex and furthermore these linkages are not able to fully close to a bundle or fully deploy to a flat surface (Susam, 2013).

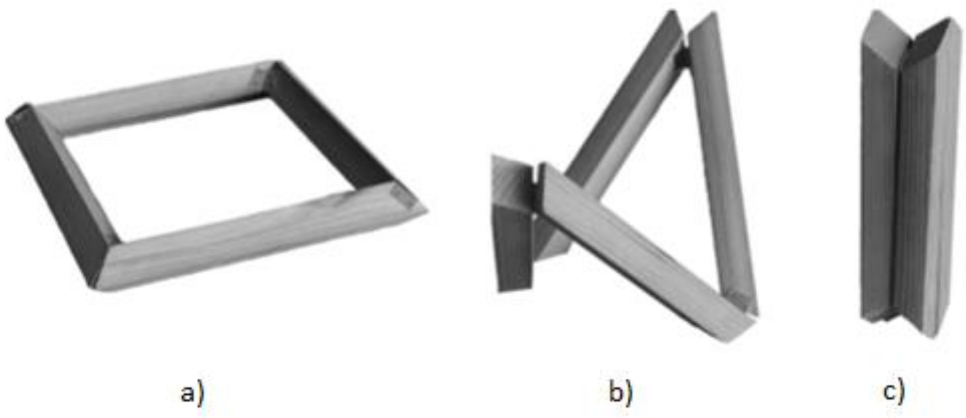


Figure 2-5: Bennett linkage: a) fully closed state, b) deploying state, c) forming a compact bundle of bars (Guest & Fowler, 2005)

Goldberg and Myard linkage

If two Bennett linkages are joined together and the shared redundant bar is removed, a mechanism with five bars and five revolute joints is generated, which is called a Goldberg linkage. The Myard linkage is a plane-symmetric variation on the Goldberg linkage. Myard linkages are very useful to make circular arrays (Figure 2-6) (Bouten, 2015).

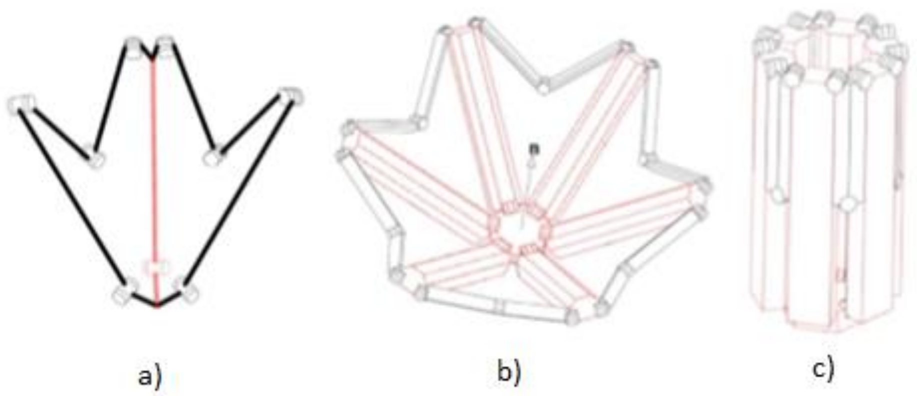


Figure 2-6: Array central connection of Myard linkages (Bouten, 2015)

Bricard linkage

Bricard broadens further with six bars and six revolute joints, also resulting in an one degree of freedom system (Figure 2-7).

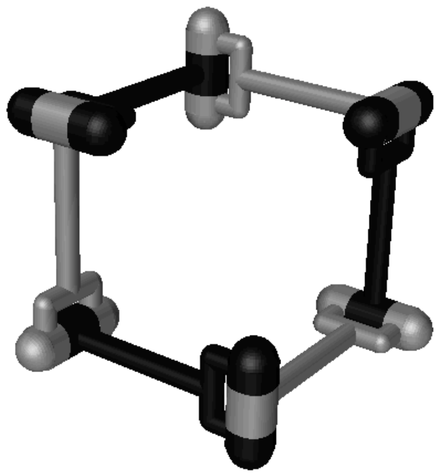


Figure 2-7: Bricard linkage (Web 2-03)

Wren platforms

A totally different structure from the linkages above is the parallel manipulator named Wren platform (Figure 2-8). This system makes use of spherical joints instead of revolute joints. The result is a moving platform that is connected to a fixed base. This can result in one degree of freedom but also two degrees of freedom mechanisms. The difference can be found in the legs that are skew or parallel to each other (Bouten, 2015).

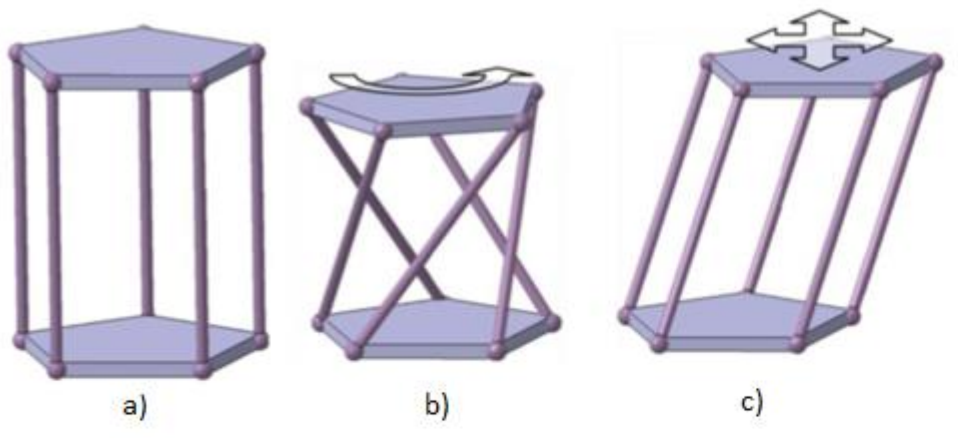


Figure 2-8: Wren platform: a) structure, b) skew legs, c) parallel legs (Bouten, 2015)

Sarrus linkage

Another parallel manipulator, invented by Sarrus, is very similar to the Wren platforms. The legs in the Sarrus linkage are built by two revolute pairs connected to the two bases (Figure 2-9). The axes that connect these legs may not be parallel and minimum two legs are necessary to make the mechanism work (Bouten, 2015).

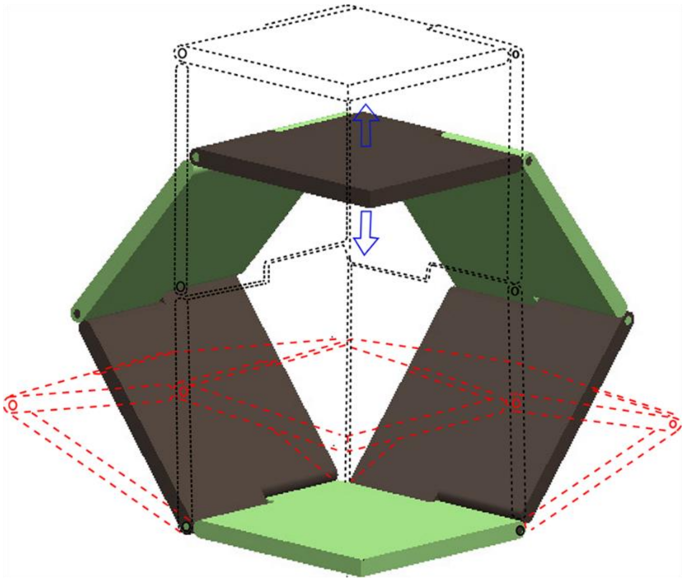


Figure 2-9: Sarrus linkage (Web 2-04)

2.3.2 Rigid links – Continuous surfaces

2.3.2.1 Rigid origami - General

The most well-known structures in the category of 'rigid links – continuous surfaces' are these inspired on rigid-foldable origami. The famous Abu Dhabi Investment Council (see Appendix A) is a solar shading system that is based on origami (Temmerman et al., 2013).

Rigid-foldable structures are also called 'foldable plate elements' or 'hinged plate elements' in literature. Rigid origami exists of strictly planar faces and only one degree of freedom, resulting from the use of straight lines. Folded plates are mostly based on a linear deployment which results in a high structural efficiency, but a high overall weight at the same time. The combination of a large structural efficiency with a foldability that offers flexibility, is a challenging combination. In addition, the foldability of these systems is influenced by the material's thickness (Hanaor & Levy, 2001).

Changing the relative in plane angle of the edges of the plate elements results in the kinetic movement of this system (Bouten, 2015). Because the rigid panels are both used as structure and as cladding, this type of structure is less labour-intensive and takes less time to set-up. In contrast, it is mostly less lightweight compared to scissor structures (Ohsaki et al., 2015).

The name 'origami' originates from the ancient Japanese art of paper folding. 'Ori' is the Japanese word for fold, 'origami' stands for paper-folding. In origami, tessellations or tiling patterns are used to make the mechanical behaviour possible. Tessellations are **geometric patterns** (Figure 2-11) that can repeat forever, which result in homogenous mechanical behaviour. Origami tessellations are constructed by Mountain and Valley folds. The kinetic behaviour results from the rotating, clock- or counterclockwise, of the plate elements around these folds (Bouten, 2015). Folding patterns can be optimised by placing the pattern along the principal moment lines in order to reduce forces and avoid peak stresses (Trautz & Cierniak, 2011).

Surface foldings (Figure 2-10) can be structured according to two main manners. Firstly, longitudinal folding is well-known. This process does not cut itself and is based on a lengthwise folding with constant edges. The second type is facetted folding. This type of folding exists of folding edges that cut themselves in points which results in facetted patches (Trautz & Cierniak, 2011).

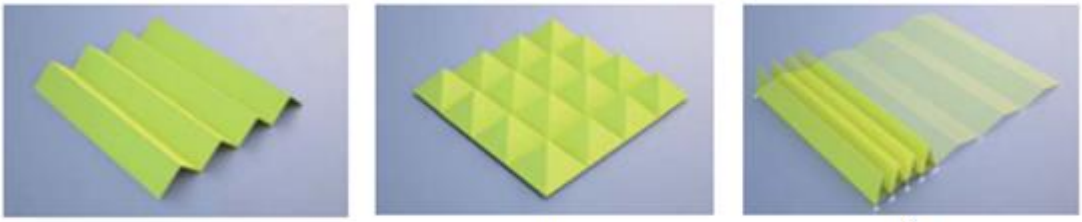


Figure 2-10: Surface folding: a) longitudinal rigid, b) rigid facetted, c) longitudinal kinematic folding (Trautz & Cierniak , 2011)

In some cases, supporting of the structure at some points is necessary to sustain the structure during the folding and unfolding process.

2.3.2.2 Tessellations

In the part below, some important patterns that are shown in Figure 2-11 are explained.

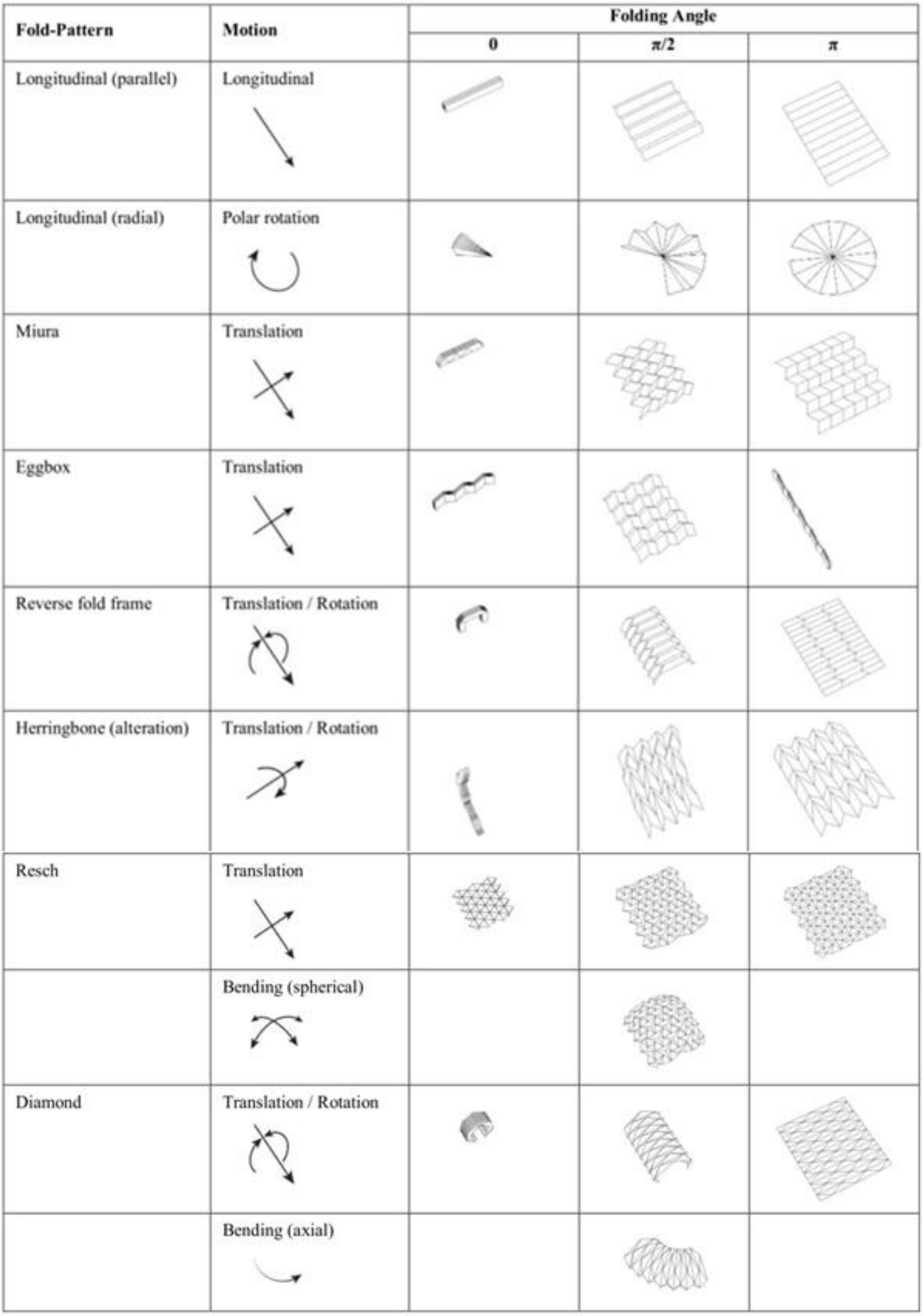
Miura-ori pattern

The most popular and widely studied example of Origami tessellations is the Miura-ori pattern, named after the Japanese inventor Miura. The advantages of this pattern are that it has only one degree of freedom and that it is compactly foldable. The pattern exists of interconnected quadrilateral plate elements. The basic, regular pattern has a planar geometry because it is based on identical parallelograms. It develops translational in two directions. The pattern has a negative Poisson’s ratio, resulting in a covered area that is larger than the area of the structure in completely folded state (Schramme et al., 2015).

Variations on the basic pattern are possible, resulting in singly or doubly curved geometries. Furthermore, it is possible to remove some of the facets of the pattern. Logically, only the facets that are not necessary for the deploying of the pattern can be removed.

Eggbox pattern

The Eggbox pattern is a variation on the Miura-ori pattern. This pattern has not the flat-foldable advantage of the Miura-ori pattern and has a positive Poisson’s ratio instead of a negative one. This results in a structure that is larger in completely folded state than the area meant to be covered (Schramme et al., 2015).



Fold-Pattern	Motion	Folding Angle		
		0	π/2	π
Longitudinal (parallel)	Longitudinal			
Longitudinal (radial)	Polar rotation			
Miura	Translation			
Eggbox	Translation			
Reverse fold frame	Translation / Rotation			
Herringbone (alteration)	Translation / Rotation			
Resch	Translation			
	Bending (spherical)			
Diamond	Translation / Rotation			
	Bending (axial)			

Figure 2-11: Folding motion of the most common patterns (Schramme et al., 2015)

Yoshimura pattern (Diamond pattern)

In contrast to the Miura-ori pattern, the Yoshimura pattern is based on triangular elements instead of parallelograms connected by hinges. Furthermore, one angle must be at least 90 degrees and all elements must have the same shape and equal apex angles. The most often seen surface with this pattern is singly curved; nevertheless doubly curved surfaces are possible as well. The Yoshimura pattern has, as the Miura-ori pattern, the advantage to be completely foldable. However, it is more complicated because it is characterised by more degrees of freedom. By increasing the number of folds, the load-bearing capacity of the structure increases. By increasing the apex angel, the clear width increases, but also the number of elements and the hinges (Ohsaki et al., 2015).

Resch pattern

The Resch pattern is named after the geometrist Resch. This regular pattern exists of triangular facets and typically has two degrees of freedom. It is characterised by two facet layers. The front layer exists of triangular facets that rotate around their normal axes through their centroid. The back layer is 'tucked in' between the front layers. The pattern not always exists of only triangular facets, but also square and hexagonal facets are often used (Bouten, 2015).

2.3.2.3 Remarks

The maximum compactness of continuous surfaces is in general much lower compared to a structure that consists of bar elements. In contrast, the distribution of forces can be very efficient, because the loads can be more spread instead of being locally concentrated.

Rigid-foldable origami is rather unexplored**.** A lot of problems, like hinges, plate thickness, waterproofing and compactness need further research. In general, the folding process of deployable surfaces is interesting for the active control of light; more research can be very promising. Furthermore, the influence of loads on the folded system and the different deployment states need to be examined. Also the material properties need further investigation. The demand for natural light is in conflict with the density of most plates. Synthetic materials can be a promising solution for this problem (Schramme et al., 2015).

A special application of scissor systems and panel systems is the deployment of linked panel units using **shape recovery of bent super-elastic alloys**. In this principle, the shape-memory and shape-recovery of super-elastic alloys act as a lightweight actuator for the deployment. The panel unit can be folded and deployed like a scissors mechanism. This system is very useful for applications in combination with solar panels (Takatsuka, 2015).

2.3.3 Deformable links – Bar elements

Strut-cable systems combine rigid bars with cables. The big advantage of this principle is that it can optimise the conflicting requirements of deploying, simplicity and structural efficiency (Hanaor & Levy, 2001). The most important and dominating concepts are the tensegrity structures. Strut-cable structures are very promising for large span applications because they have a higher structural efficiency than SLE's. SLE's have a low structural efficiency in terms of load-bearing capacity relative to self-weight. The structural efficiency of strut-cable systems is also better than conventional double-layer space trusses.

Foldable strut-cable systems (Figure 2-12) consist of three types of elements to make the deployment possible: the constant elements, active elements and passive cables. The deployment is driven by the variable length of the active elements, which can be struts or cables (Feng, 2015).

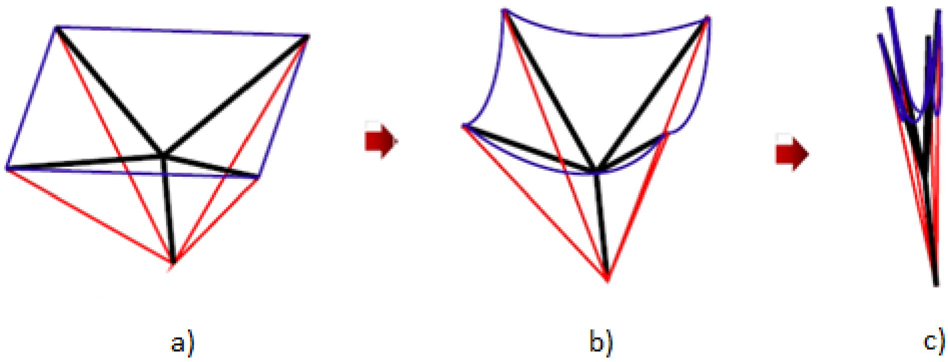


Figure 2-12: Foldable strut-cable unit (Feng, 2015)

Tensegrity structures (Figure 2-13) are a combination of discontinuous compressive elements (rigid bars) and continuous tensile components (cables). Bars are only connected to cables and not to other bars. Tensegrity structures are practical for structures that need to change shape, because structural elements and actuators can be combined. The structure can be of minimal mass. Together the bars and cables form a stable volume in space. These systems are often self-anchored and self-stressed in a closed system. The way and amount of self-stressing is responsible for the amount of load-bearing capacity. The flexibility and stiffness of tensegrity structures depends on the used material. Deploying of the structure is only possible by changing the length of the members. The bar length can be changed by hydraulic or mechanical energy supply. Or, another useful technique is pulling of cables (Susam, 2013). During design, attention should be paid to let the members not interfere with the useful space (Hanaor & Levy, 2001).

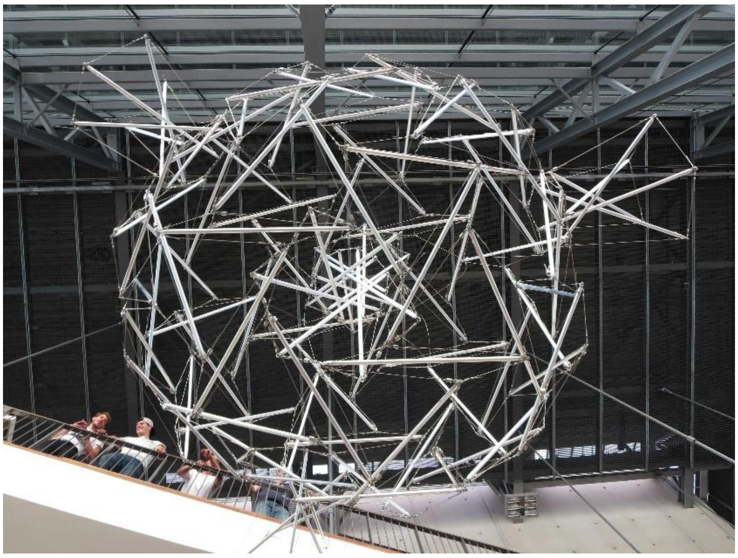


Figure 2-13: Tensegrity creation (Web 2-05)

2.3.4 Deformable links – Continuous surfaces

The most important group in this category are the **curved origami structures** with non-rigid plates. In contrast to origami in which straight lines are used, curved-line folding is characterised by the use of curved creases (Figure 2-14). The transformation process is the combination of folding (plastic deformation) and bending (elastic deformation) which results in a 3D-shape. Folding is a way to improve the structural stability of the used thin sheet materials. The folding motion results from the bending of one surface, which is followed by the transmission of forces and moments by the curved creases to the adjacent surface. The plastic deformation takes place at the fold lines and is permanent. During the elastic deformation, storage of internal energy takes place. This energy can be used to return to the initial state, resulting in a reversible folding process (Vergauwen et al., 2013). Compared to lattice bar structures, the architectural flexibility of continuous surfaces is much less.

Important in the design of curved-line folding patterns is the fact that the **crease pattern** needs to result in a folding process which is in equilibrium the whole time and has limited degrees of freedom. The most important parameter of the process is the composition and the geometry of this crease pattern. Another parameter that is important is the ratio between the length of the creases and the thickness of the material, the so-called LTR (length-to-thickness ratio). In literature, a LTR between 300 and 400 is seen as a good balance between stiffness and actuation forces that are needed to fold the structure. A last crucial parameter is the curvature of the crease pattern. If the pattern is characterised by a high curvature, the displacements are large but the actuation forces are low. For low curvatures, it is the other way around. This means that an increase of the curvature results in more bending and less folding. The number of actuation points and the path depend on the number of curved creases and their composition. It is the art to search for an intelligent actuation system that fits the overall architectural expression of the building. The energy needed for actuation needs to be kept as low as possible. The parameters named above are very useful to optimise the transformation process (Vergauwen et al., 2014; Vergauwen et al., 2013).

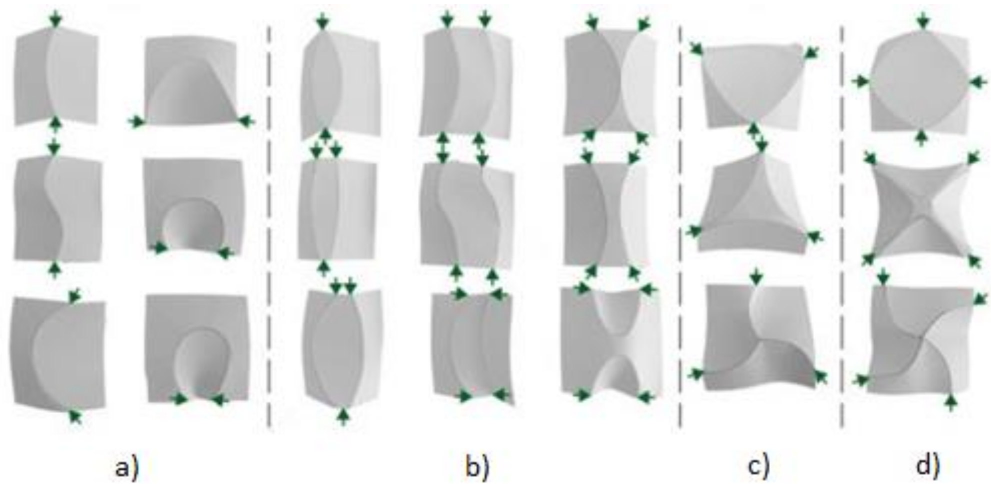


Figure 2-14: Curved-line folding based on a) one, b) two, c) three or d) four creases (Vergauwen et al., 2013)

Finite element simulations of deployable structures based on curved-line folding have shown that the folding cannot always start from a completely-flat state. The structure sometimes needs to be in a pre-bended state, because some curvature is needed to withstand external loads. Next to this, too much force would be needed to actuate the structure when completely flat. These two problems show the advantage of some initial curvature (Vergauwen et al., 2014).

Besides the curved-line folding, the membrane structures belong as well to this category. **Tensioned membrane structures** (Figure 2-15) rely on the principle of prestress to create a stable and stiffer structure. Large displacements would occur if prestress would not be applied to the membrane. Membranes are characterised by their saddle shaped form (negative Gaussian curve). These structures are not able to maintain equilibrium without the use of compressive elements. Compressive elements can interact with the membrane, forming part of the structure ('ribbed structures'). In contrast, the compressive elements can also be placed external and separate to the fabric surface. A combination of the different types results in hybrid structures. The different types of compressive elements have a certain deployability. The deployability of the compressive elements is crucial because it determines the deployability of the total structure (Hanaor & Levy, 2001).

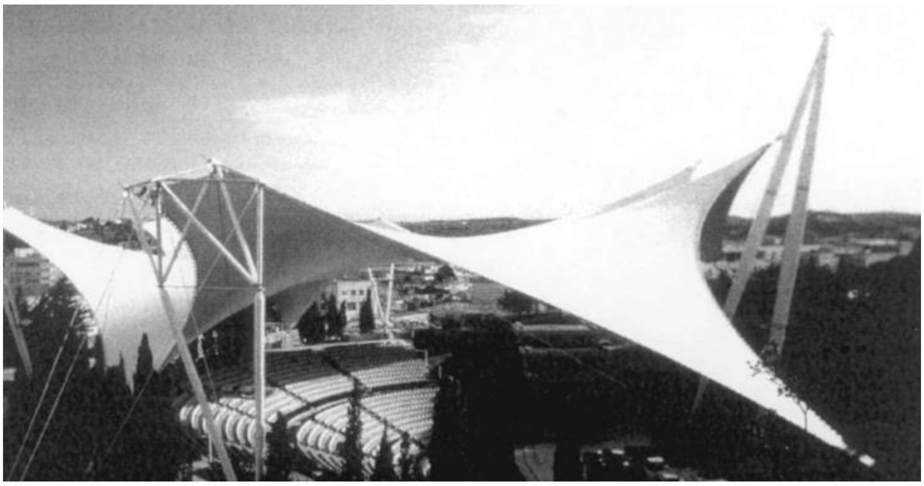


Figure 2-15: Tensioned membrane structure (Hanaor & Levy, 2001)

A popular subgroup in the category of tensioned membrane structures are the **pneumatic structures** (Figure 2-16). In these structures the required compression to balance the membrane tension is provided by air pressure. These inflatable structures have the disadvantage of being easily damaged by collapsing. In contrast, they are very useful for compactable storage thanks to the relatively small thickness of the material. The pneumatic structures can be further divided into low and high pressure structures. The low pressurised structures consist of continuously pumping the whole functional space. This in contrast to high pressurised structures in which only cells, not making part of the functional space, are pressurised (Hanaor & Levy, 2001).

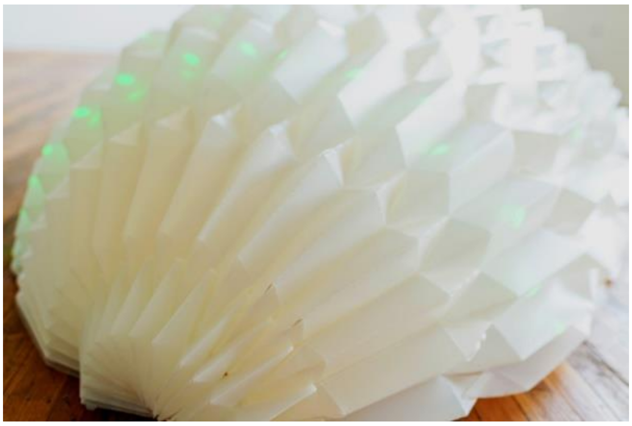


Figure 2-16: Pneumatic structure (Web 2-06)

2.3.5 Other systems

The different types in the classification of Hanaor and Levy (Figure 2-2) can be combined to form hybrid structures. The integration of mixed strut-cable systems with a covering is an example of a useful combination. This can result in very smart and promising structures but still needs further research**.** Some examples of promising hybrid solutions are explained below.

2.3.5.1 Ori-ssors

A new model that is recently explored, is a kinetic system composed by a 3D bundle of four bars (DDC unit – Developable double corrugation surface) and a Miura-ori surface (Figure 2-17). The movements of both components are linked. This new model has a structural stable and compatible initial and final configuration, but also the intermediate stages are stable. These intermediate stages are the result of rotation, sliding, folding or torsion of any component in relation to the rest. The behaviour of Ori-ssors is concurrent and uniform which means that the intermediate stages are proportioned and scaled but the function of the elements stays the same. It is a single degree of freedom structure and the only requirement for compactness is the allowance of the rotation of the two scissors (González & Carrasco, 2015). More details about the Ori-ssors can be found in the paper of González and Carrasco (2015).

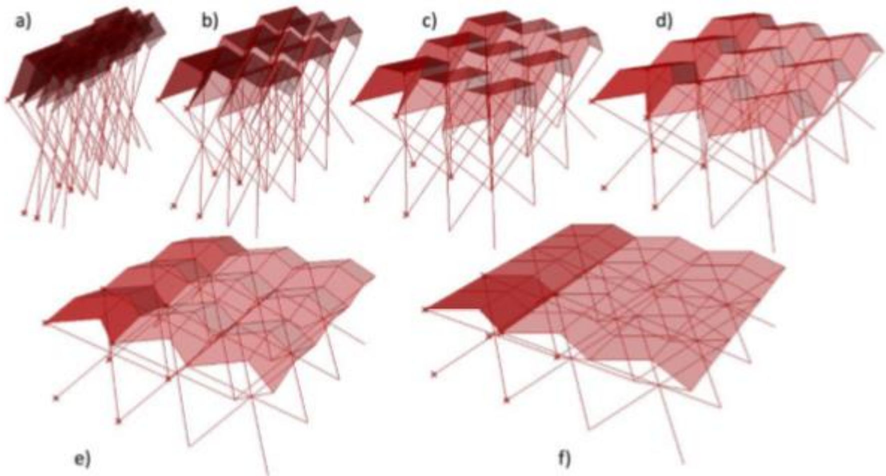


Figure 2-17: Deployment phases of Ori-ssors (González & Carrasco, 2015)

2.3.5.2 2D-deployable flat-panel structure

Takatsuka and Ohmori (2011) presented a new method to fold and deploy structures two-dimensional. The structure consist of flat panels and is suitable for huge flat constructions. The two-dimensional plane is divided into square panels. To lay the separated square-panels on top of each other, the panels need to be moved two-dimensionally. For this, the new method suggests to use a scissors mechanism which serves as a mast for deploying (Figure 2-18). Instead of stabilising the structure by use of a snap-through phenomenon, this system uses springs to design stable structures.

The scissors mechanism serves to move the square panels in a global coordinate system and uses a tilted rotational axis to move the panel two-dimensionally in a local coordinate system. To avoid collision, a shift in z-direction is necessary before rotation of the panels. The two-dimensional folding results in a more compact folded shape. The tilted rotational axis is used to form the stabiliser unit. This unit stabilises the structure by stretching the spring during transformation. The main disadvantage of the system is the high precision that is necessary to avoid collision of the panels during the folding operation (Takatsuka & Ohmori, 2011).

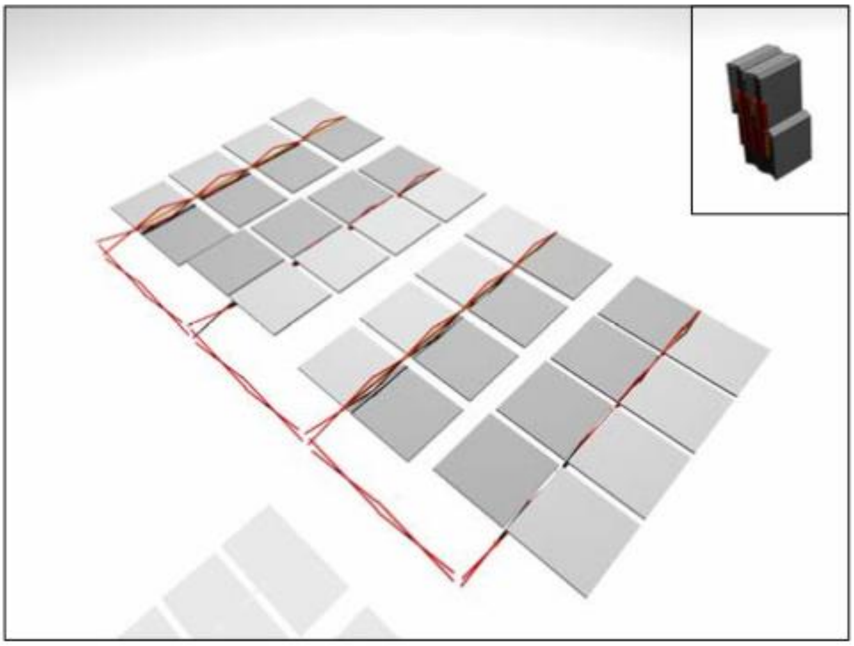


Figure 2-18: 2D-deployable flat-panel structures (Takatsuka & Ohmori, 2011)

2.4 Conclusions

The design of transformable structures is focused on the enabling of the structure to adapt to changing circumstances. This capacity implies a physical transformation triggered by a sudden need (emergency), changing climate (rain, wind, heat/cold, sun), changing functional requirements or other changing boundary conditions. This chapter focused on transformation in terms of deployment. Transformable systems require mostly lightweight structures combined with an optimal structural performance. Besides the type of transformation, the materials that are used are of great importance and have an influence on the performance as well. Deployable structures have a wide range of possibilities. However, the challenge is to provide sustainable solutions. Good designed structures can contribute in a creative way to design buildings with a low energy use and enhanced building environment.

To build adaptive façade structures, rigid links such as bar elements can form the effective base for the deploying motion. Rigid links can give the structure a high stability and often lightweight materials can be used. It allows to deploy easily from compacted to deployed state. Rigid links offer the possibility to be combined with coverings such as flexible membranes or rigid plates.

Membranes allow architects to design aesthetically pleasing building envelopes combined with improved functionality. As membranes, a wide variety of materials can be used that can create different forms and shapes, which gives the architect a lot of freedom. Furthermore, membranes can control the degree of daylight, the amount of provided shading, the ventilation, the transparency … Therefore, they can be useful to apply to reduce the energy consumption in buildings. In addition, these materials usually need only a low amount of maintenance and have a long useful life. Recently, the technology of membranes is improving, which makes their application even more attractive. They can protect the building against weather effects and deterioration. However, during design, some attention should be paid because the membranes need to be stable not only in deployed and undeployed state but also during deployment.

Next to membranes, rigid plates can be used as covering in combination with bar elements as well. Folded plates offer potential for building applications by using tessellations. Origami folding can result in limited material consumption and an implicit structural lightness. The folding techniques can have different forms, volumes and directions of deploying. The necessary actuator characteristics depend on the relationship between modules, folds and cuts. Both mechanical systems and active materials can be used as actuators. In comparison to mechanical devices, active materials can result in a reduction of actuation energy. The activation of the self-folding pattern is the most difficult part compared to the more easy deployment once the folding takes place.

Recently, a lot of successful transformable building applications were created that make use of rigid plates to create adaptive façades (see Appendix A). Besides the many applications of rigid-foldable origami, applying curved-line folding can be useful for the creation of adaptive behaviour in buildings as well. However, this domain is rather unexplored. A lot of research still has to be done to optimise the surface displacements. Shading systems based on curved-line folding need more studies about the changing of parameters that define the kinematic behaviour in relation with the building morphology. The optimisation process is not easy, the effect of the parameters on the performance need to be studied in detail and further research to improve these systems is necessary.

> ‘Green buildings are a hallmark of economically sound business decisions, thoughtful environmental decisions, and smart human impact decisions.’
>
> - Rick Fedrizzi -

BUILDING FAÇADES

3 Building façades

3.1 Introduction

All history long, people have searched for building and living conditions to make life comfortable through the seasonal weather changes. The last century and more specific the last decades, the world population keeps on growing significantly and the global warming and climate change form a challenge for our planet. The current trend is to build 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.

Façades of commercial buildings and high-rise buildings in general, contain mostly large amounts of 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. One option is to place a kind of curtain in front of the wall. Another possibility is to use a second layer of glass or other opaque materials, which is called a double façade.

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 occupant comfort by concepts such as ventilation systems, shading systems for sun control, the regulation of daylight 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.

The design of a façade has to respect the location of the building as well. Different geographical locations have different climate characteristics with other primary requirements. An increased internal comfort (better air quality, thermal comfort …) results in a better occupant health in combination with a better productivity and amenities for the occupants. Also, the current problems of running out of resources of raw materials and increasing costs of materials make the demand for innovating concepts that minimise the use of energy and material consumption more pressing. The purposes of advanced façades to reduce overall energy use and environmental impacts can only be achieved when these different aspects are respected (Lee et al., 2002).

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. Moreover, insulation from heat loss, ventilation for indoor air quality and collection of heat are possible building functions for the façade. In the following part, an overview of the several functional requirements of a façade is given. First of all, essential requirements such as the water and wind tightness, maintenance and repair facilities and fire safety are of importance. Furthermore, comfort increasing requirements like solar control, heat and energy gain, daylight control, natural ventilation and acoustic control characterise the efficiency of the façade of a building. The largest part of the existing façades currently focuses on one of these aspects.

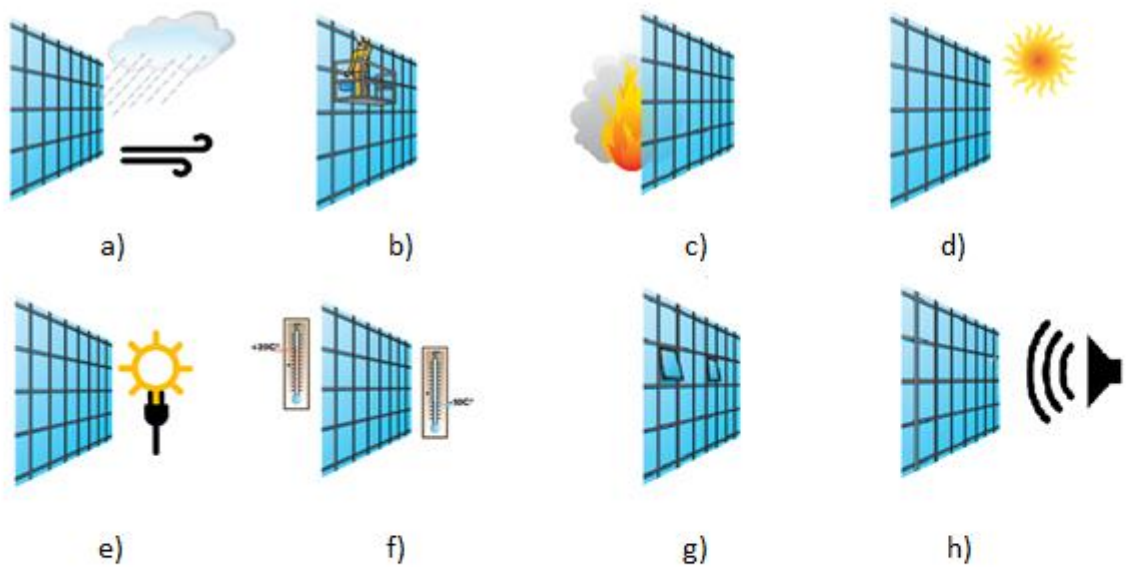


Figure 3-1: Functional requirements façade (Adapted from Web 3-01)

The different aspects that contribute to energy use are interacting, which makes the problem very complex. More specific, the interaction between heat, light and cooling is very complicated. If the depth of a shading system is low, more solar heat gain results in less need of heating systems but more need of cooling systems. Less depth of the shading system results also in more use of natural daylight, and less need of artificial light. In addition, turning on artificial lighting may influence the heat gain and cooling load of the building as well (Shan, 2014).

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 the design of a façade it is important to consider wind and precipitation. A good façade possesses an efficient **wind and water barrier**. Façades should be well sealed to avoid the penetration of rain and wind from outside. In addition, moisture may not penetrate into the façade. In case the façade is not watertight, it is important to provide measures to enable the ventilation or drainage of the entered water to the outside. The indoor quality of the buildings is directly related to air and water supply. Mold growth and deterioration can result from moisture problems and condensation due to leakages (Web 3-01).

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 fire stopping (sealing of the gap) is extremely important.

The façade should be foreseen of appropriate devices to ensure **easy service and maintenance**. During the design of a façade it is important to think about how the façade can be reached to execute maintenance and repair operations during its lifetime. In addition, a façade that needs less replacement or repair of components is better regarding the life cycle cost of a building (Web 3-01).

3.2.2 Comfort increasing functions

Except for the essential requirements, the façade is designed to fulfil some functions that increase the internal comfort of the occupants in the building, lower the energy use of the building, improve exterior views and functions related to aspects that can lower the impact of the building on the surroundings (buildings, cars, people on the street …).

3.2.2.1 Solar Control

Sun path

The sun has a major influence on the interior climate of a building. This influence is ambiguous. On the one hand, the sun is wanted to heat up and light a room. On the other hand, in summer it can lead to unwanted extreme temperatures.

The path of the sun is characterised by seasonal and hourly changes (Figure 3-2). The position of the sun is a determining factor for the solar heat gain in buildings. For an efficient positioning of shading systems, knowledge about the position of the sun is crucial.

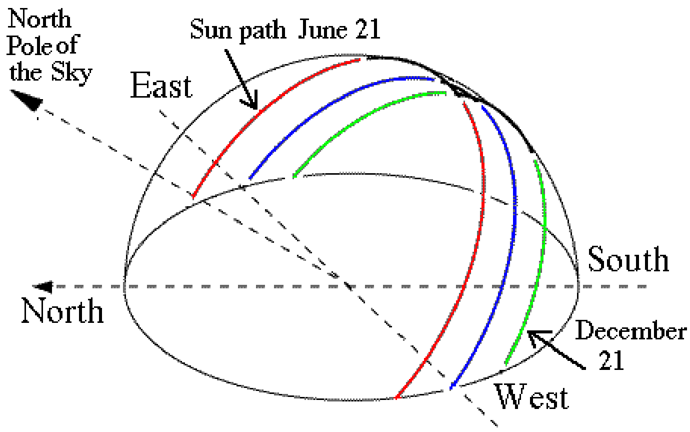


Figure 3-2: Solar trajectory (Web 3-02)

The sun rises every morning in the east and goes down in the west in the evening. The tilting of the axis of the Earth by 23.5 degrees results in a change of the sun path every day. The biggest differences are related to the seasonal changes. The tilting of the Earth is positioned towards the sun during the summer. This explains that during summer days seems longer and are warmer because the position of the sun is higher. Contrarily, in the winter the days seems shorter and the nights longer due to the lower position of the sun (Web 3-02).

From the sun's path, it is clear that a shading system for the north façade is not efficient. The radiation on the east and west façade has the same height. For the east and west façade, a vertical solar shading system will be more efficient than on the south façade. Due to the high position of the sun in the south, a horizontal shading system will be more efficient on this side of the building.

Solar control systems

Different systems exist to control the solar radiation (Figure 3-3). The most important ones are briefly explained below.

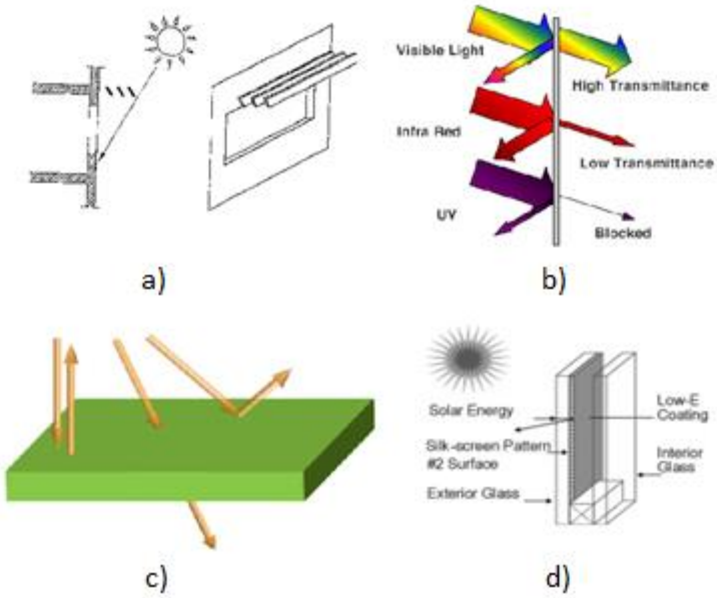


Figure 3-3: Solar control systems: a) exterior, b) spectrally selective, c) angular selective, d) solar filter

Exterior solar control

The most well-known solar system is the exterior control of the sun by overhang systems or window screens. These dynamic systems block direct sun before it enters the building. In contrast to fixed systems, they can control thermal gain, reduce glare and redirect sunlight and are far more flexible and efficient. Typical examples are louvers or blinds. 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.

The spectrally selective glazings can deal with overheating problems during summer and heat loss during winter. On the same time, these glazings permit the biggest part of the visible light to enter, 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.

Besides the traditional systems, another promising idea is to develop coatings that result in angular solar control. Up till today, no commercial products exist because the design of these angular selective coatings is not easy and is a challenging future research area (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. The thickness of the filter, the opacity and the reflectance/absorption play an important role in the effectiveness of the solar control. Solar filters can be placed interior or exterior (Lee et al., 2002).

3.2.2.2 Daylight control

Besides systems that focus on the control of solar radiation, systems that focus on the control of daylight are also well-known. By increasing the effective use of natural daylight, reduced artificial lighting and on the same time improved quality of lighting and visual comfort can be obtained. The purpose of these systems is to distribute the incoming daylight over the entire room as good as possible by using principles of reflection, refraction, diffraction and optics.

Sunlight redirection and sky-light redirection

Light-directing systems are supposed to redirect both direct sunlight and diffuse skylight. In summer, the sun is high and need to be blocked. In winter, the altitude of the sun is lower and the sun can penetrate the room. So, seasonal variations in the position of the sun are the basis for the design of these lighting systems. Systems designed to block sun are often less efficient with respect to redirection of daylight (Lee et al., 2002).

Sky-light redirection systems are designed to increase the use of daylight and have less attention for the depth of the light redirection. Systems that work with gathering of diffuse light and guiding this by using mirrors are well-known (Lee et al., 2002).

Glare

For the visual comfort of the occupants (fatigue, discomfort …) and the surrounding people and buildings, the control of glare is important. Glare in buildings results from the reflection of light from the sun on a reflective surface, such as glass. Glare can result in safety risks and can increase the solar loads on adjacent buildings by reflecting on the glass surfaces. In addition, reflected glare can hit pedestrians or drivers outside or other buildings in the surroundings and disturb their occupants. Glare can be efficiently controlled by blinds or louvers (Shih & Huang, 2001).

3.2.2.3 Energy gain/storage

Solar radiation is energy in the form of electromagnetic radiation. The amount of energy that building envelopes receive, can be used as the energy that is needed to operate the building (Lee et al., 2002) (Burton, 2012). The quantity that strikes the building’s façade depends on the weather conditions, location and orientation of the sun.

A recent principle to capture energy is the installation of **BIPVs** (building-integrated photovoltaics) in the building’s envelope. Photovoltaics are a form of renewable energy that produce energy on site directly from the sun. Photovoltaics serve simultaneously as building envelope material and power generator and provide savings in material and electricity costs which lowers the total life cycle cost of the building (Web 3-03).

3.2.2.4 Natural ventilation

Fresh air and natural ventilation are important for the internal comfort. Besides the opening of windows, other systems exist that allow natural ventilation such as the efficient use of the air cavity between two layers. In general, air movement has a strong influence on the comfort depending on the situation. When the temperature in a room is high, increased ventilation has a positive influence on the comfort. In contrast, low temperatures ask for a decrease in ventilation (Van Dijk, 2009).

3.2.2.5 Acoustic control

Most building façades focus on thermal and optical requirements. Recently, the growth in environmental noise pollution and building high-rise buildings in noisy urban areas, results in acoustic requirements for the building envelopes as well. For the façades, the control of the outdoor-indoor transmission of sounds is essential. Walls are exposed to noise sources such as cars, trains, aircrafts … The mitigation of this outside noise in office buildings is important to increase the acoustic performance of the work environment. Therefore, the occurrence and propagation of disturbing noise should be limited.

First of all, the **fitting and sealing** of the window in the façade play a crucial role for the performance. To further improve the sound insulation of the façade, different constructional measures can be used. Firstly, the **weight** of the components can be increased. Next, one can make use of **different layers** that increase the material thicknesses. In addition, both solutions can be improved by using asymmetry in the assembly. Furthermore, the **degree of absorption and the elasticity** of the building components play a significant role in the sound insulation of the façade as well (Van Dijk, 2009) (Web 3-04).

3.2.3 Conclusions

The design of a façade is a complex issue because it needs to fulfil different functional requirements. People with a lot of experience and specific knowledge are necessary to obtain good solutions. First of all, the façade has to perform perfectly with respect to essential requirements. The weather tightness, basic ventilation, fire protection and features for maintenance and repair are crucial aspects that cannot be neglected.

In addition to the essential requirements, designers have to focus on the increased performance by making the façade more efficient for the building. Most façades focus on the thermal and optical domains, which is logical because these are the domains that demand most attention and where a lot of possibilities for increased performance and lower energy use already exist. Energy gain and storage is an aspect that currently wins in recognition, which makes it a very promising aspect in future innovative façades. The air flow domain is a third aspect that is popular in the design focus of façades. The domain that gets the lowest attention is the acoustic control. Problems resulting from acoustic issues are mostly smaller in comparison with thermal and optical problems. However, it is a domain that possesses also potential to create efficient systems.

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 (Figure 3-4). 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.

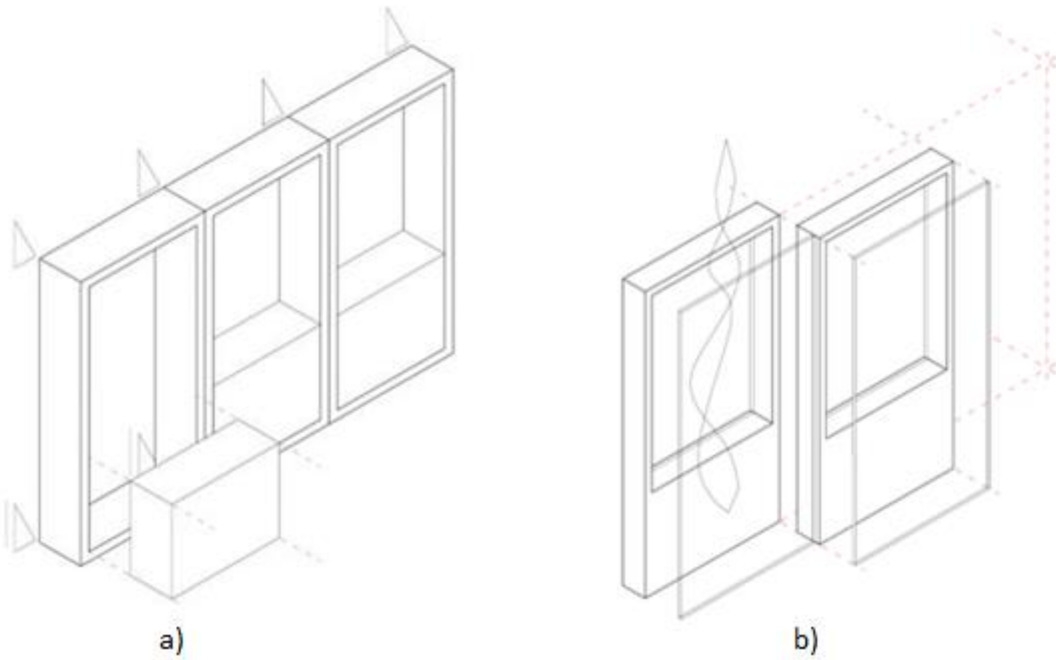


Figure 3-4: Types of façades: a) curtain wall façade and b) double façade (Knaack et al., 2007)

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 for example by making use of an IGU (insulated glass unit) (see further) (Klein, 2013).

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) .

3.3.1.1 Structural concept

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). These elements are non-structural and serve as a cladding system (Hachem et al., 2014).

3.3.1.2 Frame construction and infill panels

The first examples of curtain walls were made out of steel. Later, extruded aluminium members, filled with glass (infill panels), replaced these steel walls (Figure 3-5). The **lightweight aluminium frames** in combination with glass or other transparent panels have the advantage of making more use of natural daylight, moreover they are architectural pleasant.

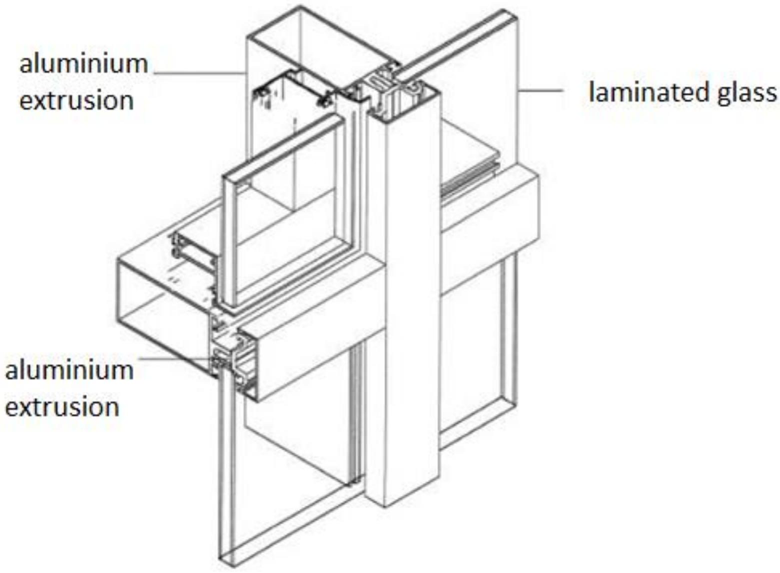


Figure 3-5: Aluminium frame and glass infill panel (Web 3-05)

The **infill panels** are the interface to the exterior and need to be windproof, waterproof and have to allow some movement (Hachem et al., 2014). When glass is used as infill panel, mostly IGU's are used. These units can be laminated on one or both sides. Usually the glass infill panels are fixed into the frame, but sometimes operable window frames are incorporated.

Instead of vision glass, **opaque panels** can be used as well. A popular example of opaque panels is **spandrel glass.** Spandrel glass can be monolithic, laminated, or insulating glass. To make it opaque, opacifiers such as a paint, film or ceramic fried are used. A second type of opaque panels are **metal panels**. Metal panels exist in some possible variations such as: aluminium, stainless steel or other non-corrosive metal, thin composite panels. To make sandwich panels, constructions with two thin aluminium sheets with a plastic interlayer or metal sheets with or without inner metal sheet can be used. A third example are **thin stone panels**, mostly made of granite. Granite has the best properties related to deformation susceptibility. Other opaque panels such as terra cotta or fibre-reinforced plastic are also possible, but these are less common (Web 3-06).

3.3.1.3 Fabrication and installation method

A curtain wall façade can be classified according to the fabrication and installation method. In general, a distinction between two main basic types is made: **the stick system and the unitised system**. In addition, a variation on these systems, the frameless system is often applied as well (Figure 3-6).

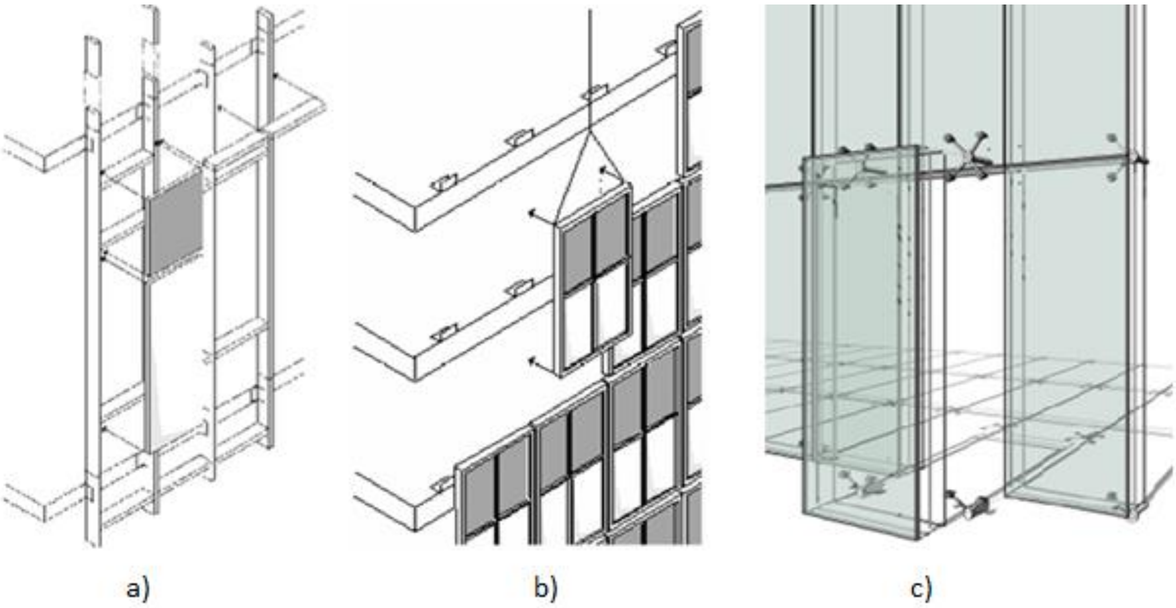


Figure 3-6: Overview curtain wall systems: a) stick, b) unitised, c) frameless (Klein, 2013) (Knaack et al., 2007)

The stick system and the unitised system can be designed as **interior or exterior glazed** systems. The choice between interior or exterior glazed systems depends on different aspects. When glazing or opaque panels form the interior side, air infiltration can happen. Interior glazed systems are only used in specific applications in which the interior of the curtain wall is obstructed as limited as possible. These systems allow adequate access. For exterior glazed systems, the repair and the replacement of parts of the structure are not easy. For the maintenance, swing stages or scaffolding are required (Web 3-06).

Stick system

The majority of curtain walls follow the stick system. This system is based on the installation of long pieces, called sticks. These sticks are a more developed manner to build the façades than by using craftsmanship (Hachem et al., 2014). The stick pieces are installed one by one on site with the panels inserted into the frame. The pieces are installed between floors in a vertical way and/or between vertical members in a horizontal way.

The structural support for the curtain wall construction is ensured by a framework of **mullions and transoms** that form the façade substructure. The mullions transfer the forces due to dead load and wind load. Furthermore they provide support for the cladding. The mullions are mostly storey-high vertical elements that are linked by the transoms. Transoms are horizontal structural elements that transfer wind loads and the weight of the panels to the main load-bearing, primary structure. The mullions and transoms are in literature also called posts and beams, which results in an alternative name: **post-and-beam façade** (= mullion-transom façade) (Figure 3-7). Two important variations on these façades are possible, more specifically the post façade and the beam façade (Sommer, 2010).

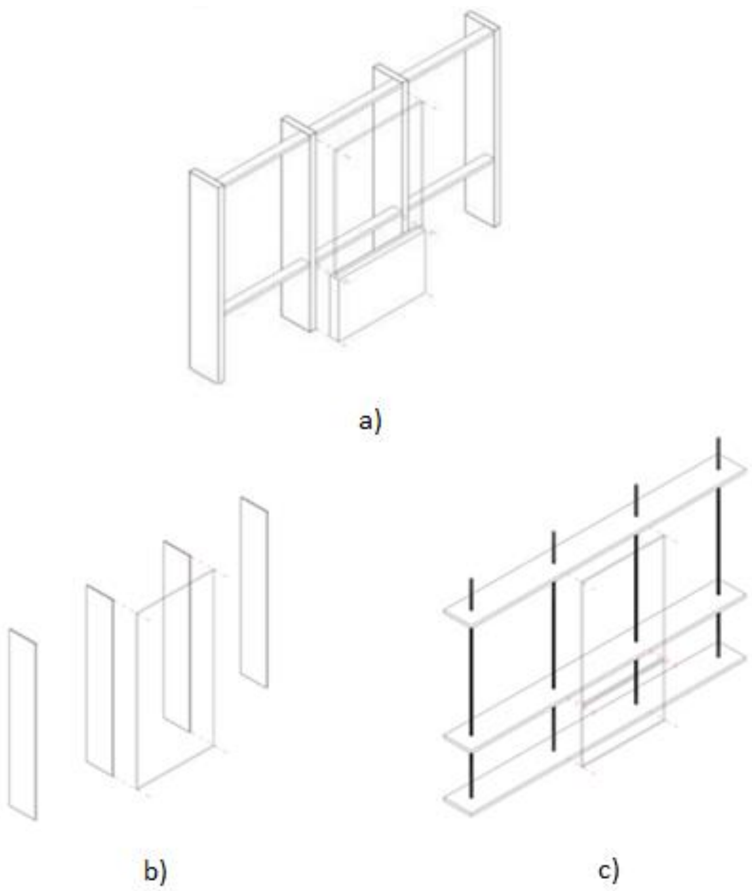


Figure 3-7: Possible façade configurations stick system: a) post-and-beam, b) post, c) beam (Knaack et al., 2014)

The **post façade or mullion façade** is the first variation on the post-and-beam façade. This variation only consists out of posts, which increases the degree of openness, resulting in an increase in transparency. A disadvantage of this system is the limit on the maximum possible distance between the posts (Knaack et al., 2007). This type of structure results in a higher degree of prefabrication which allows for a shorter assembly process on site (Sommer, 2010).

The second variation of the post-and-beam façade is the usage of only beams (**beam façade**). This system has the advantages of reducing the structural mass and avoiding buckling of the structural elements. Mostly, they are foreseen of heavy tie-rod structures for bearing the dead load. These structures are mounted near the roof. The beams only have to resist the lateral forces (Knaack et al., 2007).

To ensure more quality for the used elements of the façade, more prefabrication is desired. To make more use of prefabricated systems, the **ladder system** was invented. The ladder system is a system in which separate ladder-like elements are preassembled, followed by on site connection of the elements. The ladder system is a first transition from the stick system to more prefabricated, unitised systems (Klein, 2013) (Hachem et al., 2014).

Unitised system

A second popular system for the construction of curtain wall façades is the unitised system. In this system, prefabricated modules, made off-side, are delivered to form the building enclosure. To fabricate these modulus, independent units of typically one glass unit wide and one floor level high are firstly manufactured. In a next step, the framing members for the units are fastened together and the units are placed into the frame system. These **complete modules** are then transported to the site (Seaverson, 2009). This system only requires the connecting of pre-fabricated modules to the support structure on site. This results in a larger speed and lower cost of installation. The lower installation time makes the installation less dependent to wind and weather. However, it is not possible to make adaptions on site (Klein, 2013) (Sommer, 2010).

Besides the shorter installation time, this system improves the quality control of the modules by working in a dry and clean factory. The unitised system has some drawbacks compared to the stick system as well: a more complex frame is used than simple mullions and transoms and more material is needed to stiffen the units during transport. Unitised installation systems are cost efficient solutions for large and complex projects. For small, simple projects, the stick system seems more appropriated (Klein, 2013) (Sommer, 2010).

Stick system vs Unitised system

Table 3-1 gives an overview of the advantages and disadvantages of a stick system compared to a unitised system for building the curtain wall façade.

Table 3-1: Stick system vs Unitised system

CURTAIN WALL FAÇADE	
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**

Frameless systems

A variation on the curtain wall systems are the frameless systems, which are characterised by a high transparency. These are created because the curtain systems are often too complex to obtain a good thermal insulation. In the frameless systems, the infill panels are connected to the load-bearing structure by making use of good thermal connections (water, wind and moisture tight). A drawback of the system are the high costs. One famous example of these systems is the ‘Frog hand’ or ‘Spider façade’ (Klein, 2013).

3.3.2 Double façades

The second important group of construction types for a façade are the so-called double façades. Double façades can be realised in various ways. Double façades shift the ventilation function from the inside of the building to the façade, and can insert thermal insulation between the two layers of the double façade. Except for natural ventilation, double façades are efficient to block and control noise infiltration into the building (Klein, 2013). The second layer of a double façade is mostly a glass layer, which can be seen as a kind of curtain wall that is fully glazed around the building.

In general, there exist four types of double façades that are best-known, these are related to the climatic strategies for the double façades*:* **the second-skin façade, the box-window façade, the corridor façade and the shaft-box façade (chimney façade)** (Figure 3-8). Except for separated systems, alternating façade principles can be used as well (Klein, 2013). These variations on the double façade require large constructional efforts.

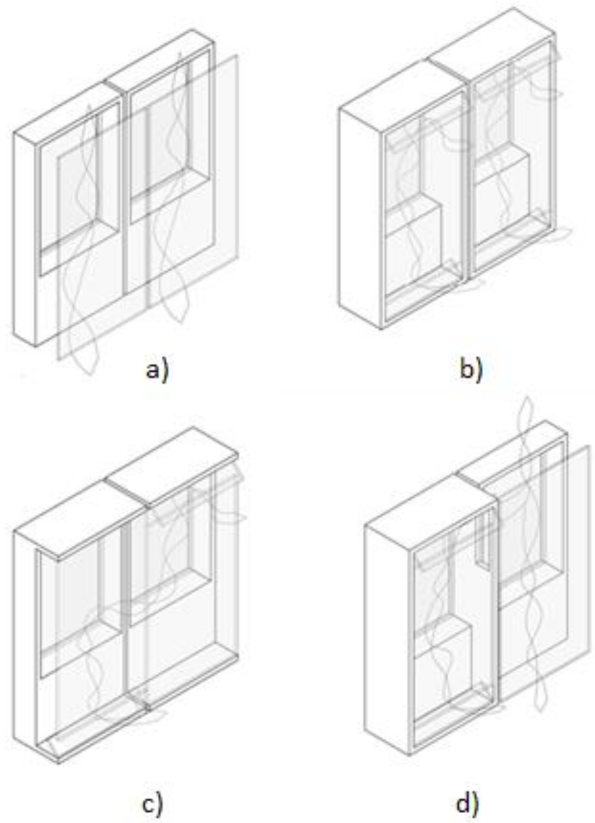


Figure 3-8: Double façade types: a) second-skin, b) box-window, c) corridor, d) shaft-box (Knaack et al., 2007)

3.3.2.1 Second-skin façade

The first and best-known type of double façade is the double-skin or second-skin façade (Figure 3-9). This basic system joins the intermediate space between the inner and outer layers vertically and horizontally around the entire building. The double-skin façade can be considered as a multi-storey façade and does not necessarily require openings all over the exterior of the façade. The second layer is placed exterior to the conventional façade and results in reduced sound levels and the possibility for more natural ventilation (Web 3-07).

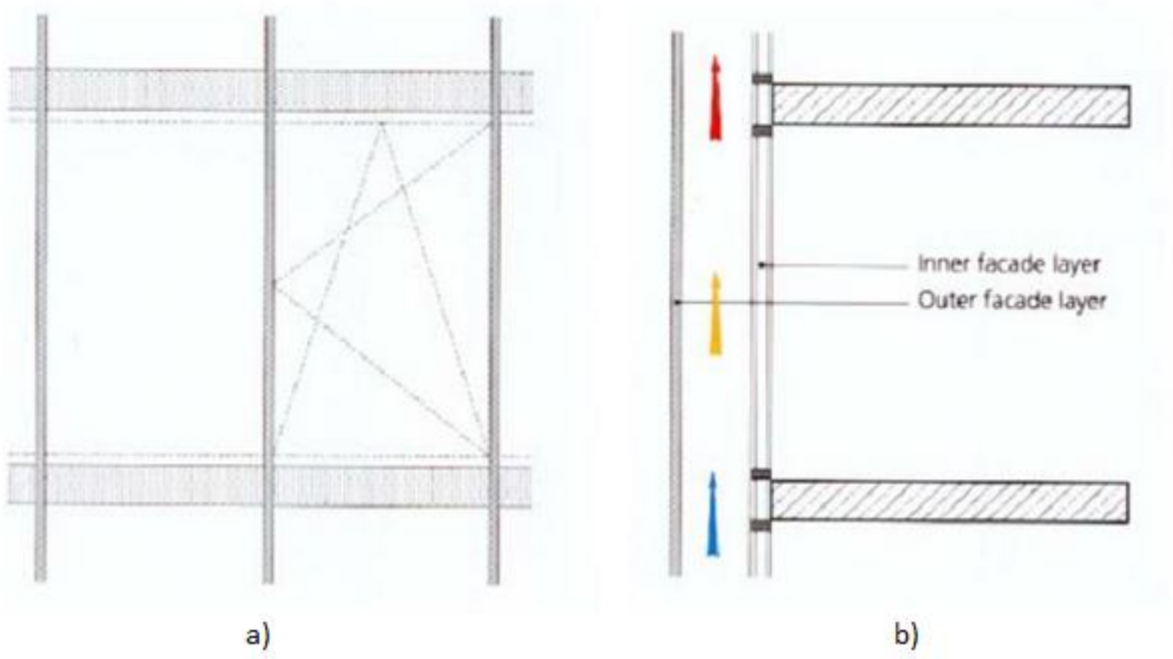


Figure 3-9: Principle of the double-skin façade: a) front view, b) side view (Web 3-07)

The main layer of glass of the double-skin façade is usually an insulating layer. The space between the two layers is a kind of insulating barrier that helps to perform better related to extreme temperatures, noise and wind. The ventilation of the cavity can be done in a natural, fan supported or mechanical way (Web 3-07).

The second-skin façades are characterised by a large technical and structural simplicity. The construction is just based on the placement of an outer single layer (mostly glass) on the inner insulated glass. The intermediate space can be ventilated in all directions. The most important disadvantages are: the limited control possibilities on the interior and the risk of overheating that remains a problem (Knaack et al., 2007).

3.3.2.2 Box-window façade

For individual control by the occupants of their own environment (individual ventilation control), the box-window façade was created (Figure 3-10). This façade consists of storey-high elements that individual users can open by ventilation flaps at the top and bottom for fresh air. This system allows to prevent overheating during the summer and cooling down during the winter. In addition, the division between different rooms helps to prevent passage of sound and smells from room to room. The disadvantage of this system is the influencing effect of the different users on each other. The quality of the incoming air can be influenced by the exhaust air from above (Knaack et al., 2007).

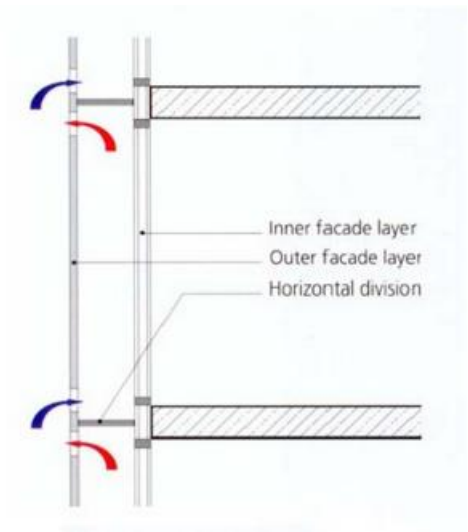


Figure 3-10: Principle box-window façade (side view) (Web 3-07) *Figure 3-11: Example of a box-window façade (Klein, 2013)*

3.3.2.3 Corridor façade

By alternating the ventilation inlets and outlets, the problem of interference between the ventilation systems of the different users on different levels of the building can be avoided. This system is called the corridor façade (Figure 3-12). Furthermore, a corridor façade exists of horizontal baffles, placed between the two skins. These horizontal connections result in the possibility of natural ventilation. However, this continuous horizontal air flow can cause noise interference problems. At the corners of the buildings, usually divisions along the horizontal length of the corridor are foreseen for acoustic protection, but in addition for fire protection and ventilation reasons as well (Knaack et al., 2007).

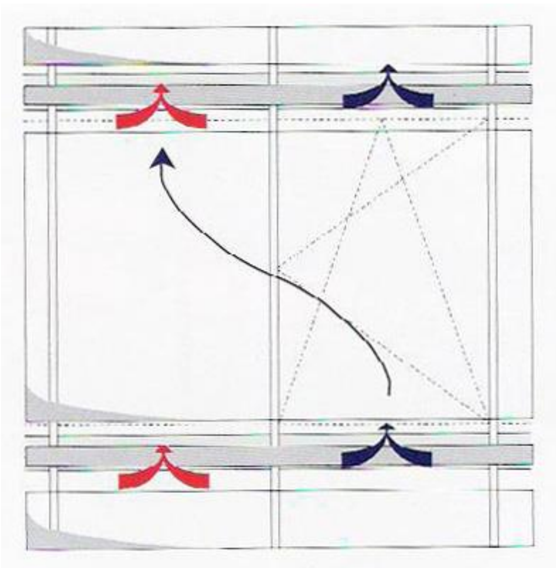


Figure 3-12: Principle corridor façade (front view) (Web 3-07) *Figure 3-13: Example of a corridor façade (Klein, 2013)*

3.3.2.4 Shaft-box façade

To increase the thermal efficiency, a shaft-box façade can be applied (Figure 3-14). This façade exists of discrete box windows, that release their air into a continuous vertical shaft, extending over several floors. The façade consists of the alternation of these boxes and shafts. This system is the most effective, but on the same time the most effort-intensive of the four double façade structures, which makes this type most suited for low-rise buildings. In every box element, a ventilation flap that leads to the shaft is required. The system requires fewer openings on the external skin, which decreases the urban noise infiltration (Knaack et al., 2007).

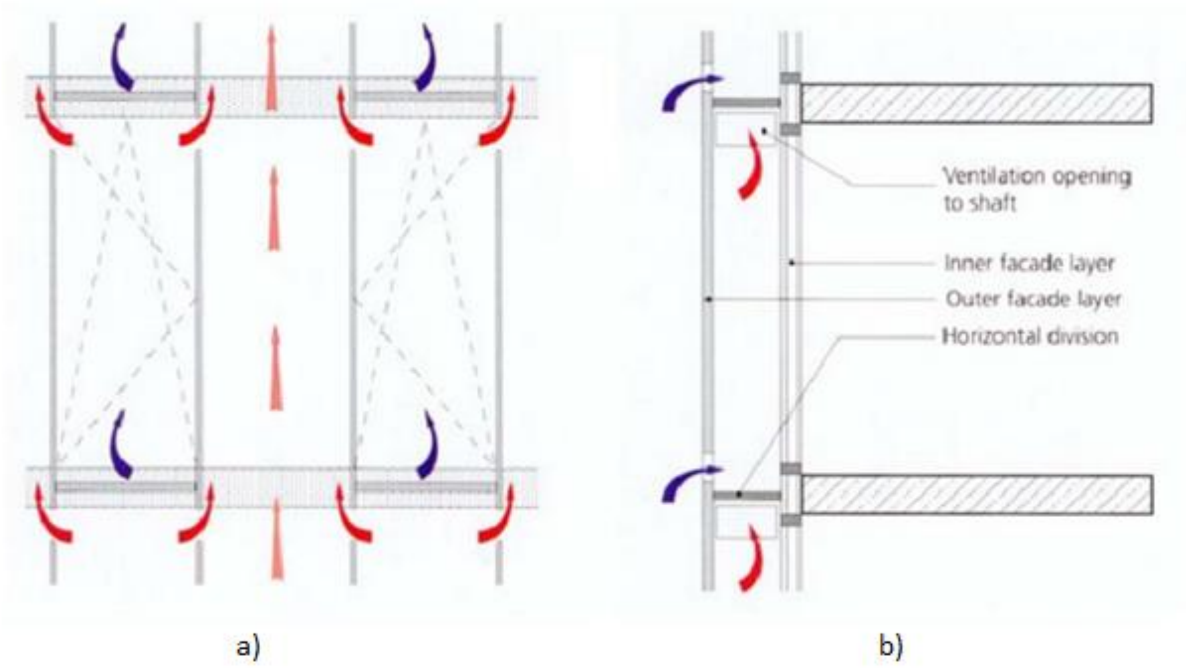


Figure 3-14: Principle of shaft-box façade: a) front view, b) side view (Web 3-07)

3.3.2.5 Alternating façades

Except for the application of one typical system, the combination of single-skin façades that locally become double façades for a local buffering effect is possible. These alternating or hybrid façades (Figure 3-15) allow the development of a more economical façade (Knaack et al., 2007).

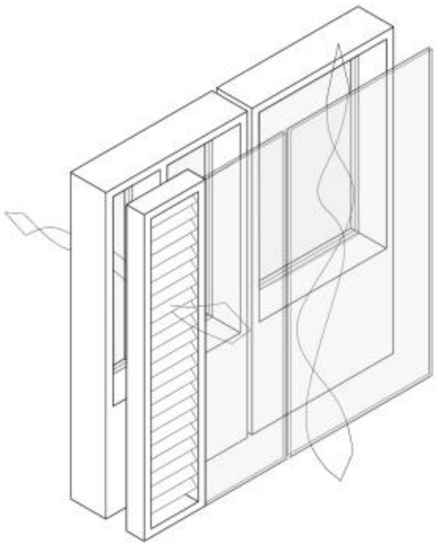


Figure 3-15: Alternating façade (Knaack et al., 2007)

3.3.3 Conclusions

Two important groups are considered as basic types for an advanced façade: the curtain wall façades and the double façades. Curtain wall systems are typically designed with an aluminium frame in combination with infill panels. For the installation, the stick or unitised system can be used. These two systems differ with respect to the amount of prefabrication and installation time on site. Double façades have different variations with respect to the coupling/decoupling of ventilation over a horizontal/vertical distance. The different systems have impact on the acoustic performance and the quality of the natural ventilation. Both curtain wall façades and double façades have the opportunity to improve the internal comfort and performance of the building. In a next step, the amount of impact that the systems have on the different comfort increasing functions of a façade will be investigated.

3.4 Integration of building functions and structures

In the two previous parts, the most important functions and the several possible façade structures were investigated. The understanding of both parts separately is important but the integration of both parts together is even more crucial. 'Which system is able to control which functions?', is an important question that has to be answered. In the following part, an investigation of the different possibilities regarding the regulation of the functions of the façades in relation to the different types of façades is worked out.

3.4.1 Curtain walls

The frame and infill panels of a curtain wall system are characterised by a complex design. The design is optimised to perform several functions to enable the façade to be as cost-effective as possible. A curtain wall needs to be able to transfer the loads to the primary structure. Curtain wall designs often span multiple floors which requires increased attention for building sway and movement and thermal expansion and contraction. The design of the joints should be done properly in order to obtain a good fire, smoke and acoustic separation. Water may not penetrate and dirt may not accumulate. Except for the essential requirements to create a good façade, the curtain walls should possess some functionalities that can improve the comfort and performance of the building.

3.4.1.1 Essential requirements

As mentioned in '3.2.1', the essential requirements (Figure 3-16) for a façade are the water and thermal tightness, the maintenance and repair facilities and the fire safety. In this section, the performance of a curtain wall façade on these aspects is investigated.

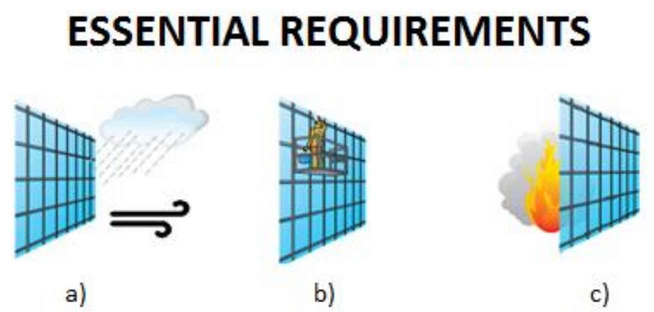


Figure 3-16: Essential requirements

Water tightness

The curtain wall systems require design for resistance to **water penetration**. The designer has to cope with the inflow of water due to five possible forces; gravity, kinetic energy, air pressure difference, surface tension and capillary action. Crucial for the design of a system with excellent water resistance is the construction of watertight frame corners and a good drainage for the glazing structure. To make a curtain wall watertight, different principles exist. Curtain walls can be classified related to the water tightness of the façade as **pressure-equalised, face-sealed or water-managed** systems (Klein, 2013).

To prevent the passage of water through joints, the rainscreen principle is the most popular. This because of the high level of resistance to air and water infiltration. The principle is based on creating an equilibrium of air pressure between the outside and inside. It is the pressure difference that is responsible for the forcing of water in the building. This results in an alternative name for this system: **pressure-equalised**. The air pressure is found in the glazing pocket between the outside face and the inside air barrier. The outer face of the glass serves as a rainscreen that sheds the water away. The equilibrium in air pressure can be created by ventilating the glazing such that the pressure remains the same at the inside and outside.

An alternative for the rainscreen principle is the **face-sealed system**. However, this system has the intention to create a 'perfect' and continuous seal which is in reality not possible due to the failing by pressure-driven moisture. Therefore, the face-sealed system is less used.

After the pressure-equalised system, the **water-managed principle** is most popular. On first sight, this seems similar to the rainscreen principle, but a larger amount of water can penetrate into the system. This water needs to be drained away by drainage holes at the exterior face of the façade. The pressure difference is greater and may result in leaks in the interior.

A second aspect and defence system to prevent water infiltration, is the installation of **back pans**. These are mostly made out of metal sheets (aluminium or galvanized steel) and are sealed to the framing around the perimeter behind the opaque panels. Eventually, an insulation between the cladding and the back pans can be foreseen (Web 3-08).

Thermal tightness

Related to the thermal tightness, the thermal break and conduction are essential parameters to create a durable system. In addition, avoiding condensation is important for the health of the occupants. A good air tightness of the curtain wall is required to avoid air leakage that can lead to heat loss.

Aluminium has a high **thermal conductivity**. The heat transfer through aluminium can be controlled by incorporating thermal breaks of low conductivity materials (such as PVC (Polyvinyl chloride), neoprene rubber, polyurethane …). These thermal breaks can take the temperature differences between the exterior and interior of the frame material. Another option is the utilisation of pressure plates and gaskets. The plates are attached to the outside of the mullions and the gaskets function as thermal breaks between the plates and the mullions (Klein, 2013).

To minimise **condensation** due to variations in temperature and humidity, careful design of air barriers and insulation is required. Large variations in temperature and humidity occur in opaque wall areas. A good placement of insulation at the perimeter is important to reduce energy loss and potential condensation issues (Web 3-06).

The performance of a curtain wall depends on the theoretical U-value, also called the **overall heat transfer coefficient** (Figure 3-17). The U-value takes aspects like convection, conduction and thermal radiation into account to come to a representative value. The value will depend on the efficiency of different aspects of the structure: profiles, isolator, pressure plate, gaskets, screw material and the IGU (Klein, 2013). The lower the U-value, the higher the efficiency.

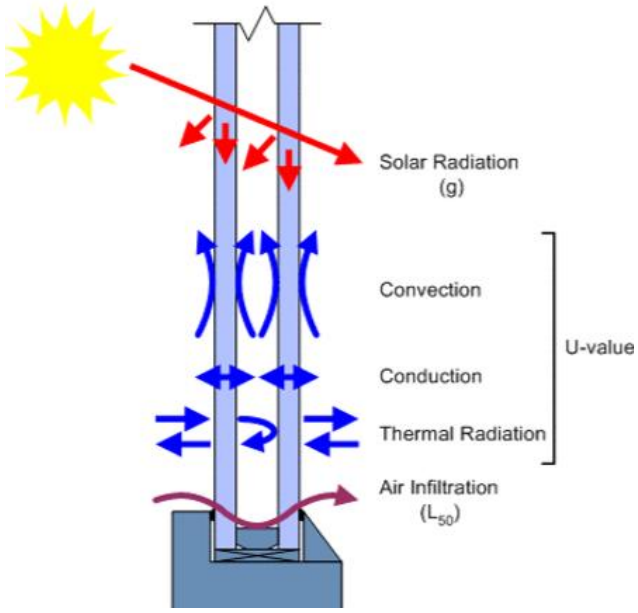


Figure 3-17: Principle of the U-value (Web 3-09)

For reaching a better thermal performance, one can make use of layers. Therefore, most panels of curtain wall systems are made of different layers (currently mostly three layers) in combination with coatings. This is called an **IGU** (insulated glass unit) (Figure 3-18). To ensure proper insulation of this unit, the edges are foreseen of interior and exterior sealants in combination with spacers filled with gases. The production of these units is standardised, but still has a lot of flexibility, which makes optimisation of the unit for a specific project possible. Units with four layers of glass would result in a too large thickness and a low visual quality, making them less useful. In addition, the weight would be too high to be carried by the supporting frames that are available today (Klein, 2013).

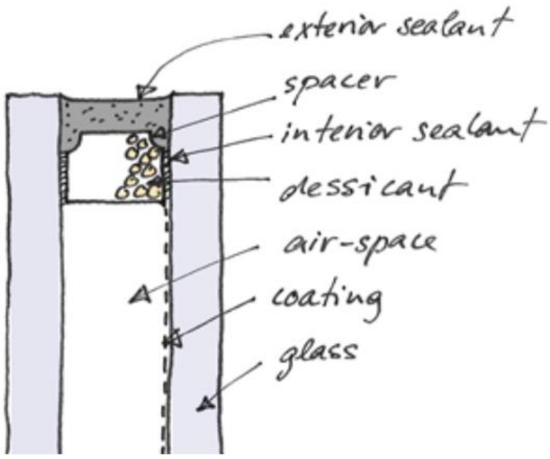


Figure 3-18: Insulated glass unit (Klein, 2013)

Maintenance and repair

The durability of the curtain walls is related to deterioration that originates from different causes. Failure of sealings due to water exposure, thermal or structural movements, UV (ultraviolet) degradation, ageing and environmental degradation in general make repair necessary. Reparation requires surface preparation and proper detailing which makes it a costly job.

Furthermore visual obstruction can occur due to the accumulation of dirt, damage, condensation … on the structure. Therefore, regular inspection and maintenance is required, which makes easy and safe access indispensable. Often, the aluminium frames are foreseen of a coating by painting or anodising, which helps the resistance against corrosion or other environmental degradation. Coatings can increase the time between consecutive periodic cleaning moments (Web 3-08).

Fire protection

When a curtain wall is constructed with an aluminium lightweight frame, the building needs to be protected against fire attack. Therefore, backup walls or suitable infill panels with independent fire resistant fixings are mostly used. The gaps between the floor slab and the back of the curtain wall need to be sealed well (Muhammad, 2010). For emergency cases, the appliance of fireman knock-out glazing panels is possible. These panels, mostly made out of fully tempered glass, make it possible to enter from the exterior on a relatively safe manner by full fracture of the panels (Web 3-08).

Differential and thermal movement

The construction of the different systems is optimised to allow the differential movement and thermal movement of the structure and the deflection due to the transfer of wind loads to the main structure. However, the design of the structure must be optimised to make sure that the deformation does not exceed the maximum allowable deflection. In **stick systems**, the mullions run vertical along several floors, making periodical splits between them possible to allow the movement and on the same time to provide resistance using lateral anchors. In **unitised systems**, the movement is also provided by an anchoring system. The anchors, situated in the floor, allow the movement in plane and lock the relative displacement out of the plane (Hachem et al., 2014) (Kassem & Mitchell, 2015).

3.4.1.2 Comfort increasing functions

In this section, the efficiency of a curtain wall façade with respect to the comfort increasing functions (Figure 3-19) like solar control, heat gain, daylight control, acoustic control, natural ventilation and energy gain is investigated.

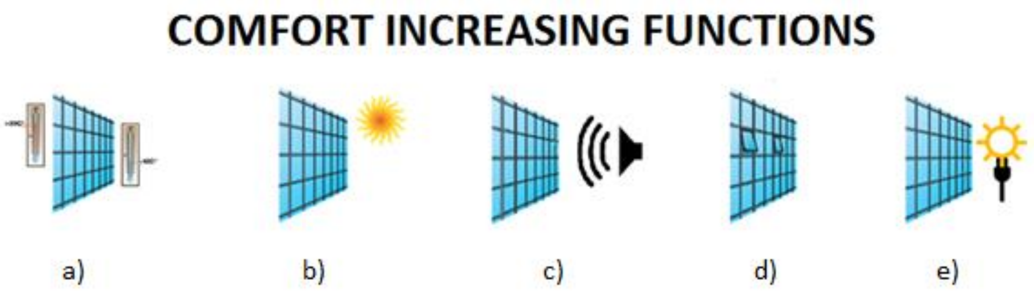


Figure 3-19: Comfort increasing functions

Solar heat gain

Heat control is of major importance for the internal comfort and energy use of the building. Reducing energy loads (cooling, heating ...) and high efficiency of energy generation can be combined in a proper way. In addition, smaller peak loads can be obtained by damping of the load fluctuations.

To control the solar radiation with curtain wall systems, the different possibilities that were explained in section ‘3.2.2.1’ can be applied to the system. When vision glass panels are used, the use of IGU’s can be very effective. Next to the application of an IGU, spectrally selective solar control, angular selective solar control, solar filters and exterior solar control are all systems that can make a curtain wall system more efficient. Reflective glass can be used to keep solar rays out of the building and to prevent unwanted heat gain. Coatings can be efficient to retain a certain amount of heat to warm the building during nights and winters (Muhammad, 2010). Another efficient system for controlling the solar radiation is making use of a solar dynamic buffer zone in the curtain wall systems. In this buffer zone, solar energy can be efficiently gathered or excluded by making use of air flow (Li et al., 2015).

Daylight control and visual aspects

Using glass as infill panel for the 'curtain wall' results in the penetration of natural light deeper in the building. The problem with glass or other used infill panels is the complexity to combine the control of thermal and visual comfort (Web 3-10).

Essential for the entering of daylight through a façade is the **transparency** of the panels. Variation of the **proportion of opaque distribution** has an effect on the light distribution and also on the heating and cooling loads and daylight illuminance. If photovoltaics are integrated in the façade (see below: energy gain), the regulation of the light transmission can be adjusted by changing the spatial distribution between the photovoltaic cells. For a good optical performance, mostly semi-transparent photovoltaic panels are used (Web 3-08).

Glass is the key factor when considering visual features, but **sightlines** are essential as well. The visual comfort is directly related to the vertical and horizontal mullions that define the sightlines of the curtain wall panels. These sightlines are related to the depth and width of the frame. The lateral load resistance of the frame is also related to the depth. The depth requirements depend on the wind loads and spans. Narrow sightlines are better for the visual comfort. To reach the necessary lateral load resistance, steel stiffeners can be used to strengthen the aluminium frame with a smaller depth and better visual performance (Web 3-06).

Glare

Reflected glare is a significant problem for curtain wall systems, directly related to the used material. The amount of glare depends on the geographic location of the project (orientation, climate …). When reflective glass is used to obtain reduced penetration of solar radiation, exterior reflections can have a negative impact on the environment. Highly reflective glazings can result in 20-40% of reflectance (Web 3-11). The tilt angles and the orientation of the panels can efficiently reduce the effect of reflected glare on the neighbourhood (Shih & Huang, 2001).

Acoustic performance

The acoustic performance of a curtain wall façade is a bit dubious. Curtain wall façades are normally designed to be as lightweight as possible. However the sound transmission is inversely proportional to the mass of the barrier. So, for sound insulation, a more heavy construction is favourable. The infill panels mainly determine the acoustic performance of the curtain wall, therefore double glazing is usually essential. Apart from double glazing, laminated glass layers that exist of a noise-reducing interlayer (polyvinyl butyral) or other sound attenuating infills can be used (Web 3-08). Furthermore, varying with the thicknesses of the glass layer in an IGU can reduce the infiltration of exterior noise as well. For the acoustic performance, the air tightness of the system is also of main importance (Kassem & Mitchell, 2015).

Ventilation

Curtain walls can allow large windows which are very efficient related to natural ventilation in summer. In the design, the opening of the windows should be taken in mind by allowing the curtain to roll up or to be removed to maximise the opening area. Larger opening areas result in larger ventilation rates.

Energy gain

As previously mentioned, curtain walls are capable of efficient energy gain by the use of for example photovoltaic curtain walls. The integration of photovoltaic cells and the filtering of UV and infrared radiation make these walls very qualitative. Photovoltaic curtain walls can be efficient for thermal and acoustic insulation as well (Web 3-12).

3.4.1.3 Advantages and disadvantages

Curtain wall façades can be very efficient to create buildings with a good energy performance. Table 3-2 below gives an overview of the properties of a curtain wall façade.

Table 3-2: Advantages and disadvantages of curtain wall façades

CURTAIN WALL FAÇADE	
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	

3.4.2 Double façades

Similar to the design of curtain wall façades, the design of double façades should be optimised to fulfil not only the essential requirements but also functions to improve the comfort and performance.

3.4.2.1 Essential requirements

The design of a double façade needs increased attention for **fire protection**. Problems can be caused by the smoke transmission from room to room in case of fire. The risk depends on the type of double façade. In a double-skin façade all rooms are linked with each other, which forms a high risk for fire transmission. A box-window façade performs much better in terms of fire protection because the different rooms are not linked to each other. In shaft-box façades, the only connection between the rooms is the ventilation shaft, so the risk for fire transmission stays low. The corridor façade performs less in terms of fire protection because the linking of the rooms on the same storey increases the risk factor for fire transmission (Poirazis, 2004).

Applying shading systems in the intermediate space of double façades is efficient for the **maintenance**, because these systems are not exposed to the exterior weather conditions. However, when building a double façade, attention has to be paid for the accessibility for maintenance and repair. A platform can be used to reach the interior space for cleaning. If there are shading systems in the cavity, they must be able to be moved to facilitate access. In buildings that make use of more divided air cavities (corridor, shaft-box, box-window façades), the interior panel layer can be used as access panel to enter the space (Boake et al., 2003).

3.4.2.2 Comfort increasing functions

The double façades are mostly optimised to have efficient performance with respect to ventilation and the control of solar radiation (Lee et al., 2002). If occupants are able to control light penetration by controlling louvers or other shading devices that are installed in the air cavity, the productivity of the working people will also be influenced in a positive way. In addition, the regulation of air movement and temperature is possible with operable windows, which has a positive influence on the health of the occupants.

Solar heat gain

The primary purpose of a double façade is mostly to reduce the solar heat gain. This to make natural ventilation or low energy techniques sufficient for a good interior comfort. External shading elements are very efficient to reduce solar gain, but they decrease the exterior views and have complex maintenance requirements. Therefore, double façades with intermediate shading systems are often an interesting solution.

Intermediate **shading devices** help to improve heating and cooling problems. These devices are placed in the air cavity. This is also called a heat extraction double-skin façade. The shading devices offer opportunities for heat recovery and heat extraction depending on the situation. Mostly the shading devices are operable blinds, controlled by the occupants or by sensors. These shading systems are a kind of vertical shield that is efficient for all solar angles. In addition, they can be raised in case of cloudy weather conditions. Except for controlling the solar heat gain, the efficient use of daylighting combined with the maintaining of good exterior views is possible (Boake et al., 2003) (Lee et al., 2002). The precise position of the shading systems in the intermediate cavity is important because there has to be adequate room for air circulation on both sides. Inadequate air flow can occur if the system is placed too close to the inner layer. Mostly the shading systems are positioned in the outer half of the cavity (Lee et al., 2002) (Poirazis, 2004).

A double-skin façade has the additional advantage that it can reduce the heat losses during **winter**. The rate of the heat transfer on the panels is lowered by the increased temperature in the air cavity. This results in a higher surface temperature of the inside panel. For the winter, thin cavities are the best because they have the highest efficiency for preheating of the ventilation air due to a higher air velocity inside (Poirazis, 2004).

During **summer,** the warm inside air in the cavity can be extracted during ventilation and reduce the cooling loads of the building. This is based on the stack principle that takes additional heat with the rising air and acts as a thermal buffer. The stack effect in a double-skin façade is a process that is related to the air density between the exterior and interior layers of the double-skin. This density increases due to heat generation from the greenhouse effect (air that enters the building is continuously heated by solar gains). This increase brings pressure and temperature differences in the space between the interior and exterior layers. The heated air will rise and escape through the openings at the top and cooler denser air will enter at lower openings (Web 3-13). The stack effect can be optimised by the use of vertical divisions (shaft-box façades), which makes division between low and high occupied spaces possible (Poirazis, 2004). In addition by using 'spectrally selective glazing' the light can enter the building while the heat is kept out by only allowing the entering of that part of the sun's energy that is useful for daylighting purposes (Lee et al., 2002).

Ventilation

Natural ventilation

Natural ventilation uses air flow to cool and ventilate the space instead of mechanical means. A double layer creates a layer of air next to the first layer that forms the wall of the building. This creates a buffer zone which allows occupants to make efficient use of natural ventilation. For a better natural ventilation the buffer zone can be split up in compartments using the box-window, corridor or shaft-box façade. This can reduce the heat transfer (but also smoke and noise transfer) from one area to another area. The box-window façade has the opportunity to open windows for proper natural ventilation without grouping together of air of different rooms. Corridor façades can be efficient to maximise natural ventilation as well. These façades possess fresh air and exhaust intakes at every floor. In shaft-box façades, a number of cavities are grouped into a single shaft. For both corridor and shaft-box façades, caution should be paid to the mixing of fresh and foul air (Boake et al., 2003) (Poirazis, 2004).

Night-time ventilation

In climates with enough variation in diurnal outdoor temperatures, advantage can be taken to cool down the thermal mass of the building during night. This to avoid problems with accumulated heat during the day. Night-time ventilation results in lower indoor temperatures during summer in the morning and provides thermal comfort and improved air quality. By using this kind of pre-cooling principle, the need for mechanical air conditioning can be reduced (Lee et al., 2002).

Mixed mode

A good solution is to combine the mechanical active ventilation and cooling with natural passive ventilation. This combination can improve the indoor air quality and results in mixed-mode or hybrid ventilation. Mixed mode ventilation is possible in different ways. Firstly, alternating operation and changeover operation are possible. In addition, concurrent operation, in which both systems work at the same time is an option as well. To work more efficiently, some buildings are partitioned in zones where one applies different conditioning strategies (Lee et al., 2002).

Daylighting and glare

The double façade can improve the use of natural daylight by applying the right infill panels such as glass panels. The **transparency of the panels** is directly related to the amount of daylight that can enter the space. The daylight improvement by a double façade is not spectacular. Mostly the daylight properties are the same as single skin glazed façades. However, the additional skin results in a reduction of the quantity of light that enters the building. This is compensated by the allowance of larger areas of glazing in double façades, which increases the amount of daylight that can enter. The most complex aspect in the design is to combine a transparent façade with a good energy performance and indoor thermal climate (Poirazis, 2004). When a completely glazed façade would be used, this would result in excessive glare (and heat) at certain times of the day. To reduce the problem of glare, solar shading devices can be efficient.

Acoustic performance

In a few cases, a good sound insulation is the primary reason for applying a double façade. In that case, a double façade is more efficient than a curtain wall façade. With a double façade, the possibility exists to lower the external noise transmission. An extra layer can create an acoustic buffer against exterior noise. In addition, the application of an extra air path by the intermediate space of the double façade results in more control over the noise infiltration into the building. Moreover, using a double façade instead of a single skin lowers the effect of opening a window on the noise infiltration into the building. The acoustic transmission from room to room can be lowered as well. The type of double façade and the number of openings are the primary parameters for the acoustic performance (Poirazis, 2004).

The most efficient **type of double façade** depends on the performance that the designers want to achieve. A double-skin façade performs good in terms of external noise levels, but it has some problems with the sound transmission within the intermediate space between adjoining rooms and levels. A box-window type is good when both the external noise and requirements about the sound insulation between adjoining rooms are important. In contrast, a shaft-box façade performs better in comparison with a box-window type when the primary objective is the external noise insulation. This is a result of the fewer air openings in the shaft-box façade compared to the box-window façade. Corridor façades are not suitable for acoustic performance because of the large problems with sound transmission from room to room (Poirazis, 2004).

The sound insulation depends on some more factors such as the **weight** and **configuration** of the glass. In addition, the **depth of the cavity** is of major importance. Heavier glass, applying different thicknesses and a deeper air cavity will result in better sound performance of the double façade.

3.4.2.3 Advantages and disadvantages

Based on the study about the possibilities to improve the performance of the building by the design of a double façade the following table (Table 3-3) with advantages and disadvantages is obtained.

Table 3-3: Advantages and disadvantages of double façades

DOUBLE FAÇADE	
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	

3.4.3 Overview curtain wall façade and double façade and cost comparison

In the two previous parts, the performance of the curtain wall façades and the double façades in relation to the different functions that may improve the comfort in a building was studied.

Table 3-4 gives, based on the knowledge that was obtained, a good overview of the different types and functions. This makes it more easy to compare the different possibilities and to make an efficient and knowledge based decision for applying a specific type of façade for a certain type of project. To decide which type of façade will be the most efficient, the specific situation must be carefully considered and the functions that one wants to optimise should be defined.

Table 3-4: Overview diagram for façade types and functions

FUNCTIONS / TYPES	Thermal comfort	Daylight	Glare	Visual comfort	Natural ventilation-air quality	Energy storage	Acoustic control
Curtain wall façade	+++	+++	+/-	+/=	+	++	+
Stick							
Unitised							
Frameless							
Double façade	+++	+	+	=	+++	+	++
Second-skin					+/-		+/-
Box-window					+++		++
Corridor					++		-
Shaft-box					++		+

3.4.3.1 Highlights curtain walls

When curtain walls are designed in a proper way, they have the capacity to perform better related to energy (less need for HVAC (heating, ventilation, and air conditioning) installations), resistance to condensation, internal comfort, view and light quality and resistance to rain penetration and sound control. Curtain walls that use glass infill panels can give huge benefits for daylighting. The filtration of natural light into the building is possible. However, if glazed curtain walls are used, it is difficult to control the solar gain on the same time.

Curtain walls can range from standardised products out of catalogues of manufacturers to specialised custom walls. When the area of the wall increases, the cost becomes competitive with standard systems. Curtain wall systems are able to recycle a lot of material and take less useful place of the building than double façades.

Besides the many advantages, curtain walls have some drawbacks as well. First of all, regular maintenance is necessary, certainly for the sealants that are applied to the curtain wall for keeping the moisture and wind out. Secondly, the installation of a curtain wall is an extra cost and requires time. To gain installation time, the unitised system can be used instead of the stick system. The disadvantage of unitised systems is the extra cost for shipping and storage of the prefabricated modules.

3.4.3.2 Highlights double façades

Double façades can lower the costs for the use of HVAC systems by increasing the natural ventilation in the intermediate cavity. In addition, a better control and an increased access to daylight are possible as well. By placing shading devices inside the cavity, protection against heat and heat extraction are realised. In that way, a good performance of thermal insulation can be achieved both during winter and summer (Boake et al., 2003).

The double façades have also some drawbacks. Firstly, problems with condensation on the inner side of the outer glass panel are possible. Secondly, double façades need a certain space of the building volume. To avoid overheating problems by the increase of the temperature in the cavity, the cavity between the layers should not be too thin. A wider cavity is good for less transmission of heat by convection which results in improved thermal comfort conditions next to the walls. The thickness of the intermediate cavity can vary from 20 cm to several meters. This is a loss of useful space for the interior of the building. If this thickness is kept over the whole cladding of the building, this will result in larger costs. In general, double façades will be more expensive than normal curtain wall systems. The optimum depth finds a balance between the space losses by making it deeper and the thermal losses by making the cavity more narrow (Poirazis, 2004) (Web 3-07). The total cost of the double façade depends on the used configuration, the used façade skin, integrated shading systems … To lower the total cost, standardisation and large scale production is necessary. Except for higher costs, the design of double façades requires a lot of engineering expertise and contractor expertise and experience. The drawbacks of the system often makes it only cost-effective for noisy locations and high-rise buildings.

In Europe, double façades are twice as expensive as conventional types. In the U.S., this can be even four or five times the cost of a conventional façade. This difference is related to the higher engineering costs and higher installation costs due to a lack of experience of the craftsmen in America. In contrast, Europe has a higher energy utility cost which makes the investment of a double façade more beneficial by a faster compensation of the initial cost due to less need for mechanical HVAC systems (Lee et al., 2002). In addition, the working conditions for occupants of the building are better by the improved indoor quality, which results in more productivity and a better health of the employees. This has a positive effect on the labour cost. The operational costs of double façades are lower but the maintenance of the façade involves a higher cost than for the conventional façade.

Double façades give obviously increased installation and maintenance costs. Therefore, it is most reliable to use these façades only on the places where there is need for, which is in most situations not on all sides of a building. This alternating application of a double façade and a single façade can result in more cost-effective and economic solutions.

3.4.4 Orientation of the façade

The different adaption to physical functions for obtaining a good interior comfort (related to day and night situations) depends on the orientation of the façade. Table 3-5 gives an overview of the differences between the different orientations and is reflected in plusses and minuses to give the level of adaption.

Table 3-5: 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 façade is different
Dehumidification	--	++	--	++	--	++	--	++	Similar for every orientation
Natural ventilation	--	--	--	++	--	+	--	+	North façade is different
Daylight	--	o	--	++	--	+	--	+	North façade is different
Overheating control	--	-	--	++	--	+	--	+	North façade is different

This table is interesting in order to know how much the façade should be able to adapt. The term 'absolute' refers to the fact that the absolute differences that occur during all seasons are showed and not for every season separately. 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 (Van Dijk, 2009).

3.4.5 Conclusions

This chapter investigated the opportunities of the different types of façades to improve the indoor comfort and performance of the building. Both curtain wall façades and double façades possess qualities to be designed to improve thermal comfort, control of daylight and glare, exterior views, natural ventilation, energy gain and acoustic control.

Curtain walls perform best with respect to internal thermal comfort, exterior views and daylighting benefits. The acoustic control is mostly sufficient as well. In addition, curtain walls possess the opportunity to recycle material and lower the energy use in an significant way. Double façades have a huge opportunity for better natural ventilation and night-time ventilation. In addition, the shading devices that are placed in the intermediate space are better protected. The double-skin can increase the thermal insulation and saves a lot of energy.

Except for their advantages, both systems have some drawbacks as well. Both systems result in an increased installation cost and time. The combination of a good daylight control with thermal comfort is mostly complex, certainly when glazing panels are used. Double façades have the main disadvantage that they use a lot of useful space of the buildings. In addition, the thickness of the double façade results in an even higher increased cost. Depending on the type of double façade, the occupants can be faced with acoustic problems as well.

The needed level of adaption depends on the orientation of the façade. A promising solution is to use a simple wall construction for the whole building, combined with an advanced façade system on the façades where it is most efficient. The places where the construction of these extra systems is the most efficient are usually the south and west/east façades, on which the solar and daylight control is most necessary. An exterior façade shading system (curtain wall façade) can be effective on a south façade because of the high position of the sun. West and east façades can be problematic due to the lower solar angles. Double façades can be efficient on these places because they foresee a vertical shield that is effective for the lower position of the sun.

3.5 Climate zones

In the previous parts, the type of façade and the different functions were discussed. However, the need for a façade to optimise one or more specific function(s) of the façade is different for different geographical locations in the world. For the design of a building and its façade, it is important to know the climate conditions of the region. 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. For the division, annual and monthly average temperature, precipitation and seasonality of precipitation were taken into consideration. The classification system divides the world into five main groups of climates (Figure 3-20): the **Polar, Cold, Moderate, Subtropical and Tropical** climate (Web 3-14). The building related problems are specific for each zone. In the following chapter, the different problems for the climate zones are studied. This overview can help to know which functions should be optimised in the design of the façades.

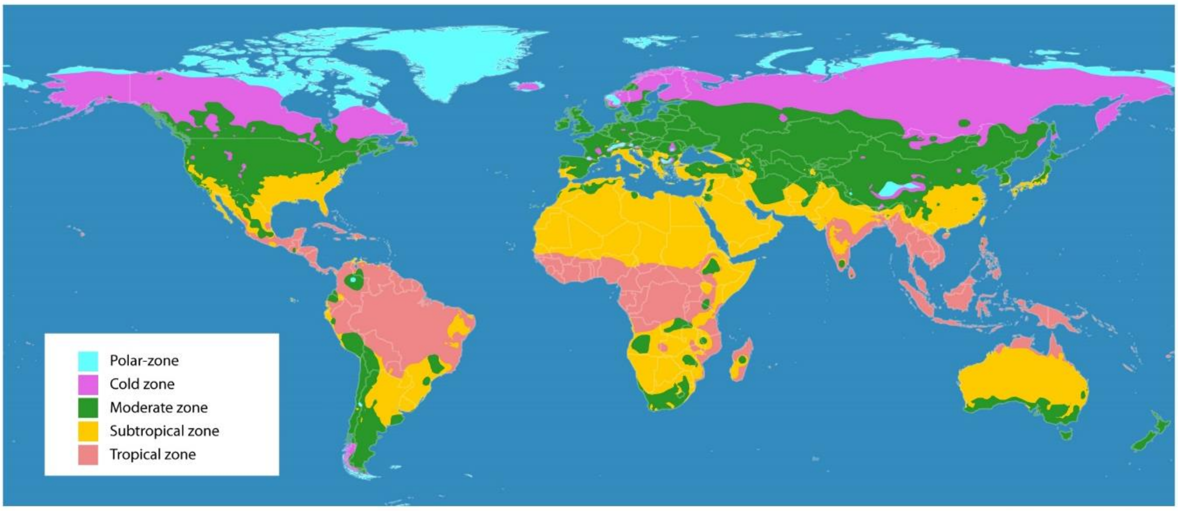


Figure 3-20: The five climate zones (Web 3-14)

Figure 3-21 gives an overview of the typical temperature fluctuations and the amount of precipitation for each climate zone.

Climate zone	$T_{average}$ (°C)			Precipitation
	year	hottest month	coldest month	mm/year
1. warm and humid (Paramaribo)	26	27	25	2800
2. warm and dry (Cairo)	19,5	24	15	80
3. moderate (Netherlands)	13	23	4	800
4. boreal (Siberia)	1,3	20	-14	500
5. ice climate (Greenland)	-8	4	-20	580

Figure 3-21: Temperature and precipitation of the climate zones (Van Dijk, 2009)

3.5.1 Humid-warm climate / Tropical rain / Equatorial

The first type is the tropical climate which is situated around the equator and his adjacent regions (Amazon Region, South and Central America, Central Africa, Southeast Asia, India, Northern Australia). 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.

This climate type needs **sun protection and ventilation** elements. A continuous air circulation for heat dissipation and natural ventilation are essential. Shading to protect the building from the sun is crucial as well. For cooling the houses, adiabatic cooling can be used. Buffer zones are often integrated to create micro-climates in the buildings (Barbosa et al., 2015) (Bilow, 2012).

3.5.2 Dry climate / Arid / Subtropics

The transition between the tropics and the moderate zones is formed by the dry climate. Regions like North and South Africa, North American West Coast, southern parts of South America, Australia and parts of China make part of it. 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). Protection against the high heat absorption from direct solar radiation is critical in a dry climate. The large daily temperature fluctuations can be used in an effective way to protect against overheating. For the **cooling** needs, the air exchanging principle can be applied. Apart from cooling, the supply of **daylight** should be controlled and a maximum **natural ventilation** should be foreseen (Bilow, 2012).

3.5.3 Warm moderate rain climate / warm temperate

Locations like Berlin, Belgium, Shanghai, New York, London … are situated in the warm moderate climate zone. 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 transition periods between the coldest and the hottest months extend with increasing distance from the equator. 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).

3.5.4 Boreal or snow forest climate / Cold

The boreal climate is typical for the northern areas including large parts of Russia, northern parts of Canada and Greenland. A good covering and **mass** of the houses is necessary to keep them warm and insulated by acting as a **temperature buffer**. A summer-cold climate needs a low thermal conductivity in their building material to provide a good insulation. 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. It is important to use **air flow efficient** to heat these buildings, in combination with mass as storage medium (Grynning et al., 2014) (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. Strong **insulation** and **wind protection** is crucial. The application of a layering principle can be very effective in a polar climate. Transparent glass can only be used in combination with good insulation by the application of for example double glazing (Bilow, 2012) (Muhammad, 2010).

3.5.6 Sun path

The path of the sun differs a lot in the different climate zones of the world. The characteristics of the path are essential for the sunshade requirements and efficiency. Figure 3-22 gives an overview of the characteristics of the sun's path for each zone.

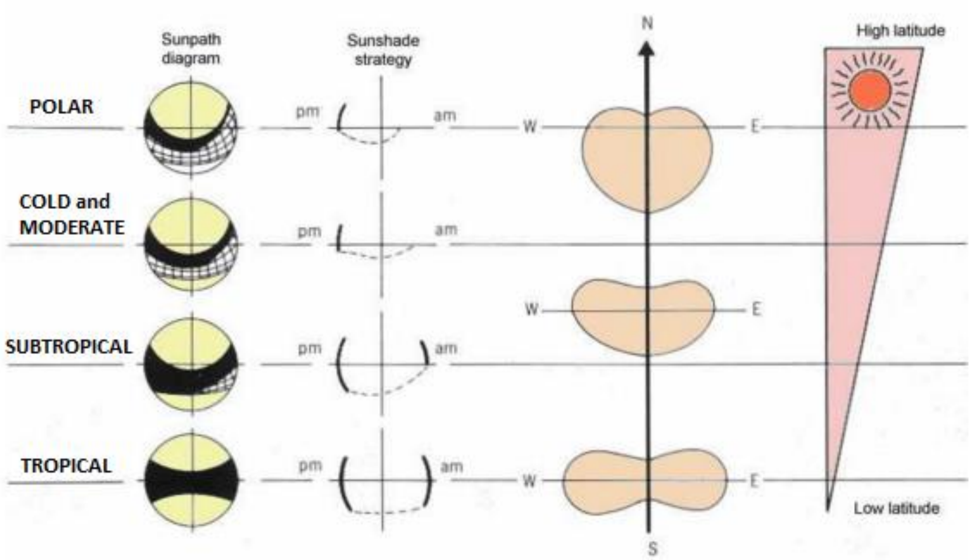


Figure 3-22: Sunshade analysis (Web 3-15)

In the **tropical zones**, with a low latitude, the sun path diagrams is shaded over the whole area where the sun will come during the year. This means that there is total overheating. In zones with a higher latitude, overheating only occurs during the summer months (**cold** and **moderate zones**). As mentioned before, the efficiency of a horizontal or vertical sunshade element depends on the situation. In the morning and the evening, vertical sun shading is efficient to block sun from low sun angles. Horizontal blocking is most efficient for high sun at noon. Tropical regions need both horizontal and vertical sun shading elements during the whole year. The higher latitudes only need shading on the south facing façades because the sun path is more southwards than the heart-shape pattern of a tropical climate. **Solar heating** is important for the higher latitudes and **solar shading** is more important for the lower latitudes (Web 3-15).

3.5.7 Overview

Based on the knowledge that was obtained in the previous parts, an overview of the required principles for the buildings of the different climate zones is given in Table 3-6.

Table 3-6: Characteristics for each climate zone (Adapted from (Bilow, 2012))

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*

The table shows that every climate has a main problem that has to be tackled in the building design. In cold and polar climates, the main problem is the lack of heat. A moderate climate is characterised by the seasonal variation between the need for heating and the protection against overheating. The subtropical, hot-dry climate, has the main problem of overheating but this climate has the advantage that the air is dry. In addition, large diurnal temperature variations occur in this type of climate. The tropical, warm-humid climate, also suffers from overheating (but not as much as in subtropical climate). In this zone the effect is aggravated by the high humidity and small diurnal temperature variation.

The total solar excess degree does not differ much between the different climates, it is the distinction between the **cooling degree** and the **heating degree** that varies between the climates. The cooling degree is largest in the tropical climate and subtropical climate. A temperate climate has a lower cooling degree than the tropical and subtropical climate. Contrarily to the cooling degree, the heating degree is (almost) zero in a tropical climate. A subtropical climate has a low (but not equal to zero) heating degree, due to the large diurnal temperature variations. In the temperate climate, the heating degree increases and it is largest in the cold and polar climates (Haase & Amato, 2009).

The **optimum orientation** for a building differs for the climate zones as well. The orientation should be optimised to face minimum solar radiation during overheating periods (summer) and maximum summer radiation during winter. Most often, the two optimum orientations are not 90 degrees in shift to each other, so a compromise between the two orientations must be found. In a tropical climate, the smallest façade should be oriented towards the highest radiation and the largest façade 90 degrees to that orientation. The façades in a subtropical climate need to be oriented for maximising the use of the winter sun and still avoiding overheating problems.

Natural ventilation can be efficient in tropical, subtropical and moderate climates. A tropical climate can have a high ventilation efficiency during the whole year. In a subtropical climate, the efficiency is lower and more situated in the months April, May, September, October and November. A temperate climate is characterised by its seasonal need for ventilation. During winter, ventilation should be kept as low as possible. The highest efficiency can be achieved between May and September (Haase & Amato, 2009).

3.5.8 Conclusions case studies

In this section, an overview of the climate characteristics of the different zones and the required functions of a façade were investigated. When Table 3-6 is studied in combination with the case studies about realised adaptive façades and prototypes (see Appendix A), some conclusions can be taken. In the cold and polar zone, few examples exist of adaptive façades. Mostly, a cold climate only needs large heating and good insulated walls. The only profit that can be taken is to guide the buildings towards the south and gain as much heat as possible by sun energy radiation. For the cold zones, a possible innovative system could be to design a façade that exists of a thermal insulation skin that allows daylight to enter during summer and that can be shut off during winter time to insulate the building as good as possible. The designers have to try to use the low amount of available daylight in the most optimal way.

The most examples of adaptive façades are currently situated in the moderate and subtropical climates. Most façades are optimised for solar, daylight and glare control, sometimes in combination with effective natural ventilation. Both double façades and curtain wall façades are present. Mostly the adaptive structures are present at the south and/or east and west side. The tropical climate zone also possesses some examples of adaptive façades but the amount of examples are less than in the moderate and subtropical zone.

3.6 Sustainable building

The main purpose of a façade is to make buildings more sustainable (Figure 3-23). The design is focused on the creation of a building with a **low total life cycle cost, low environmental impact and high comfort** for the end-users/individuals. These sustainable buildings can result in a more efficient way of living and support economic gain, social comfort and environmental effort.

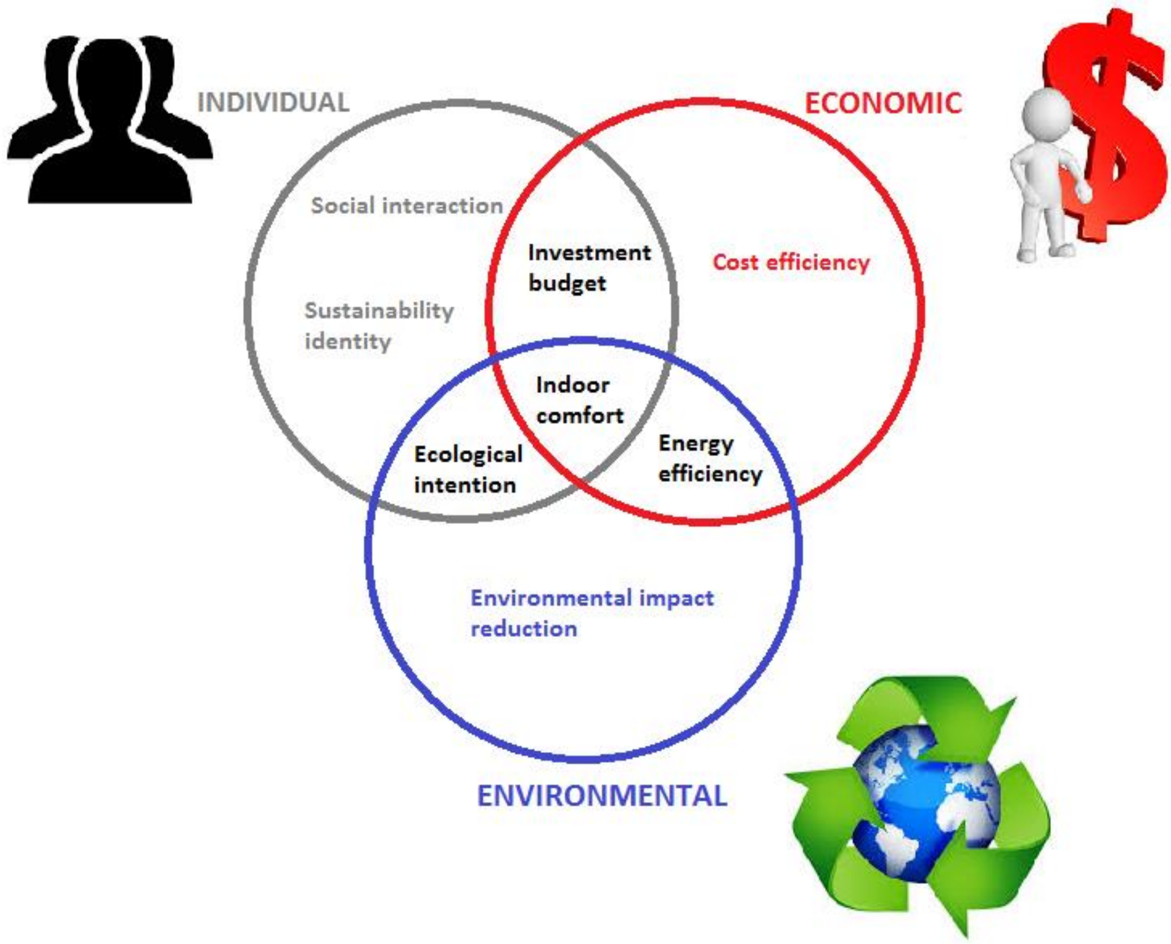


Figure 3-23: Sustainable building

Figure 3-23 gives an overview of the different aspects that are involved in the design of a **sustainable building** and more specific the façade. A sustainable building tries to lower the impact of changes in the environment. Based on the budget that the builder wants to spend on lowering the impact of the building on the environment, more efficient use of energy can be implemented in the building design and in the design of the advanced façade. The budget of the builder will also determine the amount of control that the occupants will have on the adaption of the behaviour to lower impacts based on the ecological intention of the users. The interaction of all aspects will determine the indoor comfort of the building.

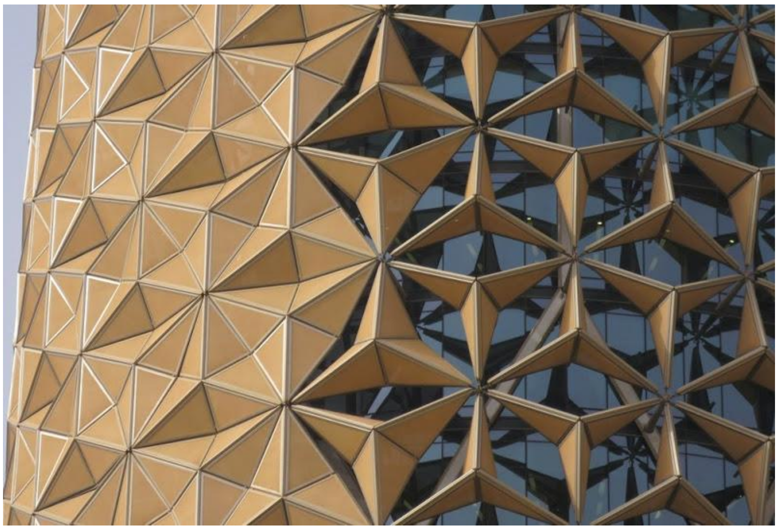
The previous parts show that different possibilities exist to improve the performance of a façade. The **envelope** is the most effective part of a building for innovative systems to save more energy and to generate alternative energy. Decentralisation of the functions of the building to the façade creates the opportunity to make energy efficient façades that are able to adapt according to the current changing climate. Curtain walls and double façades can regulate different functions that contribute to the performance of the building. Some functions are more easy to regulate than others. The climate change and waste of material are worldwide problems to which structural adaptive façades can give an efficient answer.

Advanced façades are accompanied automatically by an increased first **cost** for the clients. The advantages of these façades need to convince the clients to invest this higher building cost compared to conventional façades and to take the advantages of energy and productivity savings later. Integrated façades result in lower life cycle costs because operating, maintenance and replacement costs are reduced. The overall operating costs are linked to the annual energy cost which depends on the demand for heating, cooling and lighting. Integrated façades are not suitable for people who want to build as investment, because they want to build at the lowest possible cost.

To design an interactive façade, a **team of experts** needs to work together. The construction of a functional, comfortable, energy efficient and aesthetical integrated façade requires a lot of expertise and specific knowledge. Designing advanced façades includes knowledge about thermodynamics, material sciences, air flow, lighting and daylighting, HVAC equipment … As a result architects, engineers and natural sciences experts contribute to a multidisciplinary design culture. This team of different experts need to make important design decisions. The decisions in the early phases have the biggest impact on the project lifecycle and building performance (Kassem & Mitchell, 2015).

The design of a façade is often based on focusing on **one functional parameter** but forgets to take the interactions between different functions into consideration. Mostly the design team focuses on the thermal problem or daylight problem respectively. For façades, parameters like window dimensions, construction material, insulation thickness, glazing type, building orientation ... all are of great importance. These parameters are able to regulate different functions of the building. Therefore, focusing on only one aspect is not efficient (Lee et al., 2002). Solar control can be efficiently combined with the gain of solar energy by introducing building integrated photovoltaics in the façades. A future area in building façades should focus on the creation of integrated façades that take **more than only one function** into account to further increase the performance of the building (Klein, 2013).

Apart from the design of an interactive façade, the **construction** of a building is a complex process too. The design evolves over time and often early design decisions are changed during the building process. Different manufacturers are involved in the construction of the façade. This makes a good coordination essential. The different applied systems need to work properly together, which is not always an easy job (Lee et al., 2002).



> 'An adaptive façade has the ability to adapt, in real time, some of its functions, features and behaviour in response to changing environmental conditions, performance requirements, occupants' wishes or other boundary conditions. '
>
> - Chloë Marysse -

ADAPTIVE FAÇADES

4 Adaptive façades

4.1 Introduction

During the last years, the popularity of low-energy buildings has increased enormously due to the raising climate challenge. Buildings are responsible for a large part of the global energy consumption. 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. 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) (Ibáñez-Puy et al., 2015). During the last years, researchers have already gained a lot of knowledge about passive design strategies for buildings and further research is still going on. These efforts result and will further result in a lot of promising future applications.

Traditional, static buildings make use of fixed systems that possess no **flexibility**, which results in robust building designs. A robust design is typically oversized, with redundancy to deal with changing properties. This redundancy is necessary to manage unexpected conditions and implies a large cost. In addition, the buildings are typically equipped with a lot of HVAC systems that increase the cost of energy consumption. 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 and redundancy (Loonen et al., 2013). The adaptive quality lowers 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). It is self-evident that the adaptive systems need to be optimised for the specific type of climate in which they will be used. Next to the type of climate, the season and the daytime or night-time play an essential role for the façade (López et al., 2015).

In this chapter, the characteristics of adaptive façades and their specific type of movement and control will be examined in detail in order to come to a global classification system. This will allow to give a structured overview of which applications already exist and which domains need further examination and development. The classification is also useful to combine with the findings about the adaptive needs of the different climates to design promising applications.

4.2 Definition

The definition of the term ‘adaptive’ is not univocal. To formulate a good substantiated definition that will be used in this thesis, some definitions in literature are examined first.

Loonen (2013), who did a lot of research and wrote papers about adaptive façades, gives the following definition: ‘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) supports the use of the term ‘adaptive’ in his work about façades as follows: ‘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).

Hoberman focuses with his Adaptive Building Initiative on adaptive façades and building envelopes. He promotes the use of adaptive systems in the following way: ‘By controlling light levels, solar gain and thermal performance, our adaptive systems reduce energy usage, enhance comfort and increase the flexibility of the built environment’ (Web 4-01).

Also De Boer (2012) writes about which requirements define an adaptive façade: ‘Adaptive façade technology for increased comfort and lower energy use in the future is that buildings with climate adaptive thermal and daylight properties will have a much better energy performance while maintaining a high comfort standard. The development of CABS (climate adaptive buildings shells), based on theoretically ‘ideal’ adaptive properties, enables maximising indoor comfort and minimising energy use for heating, cooling, ventilation and lighting. This enables the realisation of nearly zero energy, or even energy producing buildings in the near future.’ (De Boer et al., 2012).

Based on the previous, the following definition will be used in the rest of this thesis to circumscribe an ‘adaptive’ façade:

> ‘An adaptive façade has the ability to adapt, in real time, some of its functions, features and behaviour in response to changing environmental conditions, performance requirements, occupants’ wishes or other boundary conditions (e.g. space efficiency). The adaption has the purpose to obtain improved overall building performance related to primary energy use (heating, cooling, ventilation and lighting) while maintaining or enhancing the comfort and increasing the flexibility during the life phase of the building.’

In literature, several alternatives for the term ‘adaptive’ are used by researchers and professionals (Figure 4-1) such as: active, advanced, dynamic, smart, intelligent, interactive, kinetic, responsive, switchable … These terms are not pure synonyms because they differ a bit in meaning (Loonen et al., 2013).

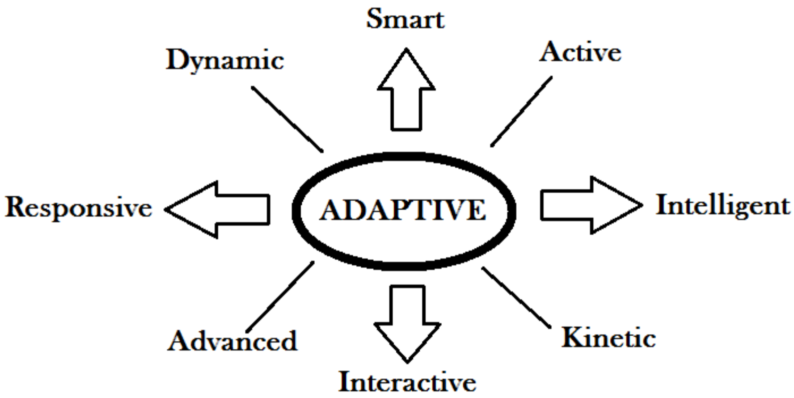


Figure 4-1: Alternatives for 'Adaptive'

'Smart' is a term that is commonly used related to materials and surfaces. The term 'smart' refers to the following basic characteristics: 'immediacy' (real-time response), 'transiency' (responsive to more than one environmental state), 'self-actuation' (internal intelligence), 'selectivity' (discrete and predictable response) and 'directness' (local response to activating events). Smart materials have the weakness that their performance is connected to a range of climatic conditions and predictable reactions. To achieve a high performance for a building, more complex systems such as smart materials in combination with sophisticated management systems are necessary (Velikov & Thun, 2013).

'Intelligent' façades are characterised by a higher order of organisation. They combine the environmental characteristics with information systems and expertise to get an increased performance. The key aspect of 'intelligence' in façades is to search for solutions that result in maximum comfort (air temperature, surface temperature …) while maintaining low energy consumption. The difference between 'intelligent' and 'smart' is related to the fact that in 'smart' façades the control of the system is mainly associated to material properties, which refers to internal power. This in contrast to 'intelligent' façades that use automation and computation as controlling elements. 'Intelligent' façades involve more external power and are less limited in operational range than the 'smart' materials. A combination of both, an intelligent façade that is developed with smart materials to make it self-actuating has a lot of potential (Velasco et al., 2015) (Velikov & Thun, 2013).

'Interactive' is a term that is less used in studies about façades. However, it sometimes shows up in literature to accentuate the use of technology (sensors, micro-processors) in the façade but still in combination with human input for the initiation of response. Feedback-based systems or other automated building management systems can help the façade to optimise the energy use and to control the comfort of the occupants on the same time (Velikov & Thun, 2013).

'Responsive' is used in the same context as 'interactive' and 'adaptive'. The term is related to the interaction between the building, the inhabitant and the environment to develop adaptability. The same aspects as in 'intelligent' and 'smart' are included in the term 'responsive': real-time sensors, smart materials, automation, user override ... In addition, the 'interactive' characteristics are included in this term as well. These interactive systems can result in self-adaption of the system and make the system able to learn over time. The systems can modify their actions to the current climate and energy use (Velikov & Thun, 2013).

Next to adaptive buildings, another rising innovative type are the **accommodaptive** buildings. Nieuwenhuizen (2015) defines accommodaptive buildings as buildings that are open for change. These buildings are not only adaptable but have the additional ability to split. This partition-ability of accommodaptive buildings makes it able for the buildings to (re)divide and combine space. Accommodaptive buildings are capable of accommodating different functions during their life phase (Nieuwenhuizen, 2015).

Different mechanisms can be responsible for the regulation of the adaption to functions of the façade (Figure 4-2). 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**. The range of adaption mechanisms is quite big. A combination of the different mechanisms can make a design very complex (López et al., 2015).

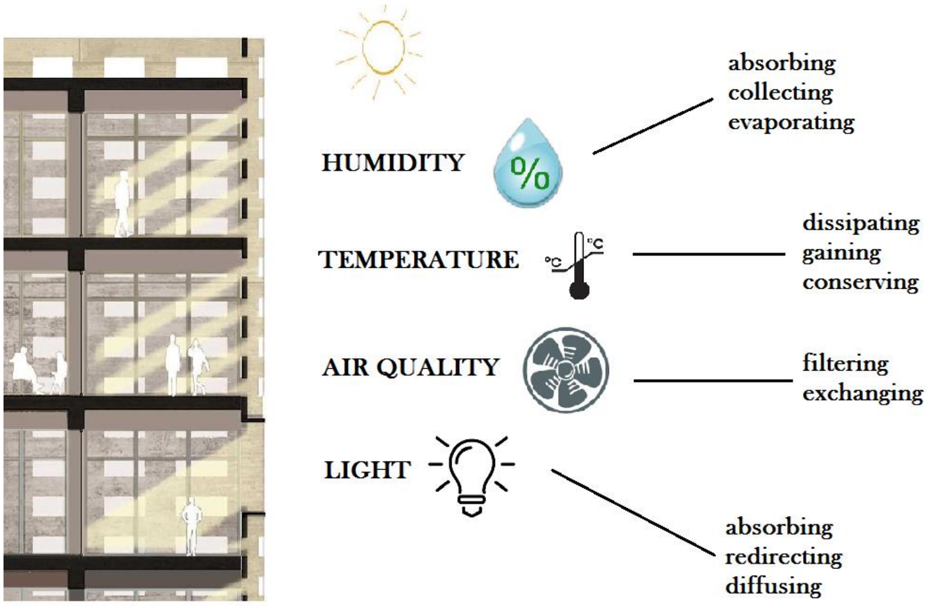


Figure 4-2: Façade regulation mechanisms

4.3 Adaptive façades

Active systems in general have the opportunity to adapt their properties to the changing climate and the preferences of occupants. Adaptive façades improve the performance of a building by making artificial energy only necessary during peak periods (Web 4-02). The primary objective of an adaptive façade is to reduce the ecological footprint of the building. Adaptive façades can be flexible in different ways. Not only adaptability, but also multi-ability and evolvability contribute to flexibility. The adaptability of a façade requires a good control and operation system.

4.3.1 General

Present mid/high-rise buildings often contain a huge quantity of glass in their skins. The success of these glass skins is related to the innovative use of large aluminium frames, which make larger windows and lighter wall systems possible. Today, these lightweight panels are frequently combined with curtain wall systems to form the main construction elements for high buildings (Premier, 2015). Next to curtain wall systems, double façades can be used which are often foreseen of intermediate adaptive shading devices and other features. However, double façades often result in higher costs and more loss of useful space.

The curtain wall systems applied to these mid/high-rise buildings can lower the energy use and increase the internal comfort by implementing **adaptive systems**. To make the adaptive systems sustainable, it is important to search for solutions that are easy to manufacture, economically responsible and can adapt according to climate related changes, occupant needs or other boundary conditions (such as a changing arrangement of the surrounding buildings). Adaptive façades will automatically result in a higher initial cost, but the operational cost of the building will be lower (Kirkegaard, 2011) (Lee et al., 2002).

However, except for many advantages, adaptive façades have some **important drawbacks** as well. The variety in sources that contribute to the adaptive requirements, often results in complex systems. To provide efficient energy use, they often require automatic control. This automatic control diminishes the personal control from the occupants on the internal environmental characteristics. That is the reason why 'intelligent façades' are often replaced by the term 'adaptive façades'. It is not always easy to obtain maximum comfort for the occupants (Loonen et al., 2013).

In literature, the adaptive façades are also called **CABS.** CABS are only one concept of adaptive architecture. The difference with responsive, kinetic architecture is that the adaption takes specifically place at the building shell level itself and not over the whole building. The difference between CABS and active façades is that the active systems do not essentially have the purpose to influence the indoor climate. The active façades only include the introduction of dynamic aspects to the building. An example of active façades that do not belong to the category of CABS are the media façades (Loonen et al., 2013).

4.3.2 Dynamic Interfaces

Adaptive façades belong to the category of '*dynamic interfaces*' (Figure 4-3) and are able to react in an active way with the external environment. The building envelope is no longer seen as just a shield but as a surface that can control efficiently the mass 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).

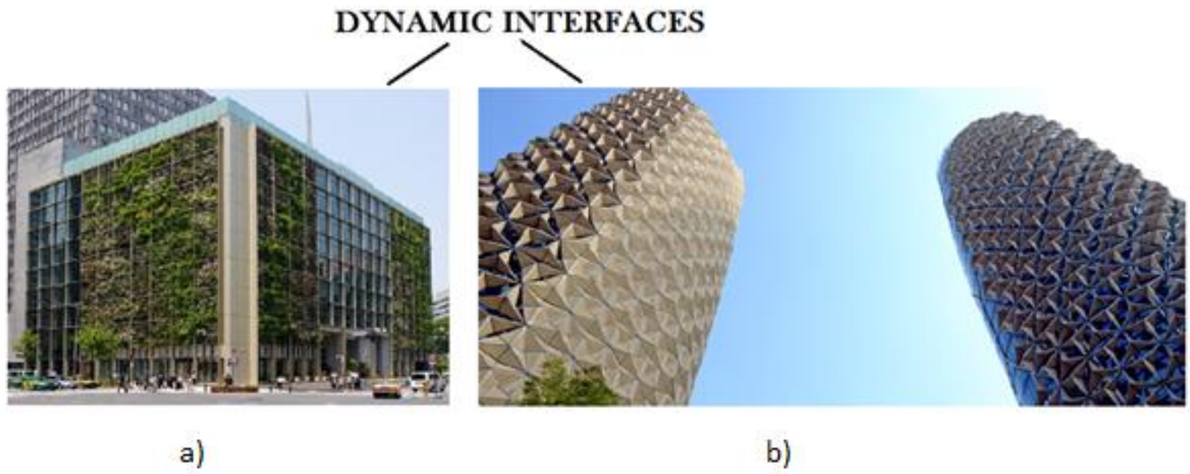


Figure 4-3: Types of dynamic interfaces: a) green façades, b) adaptive façades

The first type of dynamic interfaces are related to the integration of green into the surfaces. This principle is inspired on the natural climbing of plants on the façades and is a passive approach to save energy. These façades are also called **green façades** and can be seen as natural sunscreens. Green façades are a kind of vertical gardens. The construction leaves the conventional treatment of making a clear distinction between the natural environment and the man-made façade (Premier, 2013). The plants can be installed at different levels of the building or can grow in gardens at the base of the building (Web 4-03). The plants improve the internal comfort by reducing the solar gain with their shadow. They form not only a sun barrier but protect the building also against wind deterioration. In addition, buildings with green façades are more sustainable by the reduced heating and cooling load because of plant evaporation (Pérez et al., 2011).

The second category are the **adaptive façades**. Adaptive façades have a one-way relationship with their environment and make use of artificial materials instead of plants. The most common type in this category are the sun shading systems, often in combination with smart materials and innovative technology (Premier, 2015).

It can be questioned if green façades belong to the group of adaptive façades. Vegetation can be seen as an adaptive component. Some researchers consider vegetation as a separate group because plants are purely natural screens. It is difficult to make a clear distinction between the two cases because they both are characterised by an adaptive behaviour related to the changing environment.

The growing interest and evolution of dynamic façade systems as high performance solutions for buildings is related to two governing factors. First of all, the dynamic façades are more adapted to the environmental conditions and help to cope with the current environmental problems. In addition, the recently growing capabilities of computational tools and electronic devices facilitate the design and the control of dynamic systems. Planning, simulation, fabrication and control of the dynamic processes are the key factors for the construction. The equipment related to these processes includes micro-processors, sensors and actuators (Velasco et al., 2015).

The design of dynamic interfaces is often accompanied by **innovative technologies**. These technologies have a higher risk factor which can result in higher investment, maintenance and failure costs. For well-informed design decisions, computational tools are indispensable. These tools 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).

4.3.3 Ecological footprint

Often, a primary objective of the design is to reduce the ecological footprint of buildings (Figure 4-4). Approximately one third of the world's energy use takes place inside buildings. The most crucial point herein is to diminish the dependency on energy intensive 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 (Ogwezi et al., 2012). 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).

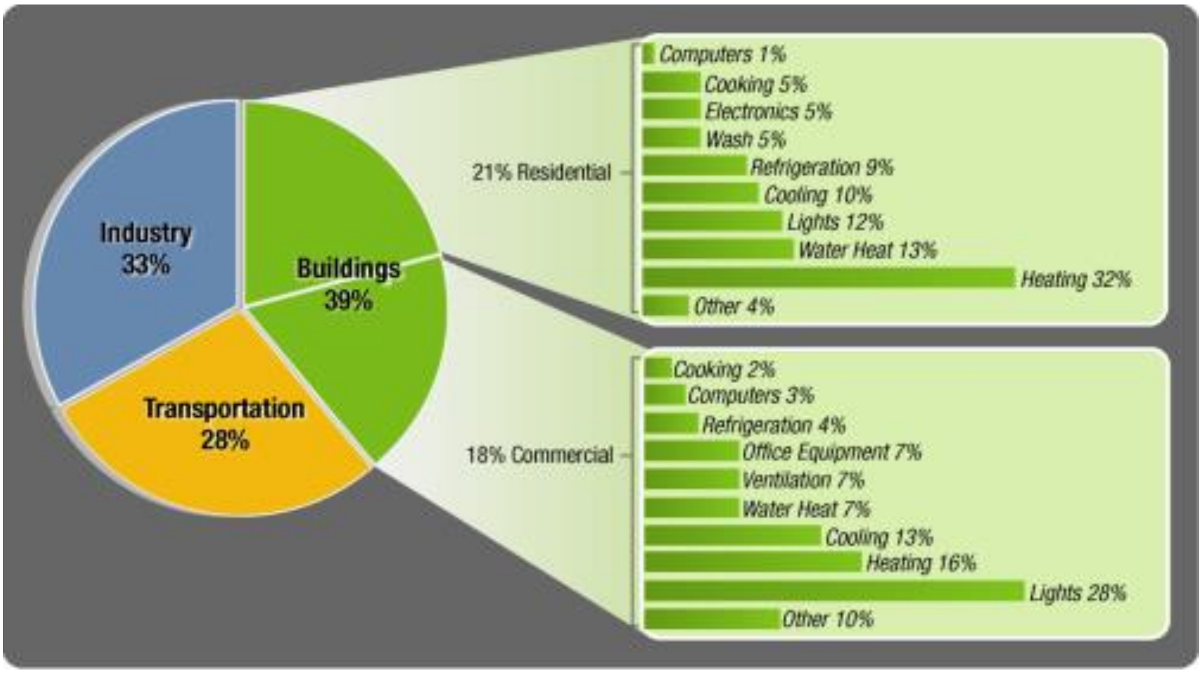


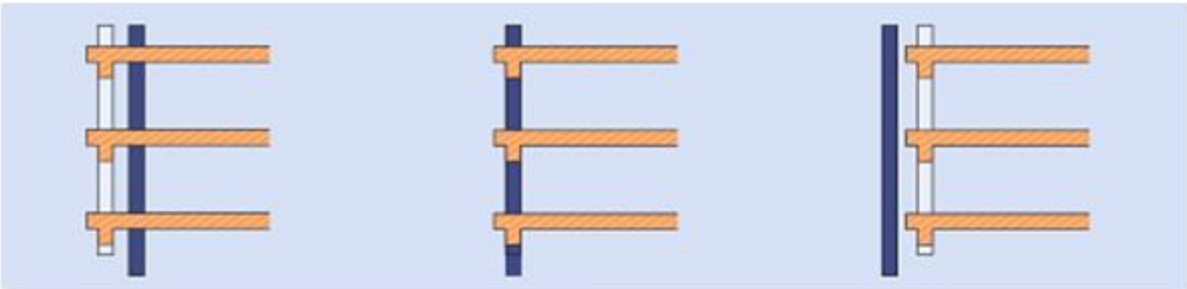
Figure 4-4: Ecological footprint of buildings (Web 4-04)

For a long time, efforts and attention were focused on static solutions such as increased thermal insulation in the envelope of the buildings. The ultimate target, a **'Zero Energy Building'**, is however unreachable by using only traditional design concepts. To reach this target a shift from a static to a dynamic façade is crucial. This required shift is logical considering the constant change of the environmental conditions of a building. Dynamic façades can react continuously and pro-actively to reduce the energy demand in a significant way (Velasco et al., 2015).

From an ecological point of view, one may not forget that the adaptive behaviour of the systems requires various elements that need some electricity to be able to function. Examples of such elements are actuators, power sources, processors, sensors, networks … 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).

4.3.4 Structural placement

A first decision in the design process of an adaptive façade is the structural placement (Figure 4-5). This placement was already discussed in detail in the previous chapter ('Building façades').



a) b) c)

Figure 4-5: Position of the façade: a) in front, b) in the skin, c) behind (Sommer, 2010)

A first (most often applied) possibility is to place the system **in front of the building wall** or outer skin of the building, also known as the curtain wall system. On this position, the façade plays a major role in the determination of the character of the outer skin. This type is very advantageous for solar protection. However, on this position, the risk of damage is large. In addition, external placement results in greater wear and tear, which consequences a shorter lifespan and risks of malfunction of the system. Exterior placed systems will also result in higher maintenance costs. A second option is to hide the adaptive system **in the double-skin systems** (integrated in the primary structure). This makes the glass surface stand out more and has less impact on the visual view of the façade. When the dynamic surface is placed in the structure, dust particles cannot enter the system. Contrarily to external placed systems, no risks exist for reduced effectiveness of the operation of mechanical systems. A last possibility is to **place the façade behind** the primary structure. This position eliminates completely the risk of being damaged (Sommer, 2010) (Premier, 2015).

4.3.5 Movement

The adaptive mechanisms of adaptive façades are roughly dividable in **two classes**. One class results in changes in properties at macro scale level and one class at micro scale level. The largest part of the existing façades belongs to the macro scale category.

The **macro level** is related to mechanical movement. Macro scale changes have an impact on the configuration by moving parts resulting from sliding, expanding, creasing, rolling, inflating … This can be done by supplemented components external to the building shell, subsystems of the building shell itself, movement of the entire façade or the building as a whole. Except for mechanical moving, the transportation of fluids is also a possibility. This can be the flow of air, use of foam bubbles, phase change materials, transparency of water, opaque constructions … (Loonen et al., 2013) (Velasco et al., 2015) (Web 4-05).

The **micro level** refers to movement that is controlled by the material properties. Micro scale changes are related to changes in thermophysical properties, transformation of energy or changes in opaque optical properties. In general, the response can be of different types: responding to surface temperature, light, incident radiation, external control signals … (Loonen et al., 2013) (Velasco et al., 2015) (Web 4-05).

4.3.6 Flexible systems: adaptability, multi-ability and evolvability

Adaptive façades emphasise flexibility during the life phase of the building. A building with an intelligent façade makes optimal use of the energy from the external environment. This lowers the amount of artificial energy that is necessary for achieving comfortable internal conditions (Ibáñez-Puy et al., 2015).

The flexibility in adaptive façades can be subdivided in **three different aspects**: adaptability, multi-ability and evolvability. The building industry has a lack of focus on adaptive aspects which results in a lot of energy waste, which is not suitable considering the changing climate (Hoberman & Schwitter, 2008).

Adaptability is defined by Ferguson (2007) as 'the ability of a system to deliver intended functionality considering multiple criteria under variable conditions through the design variables changing their physical values over time'. The façade acts as climate mediator between comfort needs and what is available in the environment.

Multi-ability is referring to non-simultaneous performance requirements. This means that the façades are able to play different roles over time. In contrast to the term 'adaptability', multi-ability refers to the fulfilling of multiple objectives consecutively instead of concurrently. Multi-ability implies also that the functions to which the adaptive façade is optimised, can have a spatial variability to obtain the most efficient solutions. The spatial variation of the building's properties makes that different parts are working independently (Loonen et al., 2013).

Evolvability, sometimes also called survivability, is more related to the long-term capacities of the façade. The evolvability refers to the capacity of the façade to react to changes in the future. These changes can come from both the outside or the inside (changing urban environment, functional changes of the building …). It is important that the façade has the opportunity to continue operation as intended. The building may not suffer remarkably from impacts of changes in the future (Loonen et al., 2013).

4.3.7 Environmental impacts during the building's lifetime

The changes in the environment can be of different orders of time. First of all, the building's envelope is influenced by short-term fluctuations which change in order of **seconds**. These are mostly stochastic processes. An example are the wind speed and wind direction. Next, changing conditions in the order of **minutes** are possible, such as cloud cover and daylight availability. Most climate adaptive façade systems are designed to lower the impact of these changes. They play with the degree of transparency to increase the comfort. Furthermore, 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**. Furthermore, diurnal changes are present as a consequence of the occupants' behaviour in the building and meteorological boundary conditions. The availability of solar radiation can be efficiently adapted by using thermal storage principles. The last group of changes are the **seasonal** changes during winter, summer, spring and autumn. The different seasons have different boundary conditions, such as the altitude of the sun (Loonen et al., 2013). Figure 4-6 gives an example of the interaction of functions and the environmental changes in different orders of time. The example is based on the behaviour of a west façade.

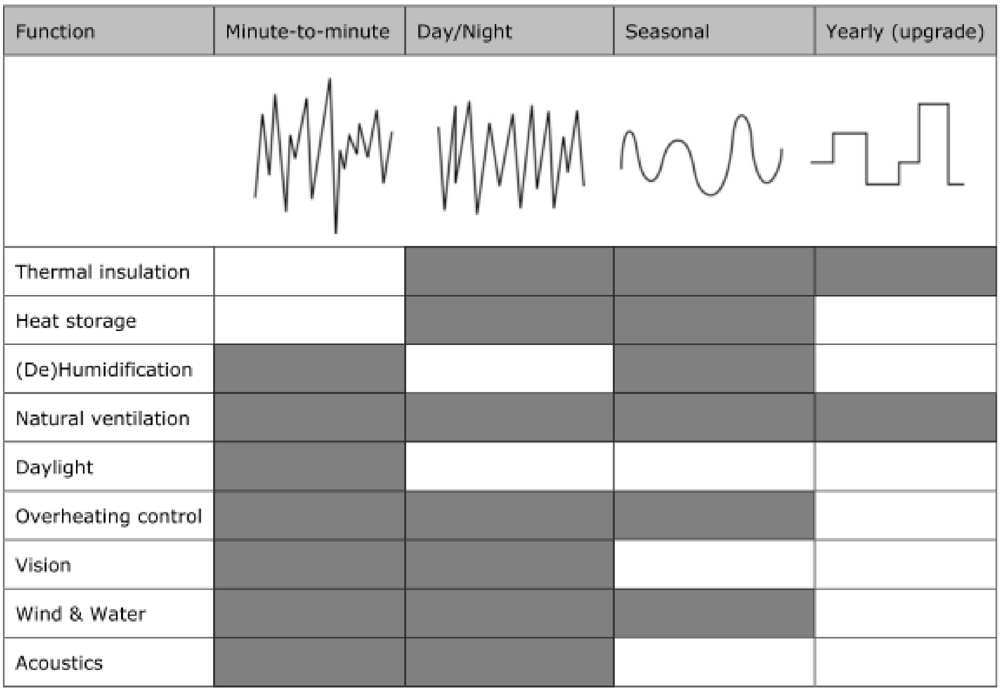


Figure 4-6: Level of adaption for a west façade (Van Dijk, 2009)

The figure allows to draw some important conclusions. The **thermal insulation** is mainly characterised by the extreme seasonal climate conditions. Summer days need low insulation but during winter, thermal insulation is important to keep the heat inside. In addition to seasonal adaption, changes in behaviour during day and night can be efficient for the insulation as well. **Heat storage** is important during summer to be sure that the building will not overheat; this storage can be eventually cooled off during night. Heat storage does not depend on minute-to-minute changes because heat accumulation needs time.

Moisture is mostly related to the seasons, due to the high relative **air humidity** in summer and dry air in winter. However, minute-to-minute change can be convenient if the moisture level changes due to a changing amount of people in the building. The regulation of **ventilation** is important on all levels. The amount of necessary ventilation depends on the season. Moreover, the amount of people will influence the daily and minute-to-minute adaption.

Daylight is related to the visible light and radiation. The influence of the sun can change from minute-to-minute. Moreover, the sun's energy can cause unwanted overheating during summertime. **Overheating** needs to be regulated on all time levels. Shading during daytime can be very efficient to control overheating. **Vision**, **wind** and **water** barriers and **acoustics** have no clear seasonal relationship and depend only slightly on day and night cycles (Van Dijk, 2009).

4.3.8 Control

To design a successful adaptive system, **control** is essential. This can be done in an extrinsic or intrinsic way. The **extrinsic** control systems translate feedback that results from the comparison of the current configuration and the desired state, into the required adaptation. The adjustment is based on sensors, processors and actuators. The control can be done by implementing local systems, which distribute the control over the whole building. In contrast, a centralised driven system can be used for a more global control.

Intrinsic systems do not make use of external decision making components, but are based on direct control by transforming environmental impacts. These environmental inputs, such as temperature, wind speed, solar radiation ... trigger the automatic adaption of the façade. In intrinsic systems, both actuators and sensors are combined in one step. Intrinsic systems have advantages and disadvantages compared to extrinsic systems. They do not need electricity or fuel to make the transition possible. In addition, their number of components is limited. The main disadvantage is that the tuning of the properties and variables of the system is done on a range of expected conditions. If the variations go further than expected, the system will not be able to adapt in response to the unexpected conditions.

As previously mentioned, most CABS belong to the macro scale category. These systems are mainly driven by extrinsic control types. The CABS that belong to the micro scale category are combined with an intrinsic or extrinsic control type, depending on the situation. To work really efficiently, automated systems that provide conditions of the average person need to be combined with options to meet personal preferences. However, it is difficult to integrate these systems in the building's envelope. To facilitate the working principle, it is possible to constrain the rate of change to certain boundaries (Loonen et al., 2013).

4.3.9 Operation

Not only the design of CABS is very complex, the **operation phase** is complicated as well. The multiple, adaptive, independent performance requirements are often competitive and conflicting. However, the various systems have to work together. A lot of trade-off options have to be solved, such as daylight vs. glare, views vs. privacy, fresh air vs. draught risk, solar shading vs. artificial lighting … For adaptive façades, strategies that evaluate several alternatives are necessary. For this, model based predictive control strategies supplied with weather forecasts are useful. A good cooperation between the control of the adaptive system and other building services is critical (Loonen et al., 2013).

4.4 Classification

4.4.1 Proposal of a new classification system

In the domain of adaptive façades, no general classification for adaptive façades exists. However, a clear and scientifically sustained classification model is necessary to make a more objective choice for the adaptive system. Recently, a proposal for a classification was done by Velasco et al. (2015). Their classification (Figure 4-7) is based on the consideration of different classification systems in recent literature.

The proposed classification considers movement and control as the fundamental factors. Control factors are often not taken into account in other existing classification systems, but the type of control system is a fundamental aspect in the design and operation of dynamic façades.

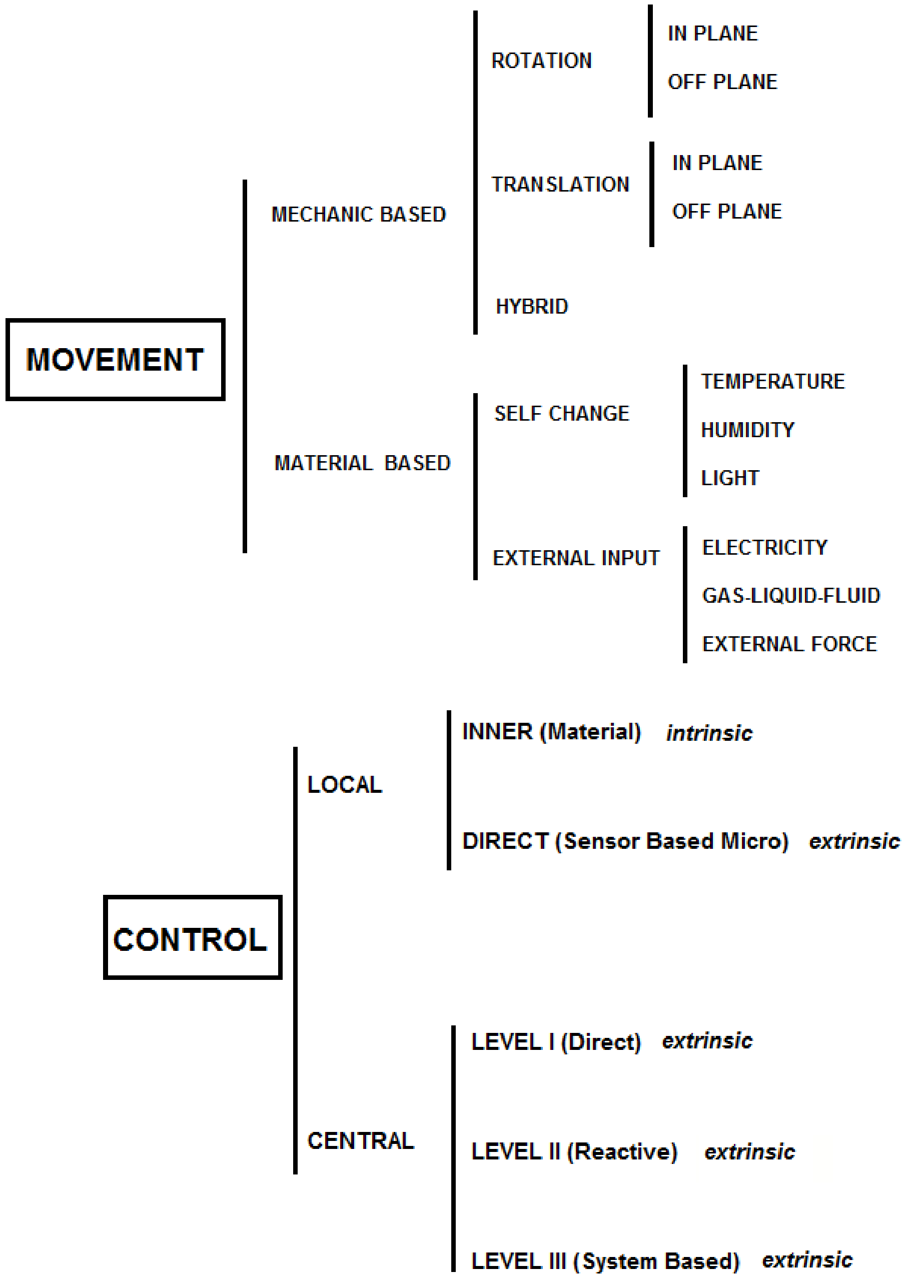


Figure 4-7: Proposal of new classification system (Adapted from (Velasco et al., 2015))

4.4.2 Movement

The movement is divided into a category for **mechanical movement** and a category for **changing material properties**. As described in section '4.3.5', mechanical movement belongs to the group of changes at macro level. The mechanical based deformation can be a ***translation, rotation or hybrid movement***. Translation and rotation can be further subdivided in 'in plane' and 'off plane' movements. The hybrid systems can mostly not be specified as being 'in plane' or 'off plane' because most transformations will act in different ways.

The material based deformation is subdivided according to the factor that causes the deformation, such as temperature, humidity or electricity. Material based deformation is characterised by changes that occur at micro level. When movement is caused by material deformation, not the connections but the components play the major role. The physical characteristics of the components will be of high importance. The first subgroup in this category are the ***self-changing materials***. These materials are able to transform energy that is available in the environment to particular kinds of movement. The sources of energy can be related to differential humidity or temperature levels. The second subgroup are the materials that need a direct ***external input*** to make material deformation possible. This artificially controlled force can be caused by electrical current, a fluid in movement or an external source of movement. In the classification of Velasco et al., materials that react to light have no specific category where they belong to. An extra branch under the classification of self-changing materials can be light. This will make the classification system more complete.

4.4.2.1 Mechanic based deformation

Mechanic based façades need sensors and mechanical components that can react to changes in the internal or external environment. Mechanical deformation is mostly driven by electricity, but combinations with user interaction are also possible. All physical aspects of a façade can be regulated in an adaptive way by mechanical components.

Sun shading systems are the best-known examples of mechanic based deformation in façades. They allow to block sunlight and prevent overheating problems. In addition, they can improve exterior views as well. As previously mentioned in section '4.3.4' , three types of sun shading exist, the external ones, the internal ones and the intermediate placed systems between two glazing layers. The most well-known example of sun shading types are **blinds**. Next to the horizontal and vertical venetian blinds, roller blinds are frequently applied as well. Furthermore, there are the awning blinds and canopies. Table 4-1 gives an overview of different ofther mechanical components that are currently used in adaptive façades and the physical function on which they have an influence.

Table 4-1: Mechanical components and their function (Adapted from (Van Dijk, 2009))

Function	Components		
Thermal insulation	Air cavity	Vacuum	Heat Engine
Heat storage	Heat engine	Heat pipe	
(De)humidification	Ventilation	Heat engine	
Natural ventilation	Air cavity	Register	Window
Daylight	Blind	Diaphragm	Fabric
Overheating control	Sun shading	Heat pipe	
Vision	Blind	Diaphragm	Sun shading
Acoustics	Register	Vacuum	Window

Blinds or other types of sun shadings and **diaphragms** can be used to regulate the daylight that enters the building. Blinds can efficiently protect against glare as well. **Windows** and **registers** help to improve the natural ventilation into the building and can contribute to an improved sound insulation. The disadvantage of the use of windows is the increased acoustic problems during opening. A better solution is a register, which can be placed above a window. It can be integrated in a window to allow natural ventilation and it does not disturb the outside view. Furthermore, making use of **vacuum** can be efficient to come to high insulation values in the façade. Moreover, it saves material because it is lightweight and it contributes on the same time to a better acoustic insulation of the façade. A **heat engine** can be used to convert thermal energy to a mechanical output. Heat engines are moreover very promising because they can influence the thermal insulation, the heat storage and the dehumidification in a room. Another mechanical system that can be applied in the façade is a **heat pipe**. A heat pipe transports heat to a medium (e.g. water) that needs to be heated. It can be applied in a façade to extract surplus heat and to lower the overheating problem. However, more research needs to be done about heat pipes and heat engines (Van Dijk, 2009).

4.4.2.2 Material based deformation

Adaptive systems that belong to the category of material based deformation mostly make use of active materials. An alternative name for active materials often used in literature is **'smart' materials**. Active materials can change their properties by stretching, folding or bending in reaction to an environmental stimulation. Except for their shape, smart materials can also change their colour, stiffness and transparency. The changes that active materials can make are usually **reversible and repeatable**. The materials need to remain stable in their different configurations and during changing. These materials are capable of exchanging energy without the use of external power (López et al., 2015) (Velikov & Thun, 2013). Table 4-2 gives an overview of the different smart materials and the function on which they have an influence.

Table 4-2: Smart materials and their function

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			

Humidity reactive materials

A first example of active materials are humidity reactive materials**.** The most well-known example are **hygroscopic materials**. Hygroscopic materials can be classified under the group of breathable fabrics. They possess the ability to interact in a dynamic way with the internal humidity and have an important impact on the thermal comfort. Their dynamic behaviour results from the absorption of moisture from inside. This absorbed moisture is closed up in the fabric in a first phase. In that way, the material can prevent humid air from entering. In a second phase, the fabric pores open and the air flows out of the building. By using hygroscopic materials, the need for air conditioning diminishes or disappears completely (Ogwezi et al., 2012).

Temperature reactive materials

A second group are the temperature reactive materials**.** A first example are the **Thermo-Bimetals**. These are different metal alloys that are laminated, which results in a bending deformation when the different materials are expanding at different rates during heating. The second example are the **shape memory alloys** that are triggered by heating above their transformation temperature, resulting in a return to their original shape. They possess a super-elastic behaviour in a limited range of temperatures. Next, the **shape memory polymers** are well-known. Shape memory polymers are inexpensive, simple and flexible in use. They can return from a deformed state, triggered by e.g. a temperature change. Additionally there are the **thermochromic polymers** or glasses that change their colour due to a change in temperature. **Thermotropic materials** are characterised by a change in transparency due to temperature variations. In addition, thermotropics possess the quality to absorb thermal energy (Van Dijk, 2009). A last example are the **phase change materials**. These materials can be used to store thermal energy by changing their phase due to heat absorption (mostly from solid to liquid). Phase change materials can be seen as an example of 'artificial' thermal mass. They can reduce peak loads in buildings that are built in climates with high differences in temperature during day and night. Absorbed heat can in a next step be released by night-time ventilation (Web 4-06).

Dioxide reactive materials

A third group of active materials are called the carbon dioxide reactive materials**.** These are for example the **CO_2 polymers** (carbon dioxide polymers) that are triggered to absorb CO_2 from the surrounding air (Velikov & Thun, 2013).

Light reactive materials

A last group are the light reactive materials such as **photochromic materials**. These are able to absorb light due to opening of the molecule. The exposure to UV light results in a change of colour. Next to photochromic materials, **phototropic** materials exist as well. Phototropic materials change their transparency by exposure to light. Furthermore there are the **light responsive polymers**. These polymers change their shape induced by light effects. The elastomers in the polymers can contract and bend. In that way, volume changes in the gels are possible. Light-sensitive materials can control transparency and thermal gain. When applied in surface materials, they are able to gain and save energy from the environment. As already mentioned, the integration of **photovoltaic cells** in the moving systems can bring efficient generation of power into the façade as well as the control of the solar radiation (Velikov & Thun, 2013).

Chromogenic materials

Next to thermochromic and photochromic materials that change their visible appearance (colour or opacity) by variations in temperature and UV illumination respectively, other chromogenic materials exist as well. The change in visible appearance can also be obtained by electrical energy (electrochromic materials). This is an example of external activation. In general, **chromogenic switchable glazing** can help in an efficient way to deal with the conflicting performance requirements (mitigate energy loss, unwanted energy gain and visual discomfort (glare)). Another possible type of switchable glazing to change the transparency of a glass element is to make use of **liquid crystals**. This system is based on the use of electricity to organise and align particles that are suspended between glass plates, which results in an increased transparency. If no electricity is present, the random organised particles block the light that tries to enter the building. Liquid crystals and **suspended particle devices** (classified under external activated chromic materials) more in general can control the amount of daylight and heat that passes through the window (Van Dijk, 2009) (Haldimann et al., 2008).

Other smart materials and techniques

More smart materials exist such as electroactive polymers and piezoelectric materials. **Electroactive polymers** change their shape by stimulation through electricity. They are often used in actuators and sensors. **Piezoelectric materials** are able to transform electrical energy into mechanical energy and vice versa. They are often applied in façades to convert the elastic energy from acoustic vibrations into electricity. In that way, they contribute to the reduction of the amplitude of the acoustic vibrations (Van Dijk, 2009).

A recent, very promising approach for the domain of adaptive architecture is **4D-printing**. This principle adds the extra dimension of time to 3D-printed structures, which turns into printed structures that can adapt themselves. Moreover the behaviour can be controlled in a predictable way by subjecting the structure to thermal and mechanical forces. The next future step is to make hybrid materials by the union of different materials with different features, resulting in multi-material printing that can support multiple functionalities (López et al., 2015).

4.4.2.3 Overview existing applications

Figure 4-8 gives, based on the case studies in the appendix (see Appendix A), the amount of applications that use a certain type of movement. Most recent applications use principles that are based on **mechanic based movement**. The most popular category is the principle of movement based on **off plane rotation**. A second popular group is the **hybrid deformation**. The groups of in plane rotation and off plane translation are less popular in existing applications. However, the existing mechanical applications can further be improved. Also the further development of **material based deformation** forms an interesting subject.

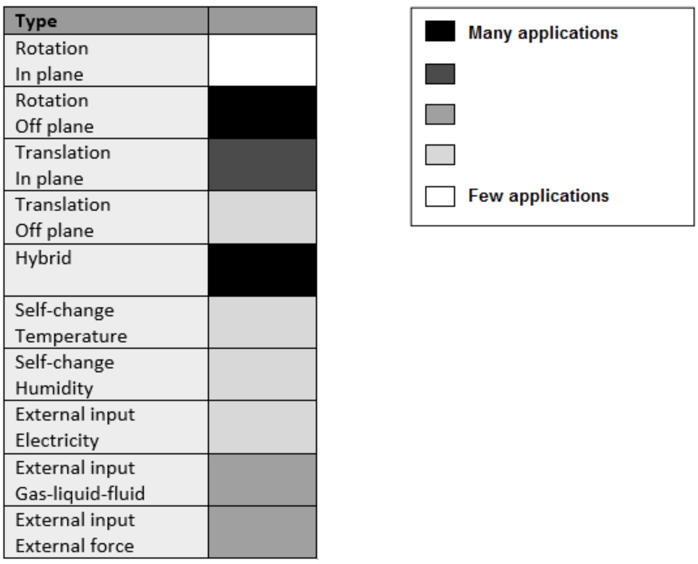


Figure 4-8: Overview movement of existing systems

Nowadays, the largest part of the existing adaptive façades are specific solutions for an individual case. These individual cases are interesting because they form the basis for further developments. In the future, adaptive façades should be developed on a more regular base. This makes large-scale production of the materials and components possible. More standardisation for application of adaptive façades in mid/high-rise buildings with high budgets, may result in cost-effective solutions (Loonen et al., 2013).

4.4.3 Control

The second important factor, next to movement is the control factor. Two important groups are distinguished here: **Local and Central control**. Local control implies that each actuator is autonomous and linked to an exclusive sensor-control system. The local control can be embedded in the ***inner*** material that reacts against external conditions. This is a type of *intrinsic* control. However, a ***direct*** local control system is also possible when the component is controlled by an external system (*extrinsic* control). This can be done by a sensor, microprocessor or actuator that is related to one component. When different components are grouped together as a central controlled system, they do not belong to the local but to the central category. In central control systems, the actuators or group of actuators are linked to one single control system. It always implies that a number of components is linked to a central processor. Depending on the complexity of the processes a further subcategorisation is possible. If no external inputs (sensors) are needed and the system is a pure pre-programmed unit, a ***direct*** system is created. When sensors can influence the behaviour, a more deterministic system is created based on Boolean expressions. This makes the complexity of the system larger and is called a ***reactive*** control system. In a last step, even more complexity is added to the control system by using multi-deterministic and stochastic processes to solve complex problems. This last group is called a ***system based*** central control (Velasco et al., 2015).

4.4.4 Relevant physics

In addition to the classification system from Velasco et al. (Figure 4-7) that classifies systems according to movement and control, the relevant physics to which the façade is optimised can specify the type of adaptive system in more detail. The building façade influences **physical interactions** between the indoor zones and the outdoor environment. To classify the façades in accordance with the physical interactions on which they have an influence, four general domains can be distinguished. These domains are: Thermal, Optical, Air flow and Electrical.

Adaptive façades that have an impact on the thermal domain cause changes in the energy balance of the building by conduction, convection, radiation and storage of thermal energy. The optical domain is related to the visual perception of the occupants that changes due to transformation of the transparency of the surfaces of the building shell. Air flow is related to a flow near the boundary of the façade or effects of wind direction and wind speed. The electrical domain refers mostly to the conversion of energy into electricity. However, the electricity that is needed for the adaptive behaviour is also related to this domain (Loonen, 2010).

Most of the adaptive applications influence more than one domain. The overlap between the different domains results in interaction and can be efficiently visualised in a **Venn-diagram** (Figure 4-9). Overlap between the four different basic domains results in a total of 15 different possible combinations.

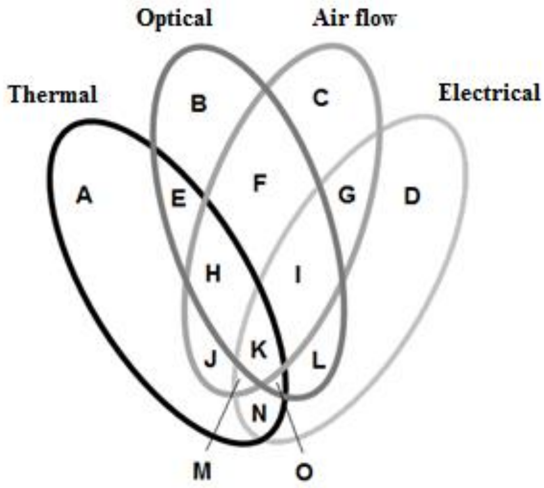


Figure 4-9: The four physical domains and overlap zones (Adapted from (Loonen, 2010))

The thermal domain is present in almost all existing systems due to the fact that the thermal environment is constantly changing. Optical effects play also very often a role in the systems, because mostly controlled daylighting is part of the CABS strategy (Loonen et al., 2013). Studies (Loonen, 2010) show that most adaptive façades can be classified in zone E, which is the thermo-optical overlap zone. The second popular combination is the thermo-optical domain in combination with air flow (represented by zone H) or in combination with electricity (zone O). In one third of the cases the air flow domain is present in the strategy as well. According to the studies of Loonen (2010), the electrical domain is more or less present in one fourth of the cases. This is mostly related to the use of photovoltaics to gain energy (Loonen, 2010).

Figure 4-10 gives an overview of the different physical domains that are involved in the adaptive systems studied in Appendix A. The thermal domain makes almost always part of the adaptive structure. The *red and orange zones* show the areas with a lot of existing applications. The *blue zones* are the areas with an intermediate amount of applications. The *green areas* indicate zones with a few existing examples. The *white areas* are not really interesting because most adaptive systems have automatically an influence on the thermal comfort in some way (direct or indirect). The same zones and indexes as in Figure 4-9 are used.

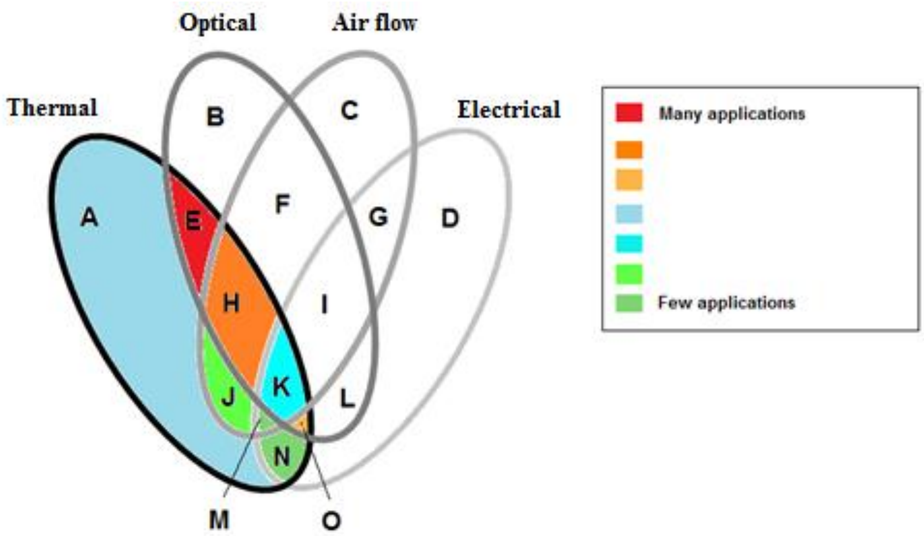


Figure 4-10: Overview distribution of applications

4.4.5 Biomimetics

Another reason for the growing success of adaptive façades is the application of **biomimetic principles**. Biomimetics is a combination of the Greek words bios ('life') and mimesis ('imitate'): the abstraction of good designs from nature, which implies structures that are based on natural elastic kinematics. Plants can react in a specific way to light, temperature, fire, darkness, water and drought. Biological responses to the changing environment result in an optimal adaption. The plant responses are multi-functional. The adaption strategies do not require complex electronics, sensors or actuators, which make them very effective (López et al., 2015).

The stomata of the plants form the basis for the changing mechanism. Stomata are pores, in the epidermis of the leaves, that are used to control gas exchange. These pores are bordered by guard cells (specialised parenchyma cells). The stomata open in response to light, high temperatures, high humidity levels and a decrease in atmospheric concentration of carbon dioxide. The stomata interchange gases by respiration and photosynthesis. In addition, stomata can trigger the formation of water vapour when there is an excess of water. In that way, it can contribute to cooling (López et al., 2015).

The most difficult issue is the translation of the plant principles to adaptive solutions for artificial systems and their technical implementation in façades (López et al., 2015). In general, the biomimetic systems can result from two types of processes. The first one is the top-down process, which starts from a technical pull (problem) and finds a solution based on a principle in nature. The second type is the bottom-up approach, which starts with a finding in biology (biology push), resulting in a technical concept. These structures generate their geometrical form and their rigidity by elastically deforming their members, which replace the hinges.

Biomimetic systems allow a high degree of flexibility but can still guarantee a sufficient structural stability. The structural stability is guaranteed by the combination of bending and tension prestress or coupling of multiple elements. Linking of elements results in a sequence movement based on transmission of forces and torque. The deformation of one element triggers the deflection of an adjacent element. The biomimetic systems use material properties in an efficient way and are much simpler than mechanical systems. This results in reduced material use, weight and energy consumption.

An example of biomimetic systems is the 'Flectofin' principle (Figure 4-11) based on the flapping mechanism of the Bird of Paradise. The flipping motion is based on the bending of the central portion that triggers the flapping of the marginal portion. This can be translated in a curved-line folding principle (Lienhard et al., 2011) (Suralkar, 2011).

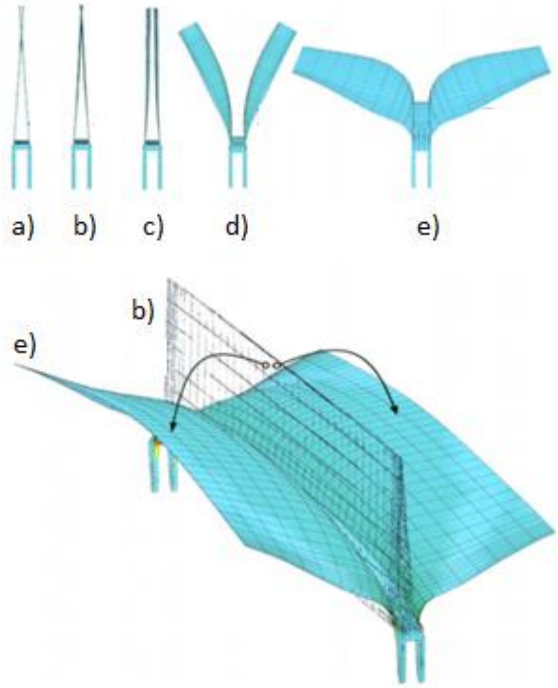


Figure 4-11: Flectofin principle: a) theoretical position of the wings, b) real position of the wings pushing against each other, c)-e) opening of the wings due to bending of the backbone (Lienhard et al., 2011)

Another inspiration in nature is the 'Dermaptera' wing (Figure 4-12), which consists of two folding mechanisms. A basic folding mechanism of four folded plates and a radial folding mechanism. An external effort is necessary to start the folding process. After starting, it goes through a snap-through and it is finally locked in the deployed shape (Hachem et al., 2014).

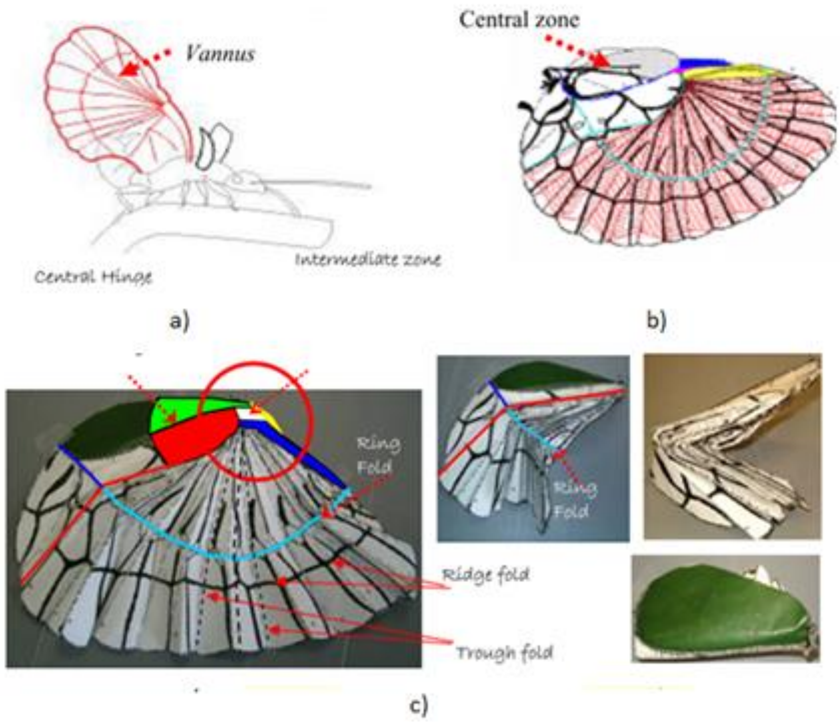


Figure 4-12: a) winged Dermaptera male, b) the hind wing of the Dermaptera, c) paper model simulating folding of the fan part of the hind wing (Hachem & Hanaor, 2006)

4.5 Conclusions and future perspectives

For a long time, the attention and efforts of building designers were focused on optimising the thermal insulation of envelopes. Further upgrade of this envelopes is necessary to increase the energy efficiency. This upgrade requires a shift from static to dynamic systems. In the future, the building's envelope will actively regulate the flow of heat, light, air and water from outdoor to indoor and vice versa by acting as an interface that continuously and actively adapts to changing conditions (Perino & Serra, 2015).

The low-technological examples of adaptive façades have the current trend to become more high-technological and complex. However, simple constructions for adaptive façade elements can still be very efficient and effective to obtain 'zero energy' houses. High-rise buildings require often more technological and mechanised actuation and sensor systems. Systems equipped with new performative materials, sensors, actuators and computerised intelligence increase in popularity to control functionalities such as light, air flow, sound transmission, thermal transfer and interior humidity quality. In addition, biological models are increasing in popularity and form the inspiration for simple efficient adaptive façades (Kolarevic & Parlac, 2015) (Velikov & Thun, 2013).

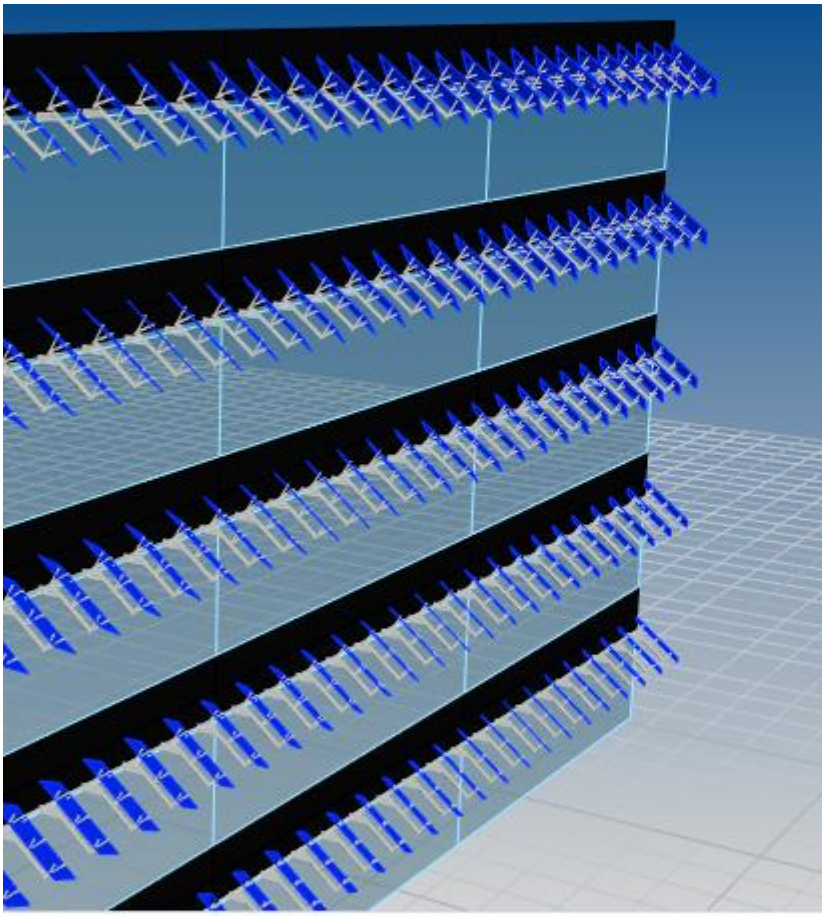
Adaptive systems that have a movement principle that is mechanic based offer a lot of opportunities for efficient control of energy use. Future systems could combine mechanic and material based principles to create new concepts. The most applications that currently exist in the category of mechanical deformation are based on an off plane rotation principle or hybrid deformation. Hybrid movement is most interesting because it offers a wide range of possibilities.

A combination of possibilities for human adjustment and control of the systems with the avoidance of user override, requires feedback systems. Extrinsic control of the systems is promising because this type of operation control is most effective to combine automated strategies with personal control.

From the study about the different physical domains, it can be concluded that the thermal and optical domains are closely coupled. Their fluctuating behaviour on daily and monthly level are often more important than seasonal fluctuations. Therefore short-term adaptive systems look more interesting for future developments. The Venn-diagram shows that the electrical domain has currently a low number of applications. However, the integration of photovoltaic cells in the adaptive systems is very promising to gain energy. A high performance can be obtained by combining the use of photovoltaic cells with adaptive elements that improve thermal, optical and/or air flow quality. The current objective is to create building envelopes that integrate multiple functionalities to obtain almost self-sufficient systems in terms of energy. The challenge exists in developing these systems in a cost efficient and standardised way to make it possible to use the systems in façades of multiple high-rise buildings in the future.

Adaptive façades belong to a domain that is far from saturated and mature. There is a lack of monitoring and evaluating of the performance of existing adaptive façades and post-occupancy evaluation methods. In the future, new simulation tools and whole-life evaluation methods for the adaptive façades as an integral part of the building should be developed. These tools and evaluation methods are necessary because the development of adaptive concepts is often very challenging as a result of the increased use of innovative technologies. The high risks make that designers often take too conservative decisions. In the future, more expert modelling and experience will be required to develop accurate evaluation tools (Favoino, 2015).

PART II. Design of prototypes



> ‘Design is where science and art break-even.’
>
> - Robin Mathew -

PROTOTYPE I:

A PHOTOVOLTAIC SOLAR SHADE SYSTEM

5 Prototype I : A photovoltaic solar shade system

5.1 Case definition

Based on the literature review in PART I that dealt with transformable structures, building façades and especially adaptive façades, a well-thought case can be defined to form the basis to develop a first structural adaptive prototype. The purpose is to create an **economical efficient prototype** for a specific location with circumscribed environmental and operational conditions. The prototype must contribute to a more sustainable building. The case definition is shown in Table 5-1.

Table 5-1: Case definition

Case definition	
Building façade	• South façade; • Mid/High-rise building; • Curtain wall.
Climate zone	• Moderate zone; • Continental climate; • City.
Movement system	• Mechanic based; • Rotation.
Transformable structure	• Hybrid structures: Bar elements + Rigid panels/Membrane.
Control system	• Extrinsic; • Direct.
Relevant physics	• Daylight; • Solar control; • Energy gain.

An ideal size of façade for the application of an adaptive prototype is a mid- or high-rise building. The higher application area makes it easier to win the initial investment back by a high reduce in operational costs for the building. This makes it possible to generate an economical façade. The sun has the highest position at noon in the south direction. For a high position of the sun, a curtain wall system is most efficient. Moreover, a curtain wall system does not take useful building space.

A moderate climate zone 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. The system will be optimised for both solar protection and energy gain. In addition, there is need for daylight control. The efficiency of an adaptive prototype can be especially high on the south façade because this orientation is optimal to maximise the gain of sun energy. The combination of focusing on solar, daylight and energy control makes the choice for a curtain wall very powerful. More specific than the moderate zone, a city environment in a continental climate is chosen. This is a suitable place to build mid/high-rise buildings with a structural adaptive façade (e.g. commercial buildings in business districts).

Solar heat control is the most self-evident factor for an adaptive façade. Next to heat control, the control of daylight that enters the building is a second important aspect. Most façades focus on the thermal and optical domain, which is logical because these domains are strongly coupled and possess the highest qualities to increase the building performance and lower the energy use. Their behaviour fluctuates not only on seasonal, but also on a daily and monthly level, which makes short-adaptive systems interesting. Therefore, emphasising these factors in the design is logical and smart. However, the prototype will also pay special attention to the gain of solar energy by making use of building integrated photovoltaics. These photovoltaics can result in adaptive systems that are self-sufficient and do not need external energy.

The movement system for the adaptive façade is chosen to be mechanic based with the purpose of structural adaption in mind. Due to the fact that the position of the sun forms the focus of this prototype, a rotational movement is indispensible. The control system is chosen to be extrinsic, which implies the use of actuators. A direct control system is best suited for programmed automatic systems. According to the wishes of the client, this can be eventually combined with local control by the individual users.

For a good design, some important factors have to be taken into account from the beginning. Not only the structural, but also the architectural and economical aspects are of great importance for the creation of a concept. Below a list of the key design aspects is given (Table 5-2):

Table 5-2: Overview design aspects

Design aspects	
Standardisation	Easy to design for different buildings Expandable without fundamental changes
Functionality	The functionality of the concept is more important than the originality
Weather resistance	Good rigidity and durability against different weather conditions
Economical	Looking to what type of fabrication of panels/membranes already exist ➔ More economical to use Economic profit > required investment ➔ Looking for energy gain solutions
Simplicity	Simple mechanic systems Easy maintenance and repair
Comfort	Minimal disturbed visual outside view
Double principle	Shadow and energy gain simultaneously

5.2 PV panels

The defined case mentioned energy gain as a major focus aspect. The combination of providing shadow with the gain of energy forms the starting point for the prototype. The first aspect in the design is to choose between using **rigid panels or membranes**. To make a reasoned choice, two important factors need to be considered. Firstly, the possibilities of PV (photovoltaic) panels have to be listed and secondly, the stability and functional strength of the two choices has to be weighed against each other.

5.2.1 PV panels: general

5.2.1.1 Working principle

PV cells are made of semiconductors that generate electricity directly from sunlight (photoelectric effect) with no pollution. The photons in solar light strike the PV panel and part of them are absorbed. These absorbed photons break the atomic bond between electrons. The semiconductor structure in the PV panel initiates an electric stream of free electrons (which is called a current) in a certain direction (Web 5-01).

5.2.1.2 Types

The main distinction in PV panels is between the so called 'first generation' panels and 'second generation' panels. BIPV panels (Building-integrated photovoltaic panels) can be of both types. The **'first generation'** panels are cut from a single silicon crystal (monocrystalline – mono Si) or exist of a slice cut from a block of silicon (polycrystalline – poly Si), with a large number of crystals. Polycrystalline panels are slightly less expensive but a bit less efficient than monocrystalline panels on the same time. The **'second generation'** panels exist of the placement of a thin film (amorphous silicon or non-silicon based) onto a surface. Besides amorphous silicon, other materials can be used as well (Jelle et al., 2012).

In Table 5-3 an overview of a comparison between 'first generation' panels and 'second generation' panels is given (Jelle et al., 2012).

Table 5-3: Comparison rigid and flexible panels (Based on (Jelle et al., 2012))

PHOTOVOLTAIC PANELS	
Rigid panels ('First generation' panels)	Flexible panels ('Second generation' panels)
Advantages:	**Advantages:**
+ High efficiency (15-20% efficiency) + High space efficiency + No (large) degradation + Multiple standard sizes	+ Less manufacturing costs + simple mass production + Flexible (foldable, rollable …) and lightweight + Better low light performance + More homogenous appearance
Disadvantages:	**Disadvantages:**
- Expensive to manufacture	- Less efficient - Low space efficiency - Power output reduces over time (during first months, afterwards more stable) - Degrades faster - Much more care and maintenance needed - Standard size
Applications:	**Applications:**
• Long-term investments; • Application for maximum power; • Small installation footprint; • Residential situations.	• Environments with mostly interrupted sunlight; • Large installation footprint.

The **rigid panels** are mostly constructed by using glass panes or aluminium frames. These structures do not degrade over time, which makes them very suitable for long-term investments (Web 5-02). The crystalline silicon panels are the most commonly used panels today and represent a percentage of 90% of all PV panels in the world. Monocrystalline panels have an efficiency that is typically four times higher than thin film panels which makes them the most space efficient of all types. A more detailed comparison between **mono- and polycrystalline** PV panels is given in Table 5-4 (Web 5-03).

Table 5-4: Comparison crystalline silicon PV panels (Based on Web 5-03)

CRYSTALLINE SILICON	
Monocrystalline silicon PV panels	Polycrystalline silicon PV panels
Advantages:	**Advantages:**
+ Highest efficiency (15-20%) + Most space efficient + Longest life expectancy + Better performance at low light conditions + Good performance at high temperature	+ Less costs for manufacturing + Less waste of silicon
Disadvantages:	**Disadvantages:**
- Most expensive - Lot of waste of silicon	- Lower heat tolerance than monocrystalline - Lower efficiency (13-16%) - Lower space efficiency - No uniform look

Thin film panels are manufactured by depositing one or several layers onto a surface with a vacuum-deposition technique. The thickness of **thin film panels** is only 1% of the thickness of rigid panels. This explains the need for less material to manufacture thin film panels compared to rigid panels. As a result, the unit cost is only 40% of the cost of rigid panels. Different materials can be used to form the thin layers and the categorisation of the panels is according to the used material. The thin film panel made out of a-Si (**amorphous silicon**) is the oldest and best developed example. The efficiency of amorphous silicon is lower (between 7-13% efficiency) than crystalline silicon because the flow of electrons is more interrupted. In contrast, the manufacturing is more easy because the silicon atoms can just be deposited on a substance. There is no need for a frame or grid to support the conducting behaviour, which results in an easier manufacturing process. The amorphous silicon has a better performance in environments with lower light intensities. Besides a-Si, also CIGS (Copper Indium Gallium Selenide) or CdTe (Cadmium Telluride) can be used to form the photoelectric layer of the thin film panel. However, the thin film technology is currently not very well-known and there is only knowledge of a laboratory efficiency up to 15% (Web 5-02) (Web 5-03). A comparison between different thin film possibilities is given in Table 5-5.

Table 5-5: Comparison thin film panels (Based on Web 5-03)

THIN FILM PHOTOVOLTAIC CELLS		
Amorphous silicon	Cadmium telluride	Copper indium gallium selenide
Silicon based	Non-silicon based	Non-silicon based
Less silicon required (1% of the amount required in crystalline silicon panels)	Good cost efficiency	Less amount of toxic material
Efficiency around **6-8%**	Efficiency around **9-11%**	Efficiency around **10-13%**
Brownish or reddish brown colour	Dark green or black colour	Dark colour

5.2.1.3 *Cell cost and life expectancy*

One of the most important aspects to make a sustained choice for a PV panel is the **price**. However, the installation cost of BIPVs is only a small extra cost compared to the overall commercial building cost. The technology of PV and BIPV panels in particular is still growing and therefore quite expensive at this moment. In the future, a decrease in price is expected. Factors such as improvement of technology, manufacturing on a larger scale and more experienced and trained installers will be responsible for this decrease. This makes that the cell cost will determine the total cost. A comparison for the different PV types is given in Table 5-6 (Jelle et al., 2012).

Table 5-6: Comparison cell efficiency - cost (Based on (Jelle et al., 2012))

<table>
<tr><td colspan="7">Cell Cost</td></tr>
<tr><td rowspan="5">Cell efficiency</td><td></td><td colspan="2">HIGH</td><td colspan="3">LOW</td></tr>
<tr><td rowspan="2">HIGH</td><td>Mono Si</td><td colspan="2"></td><td></td><td></td></tr>
<tr><td></td><td colspan="2">Poly Si</td><td></td><td></td></tr>
<tr><td rowspan="2">LOW</td><td></td><td colspan="2"></td><td>CIGS</td><td></td></tr>
<tr><td colspan="2"></td><td colspan="2">a-Si</td><td>CdTe</td></tr>
</table>

A second important aspect is the **life expectancy**. PV panels need to be resistant to heat and cold cycles and changing weather conditions. These factors determine their long-term durability. The panels will degrade faster if the exposure to wind and weather is higher, which is an important aspect for mid- and high-rise buildings. Next to a good manufacturing against weather conditions, the age degradation is an important aspect as well. The power output of a PV panel degrades with an average of about 0.5%/year. Typically the rate of degradation is higher during the first years. The different types of panels have a different degradation rate as can be seen in Table 5-7. The major part of the manufacturers can guarantee that their panels will produce for 10 years at 95% and for 25 years at 80% efficiency (Web 5-03).

Table 5-7: Degradation rate (Adapted from Web 5-03)

Solar cell type	Output loss (%/year)
Monocrystalline silicon (mono Si)	0.36
Polycrystalline silicon (poly Si)	0.64
Amorphous silicon (a-Si)	0.87
Copper indium gallium selenide (CIGS)	0.96
Cadmium telluride (CdTe)	0.40

5.2.1.4 Special remarks

Some care has to be taken when using PV panels for **building applications**. BIPV applications can be applied in ventilated and non-ventilated façades. For non-ventilated façades, mono- or polycrystalline modules are not efficient to use because these panels need an air gap underneath the panel. This air gap is needed to decrease the temperature for maintaining a good performance. Thin film panels depend less on the temperature than crystalline panels (Jelle et al., 2012).

5.2.2 Flexible versus rigid cladding

For the performance of a cladding system, different aspects are of great importance. The system has to be resistant against weather conditions, but also strength and rigidity are of major importance for durability and costs. Furthermore, aspects such as control of thermal movement and maintenance and repair are important design considerations.

Rigid panels are more stable than flexible systems. Flexible PV panels have their lightweight as major advantage but they possess some important disadvantages that make their application in façades less attractive. When temperatures in the environment are extreme, the panels will slightly warp, which results in cupping. In this little cups, water, dirt, dust and sand can build up. During cleaning, the coating that covers the solar cells can be scratched. Furthermore tilting of flexible panels to the sun is much more difficult than tilting of rigid panels. Lastly, the warranty of flexible panels is only ten years, in comparison with 30 years warranty for e.g. tempered glass PV panels (Web 5-04).

Next to extreme temperatures, the wind and snow loading is an important factor. For fabrics and membranes, this can result in important ponding and fluttering problems. Furthermore, the structural capacity of flexible systems is more limited. These systems will show large displacements and large stresses under loading, directly related to the magnitude and distribution of the applied loads. Too high internal stress concentrations can result in permanent deformation. Also tear-type damage can propagate which will result in membrane failure. To provide sufficient load-bearing capacity, the flexible systems need to be foreseen of double curvatures and pre-tensioning, which is difficult to apply in a solar array system (Liapi, 2002) (Beccarelli, 2015).

During transformation of an adaptive façade system, the tension in the membrane surface will need to be controlled to remain structurally effective. This is not easy and will result in important challenges regarding the material behaviour. During the different transformation phases, it is important that the geometrical stiffness is sufficiently high (Brancart et al., 2014).

There is currently not much experience with the application of membranes in façade systems due to the complexity and limited tools to analyse the behaviour of these systems in different environmental conditions. There are still several unknowns in using membranes as shading systems because only simple systems are tested. At the moment, no improved building performance of membranes over rigid systems is demonstrated (Beatini & Korkmaz, 2016).

5.2.3 Decision

In the previous parts, two main factors to investigate the choice between rigid panels or membranes were investigated. Firstly, the different types of PV panels were discussed. Both flexible and rigid panels are possible. Furthermore, different PV cells can be used. Secondly, the stability and strength of the two options were compared. For a good durability and resistance against weather conditions such as wind and snow loading, **rigid panels are more advantageous**. Moreover, membranes are more complex to remain structurally efficient during transformation.

The previous research clearly points towards the choice for rigid panels. Thin film flexible panels will have lower efficiency and on a façade, a space efficient system is important. Compared to weather loads, the panel weight will only be a small fraction. Therefore, focusing on lightweight systems is not an issue. Within the rigid panels, the choice between **mono- and polycrystalline** PV cells is still possible. Due to the fact that the panels will be used in a ventilated curtain wall system, there will be no problem with the performance of the crystalline panels.

5.3 Solar tracking

5.3.1 General

To improve the efficiency of PV panels, the principle of **solar tracking** is often used. Compared to fixed systems, the trackers follow the position of the sun during the day and increase the collected sun energy and amount of output power. By moving the PV panels, the angle of incidence of the solar rays on the panel is closer to the optimal perpendicular position (further discussed in '5.3.2'). Two types of track systems exist, the one-axis (**single-axis**) and the two-axis (**dual-axis**; **double**) trackers. Single-axis trackers have only one degree of freedom, dual-axis trackers have two degrees of freedom. Different types of single-axis trackers exist: horizontal single-axis trackers (north-south), vertical single-axis trackers (east-west; azimuth tracking), tilted single-axis trackers and polar aligned single-axis trackers. An overview of the differences between single and double tracking is given in Table 5-8 (Bakos, 2006) (Web 5-05).

Table 5-8: Comparison solar tracking systems

SOLAR TRACKING	
Single tracking	Double tracking
East to west / North to south	East to west and north to south
Increase solar yield up to more or less 34%	Increase solar yield up to 37% (to 40%)
Simple, effective design	Complex design – more motors and sensors
Low maintenance	High maintenance
Lower cost compared to double tracking	Higher cost (additional parts and installation time) (more or less double cost as single tracking)
Minimal points of failure	Additional points of failure
	Less productive in the long-term

The efficiency of a tracking system compared to a fixed panel depends on different parameters: the location, the climate conditions, the period of the year, the period of the day … In general, the increase in efficiency is highest in the early morning and the late afternoon during normal clear weather conditions. In contrast, during cloudy days the efficiency of a tracking system decreases significantly (Mehrtash et al., 2012).

5.3.2 Angle of incidence

The gain in efficiency for solar tracking systems is related to the **angle of incidence**. The power output of a PV panel is highest when the solar cell is positioned perpendicular to the direction of sunlight. The relation between the power output and this angle can be visualised by a cosine relationship that is symmetric for positive and negative angles between - 90° and + 90° (Figure 5-1). The amount of losses depends on the local latitude and the climate type (Kaiser, n.d.).

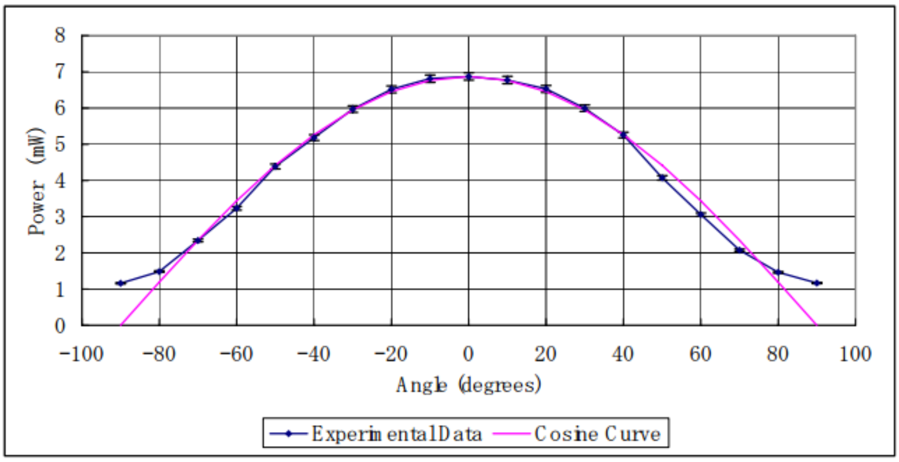


Figure 5-1: Cosine relationship between angle of incidence and output power (Kaiser, n.d.)

5.3.3 Efficiency difference tracking systems

For different locations in the world, comparative studies related to the difference in energy gain were performed for the different types of tracking systems. These studies showed that the **latitude** plays an important role. The design of this prototype is optimised for Belgium. Belgium is located on 51° northern latitude. An extensive study (Mehrtash et al., 2012) was done for Montreal (45° latitude). It is interesting to look at the results of this study as a first approach to make a decision on the type of tracking that is most suited for a location as Belgium. The tests of Montreal compared four different systems: horizontally fixed, fixed at latitude angle, single-axis azimuth tracking with tilt angle and dual-axis tracking (Figure 5-2). The study did not consider horizontal axis tracking because azimuth tracking is more efficient in general (10% more energy gain than horizontal tracking) (Lorenzo et al., 2002). The studies resulted in two major conclusions. Firstly dual-axis tracking appeared to have almost the same performance as azimuth tracking (Figure 5-2). This is a powerful reason to choose for **azimuth tracking** because it is cheaper and easier to implement than dual-axis tracking systems, which makes it from an economic point of view more attractive. Secondly, tilting of a fixed surface is efficient, except in the summer when the sun is high and a horizontal plane is more ideal (Mehrtash et al., 2012).

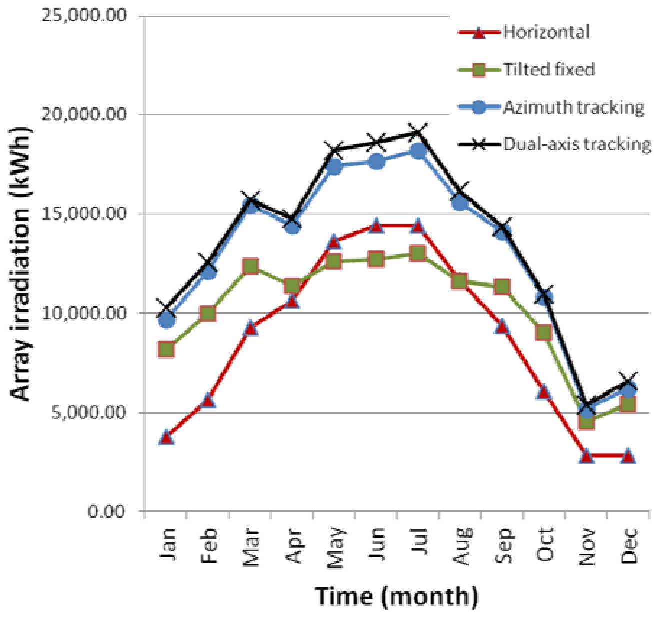


Figure 5-2: Annual array irradiation comparison (*Mehrtash et al., 2012*)

When dual-axis tracking and azimuth tracking are compared, it appears that only at noon on a summer day a clearly lower performance due to the high position of the sun is visible (Figure 5-3 and Figure 5-4).

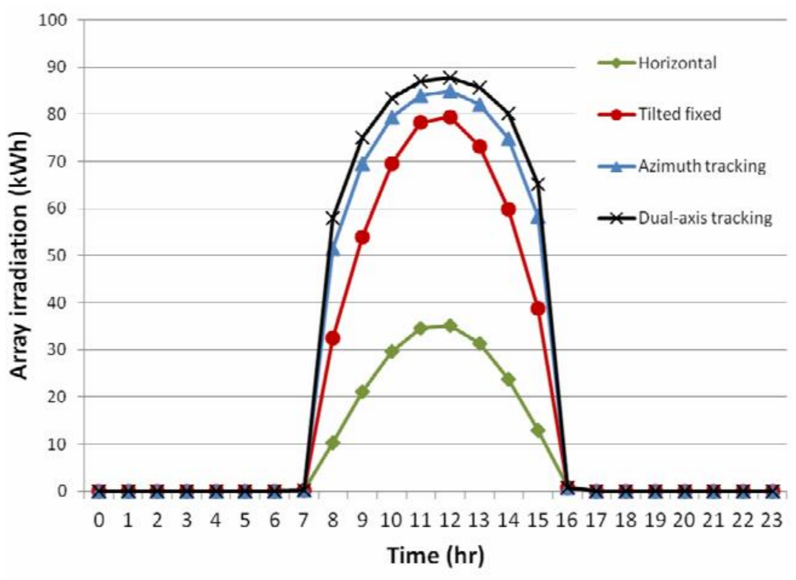


Figure 5-3: Array irradiation on a clear day in winter (Mehrtash et al., 2012)

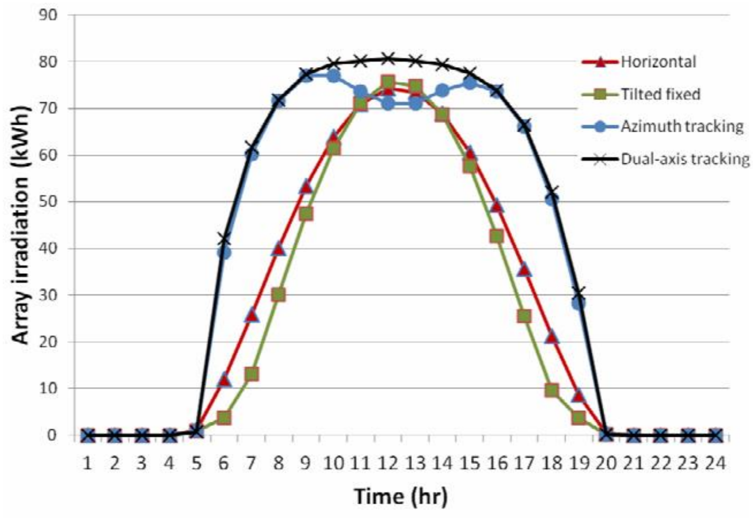


Figure 5-4: Array irradiation on a clear day in summer (Mehrtash et al., 2012)

When the different seasons in a year are compared, the study showed that focusing on **clear days** (both in winter and summer) is important. These days have much higher irradiation values compared to overcast days. During cloudy days, it can be interesting to stop the tracking of the panels and place them in an as stable as possible position to increase the resistance against extreme weather conditions (Mehrtash et al., 2012).

To further increase the efficiency of azimuth tracking, the PV panels should be positioned in an optimal, fixed **tilt** from the horizontal position. The optimal tilt angle depends on the location and geographic situation. Important to notice is the fact that the optimal tilt angle for fixed south-facing panels (mostly close to the local latitude) is not equal to the optimal tilt angle for single-axis tracking panels. Studies have proved that the efficiency of single-axis tracking panels with optimum tilt angle is about 96% of the efficiency of double-axis tracking panels. The energy collected by an ideal tilted azimuth tracker can be 25-50% higher than in case of an optimally tilted, fixed surface in Europe (Lorenzo et al., 2002).

A further possible step to increase the power output is to adjust the fixed tilt four times a year according to the different seasons. However, research showed that this would increase the efficiency by only 1.5-2.8%. Therefore, introducing a second degree of freedom (implying extra costs and construction problems) seems not interesting based on the low increase in energy gain (Li et al., 2010).

5.3.4 Optimum tilt angle (single-axis trackers) - Europe

From the previous part, it was concluded that a **single-axis azimuth tracking** system with **optimal inclined** fixed position is the best solution considering efficiency, costs, performance and maintenance. Huld et al. (2008) did an extensive study regarding the optimal mounting strategy for single-axis trackers for locations in Europe. In their study two types of single-axis sun-trackers where examined. The first is the single-axis tracking with vertical axis and optimal inclination of modules. The second type is the single-axis tracking with north-south oriented **optimally-inclined axis**. A database was formed for the European Subcontinent to find the optimum angle of inclination for both types of structures. Both types of single-axis azimuth tracking systems may differ in optimum angle, but the performance (energy output) of the two types is very similar. Single-axis tracking systems are often designed with a pivoting tube at the back of the panel. This tube forms the rotational axis for the east-west rotation. Therefore, in this part, only the second type (optimally-inclined axis) will be investigated. The optimum inclination angle for the inclined axis tracking system is given in Figure 5-5. For Belgium this inclination angle is **approximately 38°** (inclination in degrees from horizontal) (Huld et al., 2008). Interesting to mention is that studies show that a deviation from this optimum inclination angle will result in limited losses. For each degree of deviation from the optimal value, approximately 0.4% energy efficiency is lost (Lorenzo et al., 2002).

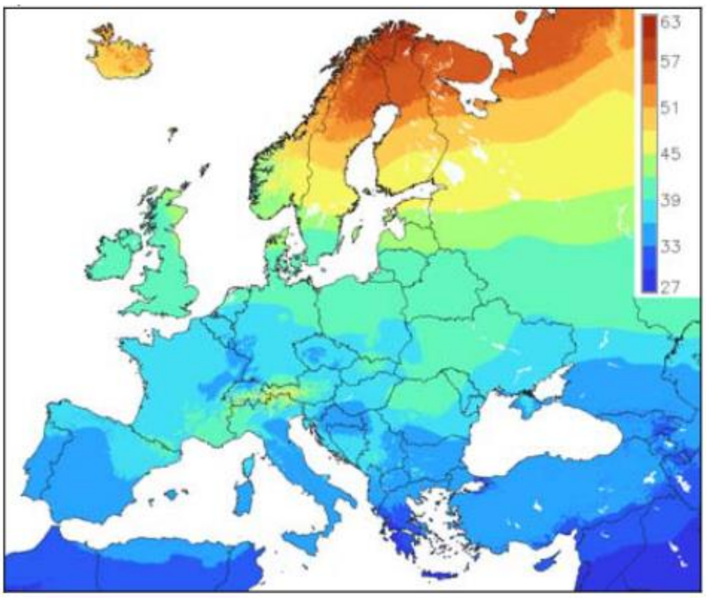


Figure 5-5: Optimum inclination angle (degrees inclination from horizontal) (Huld et al., 2008)

If the energy output is compared to the fixed systems, the largest increase is found in Northern Europe (about 50%). In Central Europe the increase is smallest (around 20-25%) and in Southern Europe the increase is about 30%. Still, in general, the increase is high compared to the fixed systems. Figure 5-6 shows that the inclined single-axis tracking system (with a fixed inclination of 38°) has only a 2.2% loss in energy gain compared to a dual-axis tracking system for the specific location of Belgium (Huld et al., 2008).

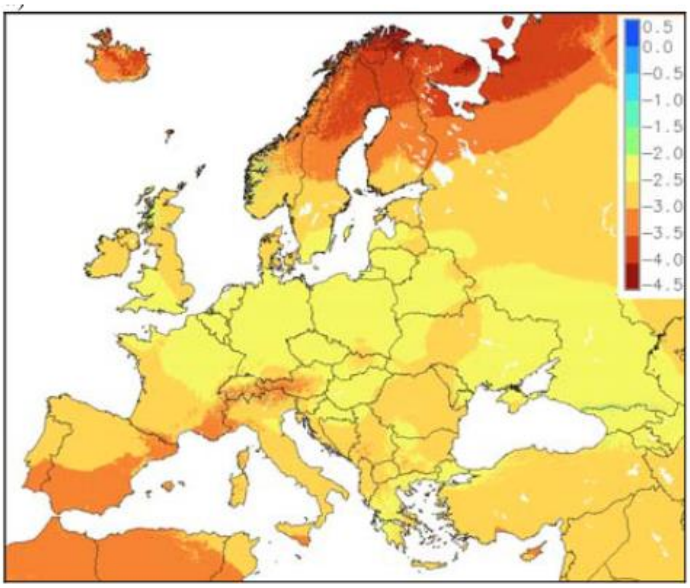


Figure 5-6: Relative difference (in %) in solar radiation (Huld et al., 2008)

5.3.5 Shadow problems

When a row of tracking PV panels is installed, **shadow problems** from neighbouring panels will occur. This shadowing will occur mainly in the early morning and late afternoon (east-west shadowing). For the optimal design of an array of panels, the combination of both costs and shadow aspects results in a difficult optimisation problem. A lower spacing between the different panels results in lower area-related costs, which is better from economic point of view (Gordon & Wenger, 1991). In contrast, the impact of shadow has a negative effect on the electricity generation of the panels (Lorenzo et al., 2002). The distance between the different panels in an array determines the GCR ('Ground cover ratio'). This term originates from the fact that PV panels were in the very beginning only placed on the ground. The shadow losses increase significantly with respect to the GCR, certainly for azimuth tracking systems. Therefore, these losses are an important aspect to consider for large ground cover ratios (Gordon & Wenger, 1991) (Rand et al., 2007).

To lower shadow problems for an array of PV panels, the distance between the panels, the limitation on the tracking angle and the number and placement of bypass diodes is of main importance (Gordon & Wenger, 1991). These factors will be discussed in this part.

5.3.5.1 Bypass diodes

The output power in case of (partial) shading depends on the **electrical connection of the cells** in the PV panel. If a serial connection of PV cells is combined with bypass diodes, the shading losses are proportional to the shaded fraction of the panel. This in contrast to the total vanishing of power output under partial shading when no **bypass diodes** are foreseen in a serial connection. The principle of bypass diodes is based on the fact that the current through a series of solar cells is limited by the highest resistance cell. Without bypass diodes, the increased resistance of one cell will limit the current of the whole PV panel. Therefore, bypass diodes placed in parallel with a series of cells are used to avoid this inefficiency (Figure 5-7). A group of cells that is protected by one bypass diode, is called a block. If one cell of the block is shaded, the power of the whole block cancels out. The diode across the block will start to conduct and in that way bypass the shaded cells. The bypass diodes are placed across a group of cells because placing a bypass diode across every cell would result in a too expensive design (Gordon & Wenger, 1991). To lower the shadow problems from neighbouring panels, the bypass diodes should be placed over the cells along the sides of each panel in the row. This because the sides are the most vulnerable places for the east-west shadowing.

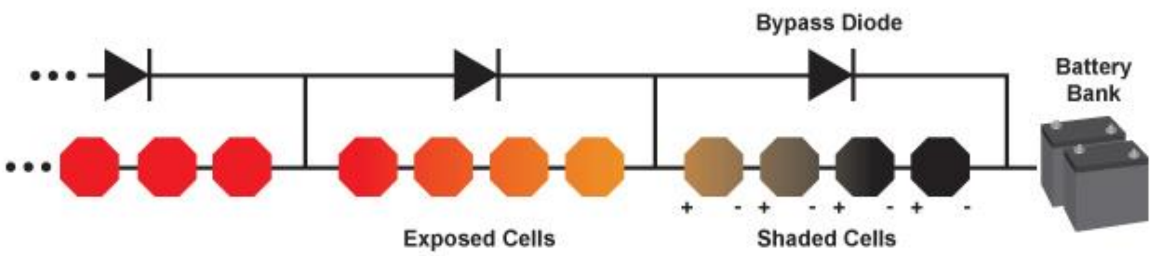


Figure 5-7: Bypass diode principle for series cells (Web 5-06)

5.3.5.2 Cover ratio and Backtracking

Shadow problems are related to the distance between the different panels which is expressed by the **GCR value** of an array. The principle of the GCR value is illustrated in Figure 5-8. The distance a is the width of the PV panel and the distance b is the distance between the different panels. For building applications, it is important to make a space efficient system. Therefore lowering the GCR value in a significant way is not possible.

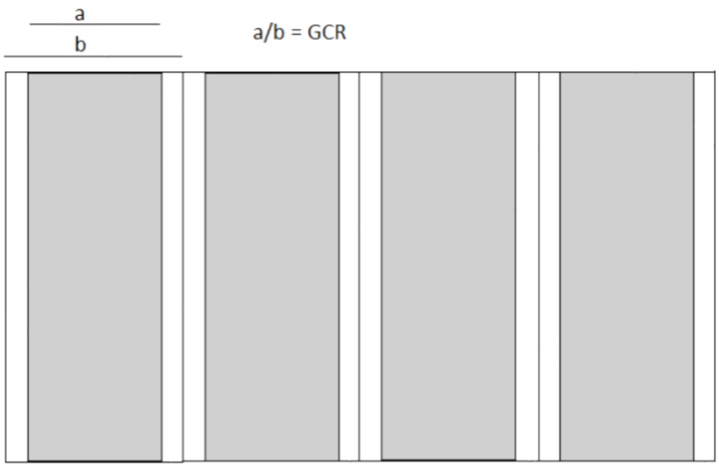


Figure 5-8: Demonstration GCR principle

A recent technique to lower the problems of shadow losses and keeping a high GCR value is **backtracking**. The concept of backtracking was developed to find a better balance between system costs, array performance and long-term reliability. This non-ideal tracking technique is based on an azimuth correction angle. Backtracking allows for a better energy performance for the same GCR value since the energy losses due to increased incidence angles are smaller than the losses that result from the shading. The normal conventional single-axis tracking system track the sun from east to west, at a range of +/- 45-65°. During a backtracking cycle (illustrated in Figure 5-9), the panel array moves such that no inter-array shading occurs. The array panels start from a zero tracking angle in the morning (facing south) and end also in this position. They gradually rotate during the morning towards the east at a certain rate such that no inter-array shading occurs. At a specific moment during the morning, they reverse direction and rotate west to minimise the sun incidence angle. This reversion moment depends on the season and location. During midday hours, the backtrack strategy is equivalent to the conventional, ideal strategy. The gain of backtracking increases significantly with the GCR (Panico et al., 1991) .

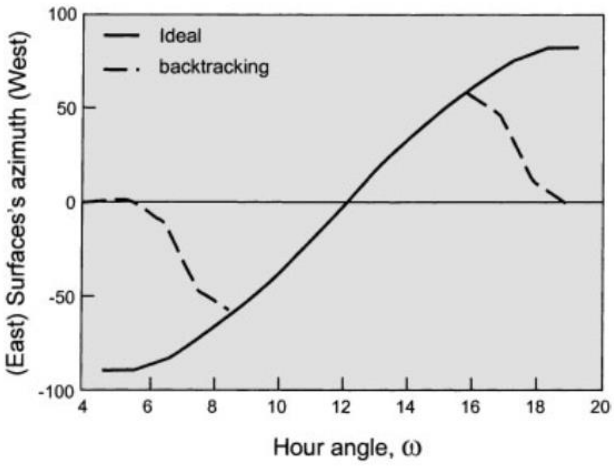


Figure 5-9: Demonstration backtracking strategy (Panico et al., 1991)

5.3.5.3 Limitations on tracking angle

A good consideration of the tracking angle is important from an economic point of view. A more **limited tracking angle** will result in lower tracker costs. Tracking ranges have been studied intensively during the past. These studies showed that for normal ranges of distance between the panels, the energy loss from a single-axis tracking system with a tracking range of +/- 45° is negligible compared to a higher range of for example +/- 60°. Therefore, a limitation of +/- 45° is acceptable for the tracking angle regarding the energy sacrifices that will occur (Gordon & Wenger, 1991) (Panico et al., 1991).

5.3.5.4 Shadow problems and daylight optimisation

For the design of a shading system for mid/high-rise buildings, the **daylight aspect** is an important factor. When a low GCR value is chosen, daylight will pass between the neighbouring PV panels. This is illustrated in Figure 5-8. The white area between the grey PV panels shows that in case of a GRC lower than one some daylight can pass. Therefore it is more optimal to choose for a GCR equal to 1.0, which implies that the edges of two neighbouring panels (when facing south) have no space between each other. In that way, the view of the persons inside will not be obstructed by disturbing daylight lines. A GCR of 1.0 will however result in more shadow problems. These can be solved by making optimal use of the above mentioned methods (bypass diodes, backtracking and limitation on tracking angle).

5.3.6 Practical study: Belgium

To optimise the prototype design for Belgium, a perfect knowledge of the position of the sun is necessary. With the use of Matlab and Solar software, some graphs are generated of the solar elevation angle in Belgium. Firstly the inclination angle of the sun on a winter (December 21) and a summer (June 21) day are generated (Figure 5-10). This explains the optimum tilt that was found in '5.3.4' for Belgium (38°). This angle is situated in between the lowest angle of the winter sun (16°) and the highest angle of the summer sun (62°).

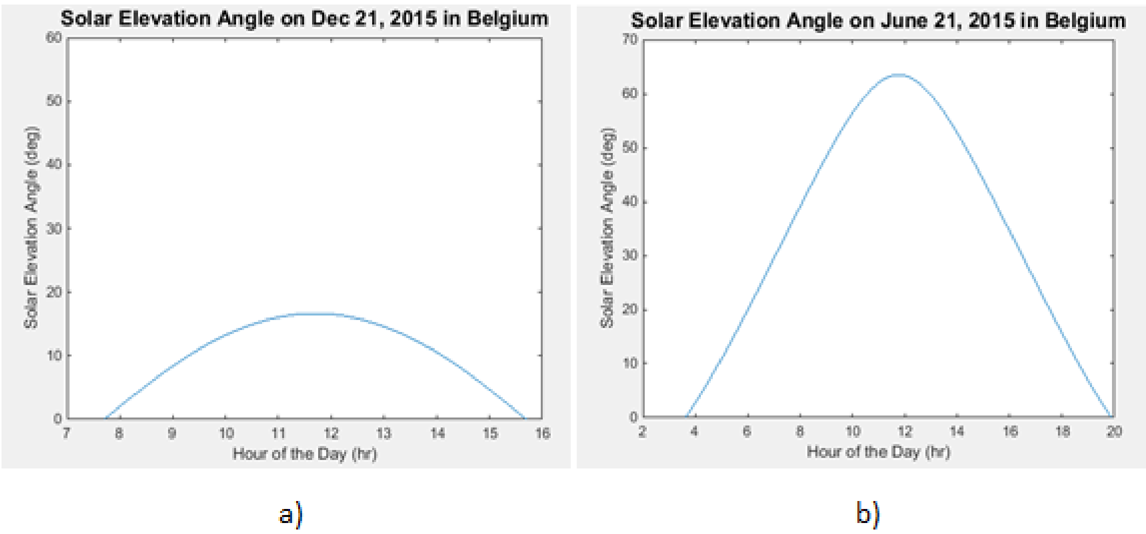


Figure 5-10: Solar elevation Angle in Belgium: a) Dec 21, b) June 21

In a next step, the tracking angle for ideal tracking and non-ideal backtracking are generated. From Figure 5-11 and Figure 5-12 it can be concluded that the tracking cycle starts earlier and ends later on a summer day compared to a winter day. In the figures, the blue, red, orange and purple lines represent the tracking angle, the sun elevation angle, the sun azimuth angle and the angle of incidence respectively.

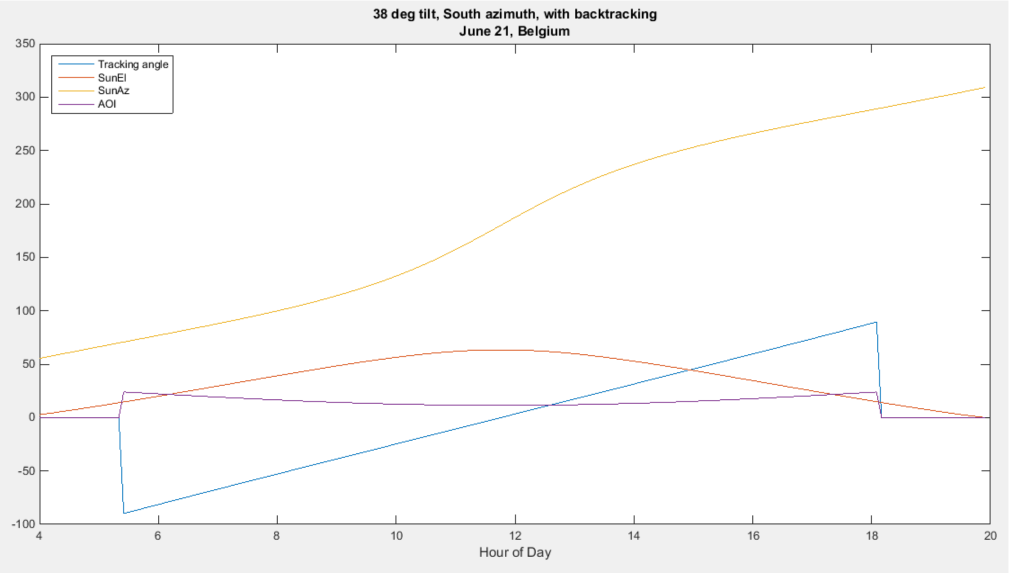


Figure 5-11: Tracking angle (blue) for no backtracking on June 21

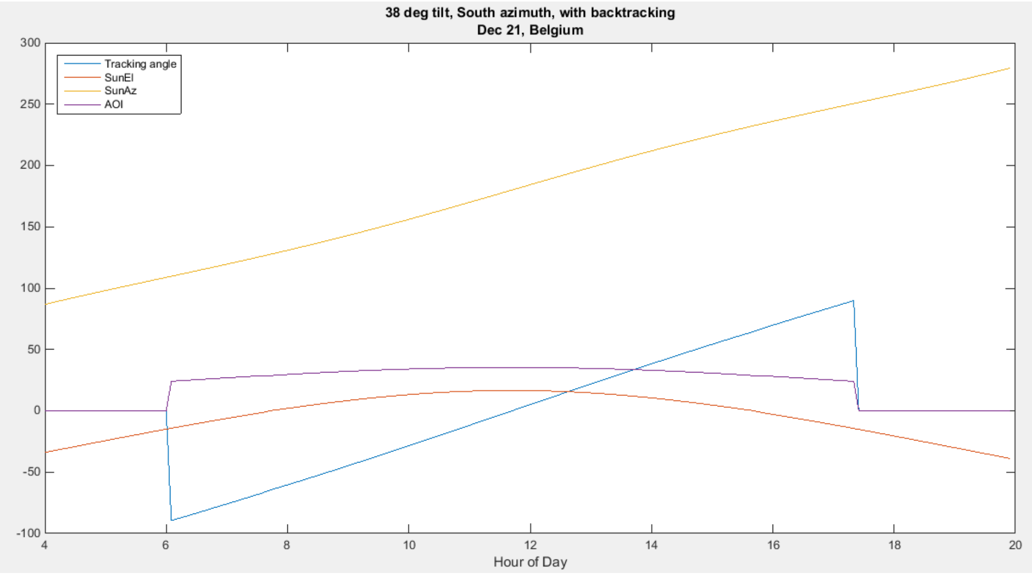


Figure 5-12: Tracking angle (blue) for no backtracking on Dec 21

As an illustration, the backtracking cycle for an angle of +/- 45° with a GCR of 0.75 is shown for a summer and winter day in Figure 5-13 and Figure 5-14. These figures show that there is a shift in reversing point for different days of the year. Backtracking systems will increase the efficiency but need **a complex computerised design system** to achieve a good backtracking cycle on each day of the year. Therefore, limiting the tracking angle in combination with placing bypass diodes along the sides of the panel seems a more attractive solution to lower the shading problems. This solution will be implemented in the design of the prototype.

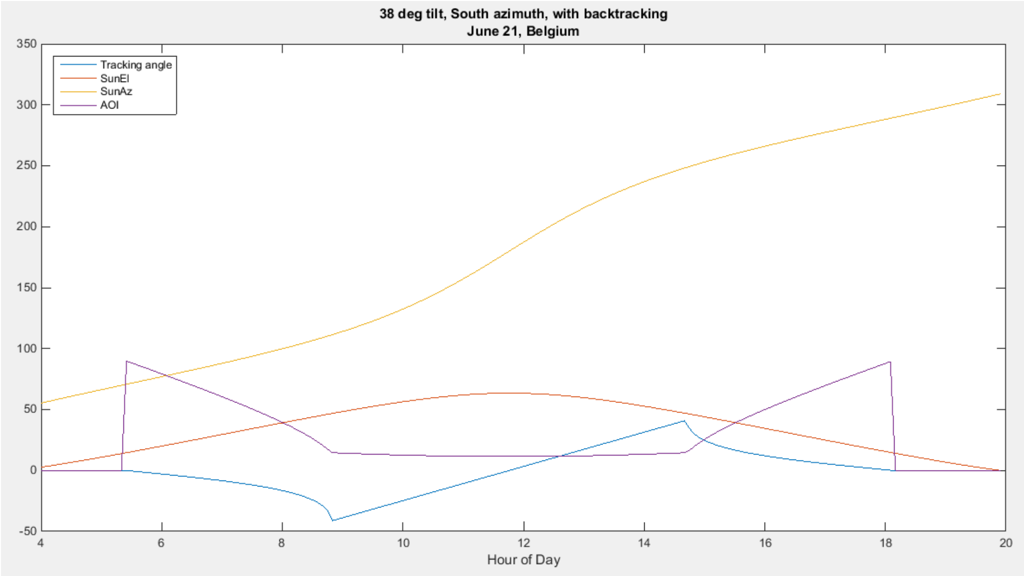


Figure 5-13: Tracking angle (blue) for backtracking over 45° and GCR 0.75 (June 21)

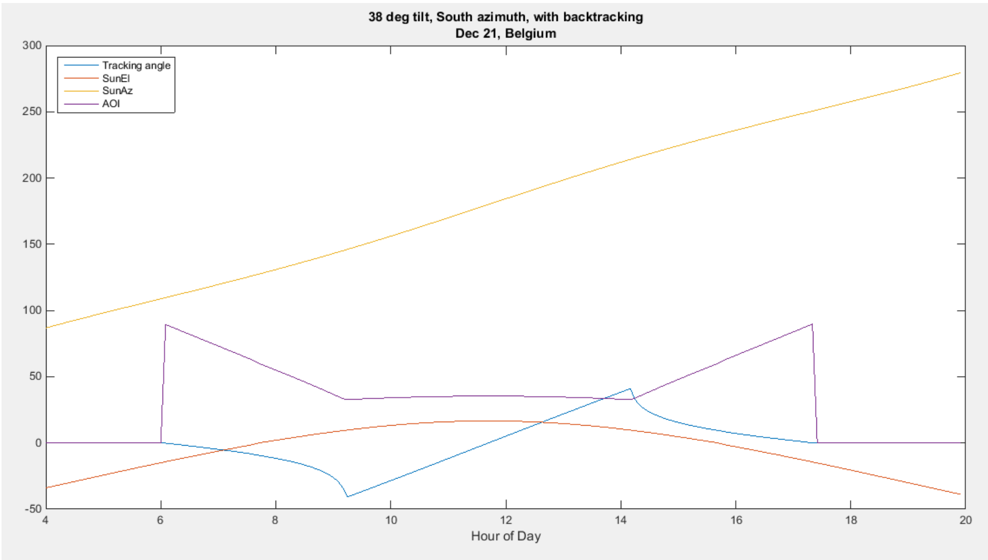


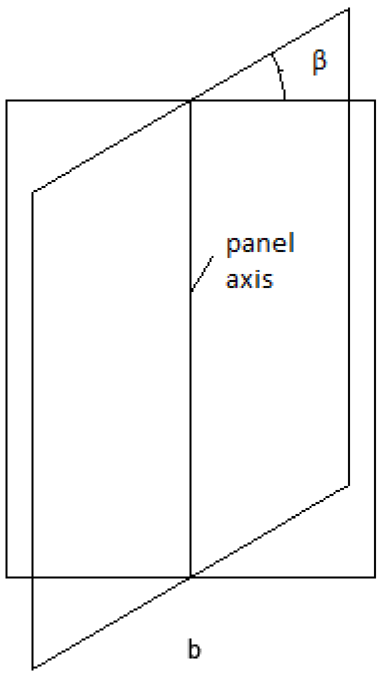
Figure 5-14: Tracking angle (blue) for backtracking over 45° and GCR 0.75 (Dec 21)

5.4 Creation of a prototype

In this part, the detailed design of a single-axis tracking system will be elaborated for mid/high-rise buildings in Belgium. The different sections deal with the optimal dimensions of the panels, the actuation of the tracking system, the materials and mounting system, the forces on the panels and the force transfer. At the end, the optimal design is suggested.

5.4.1 Dimensions

The single-tracking panels will turn around an inclined axis at an optimal angle α (from horizontal). The optimal tilt angle for Belgium is 38° as discussed in '5.3.4'. To make it possible for the panels to rotate over an angle β (during the day to track the sun), the top side of the panels have to be placed at a sufficient distance from the wall (illustrated as distance x1 in Figure 5-15). This figure assumes that the turning tube is situated in the axis of the panel. This is not possible in reality. The distance between the turning tube and the panel will be discussed in '5.4.2'.



$$x1 = \frac{b}{2} \cdot \sin(\beta) \cdot \cos(\alpha)$$

Figure 5-15: Distance x from the wall (front view)

Besides the optimal tilt angle and the tracking angle, the **dimensions of the panel** (height m3 in Figure 5-16 and width b in Figure 5-15) are important as well. To find optimal dimensions for the panel, first the window area that has to be shadowed by the panel needs to be specified. The floor-to-floor height for office and residential buildings differs. It is often stated that for unknown use, the floor-to-floor height is 3.5 m. For office buildings this will be typically higher (around 3.9 m) and for residential buildings typically lower. The floor-to-ceiling height for office buildings has a minimum around 2.6 m. For residential buildings this minimum is lower, certainly if air-conditioning is foreseen in the building (Web 5-07). For this design, an **office building** is assumed. The design is purposed on foreseeing shadow over 2.6 m (the whole window area) in case of sun in the high summer position. In the winter, the sun is positioned lower. The lower position will result in a smaller shadow area of the window such that the heat of the sun can be used in an optimal way. As mentioned before, on overcast days, the irradiation is low compared to clear days. On these days not much gain of the power of PV panels will be lost if the panel is placed in a different position from the perpendicular incidence angle. In addition, the occupant behaviour tends towards opening conventional shading systems on cloudy days. Occupants don't need blinds or equivalent systems in this situation. In contrast, they want the daylight and heat to enter the room (Van Den Wymelenberg, 2012). The design will therefore focus on the avoidance of overheating during summer and the allowance of heating during winter.

With this assumptions, an **optimal lay-out** was investigated. For the position of the sun, an angle of 62° is assumed (position on June 21, inclination from horizontal further indicated as λ). With a panel width of 1.00 m and a height of 1.30 m, a total shadow area of 2.73 m corresponds which gives a certain reserve over 2.60 m. This reserve will be needed further (see '5.4.9'). The side view of this design situation is showed in Figure 5-16 (with the panel indicated in bold). The total shadowed window area is represented by m1+m2-m4. The fact that the distance m4 is subtracted takes into account that some sun rays can pass above the panel (inclined panel with height m3). This distance m4 will be some space that is located between the ceiling and floor of two building storeys. The needed distance x1 as explained in Figure 5-15 is also visualised in this side view. The results of the calculations are given in Table 5-9.

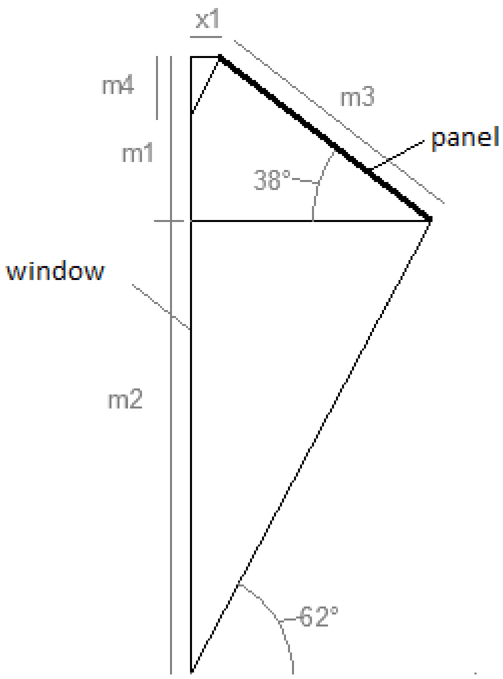


Figure 5-16: Lay-out panel positioning (side view)

Table 5-9: Results optimisation parameters panel

Input	Output
b = 1.00 m	m3 = 1.30 m
m1 – m4 + m2 = 2.73 m	m1 – m4 = 0.51 m
α = 38°	m2 = 2.22 m
β = 30° (see '5.4.2')	x1 = 0.15 m
λ = 62°	m4 = 0.29 m

5.4.2 Turning tube at a distance of the panel

In a next step, the difference in shadow area of neighbouring panels on each other while turning is examined. This shadow area will differ if the turning tube is placed at a **distance 'd'** behind the panel, instead of very close to the panel (Figure 5-17 and Figure 5-18). Placing the panel at a distance d is spatially more attractive, because this will give the opportunity to place the tube closer to the wall of the building. Therefore the tracking system that will guide the tracking panels can be placed closer to the wall of the building, which results in a more elegant solution (see '5.4.3' and '5.4.9').

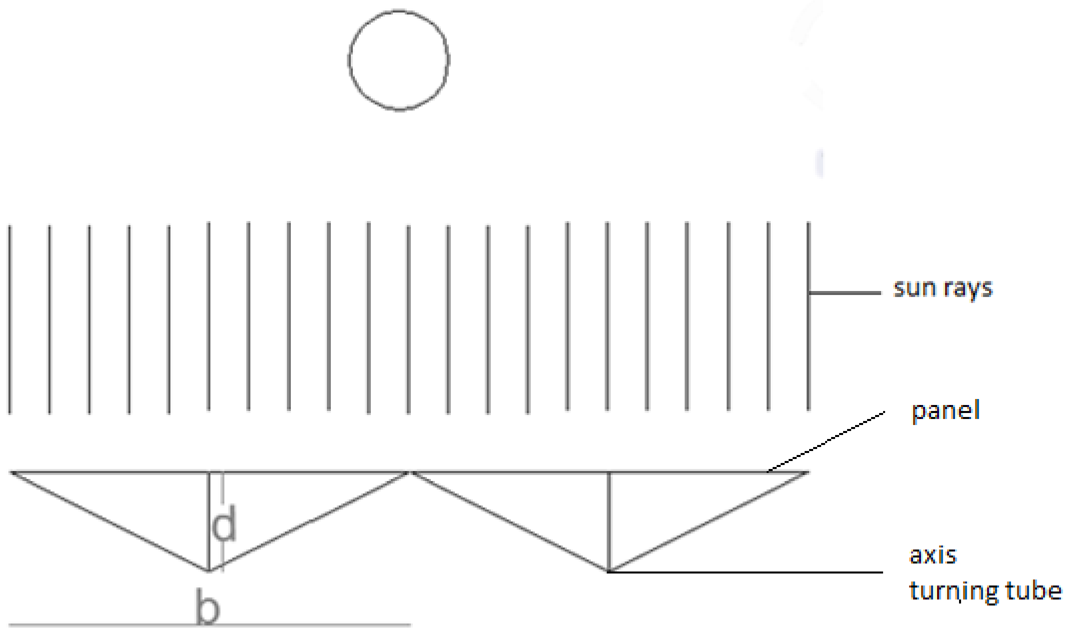


Figure 5-17: No shadow when faced south (top view cross-section)

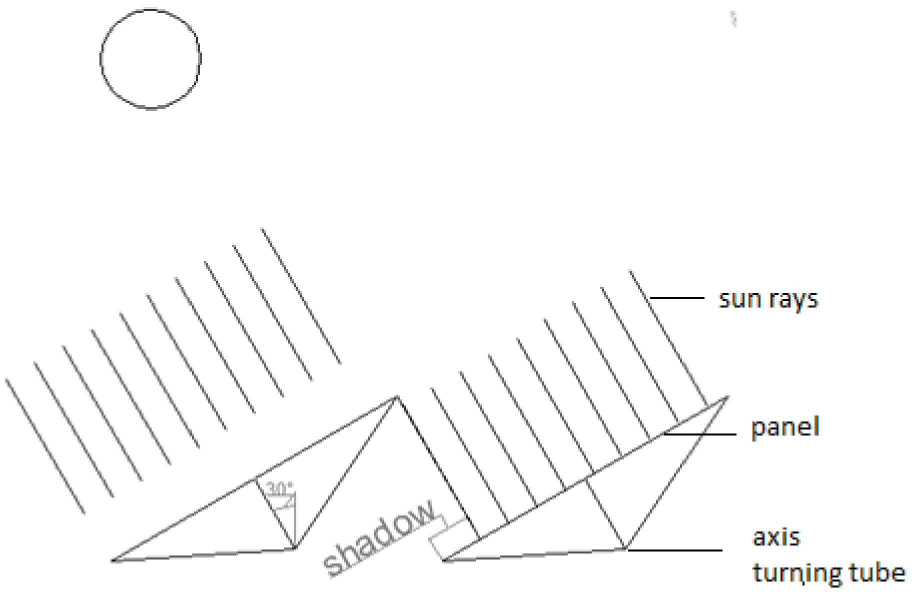


Figure 5-18: Illustration shadow area (30° turned east) (top view cross-section)

Figure 5-19 shows the tracking principle on the final designed prototype (based on the further calculations and investigation in this chapter)

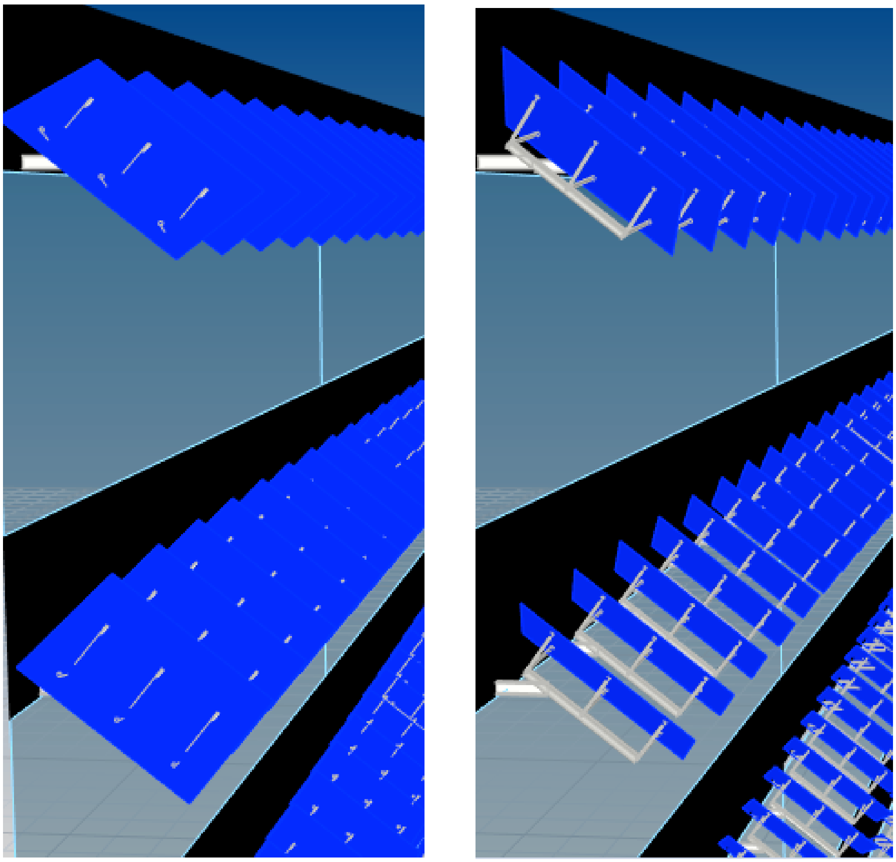

a) b)

Figure 5-19: Illustration tracking principle: a) turning west, b) turning east

In Table 5-10, the results of the investigation of the shadow area are shown. The left column shows the results in the extreme case of the tube being placed at the centre of the panel (at a distance d equal to zero). This will in reality never occur. The angle β shows the tracking angle. The results are compared for a distance d more far from the panel, and for a distance d close to the panel (0.03 m). It can be seen that the difference in shadow area is negligible for the two cases. Certainly compared to the advantage of placing the tube closer to the wall (more elegant structure and tracking system see '5.4.3'). If the solution of a larger distance d is implemented, it has to be ensured that the profile that connects the panel to the tube is certainly stiff enough.

In Table 5-10 the shadow area is also compared to half the width of a panel in the column 'fraction of half panel'. From this column it can be concluded that this fraction is quite large at 45° compared to 30°. Therefore it seems more reasonable in terms of energy gain to only **track to +/- 30° east and west** in combination with placing bypass diodes in parallel to the series PV cells at the sides of the PV panel. This decision is supported by the cosine relationship between the power output and angle of incidence as explained in '5.3.2'. If only 15° is deviated from the perpendicular incidence angle, the amount of power loss is almost negligible as this angle of incidence is still situated in the top of the cosine profile (Figure 5-1). When a limited tracking angle of 30° is set, the distance d to the panel can be lowered. A more ideal distance in that case is 0.25 m.

Table 5-10: Shadow comparison

	Tube at centre panel		Tube at distance d from panel									
b [m]	β [°]	Shadow [m]		d [m]	β [°]	Shadow [m]	Fraction of half panel [%]		d [m]	β [°]	Shadow [m]	Fraction of half panel [%]
0.5	5	0.0019		0.16	5	0.0019	0.76		0.03	5	0.0019	0.76
	10	0.0076			10	0.0076	3.04			10	0.0076	3.04
	20	0.03			20	0.03	12			20	0.0299	11.96
	30	0.067			30	0.067	26.8			30	0.065	26
	40	0.117			40	0.117	46.8			40	0.108	43.2
	45	0.146			45	0.146	58.4			45	0.131	52.4
1	5	0.0038		0.35	5	0.0038	0.76		0.03	5	0.0038	0.76
	10	0.015			10	0.015	3.04			10	0.015	3
	20	0.06			20	0.06	12			20	0.059	11.8
	30	0.134			30	0.134	26.8			30	0.127	25.4
	40	0.234			40	0.234	46.8			40	0.211	42.2
	45	0.293			45	0.293	58.6			45	0.256	51.2

5.4.3 Tracking system

The panels should turn from east to west over a certain angle during the day. Above was mentioned that an optimal angle, related to shadow on neighbouring panels is 30° east and west. Independent of this optimal angle, a tracking system should be designed to **turn the panels** during the day according to the position of the sun. Below, two concepts are discussed. Both concepts focus on tracking by connecting a system with the turning tube behind the PV panel. This makes it possible to create a concept without frame, which allows to design an elegant panel system.

5.4.3.1 Concept 1 – Pull-pull system

The first possibility to track the sun is to make use of a **pull-pull system**. For this, two pulleys are necessary at both sides of a row of panels (this row should extend over e.g. the width of a room of the building). These pulleys pull a steel cable that is connected by eye nuts to the turning tube. The steel cable should be connected by steel cable clamps to the eye nuts. During the day cycle, one pulley will pull, which makes it possible to turn the panels from east faced to west faced. At the end of the day, the other pulley should pull the panels back to their original east faced position. From this position, the cycle will start again the next day. By adjusting the length of the cable that is available on the pulley, the system can be locked so that it is only able to rotate over the tracking angle of 30° east and west. A sketch of this tracking system is given in Figure 5-20. Figure 5-21 and Figure 5-22 show the pulling principle from both sides.

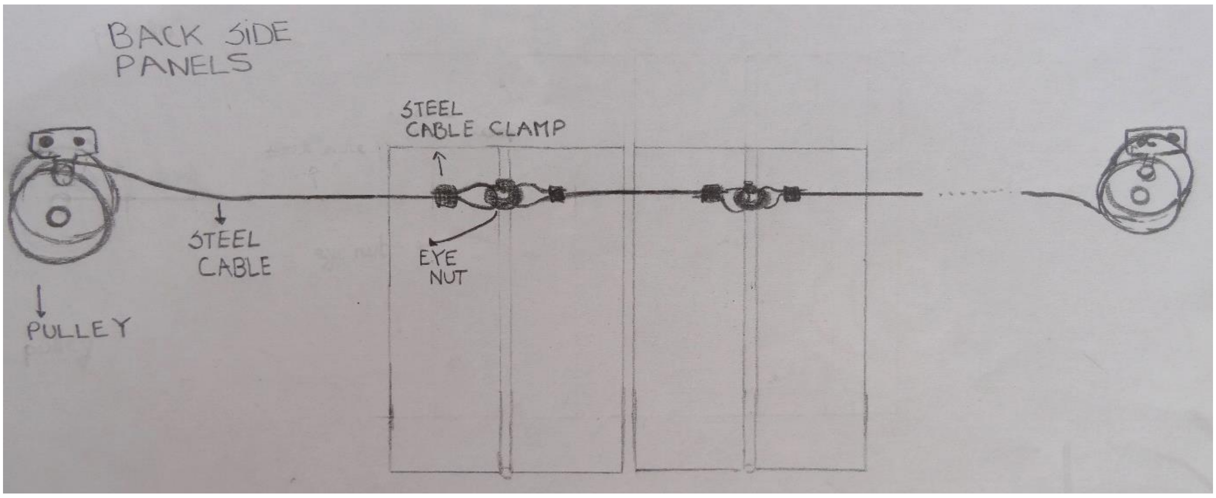


Figure 5-20: Sketch pull-pull system

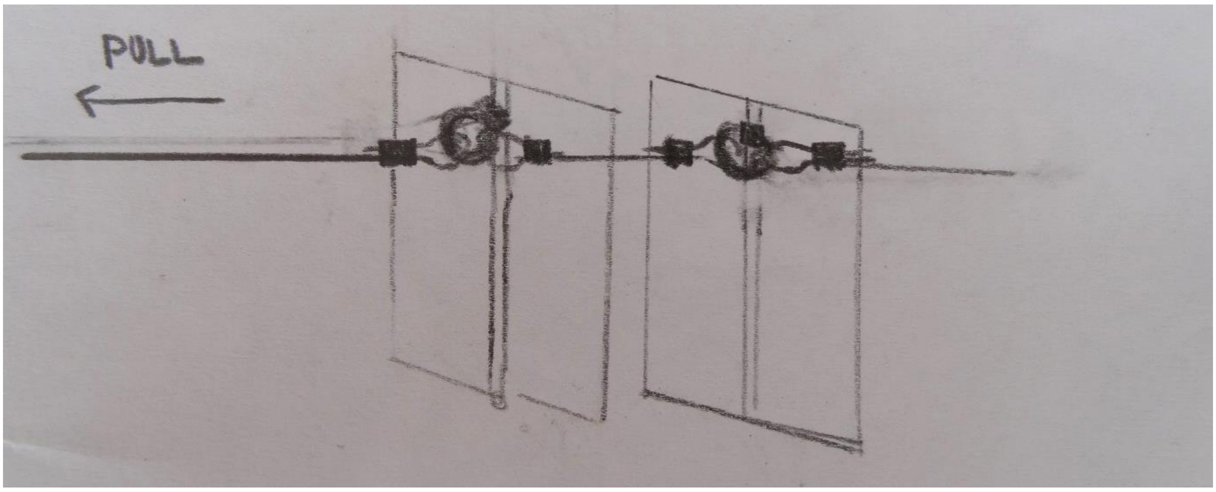


Figure 5-21: Pull at left side

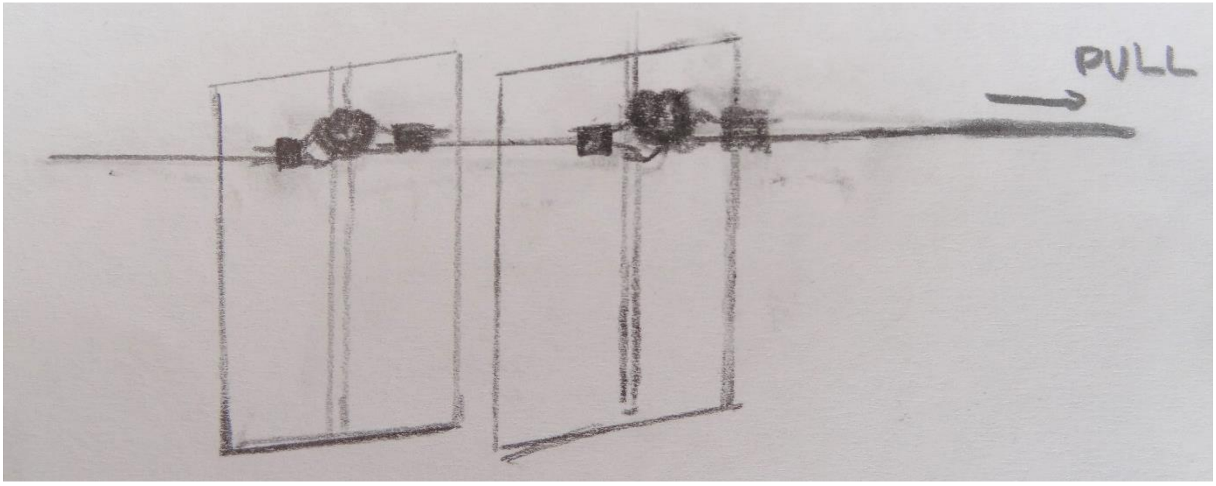


Figure 5-22: Pull at right side

A model of this tracking system is shown in Figure 5-23 and Figure 5-24. Figure 5-23 shows the system from a south-east faced top view. It should be mentioned that the dimensions of the panels, tubes and the connections to the wall are not in realistic proportion. This model is focused on showing the principle of the pull-pull tracking system.

Figure 5-23: Pull-pull system

a) b)

Figure 5-24: Detail of the system: a) top view, b) side view

5.4.3.2 Concept 2 – Push-pull system

A second possibility is a **push-pull system**. The main advantage of this concept compared to the pull-pull concept is that only at one side of a row of panels a turning actuator is necessary. More precisely: instead of two pulleys, one gear wheel is necessary. This gear wheel can push and pull from one side (Figure 5-25). It should be connected to a steel bar. At each turning tube of the panel, the steel bar should have two pinned connections connected to a tube clamp (illustrated in Figure 5-26 and Figure 5-27). This tube clamp will take care of the turning of the tube and the connected PV panel. This connection principle will make the push-pull system possible. An example of a gear wheel is given in Figure 5-28. By adjusting the distance over which the gear wheel can rotate, the system is able to lock the tracking system to only 30° east and west.

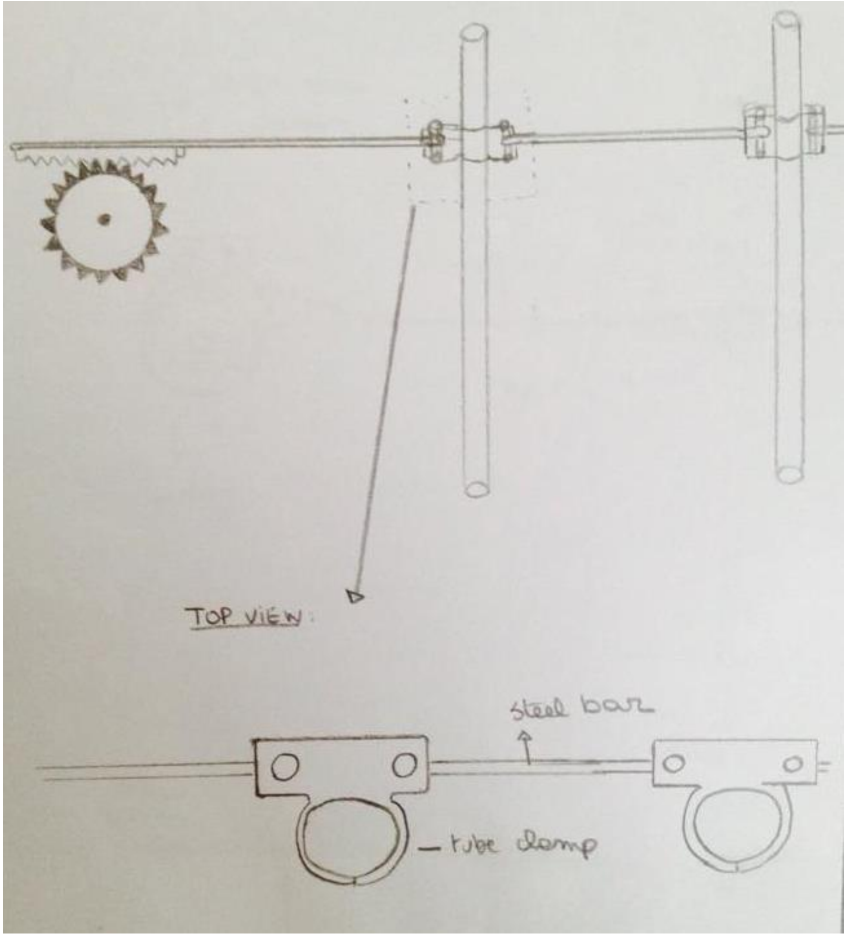


Figure 5-25: Sketch push-pull system

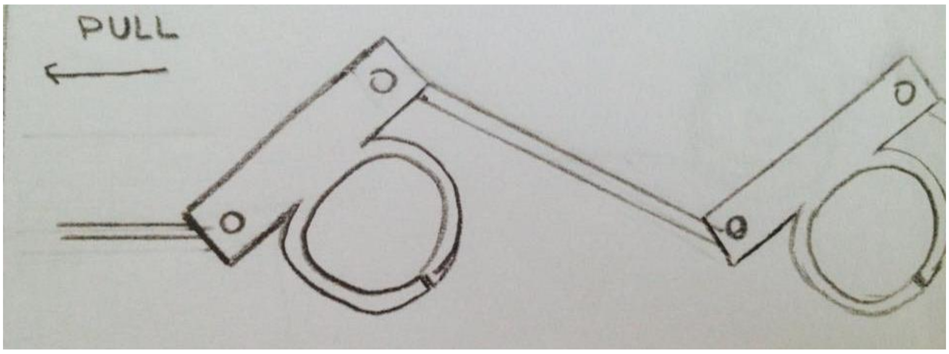


Figure 5-26: Pulling mode

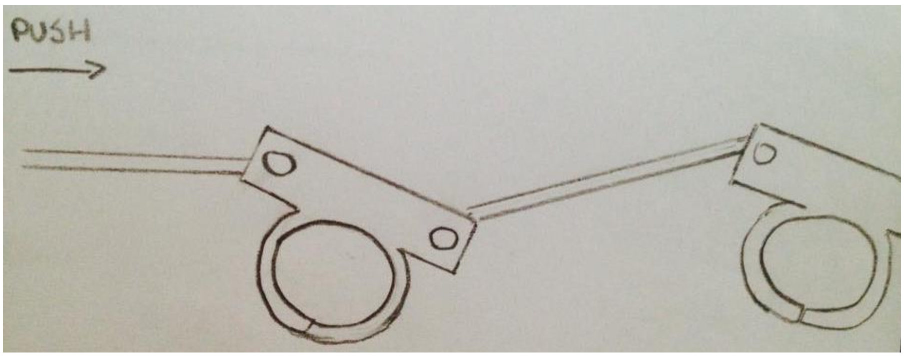


Figure 5-27: Pushing mode

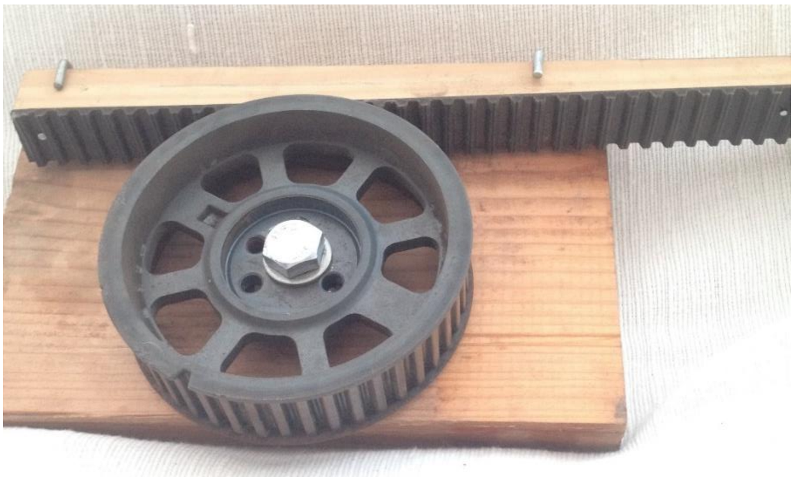


Figure 5-28: Gear wheel principle

The model for this tracking concept is shown for two panels in Figure 5-29. This model is made with a wooden block that represent the double pinned connection. Again, the proportional dimensions are oversized. In reality, this pinned connection should be smaller.

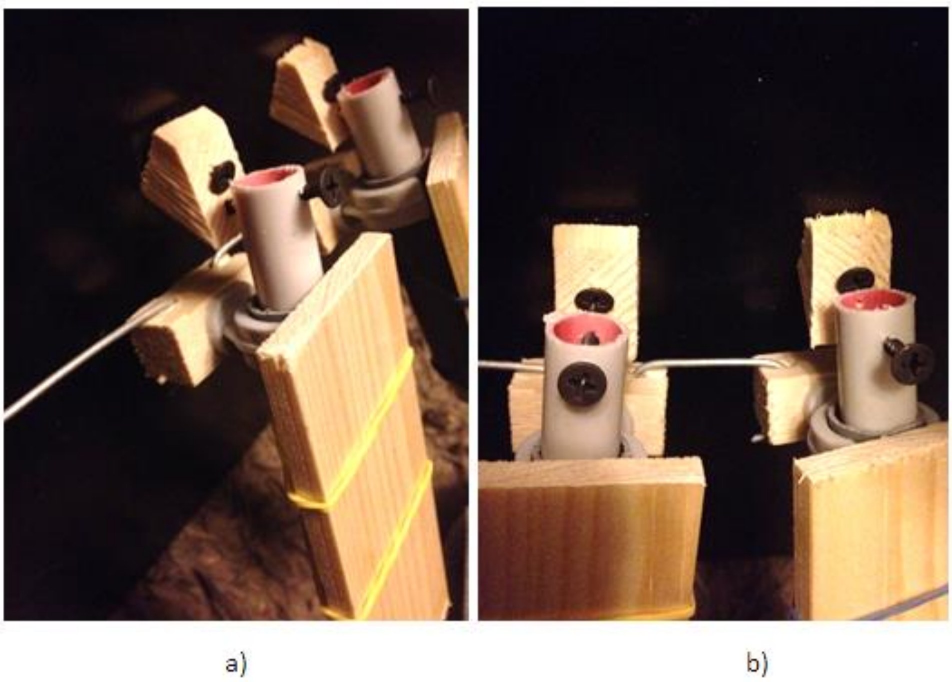


Figure 5-29: Push-pull model: a) side view, b) front view

This second concept is preferred over the first one because it allows to place only one actuator at one side, which will result in a more elegant system. Furthermore, this system has more advantages related to easy maintenance and repair.

5.4.4 Materials, mounting system and connections

For the transfer of the forces from the panel to the primary load-carrying structure of the building, **extruded aluminium and stainless steel** will be used. Aluminium has the main advantage that it can serve a double function of carrying system and guiding system for the current. It has some other important advantages: high strength to weight ratio, flexibility of design and colour options and a high resistance to corrosion. The sizes of the aluminium profile need to be dimensioned to be able to transfer the loads and to deal with the requirements of maximum allowed displacement and stresses.

The clamp and **cantilever system** that connects the PV panels and their **aluminium carrier system** to the wall can be made out of stainless steel. The shading system will be connected with the concrete floor of each storey by bolts. Concrete is a medium isolator and in that way, a possible grounding system can be made. As an alternative, this cantilever arm can be made out of aluminium as well. The cantilever arm is connected to the aluminium turning tube by a thrust bearing. This will make the rotation movement possible for the turning tube. This set-up is illustrated in Figure 5-30.

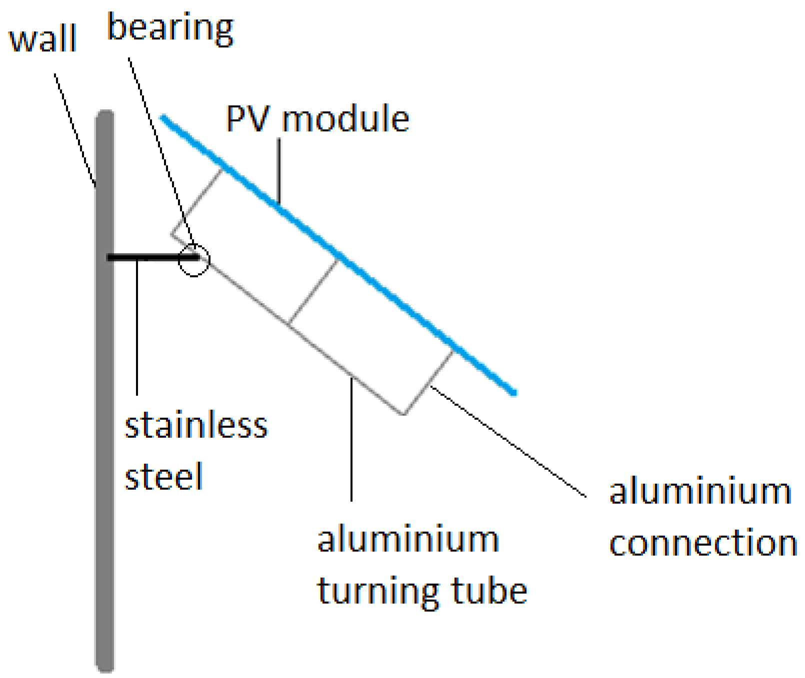


Figure 5-30: Side view of panel and mounting system

5.4.5 Forces on the panel

5.4.5.1 Self-weight

The first load on the panel is the self-weight of the **PV module**. A PV module can be designed in different ways. For the lamella, the PV cell, the module type and the frame type should be specified. The transparency of the lamella will depend on the distance between the cells. The different elements of a module are shown in Table 5-11.

Table 5-11: PV module specification (Web 5-08)

PV cell	Glazing	Encapsulation	Backsheet	Frame type
Monocrystalline	Tempered glass	Ethylene-vinyl acetate (EVA)	Plastic	With aluminium frame
Polycrystalline	Antireflective glass	Polyvinyl butyral (PVB)	Tempered glass	Without frame
Thin film				

Because the weight of the panel will be negligible compared to the wind forces on the panel, making the panel more lightweight is not an important focus aspect for the design process. Therefore, monocrystalline or polycrystalline cells will be used to achieve a space efficient system (discussed in '5.2.1'). These cells will be combined with two layers of tempered glass both at the front and the back. In between the glass and cells, an EVA or PVB encapsulation is placed. Both materials have comparable characteristics, but **EVA interlayers** are often chosen for solar applications because their properties are less temperature dependent than PVB's due to the fully crosslinking structure. A set-up of this type of PV module is shown in Figure 5-31. The two layers of **tempered glass** are able to withstand high wind loads, temperature variances and snow loads, which makes the design very durable. The choice to avoid the use of a frame is related to the purpose of an elegant and aesthetic attractive façade solution. The thickness of a tempered glass sheet can range from 3-10 mm. The encapsulated layer that will be placed between the PV cells and the glass sheets at both sides has a typical thickness of about 0.76 mm. For the design a tempered glass thickness of 5 mm is chosen, resulting in a total module weight of about 26.5 kg/m² (Web 5-09).

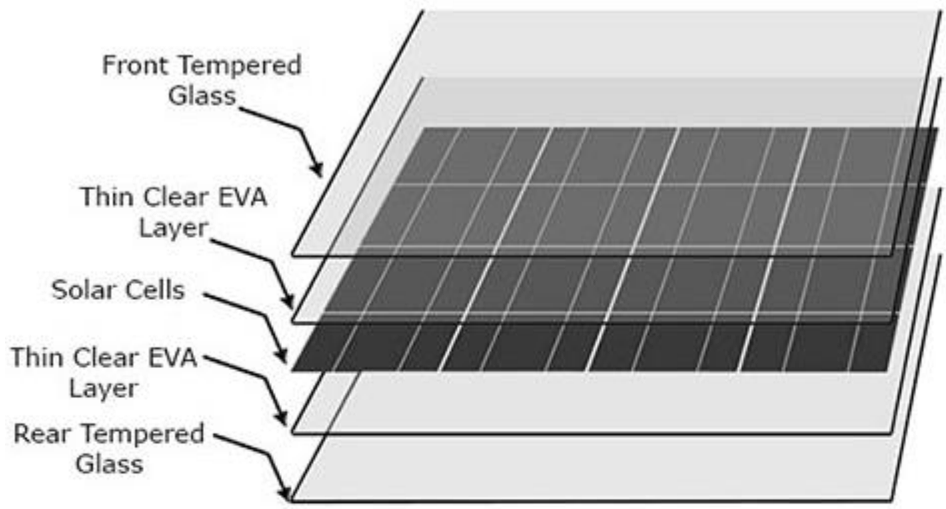


Figure 5-31: Example PV module (Web 5-10)

To determine deformations and stresses in laminated glass, the laminated glass can be calculated as a monolithic glass with an effective thickness h_{eff} (Belis, 2016):

For deformation checks, the following formula (1) can be used:

$$h_{eff,v} = \sqrt[3]{\sum_{i=1}^{n} h_i^3 + 12\omega \sum_{i=1}^{n} (h_i d_{m,i}^2)} \quad (1)$$

For stress checks, formulas (2) and (3) can be used:

$$h_{eff,\sigma} = \min(h_{eff,\sigma,i}) \quad (2)$$

$$h_{eff,\sigma} = \sqrt{\frac{(h_{eff,v})^3}{(h_i + 2\omega d_{m,i})}} \quad (3)$$

Where:

ω Coefficient to account for contribution of interlayer to laminate stiffness

$d_{m,i}$ Distance between centre of gravity of layer i and median plane of laminate

h_i Thickness of layer i

The value of ω depends on many factors (load duration, temperature, boundary conditions …). Therefore it is most safe to assume that there is no shear interaction and to take ω equal to zero (Belis, 2016). When a module of two tempered glass sheets of 5 mm is used, $\mathrm{h}_{\mathrm{eff},\sigma}$ is equal to 7.1 mm and $\mathrm{h}_{\mathrm{eff,v}}$ is equal to 6.3 mm.

The usage of glass for both the front- and backsheet is interesting for applications of BIPVs. With the purpose of partially transmitting daylight and providing shading on the same time, the opportunity of these products to offer different transparencies is very attractive. By changing the distance between the cells (normally between 3 and 50 mm), the level of transparency can be changed. When changing this distance, the effect on the amount of electricity production should be taken in mind (Jelle et al., 2012).

5.4.5.2 Wind load

The most important forces on the structure are the wind forces. PV panels placed on mid/high-rise buildings are exposed to **large wind loads** that can cause problems. The wind flow and its interaction with the panels are of great importance to minimise possible problems. Rows of PV panels have a sheltering effect on each other. The gap between the panels has only a marginal impact on wind pressures. In contrast, the angle of attack of the wind on the panel is important. The most dangerous situation occurs when the wind attacks the panel perpendicular. This situation will be dealt with in this part. The calculations of the wind force is done according to NBN EN 1991-1-4.

Wind velocity and velocity pressure

First the basic wind velocity is calculated using the following equation (4):

$$v_b = c_{dir} c_{season} c_{prob} v_{b,0} = 26\ \frac{m}{s} \tag{4}$$

Where:

$c_{dir} = c_{season} = \mathrm{c_{prob}} = 1$ The directional, seasonal and probability factor: one is a recommended safe value (wind can come from east, south and west direction, the curtain wall is a permanent construction, return period of 50 years)

$v_{b,0} = 26\ \frac{\mathrm{m}}{\mathrm{s}}$ The fundamental value of the basic wind velocity for Ghent (NBN EN 1991-1-4 ANB)

Mean wind velocity

The mean wind velocity at a height z (above the terrain) depends on the terrain roughness, orography and the basic wind velocity. The following formula (5) can be used to calculate this mean velocity:

$$v_m(z) = c_r(z) \cdot c_0(z) \cdot v_b \tag{5}$$

Where:

$c_0(z) = 1$ Orography factor: equal to one based on the assumption that the slope of the terrain is lower than 5% (assumed flat terrain)

$c_r(z)$ The roughness factor ((6) and (7)):

$$c_r(z) = c_r(z_{min}) \quad z < z_{min} \tag{6}$$

$$c_r(z) = k_r ln(\frac{z}{z_0}) \quad z > z_{min} \; (< z_{max}) \tag{7}$$

$$\text{with } k_r = 0,19 \cdot \left(\frac{z_0}{z_{0,II}}\right)^{0.07} = 0.234$$

Based on the assumption of a neighbourhood with different high-rise buildings, the terrain can be classified as terrain category IV. This terrain category is characterised by the following parameters: z_0= 1.0 m, $z_{min} = 10$ m, $z_{max} = 200$ m en $z_{0,II}$= 0.05 m. The most critical place is the highest level of the building. This is the reference height for the design, which is certainly situated above z_{min}. Therefore, the second formula (7) has to be used (8):

$$c_r(z) = k_r \, ln\left(\frac{z}{z_0}\right) = 0.234 \, ln(\frac{z}{1.0}) \quad z > z_{min} \; (< z_{max}) \tag{8}$$

Wind turbulence

The turbulence intensity $I_v(z)$ at a height z above terrain level can be calculated with the following formulas (9)(10) (for this case the second equation has to be used):

$$I_v(z) = I_v(z_{min}) \quad z < z_{min} \tag{9}$$

$$I_v(z) = \frac{k_I}{c_0(z) ln(\frac{z}{z_0})} \quad z > z_{min} \; (< z_{max}) \tag{10}$$

According to NBN EN 1991-1-4 ANB, the turbulence factor for category IV is $k_I = 0.85$. The values of z_0 and $c_0(z)$ were already determined in the previous part.

Peak velocity pressure

Finally the peak velocity pressure can be calculated. This pressure includes the mean and short-term velocity fluctuations. This pressure can be determined as follows (11) (with $\rho = 1.25 \text{ kg/m}^3$, the air density):

$$q_p(z) = \frac{1}{2} \rho v_m^2(z) \left(1 + 7 \, I_v(z)\right) \tag{11}$$

Mid-rise buildings have a height that is lower than 35 m. High-rise buildings are typically between 35 and 100 m high. A value of 100 m can be taken as a safe reference peak height z_e for the wind forces on the prototype. In Belgium, only a few buildings are higher than this height (Web 5-11) . This assumption results in a value for the peak velocity pressure of 1128 N/m².

To calculate the wind force on the PV panel, it is supposed that the building is stable under wind conditions. The wind force on the panel itself needs to be considered as a **local wind effect**. The panels act like canopies and are connected to the building. For this situation, both an upwards and downwards wind force need to be considered. This will result in **suction or pressure** on the panel. According to NBN EN 1991-1-4 ANB (part 7.4), the pressure coefficient c_p that has to be considered for local elements on a façade is equal to 2.0. This value is used for both the situation of pressure and suction. With this wind pressure coefficient, the wind pressure (12) that acts on the surface of the panel can be calculated:

$$w_1 = q_p(z_e) \cdot c_p = 2255 \frac{N}{m^2} \tag{12}$$

Since the wind force on the panel is a local phenomenon, no structural factor for structural damping needs to be considered. For the total resultant wind force on the building, the wind pressure can be multiplied with the total panel area.

As previously mentioned the wind can blow on top and from below the panel (Figure 5-32). The wind suction loading case is important for the treatment of the adhesive point fixings (see '5.4.7') on the panel. This is related to the tensile force that will be present in the adhesive connections during wind suction. The wind pressure loading case is most important for the loads and moments that will occur in the clamped connections because in that case the wind, weight and snow loads (see '5.4.5.3') are all acting in the same downward direction and do not cancel each other.

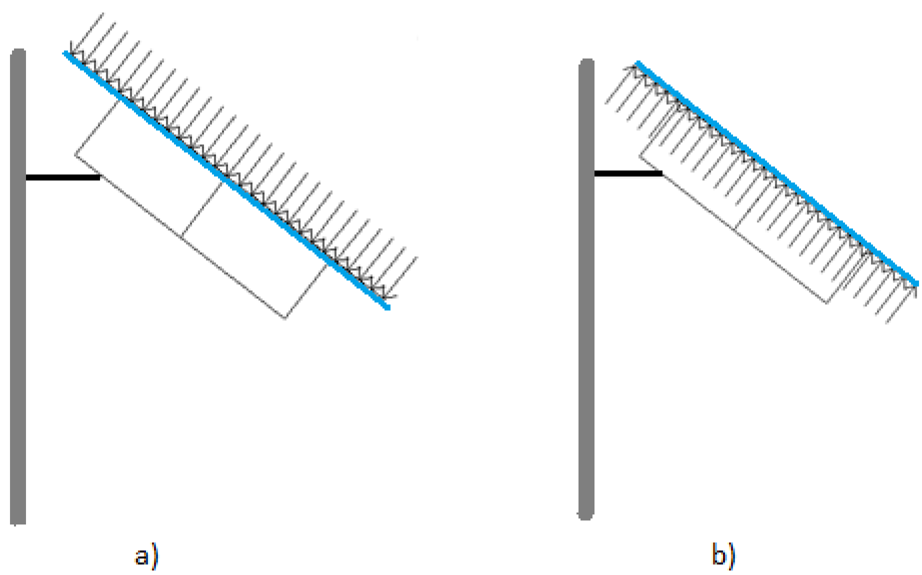


Figure 5-32: Wind force: a) pressure, b) suction

5.4.5.3 Snow load

For the calculation of the **snow load**, the specifications of NBN EN 1991-1-3 are followed. The snow load (Figure 5-33) for a tilted surface can be calculated by treating the PV module as a part of a tilted roof. This results in the following formula (13):

$$s_k = \mu \cdot C_e \cdot C_t \cdot s_k = 0.3 \frac{kN}{m^2} \tag{13}$$

Where:

μ The snow load form coefficient, equal to 0.60 for a tilt angle of 38°

C_e The exposure coefficient, equal to one for normal wind exposure conditions

C_t The warmth coefficient, equal to one for normal conditions

s_k The characteristic value of the snow load on the ground, equal to 0.50 kN/m² for Belgium

The value of the snow load is **much lower** than the wind load. When the wind blows under the panel, the snow load cancels the wind load partly. It will be assumed that in this particular situation there is no snow load on the panel. When the wind blows on top of the panel, the snow load will be taken into account. These two situations will result in the most conservative design.

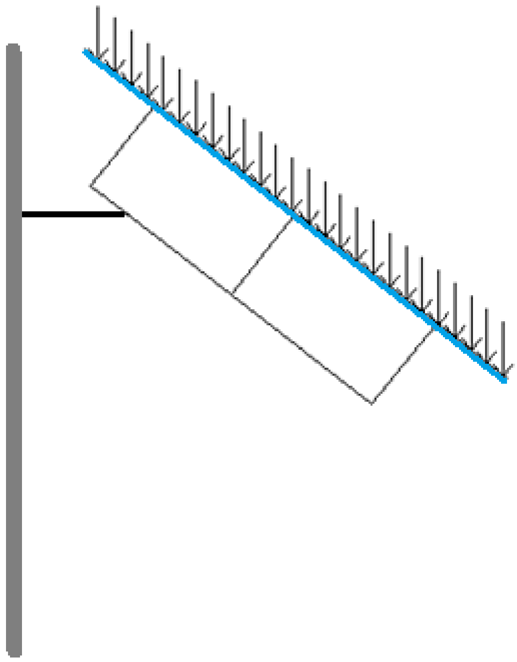


Figure 5-33: Snow load

5.4.6 Force transfer

The general design of a curtain wall system consists of a **secondary structure** that is able to transfer the forces to the **primary load-bearing structure** of the panel. In a first step, the forces on the panel are transferred by the glass to the adhesive point fixings. When the **adhesive point fixings** are distributed in a symmetric way over the surface, it can be assumed that each point fixing takes the same fraction of the total load. This symmetrical positioning will result in the most optimal distribution of stresses. Another parameter besides the distribution is the number of point fixings. In practice, it is most common to use four or six point fixings. The resulting forces and moments in the clamped connections will not change by this choice. Therefore only the stress distribution over the glass PV module is important for the choice of this parameter. Six point fixings will lower the stresses in the glass significantly (more or less by half) (Dispersyn, 2016). Hence, usage of six fixings will result in a considerable difference. The last important aspect is the edge distance of each point fixing. A close placement to the edge will have a negative impact on the stresses. For this reason it is decided to place the fixings at a distance of 1/4 of the width of the panel and at a distance of 1/6 of the height of the panel. This set-up (viewed from the back of the panel) is illustrated in Figure 5-34. In this figure, the aluminium turning tube (diameter D) and the aluminium connection (diameter d) are visualised as well. This aluminium carrier system is further explained in '5.4.8.2'.

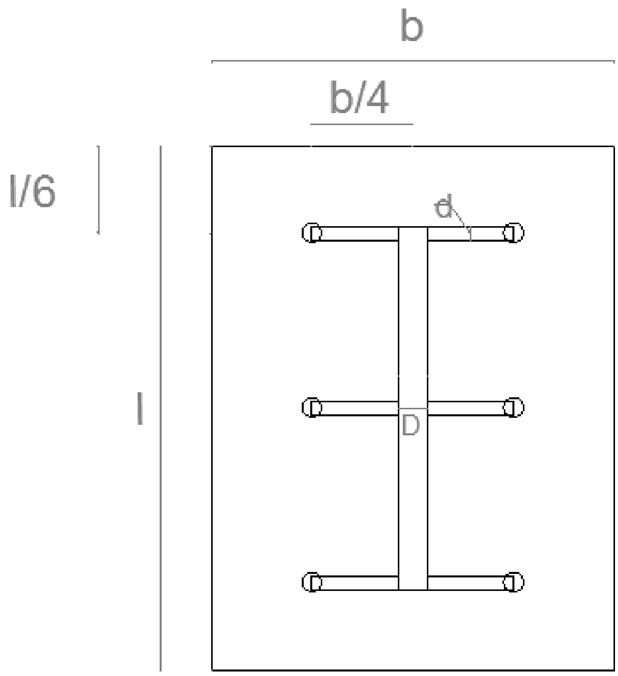


Figure 5-34: Six adhesive point fixings

Two load combinations have to be considered for the design :

- **Situation 1: Wind suction and self-weight;**
- **Situation 2: Wind pressure, snow load and self-weight.**

As mentioned before situation 1 is most critical for the dimensioning of the adhesive point fixings. For the design of these connections, the tensile force due to wind suction is most critical. In contrast, for the dimensioning of the clamped connections, situation 2 is most critical. The highest absolute values for the stresses and deformations will occur in this situation because all loads are acting in downwards direction.

The following load combinations (14) and (15) are used to perform the calculations:

ULS (Ultimate limit state)

$$\sum_{j\geq 1} \gamma_{G,j} \cdot G_{k,j} + \gamma_{Q,1} Q_{k,1} + \sum_{i>1} \gamma_{Q,i} \psi_{0,i} \, Q_{k,i} \qquad (14)$$

SLS (Serviceability limit state)

$$\sum_{j\geq 1} G_{k,j} \; + Q_{k,1} + \sum_{i>1} \psi_{0,i} \, Q_{k,i} \qquad (15)$$

$\psi_{0,i}$ for snow load is normally taken equal to 0.5. However, when a snow and a wind load are acting on the same time, this factor may be taken equal to 0.3 (NBN EN 1990 ANB). For these load combinations, the safety factors for the serviceability and ultimate limit state are applied in combination with the factor ψ. The safety factors in Table 5-12 for permanent and variable actions, taken into account (un)favourable situations, can be used (NBN EN 1990 ANB):

Table 5-12: Safety factors

Safety factor	Permanent action Υ_G	Variable action Υ_Q
Favourable	1.00	0
Unfavourable	1.35	1.50

The forces that are taken by the adhesive point fixings are transferred by the aluminium connection to the aluminium turning tube. This tube will transfer the forces to the first clamped connection (clamp 1 in Figure 5-35) at the free end of the cantilever arm. In this clamped connection a reaction moment (16), a horizontal reaction force (17) and a vertical reaction force (18) will occur. The formulas are executed for design situation 2 with six point fixings:

$$M_1 = (2P + (2G + 2S) \cdot \cos(\alpha)) \cdot (b + c - a) \qquad (16)$$

$$H_1 = 6P \cdot \cos\ (90° - \alpha) \qquad (17)$$

$$V_1 = \ 6G + 6S + 6P \cdot \sin(90° - \alpha) \qquad (18)$$

Where:

P Wind load acting on one adhesive point fixing $P = \frac{p \cdot b \cdot l}{6}$

G Self-weight load acting on one adhesive point fixing $G = \frac{g \cdot b \cdot l}{6}$

S Snow load acting one adhesive point fixing $S = \frac{s \cdot b \cdot l}{6}$

(with b = width of the panel, l = height of the panel, p = wind load/m², g = self-weight/m² and s = snow load/m²)

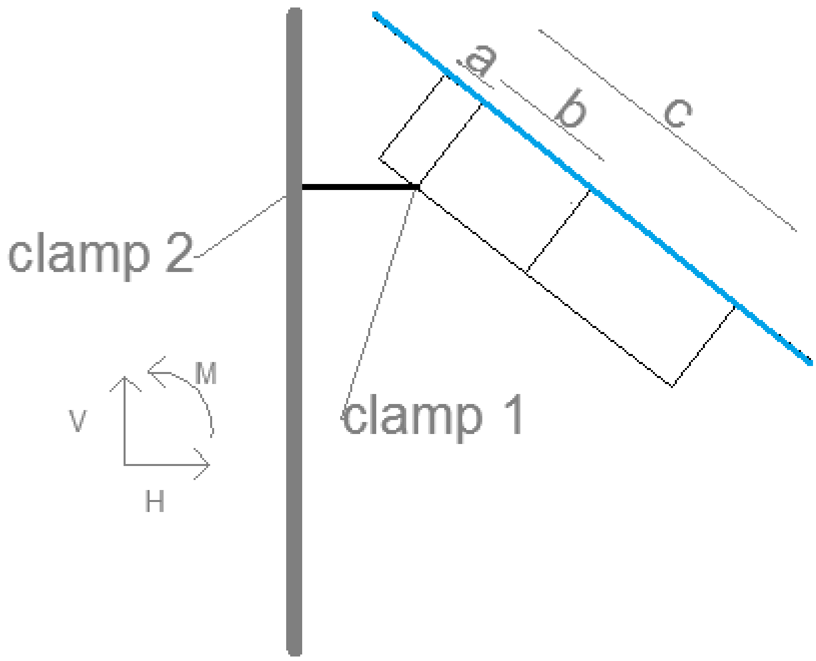


Figure 5-35: Design situation

The forces on the first clamped connection are in a next step transferred by the cantilever arm to the second clamped connection bolted to the wall of the building (Clamp 2 in Figure 5-35). This results in the following reaction moment (19) and horizontal (20) and vertical reaction force (21) :

$$M_2 = M_1 + V_1 \cdot x \quad (19)$$

$$H_2 = H_1 \quad (20)$$

$$V_2 = V_1 \quad (21)$$

With x the distance of the cantilever arm (from the first to the second clamped connection).

5.4.7 Adhesive point fixings

The forces that have to be taken by each **adhesive point fixing** (six point fixings – design situation 1) are the following ($F_{tensile}$ = tensile force (22), S_{shear} = shear force (23)):

$$F_{tensile} = P - (G + S) \cdot \cos(\alpha) \quad (22)$$

$$S_{shear} = (G + S) \cdot \sin(\alpha) \quad (23)$$

The situation for which the wind blows from below the panel is most critical for the adhesive point fixings, because the fixings are **weakest** when loaded **in tension**. As mentioned before, the snow load is not considered in this design situation. In this case, each fixing has to be able to withstand (ULS) a tensile force of 689 N and a shear force of 35 N. Taken into account that the effective depth for stresses for the laminated plate is equal to 7.1 mm (see '5.4.5.1'), it can be concluded that no problems are expected to withstand these forces with an adhesive point fixing. A connector diameter of 50 mm in combination with a strong stiff adhesive will be sufficient. The thickness of the adhesive layer is mostly determined by the manufacturer. For example, for a 3M Scotch-Weld 9323 B/a in shear, a thickness of 0.2 mm is prescribed (Dispersyn, 2016). In case of the second design situation (wind pressure and snow load) the compression force on the panel is equal to 816 N and the shear force is equal to 65 N. The suggested adhesive point fixing will be able to withstand these loads.

5.4.8 Stresses and deformations

The stresses in the different materials should be lower than the allowable limits. **Stresses** need to be checked in **ULS**, so formula (14) has to be used. The design yield strength is equal to : $f_{yd} = f_{yk}/\gamma_M$. γ_M is considered equal to 1.0 for steel (NBN EN 1993-1-1), f_{yk} is equal to 235 MPa for the used steel S235. γ_M is taken equal to 1.1 for aluminium (NBN EN 1999-1-1), and f_{yk} is taken equal to 270 MPa for aluminium. The characteristic yield strength of aluminium alloys is usually situated in the range of 200 MPa - 600 MPa.

The normal stresses are equal to (24):

$$\sigma = \frac{N}{A} + \frac{M}{W} \quad (24)$$

And should be limited to (25):

$$\sigma \leq f_{yd} \quad (25)$$

The shear stresses are equal to (26):

$$\tau = \frac{V}{A} \qquad (26)$$

And should be limited to (27):

$$\tau \leq \frac{f_{yd}}{\sqrt{3}} \qquad (27)$$

Deformations have to be checked in **SLS**, so formula (15) has to be used. The deformation limits should be specified for each project and agreed with the client (NBN EN 1990). For this design, a limit value of the span divided by 250 is chosen.

5.4.8.1 Glass PV module

At this moment, no Eurocode for glass exists, but the design should be done according to prEN16612. It is important to mention that the structural design methods for glass are still under development. In a further stage of the design, prototype testing should be done. For the calculations, **consequence class CC2** is supposed for office buildings. This class represents 'medium consequence for loss of human life' and secondly stands for the fact that 'economic, social or environmental consequences are considerable'. PrEN16612 uses the partial safety method according to EN 1990 with the following load combinations (28) and (29):

SLS load combination:

$$F_d = K_{FI} \cdot (1.G + \psi_1 \cdot Q_{k,1} + 1 \cdot \sum\psi_{2,i} \cdot Q_{k,i}) \qquad (28)$$

ULS load combination:

$$F_d = K_{FI} \cdot (\gamma_G . G + \gamma_Q \cdot Q_{k,1} + \gamma_Q \cdot \sum\psi_{0,i} \cdot Q_{k,i}) \qquad (29)$$

ψ_2 is equal to 0.3 for office buildings and ψ_0 is also equal to 0.3 for the wind and snow load that act together as stated before. ψ_1 is assumed to be equal to 1.0. With CC2 a K_{FI} equal to one corresponds. For glass, the **displacements** should be limited to the range of 1/300 – 1/100 of the span length (Belis, 2016). For PV panels typically 1/175 of the panel edge length or width is taken as the limit (Web 5-12). For a panel of 1.3 m length and 1.0 m wide this would result in a limit of 0.0074 m and 0.0057 m. For this deformation check, the software SCIA Engineer is used. The surface load (total load of 2.5 kN/m² - SLS – design situation 2), is applied on a panel with six supports and an effective thickness such as calculated in '5.4.5.1'. In Figure 5-36 a side view is given of the displacement of the panel (z-direction is the direction perpendicular to the panel). The maximum displacement is situated in the corners and has a downward value of 2.9 mm (Figure 5-37), which is below the given limits. In this figure, the location of the six point fixings is clearly visible from the deformed panel.

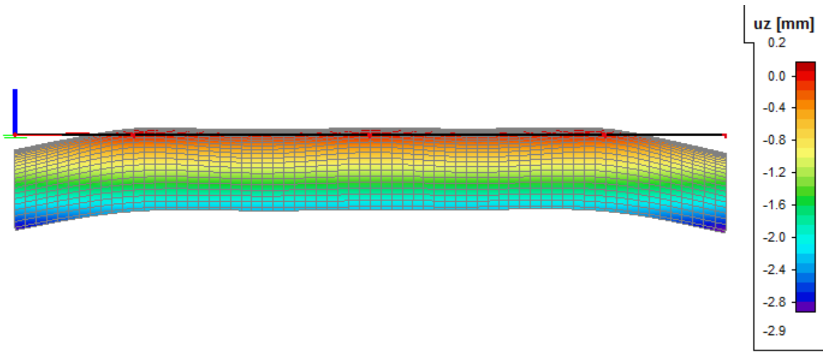


Figure 5-36: Side view deformed glass panel

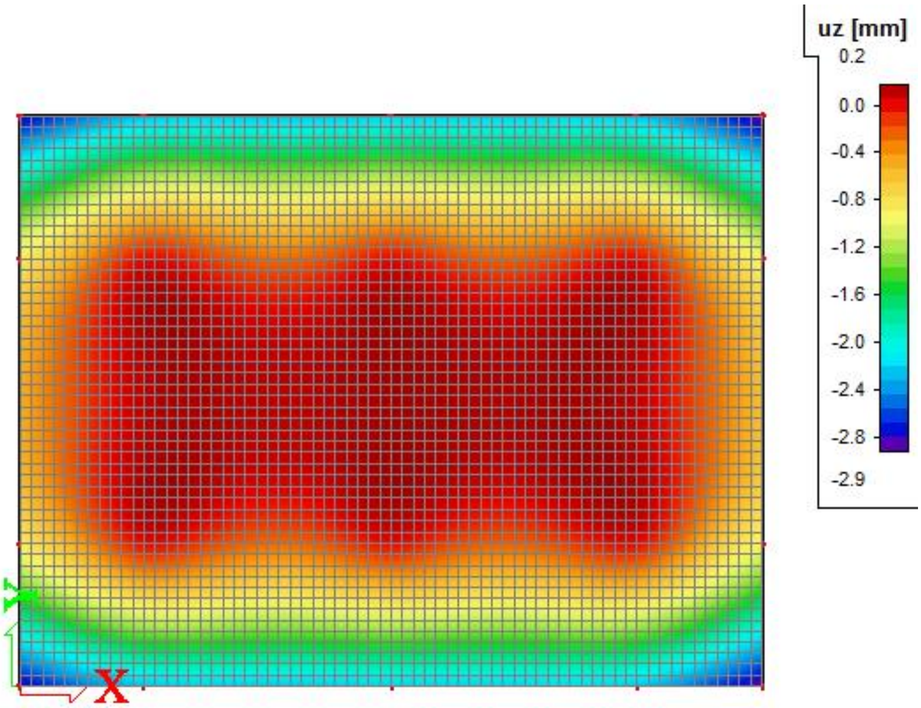


Figure 5-37: Top view displacements glass PV module

Secondly, the **stresses** in the glass PV module are checked (panel surface load of 3.8 kN/m² - ULS – design situation 2) again with an effective thickness of the module as calculated in '5.4.5.1'. The maximum stress method is used according to prEN16612. This method states that the maximum stress of an element should stay beyond the strength limit (taking the load duration into account by applying the factor k_{mod}). The strength of prestressed glass can be calculated according to the following formula (30) (Belis, 2016):

$$f_{g;d} = \frac{k_{mod} \cdot f_{g;k}}{\gamma_{M;A}} + \frac{k_v \cdot (f_{b;k} - f_{g;k})}{\gamma_{M;v}} \qquad (30)$$

For fully tempered glass, $f_{b;k}$ (the characteristic bending strength) is equal to 120 MPa. $f_{g;k}$ is the characteristic strength for annealed glass and is equal to 45 MPa. $\gamma_{M;A}$ is the material partial factor for annealed glass and is equal to 1.8. $\gamma_{M;v}$ is the material partial factor for surface prestress and is equal to 1.2. k_v is equal to one for horizontal toughening (typical for all modern processes). k_{mod} depends on the load duration and can be calculated by the following formula for load combinations (31):

$$k_{mod,c} = \frac{\sigma_G + \sigma_{Q;1} + \sum \sigma_{Q;i}}{\frac{\sigma_G}{k_{mod,G}} + \frac{\sigma_{Q;1}}{k_{mod,Q1}} + \sum \frac{\sigma_{Q;i}}{k_{mod,Qi}}} \qquad (31)$$

k_{mod} is equal to 0.29 for permanent loads, 0.74 for wind loads and 0.44 for snow loads. This results in a value for $k_{mod,c}$ of 0.62. With this value $f_{g;d}$ can be calculated according to (30) which results in a value of 78 MPa. Figure 5-38 shows the upper side of the panel when loaded with the ULS combination. Above the six point fixings, a maximum positive (tension) value of about 38 MPa occurs in x-direction (Figure 5-38), which is certainly lower than the limit strength calculated above. In between, very small negative values (compression) occur. At the bottom side of the panel, the opposite occurs.

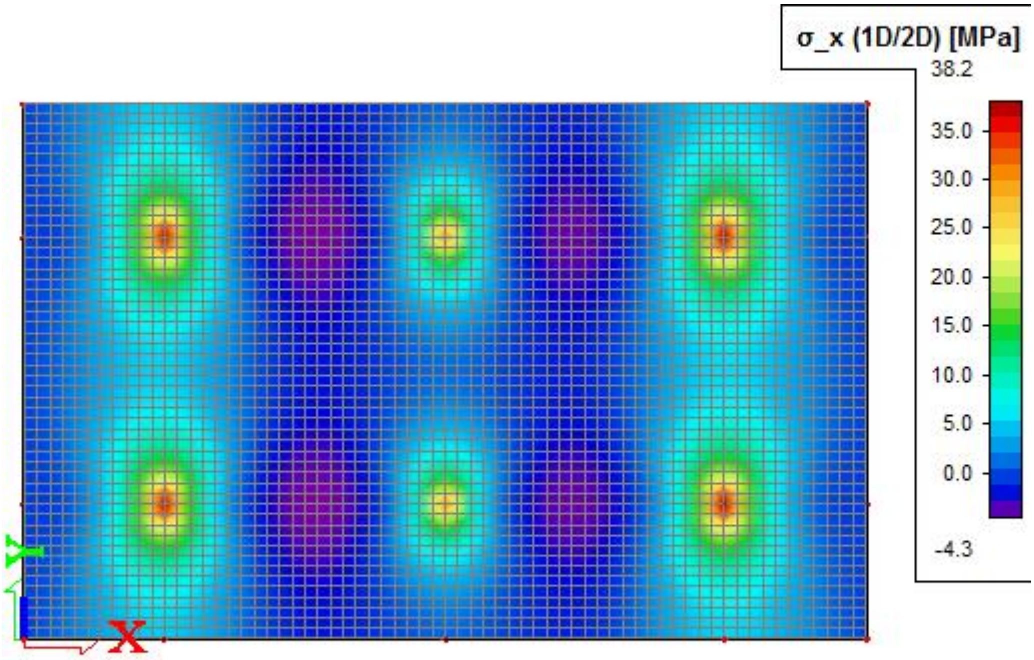


Figure 5-38: Top view loaded glass PV module (x-direction stresses)

In Figure 5-39 the stresses at the upper side of the module in y-direction are shown. From this figure can be concluded again that no problems should be expected. Also for the y-direction, the opposite occurs at the bottom side.

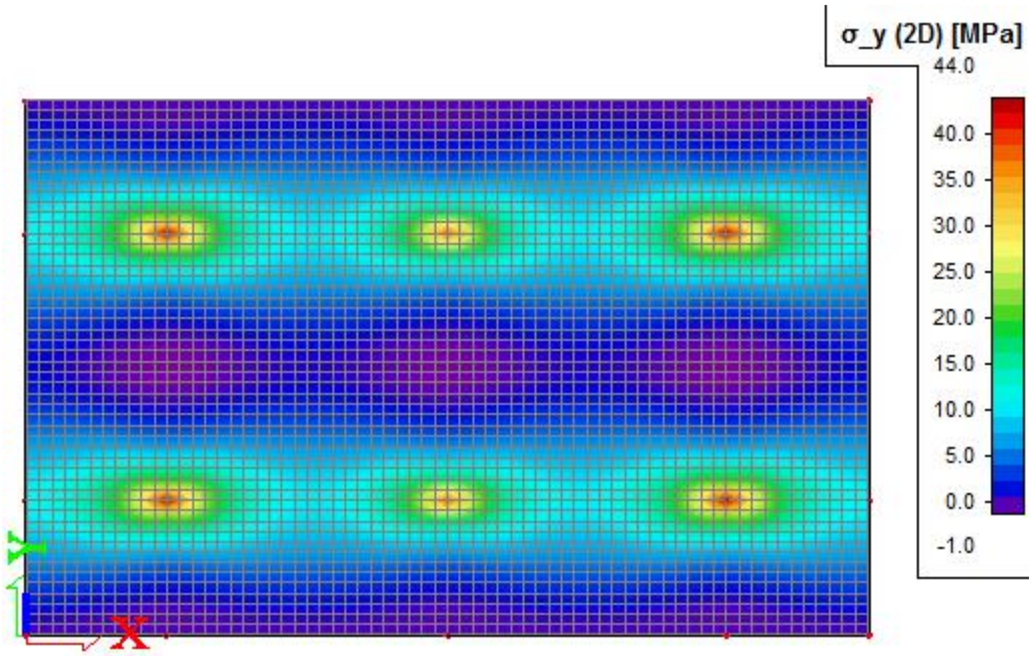


Figure 5-39: Top view loaded glass PV module (y-direction stresses)

5.4.8.2 Aluminium profile

For the aluminium profile, the stresses and deformations need to be checked as well. Again, the software SCIA Engineer is used in combination with hand calculations. The connection between the point fixings and the turning tube is illustrated in Figure 5-40, both a **basic lay-out** and an **alternative option** are suggested.

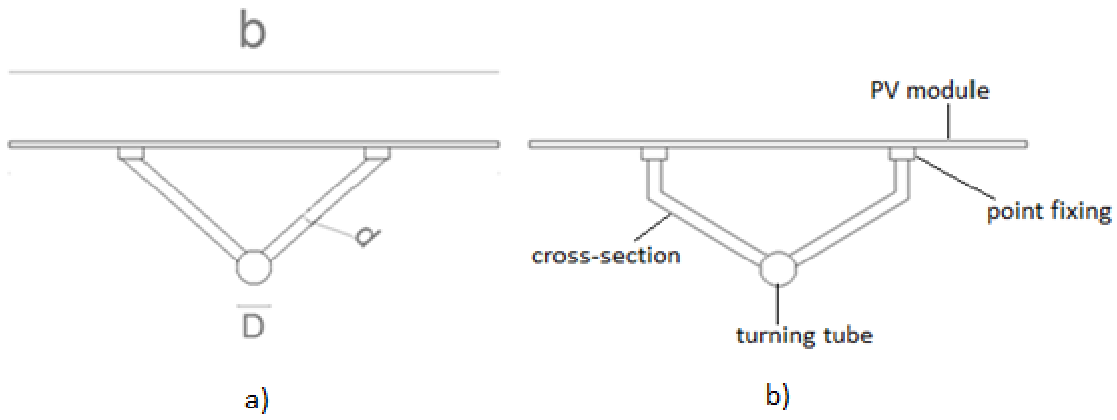


Figure 5-40: Aluminium profile: a) basic, b) alternative

Aluminium cross-section (Figure 5-40 – diameter d)

In a first step, the aluminium cross-section transfers the loads from the adhesive point fixings to the aluminium turning tube. For this connection a tube profile with an outer diameter of 25 mm and a wall thickness of 5 mm can be used. For the profile of the cross-section it is possible to start from a smaller profile at the connection with the PV module and to make it gradually thicker towards the connection with the turning tube, where the largest stresses will occur. The most critical section with maximum stresses will be located at the connection point with the turning tube. The aluminium cross-section should be fixed to this turning tube, in that way the PV module will follow the rotational movement of the turning tube. For the stress calculation, a cross-section was made in the perpendicular direction to the tube direction. This results in a shear component in the local y- and z-direction (in the plane perpendicular to the direction of the tube) and a normal component in the x-direction (the direction of the tube). The results are shown in Table 5-13.

Table 5-13: Stress check in aluminium cross-section

Aluminium cross-section		Check
M	236 Nm	
V_z	577 N	
V_y	65 N	
N_x	577 N	
σ	179 MPa	≤ 245 MPa
τ_z	1.8 MPa	≤ 142 MPa
τ_y	0.2 MPa	≤ 142 MPa

Aluminium turning tube (Figure 5-40 – diameter D)

For the aluminium turning tube, a profile with an outer diameter of 70 mm and a thickness of 10 mm is sufficient. When selecting the profiles for the cross-section and the turning tube, it is important to take in mind that the cross-section can be connected in an elegant way to the turning tube (e.g. by welding).

The reaction moment and forces that take place at the first clamping moment (Figure 5-35) are calculated (design situation 2) with formula (16) (17) (18). In addition, the stresses that occur at this clamped position in the turning tube are calculated with formula (24) and (26) and checked with (25) and (27) respectively. The results are shown in Table 5-14.

Table 5-14: Stress check clamp connection 1

Clamp connection 1		Check
M_1	1591 Nm	
H_1	2708 N	
V_1	4097 N	
σ	64 MPa	≤ 245 MPa
τ	2.6 MPa	≤ 142 MPa

The displacements are checked (in SLS) with the use of software SCIA. The result for design situation 2 is shown in Figure 5-41. Only the relevant part of the turning tube is simulated in this drawing (with a length of 1.3 m – 2/6*1.3 m = 0.867 m). The support is placed at that place that results in a distance of 1/4 of the panel length (detailed investigation in '5.4.9'). The maximal displacement will occur at the right end of the tube with a value of 3.3 mm. This is lower than the maximum limit l/250 (3.5 mm for this tube).

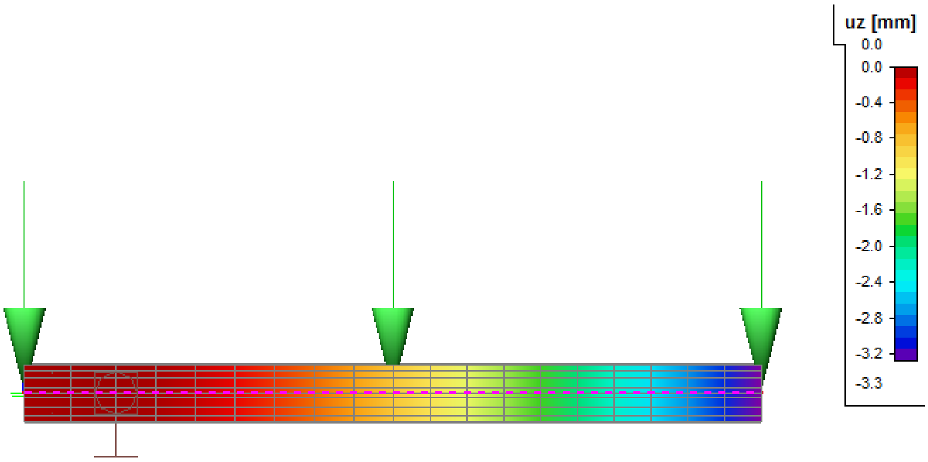


Figure 5-41: Displacement aluminium turning tube

5.4.8.3 Stainless steel profile

The stainless steel profile transfers the forces from the first clamp to the second clamp, bolted to the wall of the building (Figure 5-35). For the steel profile, an INP 80, which has a height of 80 mm and a width of 42 mm will be sufficient to withstand the forces and to keep the stresses within the limits. The results for this second clamp connection are shown in Table 5-15. The most critical point for the stresses is again situated at the clamped support. This steel profile will have to carry the aluminium profile. However, aluminium is lightweight (2700 kg/m³). For a tube of length 0.867 m and a profile ROR 70/10.0 mm (A = 0.0019 m²) this would result in 45 N which is negligible for the calculations. Besides the usage of stainless steel, extruded aluminium could also be used for this profile.

Table 5-15: Stress check clamp connection 2

Clamp connection 2		Check
M_2	2725 Nm	
H_2	2708 N	
V_2	4097 N	
σ	143 MPa	≤ 235 MPa
τ	5.4 MPa	≤ 135.7 MPa

The displacements (SLS – design situation 2) are shown in Figure 5-42. This figure shows that the displacement of this cantilever arm is very small. The maximum value occurs at the right end point and is equal to 0.4 mm, which is lower than the limit of l/250 (1 mm).

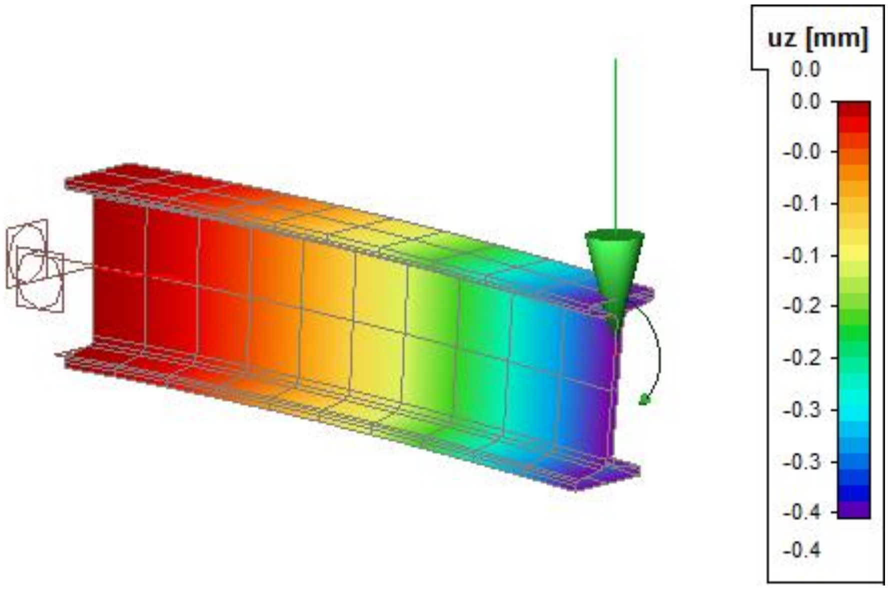


Figure 5-42: Displacement steel cantilever

5.4.9 Final lay-out – Optimisation

For the final optimisation (calculations in the previous parts have final numbers based on this section), the place where the cantilever arm is connected to the turning tube behind the panel (clamp 1) with the use of a thrust bearing, plays an important role (illustrated in Figure 5-30). This will have an effect on the maximal moments in the clamped sections. Not only these moments will change, but also the distances m_real and x_real as shown in Figure 5-43.

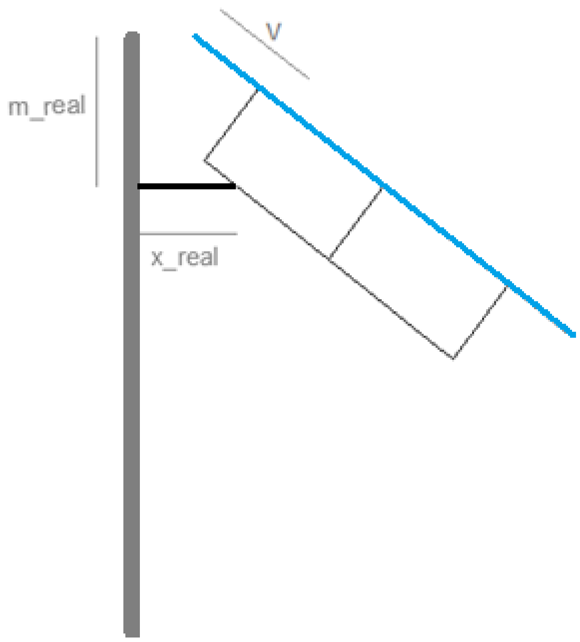


Figure 5-43: Finalisation lay-out

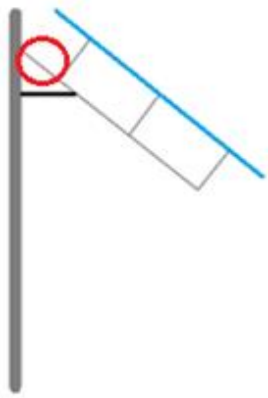
Table 5-16 shows the moments and distances for different lay-out possibilities. In the first column the place of the clamped connection between cantilever arm and turning tube is determined by placing it at a certain percentage of the total panel height (1.30 m). The distance v in the second column shows the distance from the top of the panel that corresponds to this percentage (indicated in Figure 5-43). The calculations are done for a distance d of 0.25 m between the turning tube and the panel, and a tracking angle to east and west of +/- 30° (as discussed in '5.4.2').

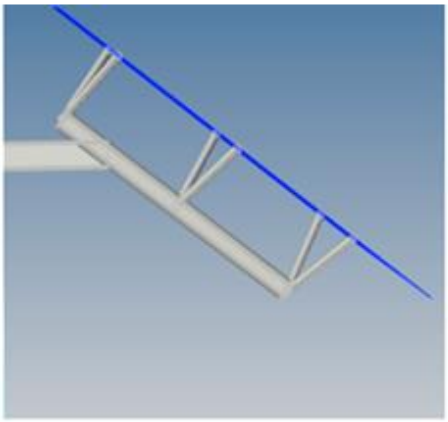
Table 5-16: Optimisation lay-out

Percent of panel height	v [m]	x_real [m]	m_real [m]	M_1 [Nm]	M_2 [Nm]
20%	0.26	0.23	0.36	1909	2833
25%	0.33	0.28	0.40	1591	2725
30%	0.39	0.33	0.44	1273	2617
35%	0.46	0.38	0.48	955	2508

The fact that a percent equal to 25% is chosen to place the clamp with respect to the top part of the panel is based on the fact that with this choice, a distance m_real of 0.40 m is related. In Figure 5-16 m4 was equal to 0.29 m for a panel height of 1.30 m. This means that some shadow area of the window, which was equal to 2.74 m in total, will be lost. The lost part of window shadow is approximately equal to 0.11 m, which means that the total shadow area will still be higher than 2.60 m. A further increase would lower the shadow area of the window and would result in a lower value than 2.60 m, which is not desirable as stated in '5.4.1'.

A further improvement is possible by **extending the upper part of the turning tube**. This will not change the transfer of the forces from the module, but it makes it possible to place the gear wheel tracking system (explained in '5.4.3.2') very close to the wall. This will make the tracking system more elegant and will facilitate the placement of this tracking system. The forces in the arm that connects the gear wheel to the wall will be lower as well, which makes the actuation system more economical. This extension is shown by the red circle in Figure 5-44 – a. Figure 5-44 – b shows the virtual set-up of the prototype without extension. The top of the turning tube can come to a distance as near as 20 mm away from the wall, if it is extended to the same level as the top of the glass plate. If this tracking system will be designed in reality, it is important to take into consideration that the turning tube must be able to withstand the forces that are needed for tracking the panels.





a) b)

Figure 5-44: Final lay-out (side view): a) with extension (drawing), b) without extension (virtual prototype)

5.4.10 Energy calculation

In this part, a comparison is made between the energy use of a typical office building and the energy output of the PV panel system. A recent study (2013) showed that the average value for the energy consumption in office buildings in Europe is 250 kWh/m²/year (Martinez, 2013). This value is higher than in former times. Birchall et al. (2014) did also a survey on the energy needs of European buildings. This survey resulted in a total average energy consumption for an office building in Belgium of **193 kWh/m²/year** (Birchall et al., 2014). A study in 2004 resulted in energy intensities for different countries in Europe as shown in Figure 5-45. The energy used for cooling of the office building makes a significant part of the total annual consumption. This cooling load is larger for warmer areas. By implementing the designed PV system, the energy used for cooling will decrease significantly. This will be the result of the shadow that the panels create when the sun is at a high position during summer. This will lower the total value of 250 kWh/m²/year with an amount depending on the specific climate characteristics.

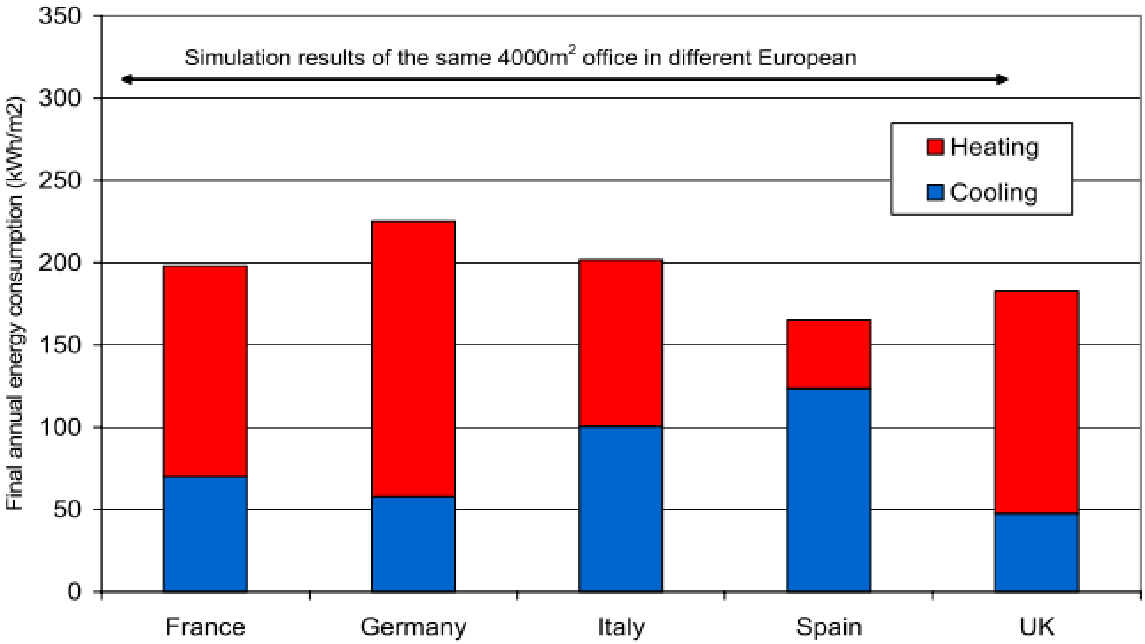


Figure 5-45: Energy intensities for office buildings in various EU countries (Hinge et al., 2004)

Apart from the decreased cooling load for the buildings, the designed system also produces electricity by making use of PV cells. The irradiation received by a solar panel differs from the actual electricity production due to losses related to temperature, angular reflectance effects, cables, inverters … A global value of the electricity production of a solar panel is calculated by making use of the Photovoltaic Information System of the European Commission. For the calculations, a crystalline silicon panel with a peak PV power of 230 Wp, located in Belgium, is assumed. Both the fixed position and the east-west tracking according to an inclined axis of 38° are considered. Figure 5-46 shows the electricity production in kWh/m²/month, in which a clear difference between these two options is visible . This figure shows that making use of the single tracking system will increase the energy production with a significant amount. The total yearly value in kWh/m² is equal to 191 for the fixed system and 276 for the single tracking system. For the used panel (width = 1 m, height = 1.3 m), this results in a value of total annual energy production of 248 and **359 kWh** respectively. This value will be slightly lower in reality due to shadow losses and the limitation on the tracking angle. However, these losses are optimised in the design by using bypass diodes and optimisation of the tracking limit.

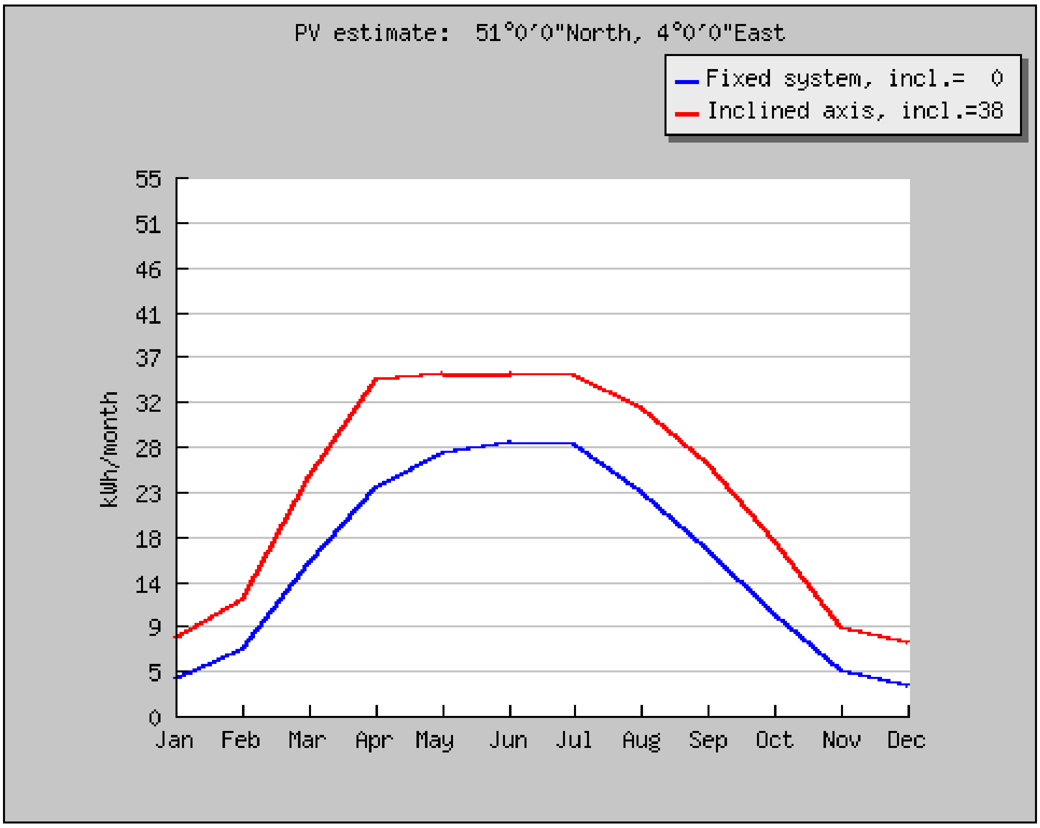


Figure 5-46: Energy production in kWh/m²/month (Photovoltaic Information System)

By placing the row of panels, without intermediate space, along the whole south façade and the whole width of each storey, this PV system can produce a significant part of the total energy use of the building. 68% of the office buildings in Belgium have an average floor area higher than 100 m² (Birchall et al., 2014). If a square office building with this area is assumed, the width of the south façade is equal to 10 m. With PV panels of a width of 1 m, ten panels can be placed next to each other in total. Ten panels with an annual production of 359 kWh will produce 3590 kWh in total per storey. For an office building in Belgium with a floor area of 100 m², the total annual energy consumption per storey is equal to 19300 kWh (= 100 m² * 193 kWh/m²/year). From these values, it can be calculated that **18.6%** of the total annual energy consumption of the office building may be generated by the PV panels on the south façade, which is a significant percentage. In reality, this percentage will be slightly higher due to the decreased cooling loads by the shadow principle of the panels. However, the shading losses and energy needed for the tracking system are also factors that contribute to the final percentage. Except for placing PV panels only at the south façade, the system can further be broadened by placing panels at the east and west façade as well. For this façades, another inclination angle will be needed to achieve the most economic design.

5.5 Conclusions

In this part, a detailed concept for a tracking PV panel array was created. The original starting point for the design was discussed in Table 5-1. The designed PV façade contains many of the purposed aspects by implementing a smart adaptive movement principle that makes use of the envelope to lower the energy use of the building in an efficient way. From this point of view, the design will result in increased first costs to install the prototype, but lower total costs over the lifetime of the building. The lower operational cost contributes to a more **sustainable building**.

The created PV system does not take useful space of the building and the individual mounting of each panel allows an easy repair and maintenance. The prototype can be classified to the curtain wall façade types. Unlike the traditional stick or unitised systems, the prototype focuses on a **frameless system** with its single separated mounting system for each panel. The choice for a frameless curtain wall increases the transparency. The design allows good exterior views and daylight benefits to be combined with improved internal thermal comfort. Due to the individual mounting, the installation time will be slightly higher. However, since the concept is relatively simple and standardised, this time increase will be limited.

As specified, a **south façade** in a moderate zone was the focus point for the design. The concept is designed for application in Belgium, but it can easily be applied at other places in the world by adjusting the optimum tilt angle. This tilt angle can be calculated for each specific geographical location. The second strong aspect of the system is that it is useful for both low and high-rise buildings. The concept is expandable for as many floors and as many rooms as desired.

As movement principle, a mechanic based rotation system was suggested in the case definition. This concept only uses a **rotational movement** to avoid an unnecessary complex design. For the transformable structure rigid panels with a stainless steel fixed arm and aluminium turning tube are used. The material choice is done to obtain an easy and not extremely expensive construction.

The **gear wheel tracking system** allows to control the concept in an extrinsic way. It makes it possible to combine automatic movement with local user control if desired in specific situations. This user control will give some small extra costs in the set-up of the tracking system, but this is an investment choice the client can make.

Considering the relevant physics, the concept takes three comfort increasing aspects into account: **daylight, solar control and energy gain**. The starting point for the concept was the focus on energy gain with the use of PV cells. By combining the energy gain with an optimised solar shading calculation, a strong but simple concept was created. The PV cells allow to gain energy, which will lower the energy consumption of the building, joining the current climate change. The system is flexible due to its ability to follow the position of the sun during the day. The density of the PV cells in the PV panels allows to adapt the amount of daylight that will enter the building to the client's wishes. By placing the system only at the upper part of the window, diffuse sunlight is used in an optimal way and the outside window view is only limited disturbed. The seasonal variation between solar shading and solar heating is approached in a clever way. The whole window area is shadowed during the summer and, during the winter, the lower position of the sun allows more heat to penetrate the building.

After the creation of this concept, a critical evaluation of the prototype with the formulated definition of an adaptive façade is done. In part '4.2' of chapter 4, an adaptive façade was defined as follows:

*'An adaptive façade has the ability to **adapt**, in real time, some of its functions, features and behaviour in response to changing environmental conditions, performance requirements, occupants' wishes or other boundary conditions. The adaption has the purpose to obtain **improved overall building performance** related to primary **energy use** (heating, cooling, ventilation and lighting) while maintaining or enhancing the **comfort** and increasing the **flexibility** during the life phase of the building.'*

This design adapts to the changing sun position. It improves the overall building performance with respect to primary energy use by implementing different aspects. Firstly by the use of PV cells. Secondly by providing shading during summer and allowing heat entering during winter. This will lower the cooling and heating needs. Moreover, by placing the system only at the upper part, it still gives a good lighting performance and a good comfort.

By making use of rigid panels and only one rotational degree of freedom, the repeatable system can easily be kept stable during transformation. The panels with aluminium turning system are carried without problems by the stainless steel profile that transfers all forces to the primary load-carrying structure of the building.

Referring to Table 5-2 it can be concluded that all design aspects that were put in front at the begin of the design are strongly represented in this prototype. The **standardisation, simplicity and functionality** were a primary focus during the design. This forms an attractive and strong aspect in the final prototype. A concept with a good rigidity against changing and extreme weather conditions was created. As finalisation, some overview illustrations of the prototype are given in Figure 5-47, Figure 5-48, Figure 5-49 and Figure 5-50.

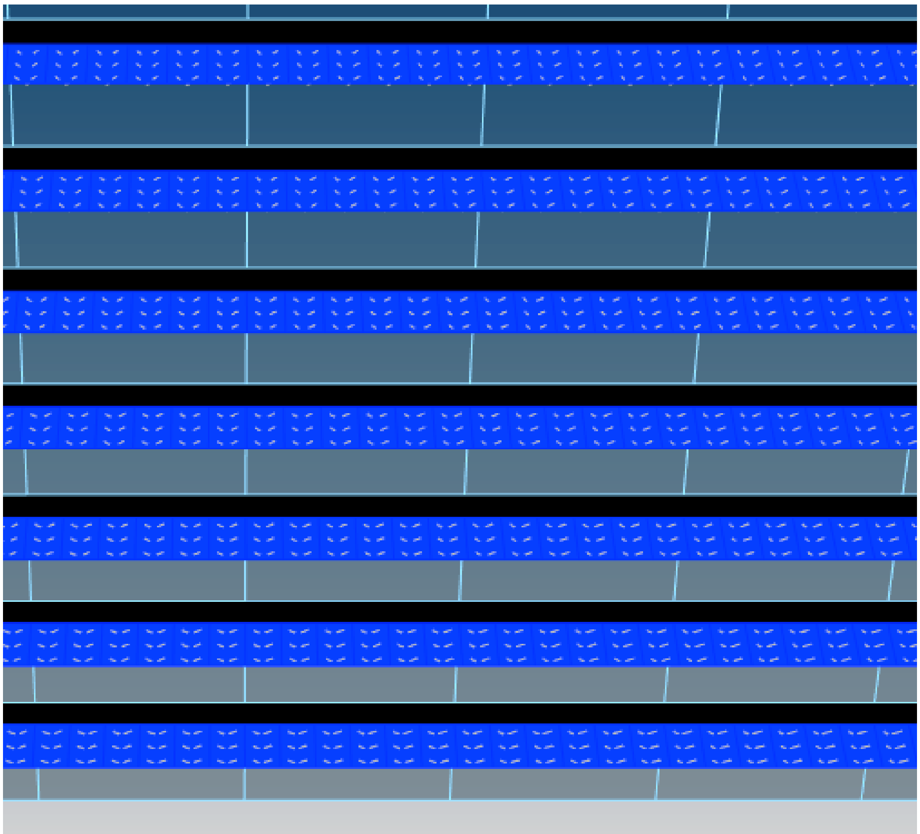


Figure 5-47: Top view, panels faced south

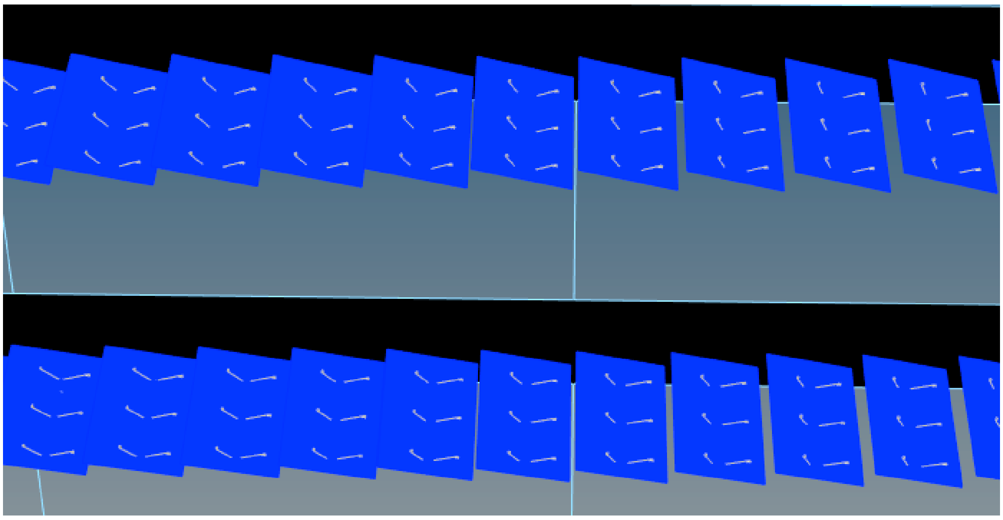


Figure 5-48: Front view

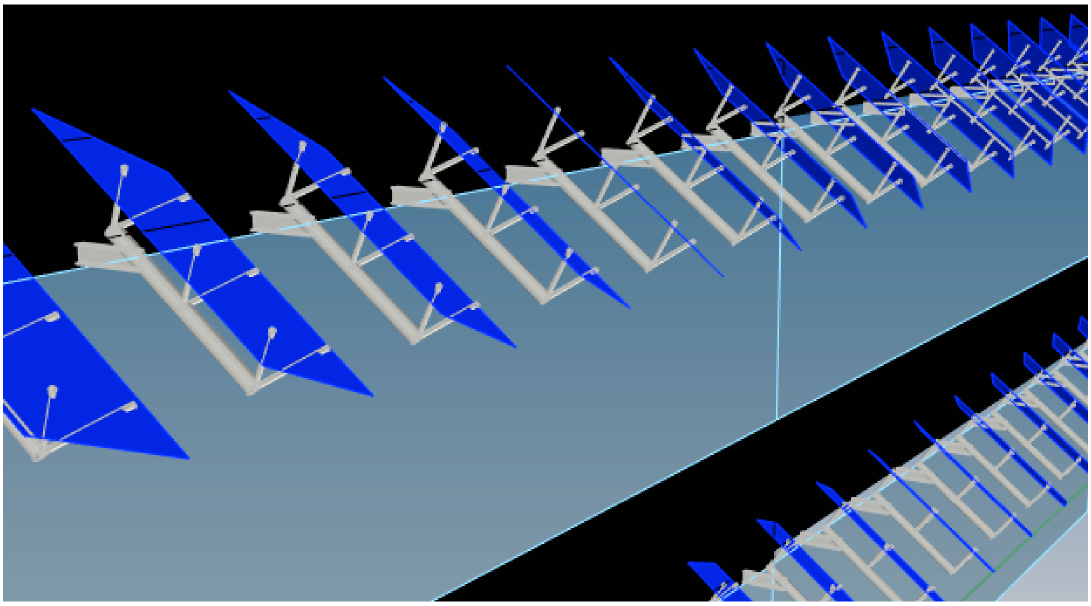
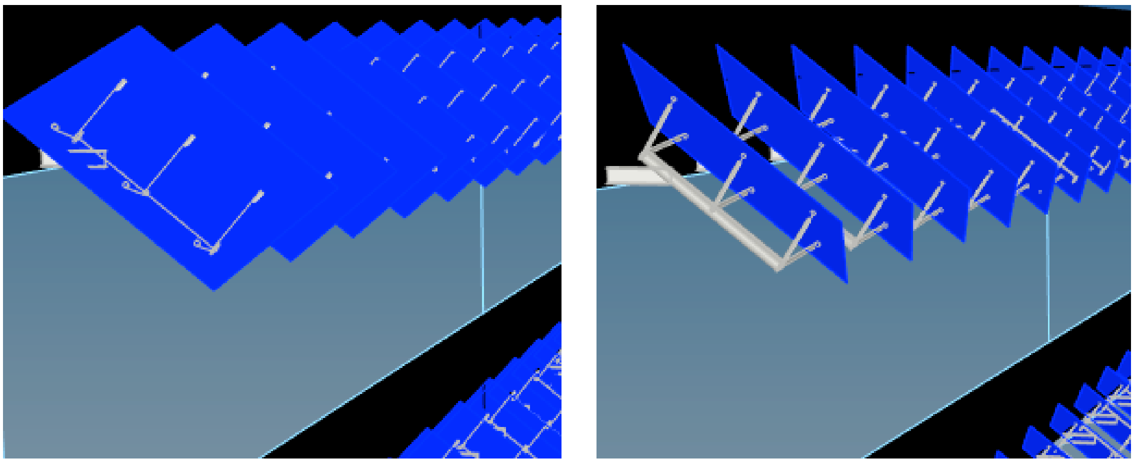
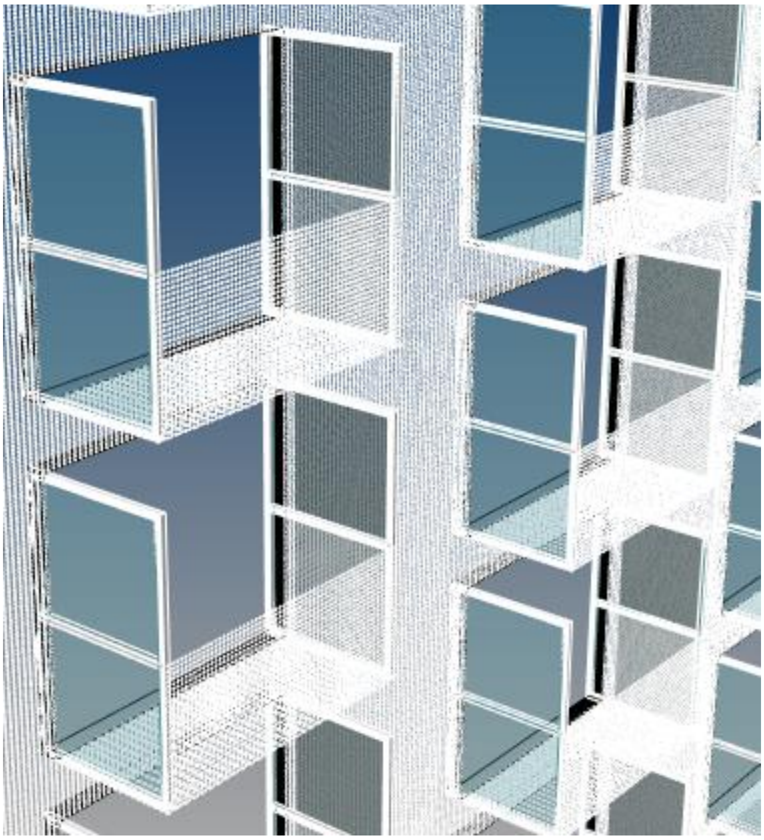


Figure 5-49: Side view



a) b)

Figure 5-50: Panels turning: a) 30° west, b) 30° east



> 'Design is about making things good and fantastic for the people who use and encounter them.'
>
> - Matt Baele -

PROTOTYPE II:
A PERFORATED BALCONY SCREEN

6 Prototype II: A perforated balcony screen

6.1 Case definition

In the introduction of the previous chapter (Prototype I) a general case was defined based on the literature research in PART I. Together with some focused design aspects, this led to the creation of a first prototype. The strong aspects of this prototype were its simplicity and functionality, which makes the design applicable on a large scale. This chapter deals with the design of a second prototype. Firstly, this design accentuates more the **transformation aspect** with allowance of complete (un)folding. In that way, a complete switch of functionality will be achieved by the transformation. Secondly, the focus is on creating a system that allows more **local user control**. These two focusing aspects provide the basis of the idea to design a balcony with improved functionality/usability. The detailed case definition for the second prototype is shown in Table 6-1. A lot of elements in this case definition are similar to the first prototype. Both prototypes have as main common characteristic the providing of solar shading at the south façade. However, instead of combining this solar shading with energy gain (first prototype), the second prototype focuses on transformability, glare and natural ventilation. The combination of solar shading with natural ventilation makes the second prototype also very suitable for (sub)tropical zones.

Table 6-1: Case definition

Case definition	
Building façade	• South façade; • Low/Mid-rise building; • Curtain wall.
Climate zone	• Moderate zone/(Sub)tropical zone; • Continental climate; • City.
Movement system	• Mechanic based; • Hybrid.
Transformable structure	• Hybrid structures: Frame/bar elements + Rigid panels
Control system	• Extrinsic; • Local-Direct.
Relevant physics	• Glare; • Solar shading; • Ventilation.

During the design of the second prototype, the originality and the aesthetic value are emphasised. The principle should allow the architect to give a personal touch to the prototype. The most important design aspects are listed in Table 6-2.

Table 6-2: Overview design aspects

Design aspects	
Originality	The originality is more important than the simplicity of the structure
Architectural	Allow some architectural freedom Aesthetically pleasing façade
Weather resistance	Good stiffness and durability against different weather conditions
Double principle	Perforated screen and balcony

6.2 Prototype idea

6.2.1 Double principle

The rich aspect of the second prototype is combining the functionality of a perforated screen with a balcony. Both have important advantages that contribute to a more sustainable and on the same time aesthetically pleasing building. The flexibility of the adaptive façade is presented by its multi-ability aspect, which means that the façade is able to play different roles over time (explained in '4.3.6').

The first function is the folded position of a curtain wall with a **perforated screen** in front of the glazed wall of the building. Perforated façade panels offer the opportunity to give the façade of the building an unique and alternative look. This creates a pleasant effect both on the outside and on the inside (Figure 6-1).

Figure 6-1: Perforated screen: a) view from outside, b) view from inside (Web 6-01; Web 6-02)

Next to their pleasing appearance, perforated panels have some other important benefits for **residential apartment buildings**. Firstly, related to the perforation ratio, the panels will **weigh less** than in case of full unperforated panels. This is an advantage for the supporting system that has to transfer the weight of the panels to the primary structure of the building. A second advantage is the fact that the panels reduce the **wind loading**. The perforations allow wind to pass through, which decreases the wind forces on the structure. Thirdly, perforated panels allow to **block partially the sun**. The panels act like sunshades that allow to control the amount of sun that can penetrate the residential building. This will contribute to a reduced energy use for cooling. The panels have a positive influence on **glare problems** and increase the visual comfort of the occupants. The perforations mitigate the glare from the sun while still allowing the entering of natural daylight to illuminate the interior of the building. The perforated panels also enhance the **privacy** for the users, especially for the lowest storeys of the apartment. Finally, perforated panels have a small influence on the **noise**. The screen can be helpful to limit the entering of outside disturbing noise in busy urban areas. All these aspects will contribute to the design of a low-energy building. If these screens are implemented on a south (or west/east) façade, larger window to wall ratios are allowed, as the screens provide enough protection against overheating (Web 6-03).

The second function of the prototype is the **balcony**. By making the screen capable to unfold to a balcony, **extra useful building space** is created. Secondly, the balcony allows for **maximum natural ventilation** rates, which enable fresh air to enter. Natural ventilation increases the internal comfort by cooling the room in hot summer conditions. During winter times, the system can be folded. The transformation principle will allow to expose the balcony not unnecessary to extreme weather conditions such as snow load and heavy storm conditions because in that case the balcony can be folded to the closed position of a curtain wall screen.

The double principle is suited for moderate zones, subtropical zones and tropical zones. (Sub)tropical zones are characterised by an increased need for maximum natural ventilation, for which the opening of the balcony is very efficient. On the same time, these zones need more control of daylight and protection against high heat absorption. For this, the perforated screen is perfectly suited by its ability to provide protection against overheating while still allowing natural daylight to enter.

6.2.2 Adaptive principle

The adaptive transformation between the folded and unfolded position requires special attention. In closed (folded) position, the perforated screen is in front of the façade (Figure 6-2 – a). The black surfaces in the picture represent the transoms and the mullions on the façade for the curtain wall. To transform the structure to the balcony, firstly the perforated screen needs to be unfolded (Figure 6-2 – b) and secondly, the two wings of the windows need to be opened to form the sides of the balcony (Figure 6-2 – c). For the lower and upper part of the perforated screen that will become respectively the floor and the parapet of the balcony, two different perforation patterns can be used.

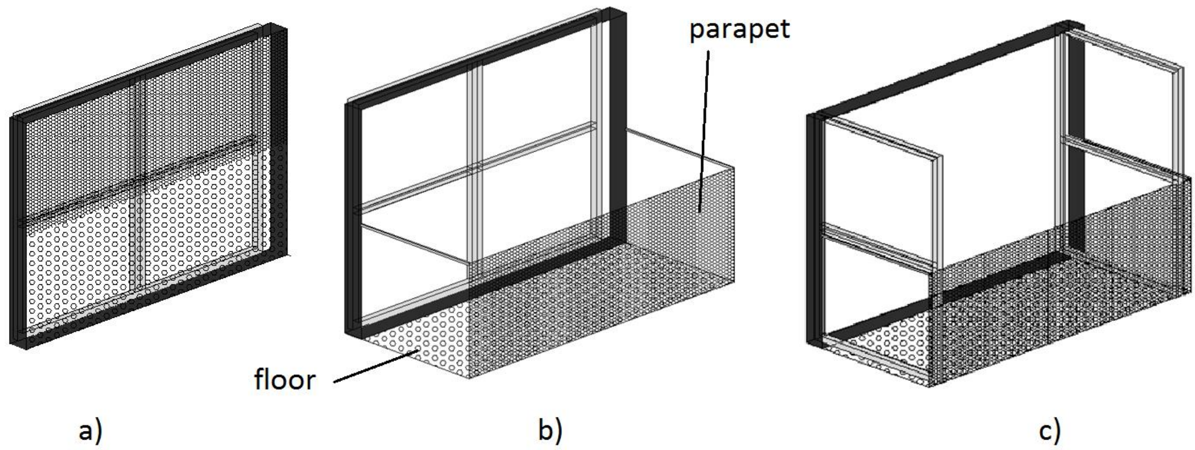


Figure 6-2: Prototype: a) folded, b) unfolded screen (closed windows), c) unfolded screen (opened windows)

Figure 6-3 – a shows how the perforated screen transforms to become the balcony floor and parapet. Figure 6-3 – b shows the two windows during opening. The two wings of the windows should open by pivoting around their sides to 90° each. At the end, they should be able to be locked in place at this position by snapping into a system provided at the two sides of the lower part of the perforated screen. In that way, the balcony floor and the window wings are connected and form a complete structure. On a cold, sunny winter day, it is possible to open the balcony screen while the windows remain closed. This allows the heating up of the room and the entering of more daylight. In this situation, the windows are not connected to the screen and do not provide support to transfer the forces to the primary structure of the building.

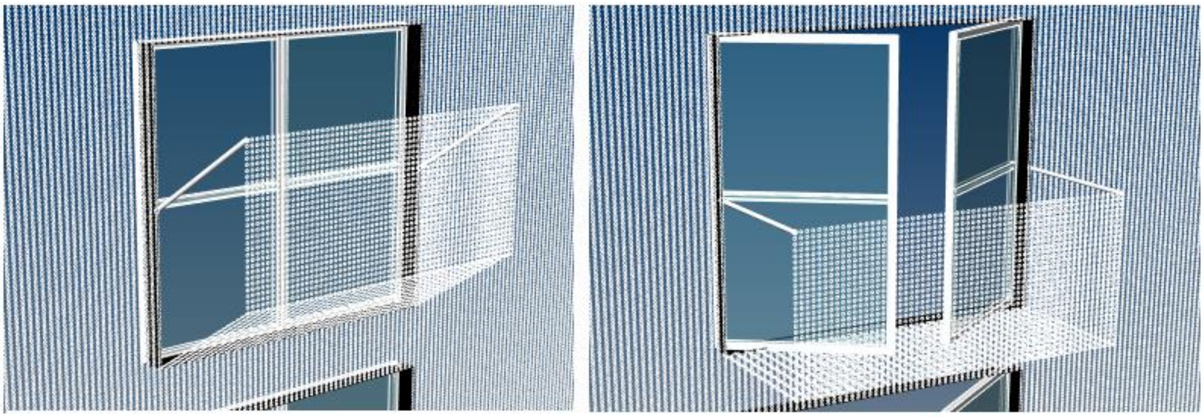

a) b)

Figure 6-3: Transformation principle: a) unfolding screen, b) opening windows

For the design, it is important that all elements fit in an elegant manner, both in folded and unfolded position. Therefore the rotating arm, connected to the upper line of the screen should be mounted to the inner side of the vertical mullions. In folded position, the perforated screen closes the 'box' formed by the mullions and transoms. The requested equipment for the transformation is invisibly hidden in the 'box' behind the perforated screen. To illustrate the movement principle for opening the screen and opening the windows, a model of the prototype is made in wood. Figure 6-4 shows the double principle of the perforated screen and the balcony. The unfolding of the screen is illustrated in Figure 6-5. The opening of the windows is illustrated in Figure 6-6. It should be remarked that the dimensions of the structural elements are not correct. For instance, the perforated screen in wood is thicker than it will be in reality. Also the window frame is bigger than it will be. The perforation ratio of the screens is also lower in the model than it will be in reality. A careful consideration of this ratio is necessary to allow enough daylight to enter (discussed in '6.3.4.3'). The main purpose of the model in wood is to show how the transformation between the two functions of the prototype is realised.

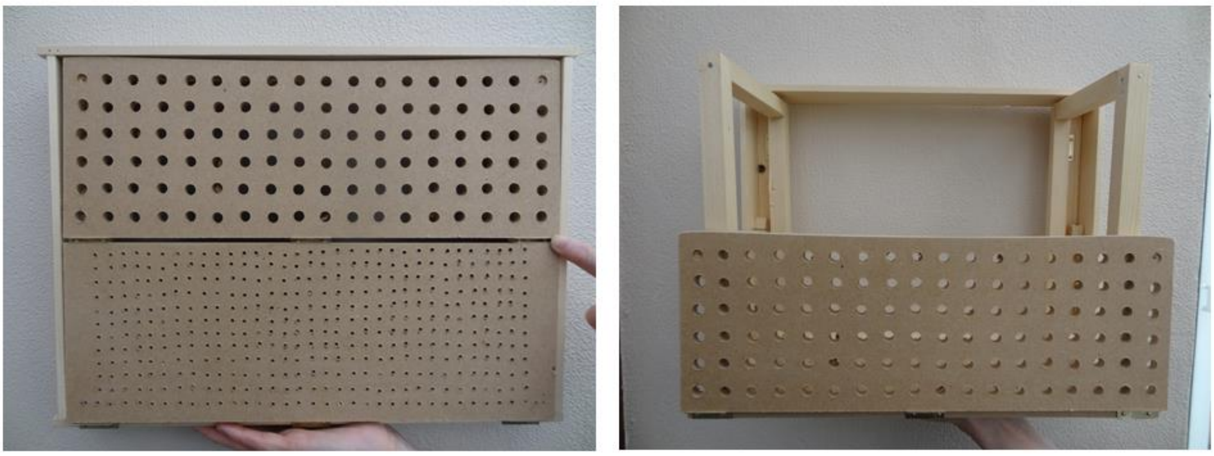
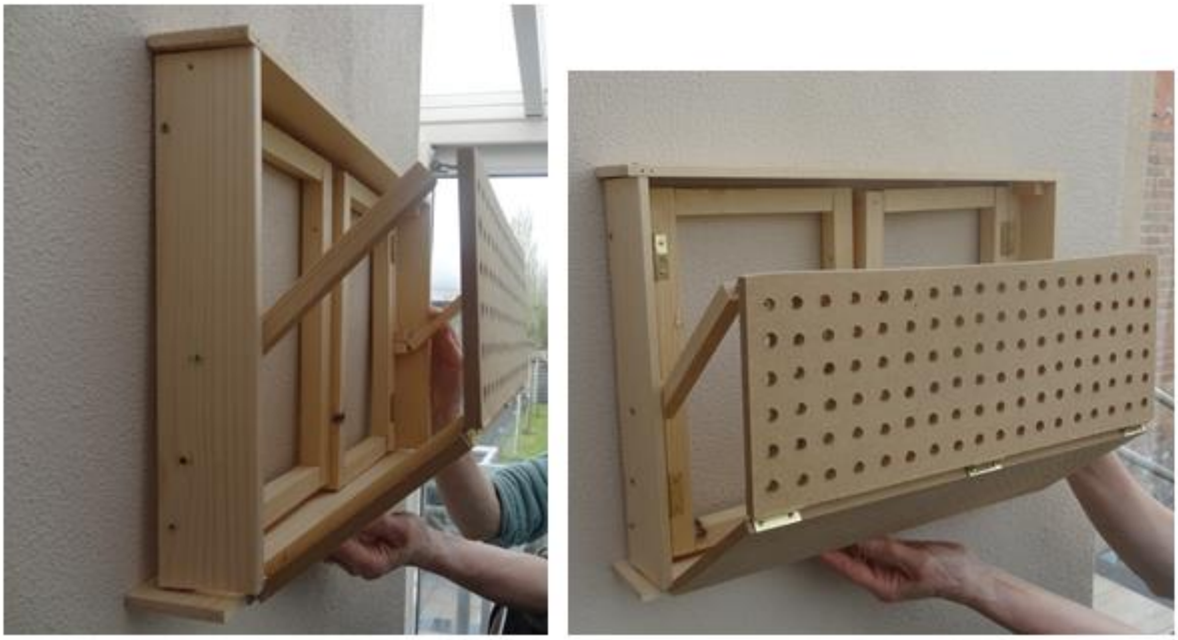
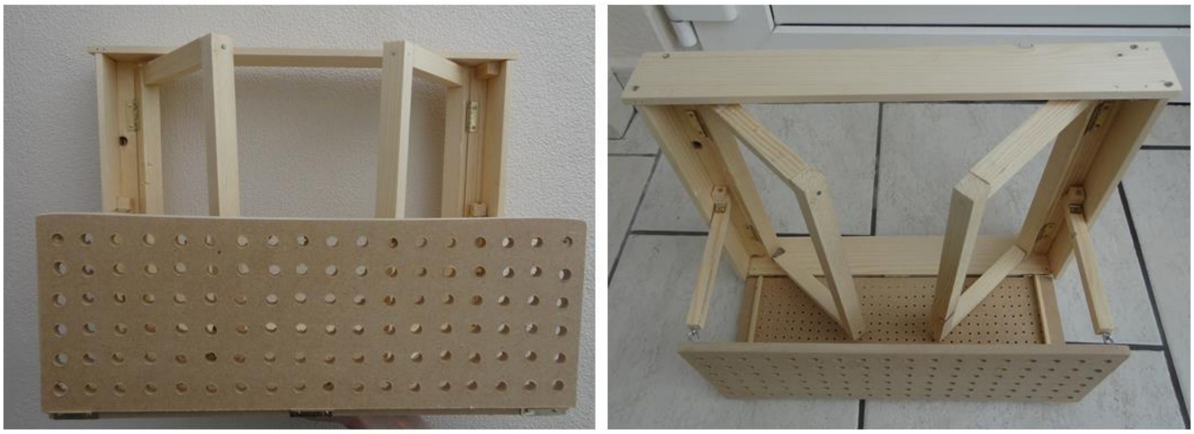

a) b)

Figure 6-4: Prototype model: a) folded screen, b) unfolded balcony



a) b)

Figure 6-5: Opening principle screen: a) detailed side view, b) overall view



a) b)

Figure 6-6: Opening principle windows: a) front view, b) top view

An extra transformation feature that can be implemented is the **Tessellate** principle of the Adaptive Building Initiative. Tessellate is a dynamic surface that creates the possibility to respond to environmental changes and regulates light, solar gain, privacy … For this extra feature, a second perforated layer is necessary with unique perforations. By moving/sliding this extra layer with respect to the first perforated layer, the opacity can be continuously adjusted (Figure 6-7). Two parallel perforated sheets create more user flexibility. The system can be controlled by a computer processer, that can be connected to a feedback system that the individual users of the building can operate. This allows to adjust the amount of entering daylight according to the occupant's wishes. Next to user control, more automatic control is also possible by implementing a system that responds to changes in temperature, light levels … (Velasco et al., 2015).

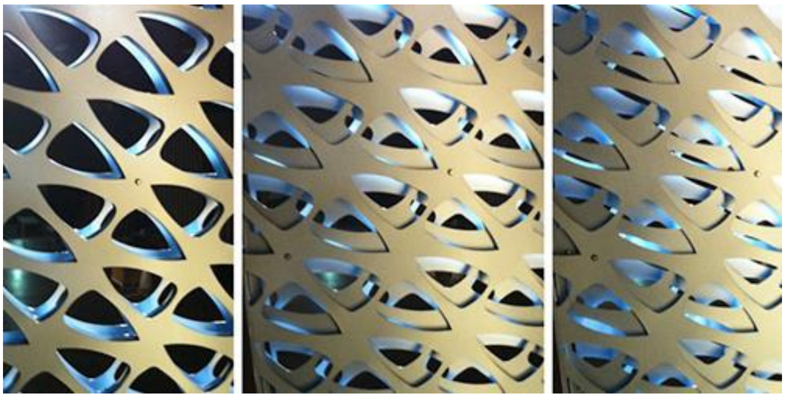


Figure 6-7: Tessellate principle (Web 6-04)

6.3 Creation of a prototype

6.3.1 Dimensions

The floor-to-floor height of residential buildings is typically lower than the floor-to-floor height of commercial buildings. For residential buildings it's typically about 3.1 - 3.2 m. For residential buildings, the floor-to-ceiling height is mostly not much higher than 2.6 m, certainly if air-conditioning is foreseen. For this prototype, the height will be assumed to be equal to 2.6 m.

For the calculations in '6.3.5', some **dimensions** are assumed (Figure 6-8). Firstly, an equal height of the floor and parapet screen of the balcony of 1.3 m is assumed. This results in a total height of 2.6 m of the perforated screen in folded position. The mullions and transoms that support the screen and transfer the forces to the primary structure are assumed to have a depth of 0.2 m from the wall. When the balcony is in unfolded position, this results in a total balcony depth of 1.5 m (transom + perforated screen: 0.2 m + 1.3 m). With this dimensions, the two windows that form the side wings of the balcony should have a width of 1.5 m and a height of 2.6 m. The total box width is assumed equal to 3.2 m. The value of this width is higher than the width of the two closed windows together. This extra space is needed to place the actuation and transformation equipment at the inner side of the vertical mullion and in addition for the fixed frame of the window. In reality, the height of the windows should be a bit smaller to make it possible to pivot from the closed to the open position without touching the balcony floor.

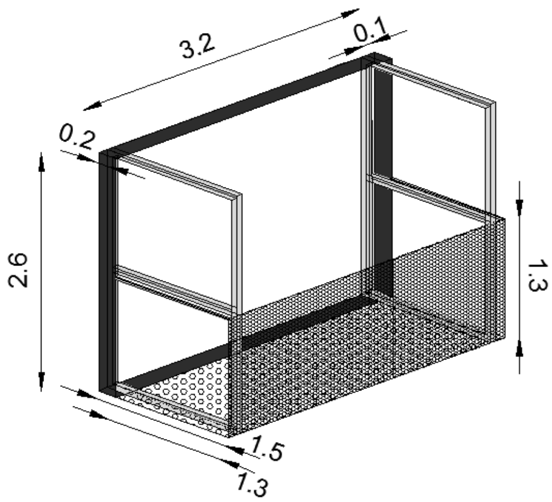


Figure 6-8: Assumed dimensions

The prototype allows some **ranges** on the dimensions, which make it suited for a larger application area. It is self-evident that there are some limits on these ranges to assure both enough safety and functionality. Firstly, the **depth of the balcony** is not unlimited. Dimensions for cantilevered balconies are usually in the maximum range of 1.5 – 1.7 m. If higher cantilevers are made, the forces will grow and the stiffness will be lower. This would result in more complex technical solutions, which will increase the costs. The minimal depth of the balcony is also limited. A lower depth allows less movement possibilities for the users of the balcony. To provide enough functionality, it is recommended to not make the depth of the balcony (equal to the width of a window wing) smaller than 1.0 – 1.1 m.

If a balcony depth higher than 1.5 m is desired, it is recommended to use a screen that unfolds at the side of the balcony, together with the perforated screen. This is certainly necessary in case of a **window width** that is smaller than the desired depth. To create an economic design, the width of the window wings is recommended to be maximal 1.5 m.

The **height of the parapet** of the balcony has also a lower and upper limit. For safety, the minimum height of the balcony is recommended to be 1.0 – 1.1 m. The upper limit is related to the visual requirements. To provide sufficient unobstructed views, the balcony should not be much higher than 1.3 – 1.4 m.

The ranges of the different parameters are not independent. If a balcony depth of 1.1 m is chosen, a parapet height of 1.5 m is necessary to cover the whole height of the storey (floor-to-ceiling). This height is too high to provide enough visual comfort. The upper limit of the balcony parapet is recommended to be limited to 1.4 m. If the parapet height is changed, the length of the depth of the perforated part of the balcony changes accordingly. If for example, a parapet of 1.1 m is taken, a balcony depth of 1.5 m is necessary to create the total closed screen height of 2.6 m. Another variable that can be changed to obtain the desired optimal result is the depth and place of the mullions and transoms. This can be set precisely to fit with the parapet height and the perforated platform depth.

Table 6-3 gives recommendations for the possible **ranges of the different parameters**. The lower limit of the perforated floor depth is set between brackets, because a lower value can be chosen in combination with a wider transom to create the desired depth. The lower limit of the window is set between brackets as well, because the solution of a side screen is suggested as option to create a higher depth than the width of the window. The width of the balcony in Figure 6-8 is equal to 3.2 m. However, it should be mentioned that the balcony can be wider than the total width of the two windows. This can be achieved by placing other window parts in between the two pivoting wings at the sides. These parts in between will stay in place and the entrance to the balcony is in that case provided by the two opened windows at the sides. A wider balcony requests a more detailed calculation to assure enough stiffness and strength. So, the ranges for the window door width in Table 6-3 are only valid for **the basic version without intermediate parts** and not for the wider variation of the balcony.

Table 6-3: Recommended ranges for the dimensions

Type of dimension	Range [m]
Parapet height	1.1 – 1.4
Perforated balcony floor depth	(1.2) – 1.5
Window door width	(1.2) – 1.5
Transom floor depth	0 – 0.5

6.3.2 Materials, mounting system and connections

6.3.2.1 Windows

As mentioned before, the window behind the perforated screen needs to exist of two wings that can pivot along their side to form the sides of the balcony in opened position. For the glass panes, an IGU that consists of two layers can be used. Between the two glass panes, a gas is present to reduce the heat transfer across the building envelope. The two layers are separated by a spacer and sealants. This unit ensures a good thermal performance, which is important for the window in closed position. The windows should be enough transparent. This transparency is in particular needed to allow good outward views when the perforated screen is in folded position. For the glass panes, annealed, heat strengthened and fully tempered glass panes are possible. However, these types have different fracture patterns. Annealed glass breaks in large pieces, while fully tempered glass breaks in small pieces (Belis, 2016). A good consideration of the specific site situation (e.g. walkway under the balcony) is necessary to ensure a safe design. The panes can also be made out of laminated glass, which will hold the broken glass pieces together in case of breakage.

According to the wishes of the user, private **switchable glazing** can be used as a part of the glass unit. Switchable glazing is more expensive than normal glazing. Therefore, it's the decision of the client to choose for this extra investment. Switchable glazing provides more privacy, which can be interesting in case of closely spaced balconies (Web 6-05).

The **frame** of the window is chosen to be made out of **steel**. Steel is a very strong material and allows to use larger glass areas and small sightlines. The strength is also important for the actuating system that has to be put on the frame to make the pivoting principle possible. Next to its good strength, steel is also a very durable material. The material allows aesthetic finishes according to the user wishes (Web 6-06).

An important aspect of the window is the **connection** between the glass pane and the steel frame. The in-plane stiffness of the glass pane can be mobilised to stabilise the framework, which is useful in façades. To connect the steel framework to the glass pane, a glued joint can be used. The type of adhesive will influence the joint strength. Glued joints have the advantage that they spread stresses and are less sensitive to stress concentrations. Moreover, these connections avoid direct glass-metal contact. The glue should be present along the whole side of the steel frame to ensure a good thermal insulation and to provide a large area to spread the stresses. For the connection, a one-sided silicone joint can be used. This flexible adhesive can accommodate the difference in thermal expansion between the metal and the glass. The thickness of this glued joint should be at least 6 mm (Huveners et al., 2007) (Belis, 2016). Apart from the glue, the lower side of the window should be foreseen of a projection at the front to enable to connect and click the system to the perforated screen when opened. This projection should connect to a second small projection, foreseen on the perforated screen. For the strength calculations, only the glass pane which is glued to the steel frame is taken into consideration. The other, second glass pane is mainly important for the thermal insulation. A detail of the connection at the lower side of the window is given in Figure 6-9. A good consideration and detailing of this section is necessary to avoid cold bridges.

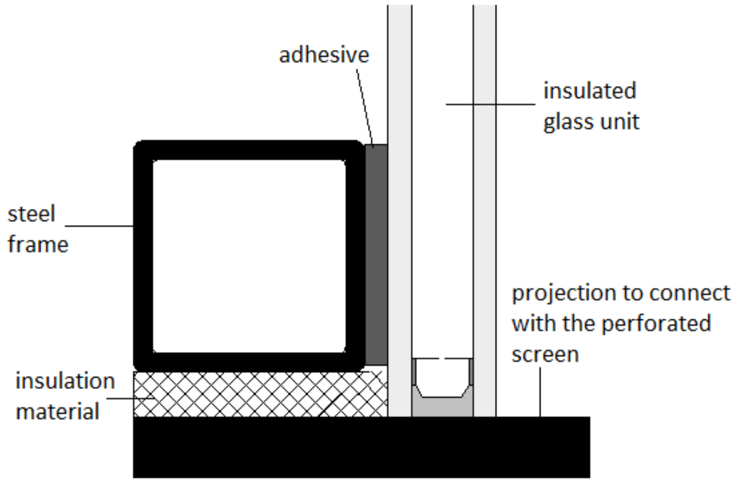


Figure 6-9: Glued glass-frame connection

Figure 6-9 shows that the window is foreseen of a projection at the lower side to connect with the perforated screen. For this connection, a second projection that is fixed to the perforated screen is necessary as well. This projection is illustrated on the wood model that was created (Figure 6-10). The projection fixed to the perforated screen and the projection fixed to the window enable to connect the two structures in unfolded position. This connection will make the force transfer from the screen to the window possible. This is important to be able to count on the window support for stability and stiffness.

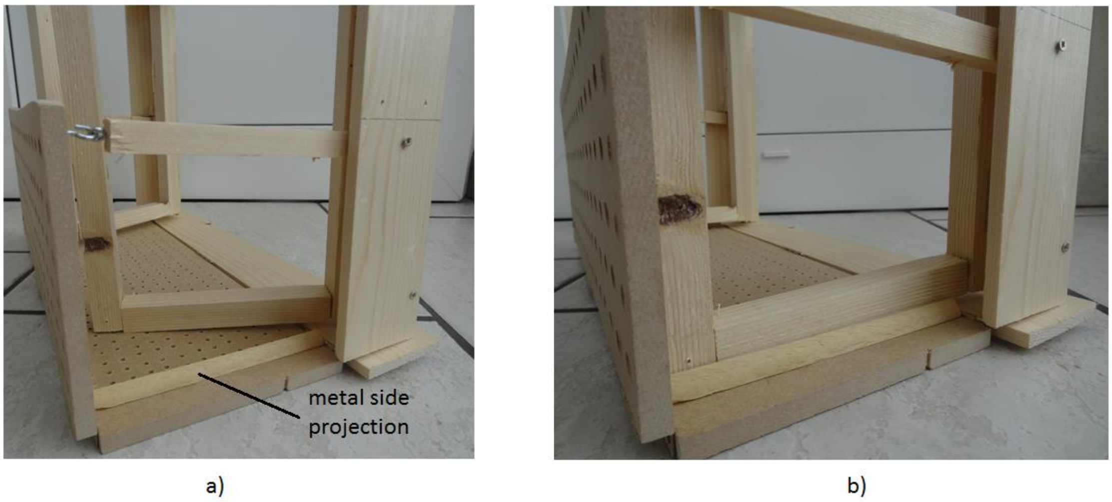


Figure 6-10: Connection system: a) metal side projection, b) locked situation

A second important aspect of the window, is the **vertical opening**. Both windows need to be able to slide downwards. This is certainly important for the system in closed position when the perforated screen is in front. The downwards sliding ability allows for natural ventilation even if the perforated screen is in folded position. The sliding principle is illustrated in Figure 6-11.

a) b)

Figure 6-11: Vertical opening: a) sliding window (Web 6-07), b) balcony illustration

6.3.2.2 Perforated screen

The perforated panels can be made out of different materials, but for outside applications, such as the balcony, **perforated steel** screens are most suited. Strong panels are necessary in unfolded position when the panels form the floor and parapet of the balcony.

The panels can have different perforation **patterns** (round staggered, round straight, square …)**, colours and finishes**. The creativity of the architect can result in original effects on the whole façade. Some examples of different patterns are illustrated in Figure 6-12. The effect of different patterns is also illustrated in Figure 6-1.

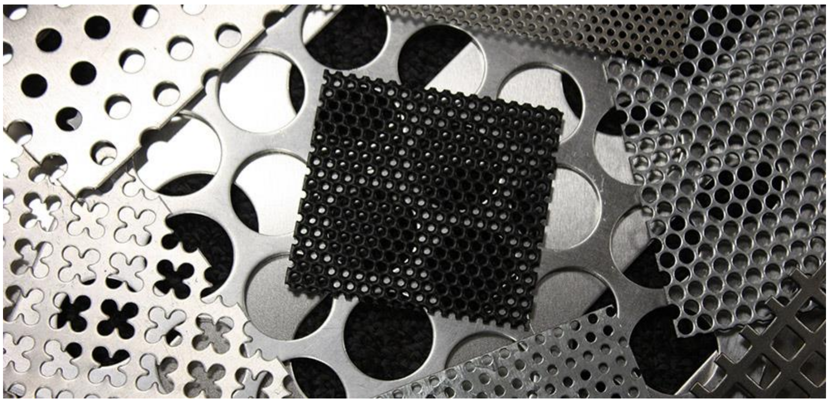


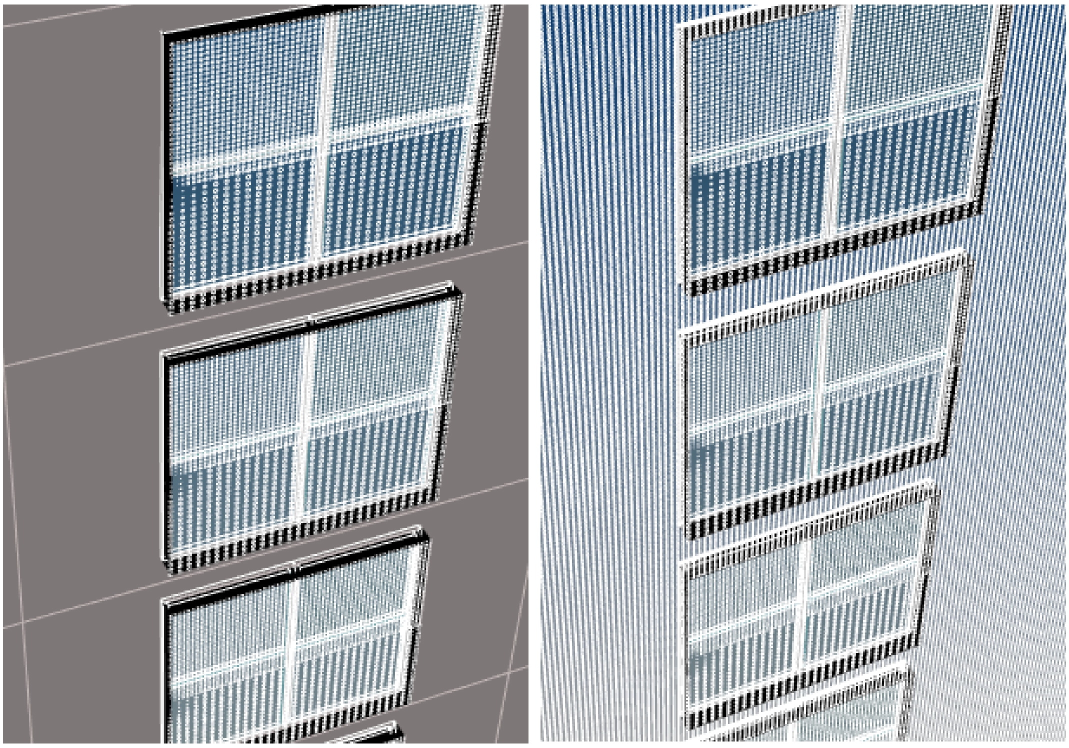
Figure 6-12: Perforation patterns (Web 6-08)

6.3.2.3 Side screen

In '6.3.1' it was suggested to use an extra side screen in case the desired depth of the balcony is too high for the window width. This side screen can be created by making use of the **Strata system** of the Adaptive Building Initiative. The Strata system (as described in 'Audiencia Provincial' and 'HelioTrace' in Appendix A) is a system that can extend to a nearly continuous surface comprised of a series of slats in opened position. In retracted state, it forms a single slender profile, which is suitable to disappear into the building's structure.

6.3.2.4 *Mullions and transoms*

The structural support for the curtain wall construction is ensured by a framework of linked mullions and transoms**.** These vertical and horizontal stiffeners form the façade substructure and are made of **steel**. This steel frame will allow to transfer the forces (self-weight, wind load, service load) to the primary structure of the building. The place where the mullions and transoms are connected to the wall allows some **mounting freedom** for the architect. This structural placement was discussed in '4.3.4'. The box demarcated by the mullions and transoms can firstly be placed in front of the ordinary wall. In this case, from outside, the original look of different separated boxes arises. The second possibility is to widen the concept of a perforated screen over the whole façade and to place the box behind this complete screen. In this case, the whole box will disappear behind the façade in closed position. Both options result in different outside views and have another aesthetic effect, which allows for a wider range of applications. The two design options (both in folded position) are illustrated in Figure 6-13**.**



a) b)

Figure 6-13: Mounting freedom: a) box in front, b) box behind

6.3.2.5 *Hinged connections*

To make the transformation principle possible, hinges are necessary. Firstly hinges are necessary at the connection of the rotating part of the window frame to the fixed frame of the window. Secondly, the two parts of the perforated screen need to be provided with hinges as well. At the connection of the lowest perforated screen to the horizontal transom, piano hinges can be used (Figure 6-14). This allows to provide aesthetically clean and elegant lines to create a smooth and streamlined floor for the balcony.

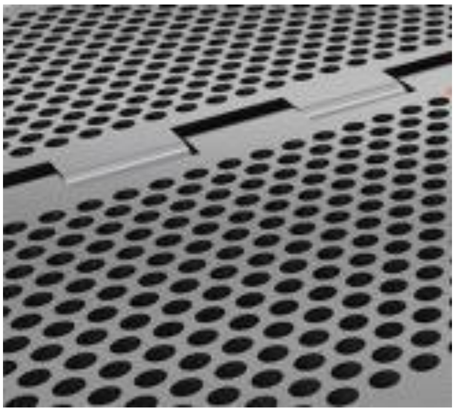


Figure 6-14: Detail piano hinges (Web 6-09)

6.3.3 Actuating and locking system

The prototype needs to be able to open and close in a fluent way. For the system both an actuation and locking system are necessary. The transformation principle of the structure consists of two important motions. Firstly, the opening of the perforated screen to the unfolded position. Secondly, the opening of the two window wings.

6.3.3.1 Balcony floor and parapet

The perforated screen needs to be able to unfold to become the floor and parapet of the balcony. For this movement, a **hydraulic device** can be used (Figure 6-15). Hydraulic actuators are chosen because these systems have a high space and cost efficiency and are able to exert a large force with a small sized cylinder. The hydraulic systems are supported by a pup and pressure accumulator. The pressure device used in hydraulic systems is oil. The main advantage of hydraulic systems is that they can serve both as blocking and actuation system. This means that the hydraulic system is able to keep the system in place when it is fully opened (Bouten, 2015). This hydraulic system can be placed at the lower part of the mullions, connected to the lowest part of the screen. This will result in the most elegant solution with respect to the visual requirements. At this height, it will disturb the views for the habitants as minimal as possible.

Figure 6-15: Hydraulic opening principle (Web 6-10)

The upper perforated part that will become the parapet of the balcony is connected to a rotating arm. This arm can make use of a 90° locking system (Figure 6-16). This system possesses a constraining bar element that can lock the rotating angle to 90° and prohibits that the system opens further (Bouten, 2015).

Figure 6-16: 90° locking hinge (Web 6-11)

6.3.3.2 Windows

The two window wings need to pivot along their sides to become the sides of the balcony in unfolded position. For this an **electro-hydraulic actuation** principle can be used for both windows as illustrated in Figure 6-17. This actuation system can be connected to the fixed steel frame of the two windows. Hydraulic equipment ensures stability in opened external position and is highly resistant to heavy wind load conditions. For the design, it is important that the two windows are actuated synchronically, which is possible with the use of feedback systems (Bouten, 2015).

Figure 6-17: Principle window opening (Web 6-12)

6.3.4 Forces on the panel

6.3.4.1 Wind load

For the calculation of the wind loads, the same procedure as in '5.4.5.2' is used according to NBN EN 1991-1-4. The terrain category for this situation is taken equal to category III, which corresponds to an area with regular cover of buildings or vegetation (such as villages). The seasonal factor is assumed to be equal to 1.0, which is the coefficient for the south and west direction. The reference height for a residential building is assumed to be 32 m, which corresponds to ten levels in a residential building. The results of the calculation can be seen in Table 6-4.

Table 6-4: Parameters wind calculation

Basic wind speed v_b	26 m/s	Terrain factor k_r	0.215
Mean wind speed v_m	26.15 m/s	Roughness factor c_r	1.006
Structure reference height z_e	32 m	Turbulence intensity I_r	0.203
Air density ρ	1.25 kg/m³	Peak velocity pressure q_p	1036 N/m²

The pressure coefficients that have to be applied differ for the different elements on the balcony. For planes parallel to the façade of the building (like balcony separations), $c_{p,net}$ = +/- 1.5 must be applied. The side of the balcony can be seen as a free wall with return corner. According to NBN EN 1991-1-4 ANB this coefficient can be taken equal to +/- 2.0.

NBN EN 1991-1-4 part 7.4.2. defines a shelter factor for the net pressure coefficient for walls or fences that are upwind and equal or taller in height. This factor depends on the relative spacing x/h. The glass panes have a solidity ratio of 1.0 and the spacing factor x/h is equal to 3/2.6=1.15. For this assumptions, the shelter factor ψ_s is equal to 0.3. This results in a total $c_{p,net}$ of 0.6.

When porous surfaces are used (like the perforated metal panels), this has an effect on the wind load on the surfaces. For surfaces normal to the wind, experiments have shown that the following formula can be used for calculating the force coefficient on porous surfaces (32):

$$C_D = C_D\ (Solid) \cdot (1 - \beta_e) = 1.5 \cdot (1 - 0.4) = 0.9 \qquad (32)$$

Where β_e is the effective porosity, which can be assumed equal to the geometric porosity. This is equal to the perforation ratio of the panel (Richards & Robinson, 1999). A perforation ratio of 0.4 is assumed for the parapet panels (explained in '6.3.4.3'). An overview of the resulting wind forces is given in Table 6-5.

Table 6-5: Overview wind forces

Situation	Pressure coefficient c_p [-]	Total pressure [N/m²]
Front (parallel to façade)	+/- 1.5	+/- 1554
Front perforated	+/- 0.9	+/- 932
Side (perpendicular to façade)	+ 2.0	+ 2072
Side sheltered	+ 0.6	+ 622

6.3.4.2 Service load

The residential building can be classified to Category A (Areas for domestic and residential activities). According to NBN EN 1991-1-1 ANB, the characteristic values of Table 6-6 should be applied for the vertical load on the balcony floor and the horizontal line load acting at the height of the parapet.

Table 6-6: Service loads

Load situation	Characteristic value
Balcony floor – Vertical load	$q_k = 4.0$ kN/m²
Parapet wall – Horizontal load	$q_k = 0.5$ kN/m

6.3.4.3 Self-weight

The calculations are done with the use of SCIA Engineer. The model is shown in Figure 6-18. The structure is foreseen of hinges along the whole length between the horizontal transom and the floor of the balcony and between the floor and the parapet of the balcony. The mullions and transoms have a depth of 0.2 m (as indicated in Figure 6-8). This means that the screen of the box is in closed position 0.2 m in front of the normal façade (with the closed windows). The two upper points at the side of the parapet are assumed to be held on place by the stiffness of the hydraulic system (Figure 6-15) and the locked arm (Figure 6-16).

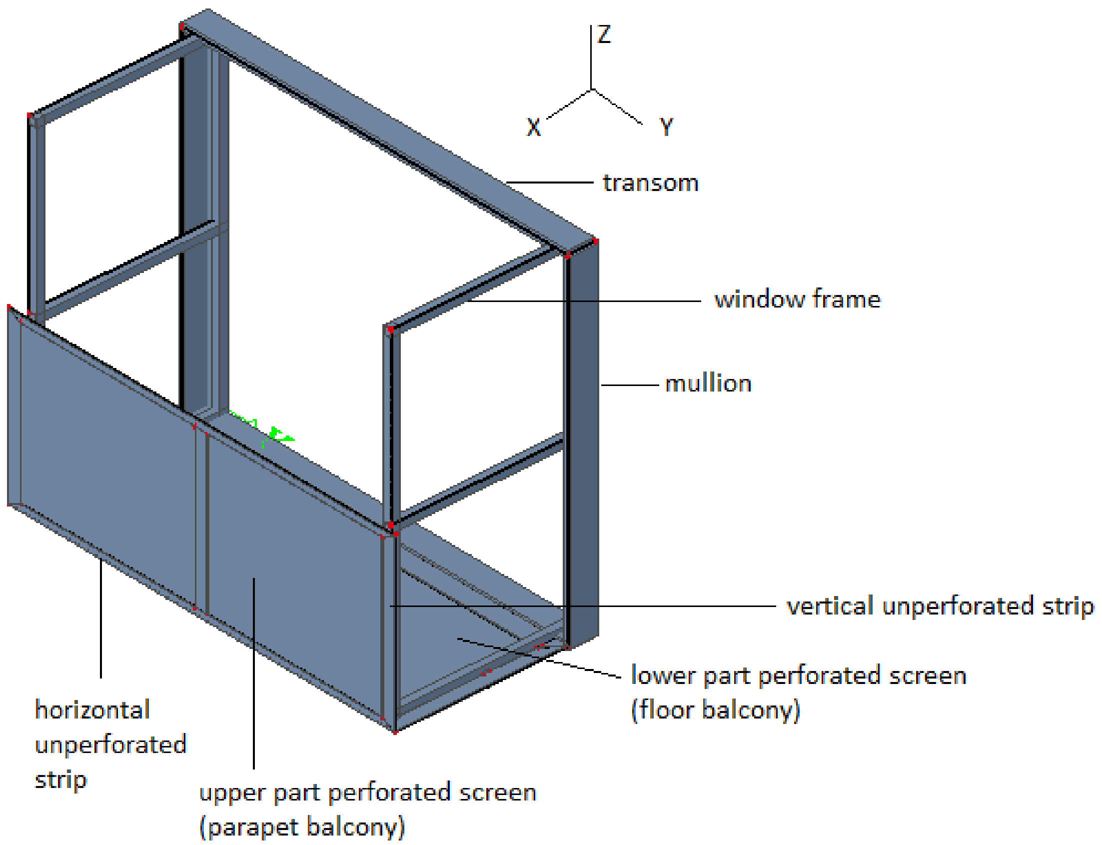


Figure 6-18: Model opened balcony SCIA

The perforated screen requires special attention. The **perforation ratio** that is most suited for a specific building application depends on many factors. The most important factors are the location and the environmental climate of the building. The ratio should provide a balance between enough daylight entrance, while maintaining the privacy and the protection against overheating. Aesthetic, visual and thermal comfort need to be optimised for the specific situation. Careful consideration of the driving parameters will result in a beautiful and good performing screen. Figure 6-19 shows pictures of perforated screens for different perforation ratios. For the calculations, a perforation ratio of at least 35% is assumed for the panels to be sure that enough daylight can enter the building in folded position.

Figure 6-19: Illustration perforation ratio (Web 6-13)

The **yield strength and elastic properties** of perforated panels for the analysis can be calculated according to the concept of equivalent solid materials (Industrial Perforators Association, 1993). For the calculations a perforation ratio of 35% will be assumed for the floor plate of the balcony. With this ratio, a strength value of about 31% of the solid yield strength corresponds (Figure 6-20 – a). The lowest of the two curves is taken to be conservative. The effective stiffness for this ratio is equal to 36% of the solid stiffness (Figure 6-20 – b). For the parapet of the balcony, a perforation ratio of 40% is assumed. This perforation ratio can be higher because this panel is not subjected to the high vertical service load (Table 6-6). The perforation ratio for the floor panel is taken a bit lower, to ensure more strength and lower deflections. With the ratio of 40% for the parapet, a strength of 27% of the solid yield strength and an effective stiffness of 31% of the solid stiffness correspond. For the steel, class S355 is assumed, to ensure enough stiffness for the screen. The sides of the two panels are foreseen of horizontal and vertical strips at the sides that are not perforated (indicated in Figure 6-18). These strips have a higher strength and stiffness. Also in the middle a vertical strip is foreseen. This strip is situated (in folded position) in front of the location where the frames of the two windows come together in closed position. In that way, the unperforated strips will not disturb the outside view.

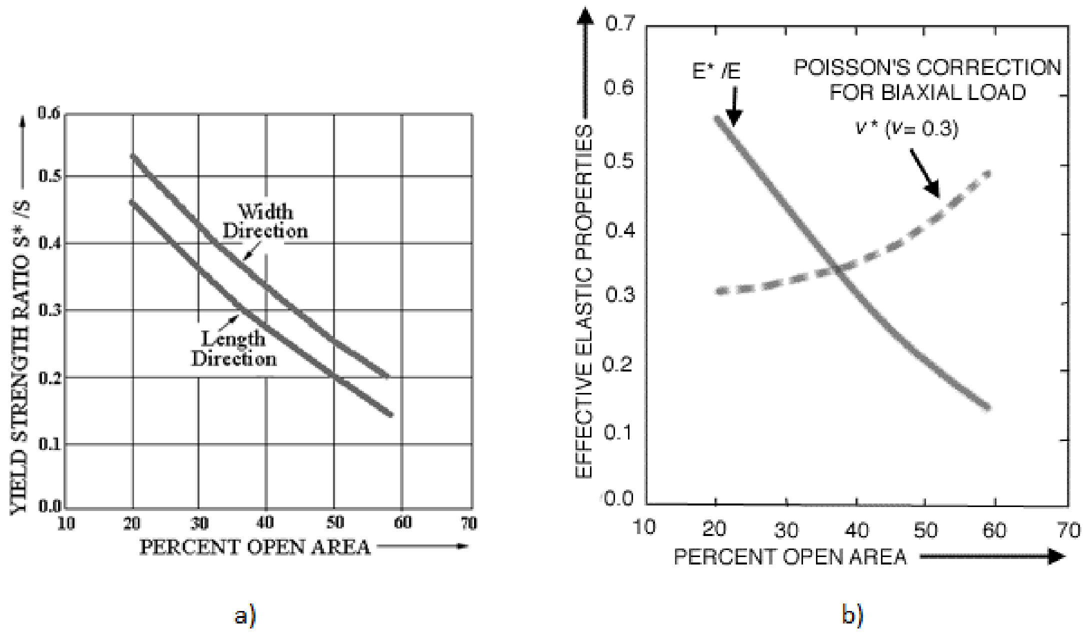


Figure 6-20: Properties perforated screen: a) yield strength, b) elastic properties (Industrial Perforators Association, 1993)

An overview of the other used materials and profiles is given in Table 6-7.

Table 6-7: Self-weight

Element	Material	E [MPa]	Weight [kg/m³]	Yield strength [MPa]	Dimensions [m]
Window - panes	Glass	70 000	2500	Type-dependent	Thickness: 0.006
Window - frame	Steel – Rectangular tube profile	210 000	7850	355	Height: 0.06 Width: 0.06 Thickness: 0.005
Perforated plate - floor	Steel – perforation ratio 0.35	75 600	5102.5	110	Thickness: 0.008
Perforated plate - parapet	Steel – perforation ratio 0.40	65 100	4710	96	Thickness: 0.008
Unperforated strips	Steel – vertical Steel - horizontal	210 000	7850	355	Thickness: 0.016 Thickness: 0.018

6.3.5 Stresses and deformations

The stresses and deformations are checked according to the ULS and SLS specifications as explained in '5.4.6'.

6.3.5.1 Perforated screens

The perforated screen forms the floor and the parapet of the balcony in opened position. Firstly, the **stresses** in the perforated screens are checked in ULS conditions. The yield strength is equal to: $f_{yd} = f_{yk}/\gamma_M$. With γ_M equal to 1.0 for steel. To be safe, the stresses are checked without the contribution of the glass pane to the in-plane stiffness of the window (as explained further). An overview of the maximum stresses that occur in both the x- and y- direction of the plates is given in Table 6-8. It should be remarked that for the floor plate, the x- and y-direction are the same as the global axis in Figure 6-18. For the parapet plate, the y-direction is the height direction and the x-direction is the width direction of the parapet. The table gives also information about the place where the maximum stresses occur. This is important because the perforated screens have a lower strength than the unperforated strips. The maximum allowable stress is given in the last column. It is clear that the maximum limit is never exceeded.

Table 6-8: Stresses in the steel plates

Stresses	Load case	σ_x [MPa]	σ_y [MPa]	Location maximum	Maximum allowable stress [MPa]
Perforated plate – floor	Service load (+ self-weight)	127.2	51.9	Unperforated strips	355
Perforated plate – floor	Service load (+ self-weight)	38.2	47.8	Perforated plate	110
Perforated plate – parapet	Wind load + service load (+ self-weight)	94.3	57.9	Unperforated strips	355
Perforated plate – parapet	Wind load + service load (+ self-weight)	10.2	35	Perforated plate	96

The **displacements** of the screens are checked in SLS conditions. Two important displacement checks should be performed. The first one is the downward displacement of the floor panel (z-direction in Figure 6-18). This should not be higher than l/250 to assure sufficient horizontality. Secondly, the horizontal displacement of the parapet should be limited as well (x-direction in Figure 6-18); for this a limit value of l/100 can be put in front. The width of the screen is equal to 3.2 m. This results in a limit value of 12.8 mm for the vertical floor deflection and a limit of 32 mm for the horizontal parapet deflection.

By locking the window frame in a projection on the perforated screen (Figure 6-10), these two structural elements are connected. The forces on the perforated screen (mainly self-weight and service load) are transferred by the windows to the primary load-carrying structure of the building. Firstly, it is assumed that only the steel frames are contributing to the force transfer and the in-plane stiffness of the glass panes is neglected. This is a safe consideration. With this consideration, the displacements in **vertical direction** are shown in Figure 6-21. It should be remarked that the displacements in Figure 6-21 – a are enlarged to give a clear view of how the structure deforms. The maximum displacement is equal to 12.1 mm and is situated in the middle of the perforated parts. Due to the stiffened unperforated strip, the maximum deflection does not occur in the exact middle of the balcony floor. The before mentioned limit of l/250 (12.8 mm) is not exceeded.

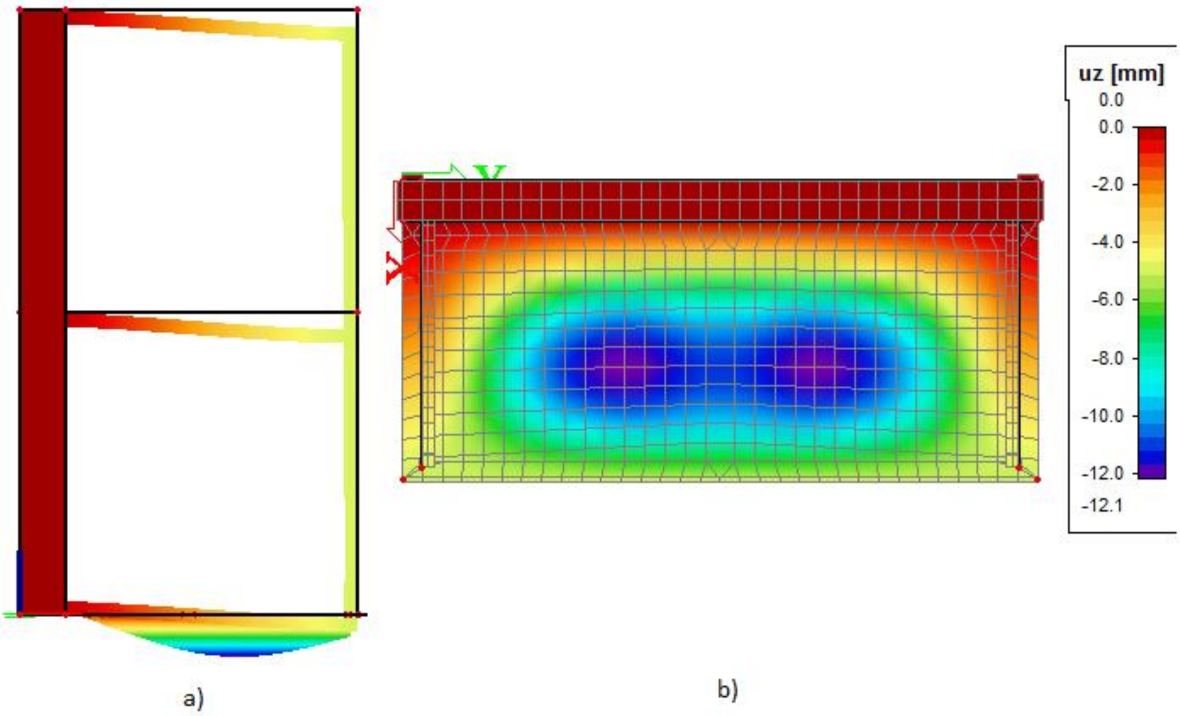


Figure 6-21: Downward displacement: a) side view, b) top view

After this, the in-plane stiffness of the glass pane is taken into account. Only the shear action of the lowest glass pane of the window is taken into consideration, because the upper part can be slid to an opened position. The in-plane deformation of the shear wall will decrease due to the contribution of the glass pane. The stiffness of the used adhesive will influence this decrease. For the calculations, the modulus of the silicone is assumed to be 1.5 MPa (Web 6-14). In this case, the maximum downward deflection of the floor of the balcony is equal to a value of 10.8 mm. This value is evidently lower than the value for the situation in which the glass pane with glued connection is not considered.

To make it possible to unfold the perforated screen on a cold but sunny day, the stability and displacement in case of an opened balcony without window support is checked. This means that the window support should only be needed for live loads. The maximum downward deflection in case the window support is not present and without the service loads is only 1.4 mm and certainly below the limit of l/250.

With the wind forces on the panel, the maximum **horizontal displacement** is equal to 21.5 mm, which is lower than the limit of l/100. Besides the influence of the wind forces, the influence of the horizontal service load at the upper line of the parapet is taken into account as well. Figure 6-22 shows the displacement in an enlarged form. By making the horizontal unperforated strip at the top of the parapet screen thicker, an even lower deflection can be obtained.

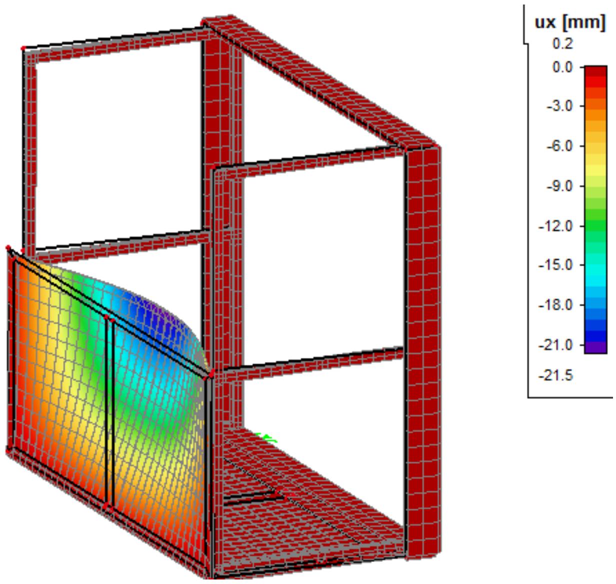


Figure 6-22: Horizontal displacement parapet

6.3.5.2 Window (steel frame and glass pane)

The window steel frame is connected to the perforated screen floor of the balcony and transfers the forces to the primary structure of the building. To create a good view of this force transfer, this part is modelled separately. The same safety factor γ_M equal to 1.0 is considered for the steel frame. The stresses in the glass pane are checked by making use of the maximum stress method. The same formulas (30) and (31) as in '5.4.8.1' are applicable. The only difference is that in this case personnel loads are present as well, for which a k_{mod} factor of 0.85 should be considered according to prEN16612. Together with the self-weight, this results in a combined factor $k_{mod,c}$ equal to 0.59, which results in a value for $f_{g;d}$ of 14.7 MPA for annealed glass, $f_{g;d}$ of 35.5 MPa for heat strengthened glass and $f_{g;d}$ of 77.2 MPa for tempered glass. In the glass pane, a tension and compression diagonal develop. Table 6-9 gives an overview of the maximum stresses that occur in the steel frame and glass pane. For the stresses in the glass pane, the flexibility of the silicone is again taken into account. The tension stress is considered because this is the most critical stress for glass (both the x- and y-direction of the pane are verified). The highest stresses occur locally at the edges of the pane. The stresses in the steel frame are checked for the conservative situation in case the glass pane does not contribute. With the contribution of the glass pane, these stresses are lower. From the table, it can be concluded that the maximum limit is never exceeded.

Table 6-9: Stresses in the steel frame and glass pane

Stresses	Load case	Type	Stress [MPa]	Location	Maximum allowable stress [MPa]
Steel frame	Service load (+ self-weight)	Normal stress	183	Left side window (connection to fixed frame)	355
Steel frame	Service load (+ self-weight)	Shear stress	68	Left side window (connection to fixed frame)	205
Glass pane	Service load (+ self-weight)	Normal stress (tension)	5	Left part (edges glass pane)	14.7 (annealed) 35.5 (heat strengthened) 77.2 (tempered)

The force transfer through the window to the primary load-carrying structure of the building needs to be realised without excessive deformation. Firstly, no influence of the glass pane is assumed, resulting in a conservative design. The vertical displacement should be limited to l/250 (z-direction in Figure 6-18). For the window width of 1.5 m this results in the value of 6 mm. The maximum displacement of the frame is equal to 5.1 mm. The deformed structure (in enlarged form) is given in Figure 6-23 – a . If the in-plane stiffness of the lowest glass pane is taken into account, the displacements will decrease. Again, the influence of the silicone is considered. With this flexible adhesive, the maximum vertical displacement is equal to 2.8 mm (Figure 6-23 – b).

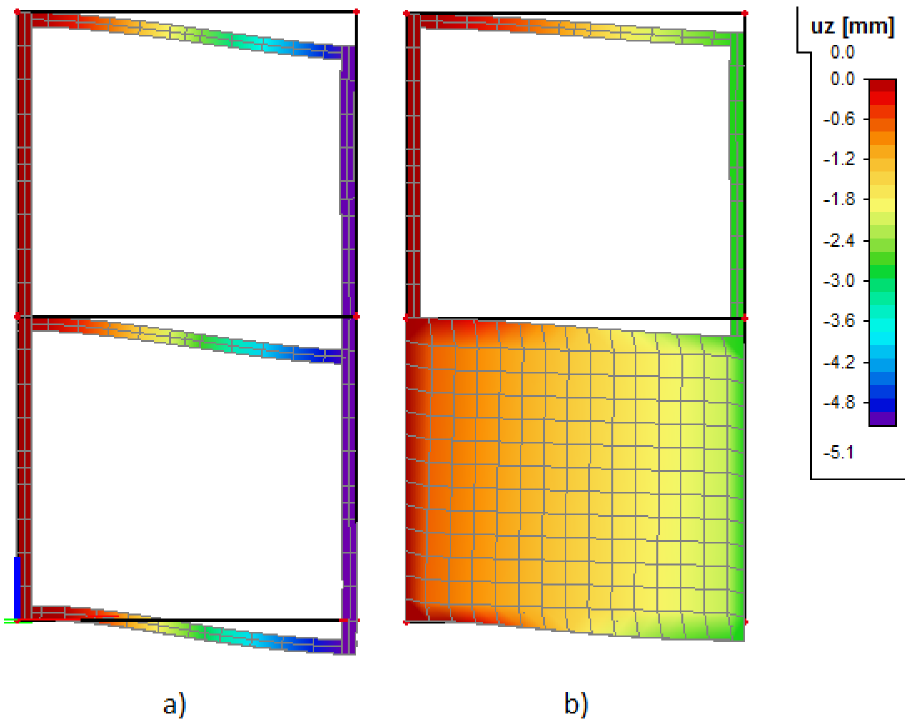


Figure 6-23: Downward displacement frame (side view): a) without glass pane, b) with glass pane

If the contribution of the glass pane is taken into account, the design can further be optimised. The thickness of the steel frame can be lowered from 5 mm to 2 mm. This will result in a maximum displacement of 3.9 mm, which is still below the limit. The stresses in case of a frame of 2 mm thickness are higher. However, due to the fact that the contribution of the glass is considered, the stresses in the steel frame stay below the allowed limit. The maximum stresses in the glass pane increase as well, but are also still below the mentioned limits.

For completeness, the **out-of-plane displacement** due to wind loading is checked in case the window is opened and the upper pane is not slid down. The displacements are checked for the most critical case of the unsheltered window. The maximum out-of-plane deflection is equal to 12 mm at the free top of the frame (with a frame of thickness 5 mm). This value is lower than the limit of l/100 (equal to 15 mm for the window width of 1.5 m). It should be remarked that this displacement will normally not occur because during extreme weather conditions with large wind forces, the windows (and balcony) will normally be in closed position.

6.4 Conclusions

This chapter discusses the detailed concept of an adaptive structure that permits to transform a perforated screen in front of the transparent glazing of a building to a balcony. The design of this prototype focused on a **complete transformation** by a folding/unfolding mechanism. The coupling of both a screen and a balcony creates a multifunctional curtain wall. The prototype allows the users to locally control the system according to their wishes. At the same time, an aesthetically pleasing façade is created, both from an inside and outside viewpoint.

The **double principle** contributes to a more sustainable building design. The perforated screen on one side provides more privacy, blocks the sun partially, lowers glare problems and reduces wind loads. The balcony on the other side creates extra useful building space and allows complete natural ventilation.

A strong aspect of the design is the option for architectural freedom. The prototype makes **original and creative** designs of the architects possible. Firstly, the perforations for the screen include many options and combinations which will result in a different appearance. In addition, the choice of the perforation ratio allows to influence the physics (for instance the amount of sun blocking) according to the specific project location. Secondly, the structural placement of the façade allows to create a different overall picture of the curtain wall. The box with the transformable structure can be placed in front of the conventional façade, which creates the look of separated boxes on the façade. In contrast, the box can also be placed behind the façade and the perforated screen can be widened all over the building façade. This creates a whole different view from outside.

The double principle is most suited for **moderate and warmer areas**. These climate zones can profit from the protection against overheating and the allowance for maximum natural ventilation. This positive influence on several relevant building physics will lower the total energy use and creates high comfort for the individuals.

The used **movement principle** to (un)fold between the two functional options is a mechanic based, hybrid system. For the transformation, two motions are of importance. Firstly, the rotation of the lower part of the perforated screen combined with the translation of the upper part of the screen. Secondly, the rotational movement of the two window wings along their side. The actuation of both motions is executed by (electro-)hydraulic devices. These systems can exert high forces and ensure a stable structure in unfolded (opened) position. The control of these devices can be carried out by making use of automatic systems and user feedback. The local user control will have a positive influence on the final energy use because it permits to use the system according to the individual wishes.

Similar to the first prototype, the design can be criticised by comparing with the definition of an adaptive façade:

*'An adaptive façade has the ability to **adapt**, in real time, some of its functions, features and behaviour in response to changing environmental conditions, performance requirements, occupants' wishes or other boundary conditions. The adaption has the purpose to obtain **improved overall building performance** related to primary **energy use** (heating, cooling, ventilation and lighting) while maintaining or enhancing the **comfort** and increasing the **flexibility** during the life phase of the building.'*

The design adapts primarily to changing occupants' wishes that are related to changing environmental conditions. It improves the overall building performance by lowering the primary energy use. This decreased energy use is the result of the reduced glare problems, increased shading options and allowance for more natural ventilation. On the same time, the system still permits the entering of enough daylight. The local user control allows for a flexible use of the system according to the individual needs.

An adaptive prototype with as main strong aspects its originality and architectural freedom was created. Of this prototype, some detailed drawings of the possible appearance of the façade are given in Figure 6-24 (with widened perforated screen) and Figure 6-25 (with conventional façade).

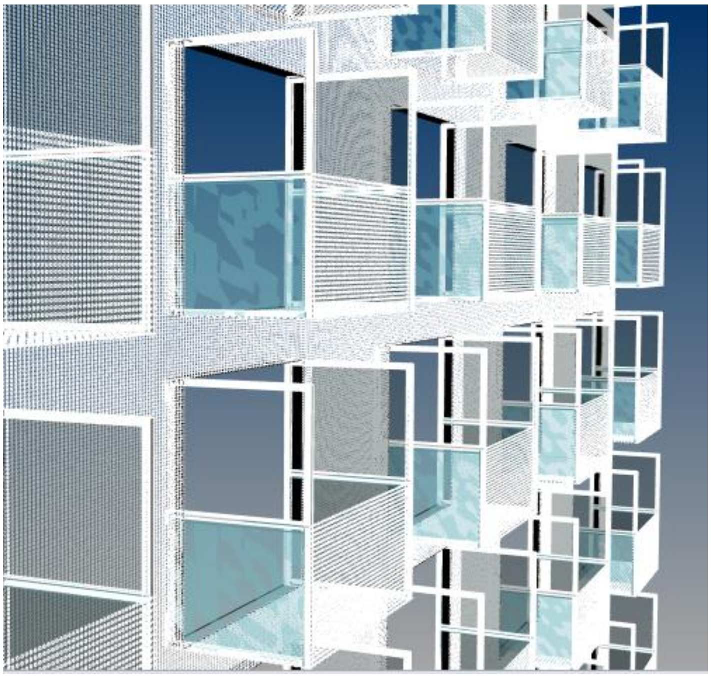


Figure 6-24: Prototype II - widened perforated screen

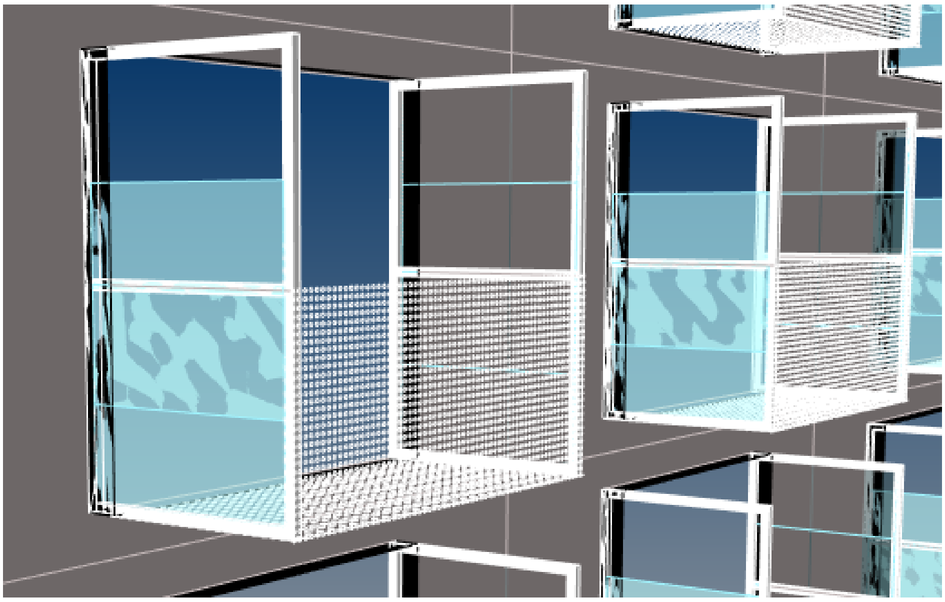


Figure 6-25: Prototype II - conventional façade and sliding window

7 General conclusion

The main objective of this thesis was to study the contribution of the building's façade in the design of low-energy buildings. The increased interest and need to improve the energy impact is triggered by the current changing climate. Structural adaptive façades use flexibility to adapt and react to changing conditions. This with the purpose to lower the total life cycle costs and environmental impact of buildings while maintaining high comfort for their habitants. By implementing the fourth dimension of time, the façade becomes a dynamic playground to optimise between energy balances and occupants' wishes.

A good understanding and investigation of the possibilities of transformable structures and building façades allowed to obtain a clear view on the type of structures and advanced façades that are best suited to design structural adaptive façades in an economic and aesthetic way. Secondly, a careful study of realisations and prototypes of adaptive façades resulted in useful knowledge and comprehension of innovative initiatives, shortcomings and potential improvements. A large part of these examples are still quite complex and building-specific. Further optimisation is necessary to facilitate and improve future designs to make them more economical and applicable on a larger scale. The research provides a better understanding of the working principles of structural adaptive façades. It is obvious that an aesthetical adaptive façade belongs to a multidisciplinary design culture that requires the gathered knowledge of different experts.

Apart from the detailed examination of the state of the art of the transformable structures, building façades and adaptive façades, this thesis zoomed in on the effective design of two prototypes. These prototypes concentrate on some specific building and design aspects. The optimisation of adaptive façades to perform well on several building physics and to maintain a high comfort is a complex challenge. Therefore, careful consideration of the focused aspects is of main importance for the end result. In this perspective, the two prototypes differ significantly. The first prototype puts the emphasise on energy gain and solar shading, while the second one mainly concentrates on glare, solar shading and ventilation. Besides the building physics, the movement and control of the two adaptive prototypes are completely different as well. The first prototype is optimised for a daily, global, rotating motion. The second prototype allows for complete transformation based on hybrid movement combined with individual user control. The first prototype emphasised simplicity and functionality, while for the second one the aesthetical effect and architectural freedom were of main importance. Both designs have a broad range of application possibilities and demand detailed optimisation for specific geographical and environmental conditions.

The two developed prototypes offered the occasion to experience that every design differs completely and has its own specific challenges that ask for an elegant solution. A careful, scientifically based analysis along with creative, gradually developing concepts and meticulous calculations, that is what makes civil engineering an ever-interesting domain!

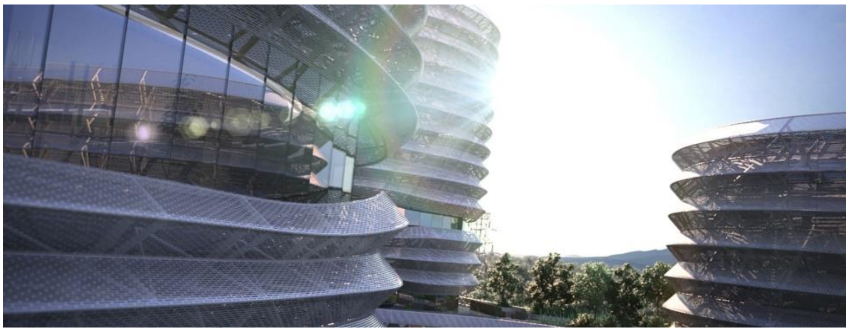
8 Future perspectives

A lot of investigation about structural adaptive façades is already performed which has led to beautiful and functional applications. However, many improvement possibilities and developing opportunities still exist. This thesis dealt with the detailed design of two potential prototypes, focusing on specific domains of building physics. However, the architectural subdomain of structural adaptive façades is far from saturated. By considering other aspects, endless opportunities are present to create new promising designs.

The two prototypes possess the capacity to be applied in sustainable buildings. To achieve a good performance of these prototypes, application-specific and context-dependent calculations are necessary to further optimise their design. A good simulation of local connections is necessary to avoid local failure and to create durable prototypes. Further investigation about the required forces for the actuators and their influence on the structural elements is necessary. Apart from this, a careful consideration of the combination of automatic and local control is strongly advised to improve the overall performance.

Once the prototypes are implemented into building façades, detailed monitoring and evaluation of the performance are highly suited to further improve the designs. These evaluation and simulation tools are helpful because the development of adaptive concepts is very challenging and often leads to too conservative decisions. In addition, these tools are not only effective for new designs but certainly also for existing adaptive façades. Experimental projects with innovative and creative ideas are often an incentive for the evolution of the mainstream.

APPENDIX A. Case Studies



‘Design is a constant challenge to balance comfort with luxe, the practical with the desirable.’

- Donna Karan -

CASE STUDIES

1 Realisations

South façade of the Arab World Institute

Name	Institute Du Monde Arabe
Location	Paris, France
Architect(s)	Jean Nouvel, Gilbert Lèzenes, Pierre Soria
Year(s) of construction	1987
Building Function	Research and information centre about the Arab world
Awards	Aga Khan Award for Architecture 1989, Equirre d'Argent for French architecture 1987
Façade type	Double-skin
Presence	South façade
Function	Thermal (solar control)
Climate zone	Moderate
Classification	Movement: Mechanic based - Rotation (In plane) Control: Local - Direct

General situation

The design of the façade of the Arab World Institute in Paris is from the French architect Jean Nouvel. It is the most famous project of an adaptive façade system. The design was done in cooperation with Gilbert Lèzenes and Pierre Soria. The concept for the façade construction finds its origin in oriental architecture concepts. The construction was opened in 1987 and is one of the earliest applications of adaptive façades.

Adaptive system

A complex system of mobile diaphragms forms the distinction between the glazed panels and the inside of the building on the south façade. The opening and closing of the diaphragms is inspired on geometric figures (mashrabiya) that originate from the Arab culture. Mashrabiya screens are already used for a long time in the Arabic culture to provide privacy and solar protection. The mobility of the diaphragms is based on an 'In plane rotation' that makes use of a local direct control system. The control is based on the use of a series of photoelectric cells that are sensitive to light. The diaphragms open when the cells (photosensitive sensors) receive less light and close in the opposite case. The south façade of the building consists of 30 000 diaphragms made out of steel. The system is similar to the shutter mechanism in a camera lens and plays with light and reflection inside.

Building physics and energy

The system is able to control the sunlight that enters the building and can lower the energy use of the building. The design of the façade of the Arab World Institute was an important step for the evolution of the design of sun shading systems. Nevertheless, the system has some important disadvantages of which the main one is the high number of mechanical devices that require a lot of maintenance. Today the system does not work anymore.

References:

(Velasco et al., 2015) (Premier, 2015)

(Web A-01; Web A-02)

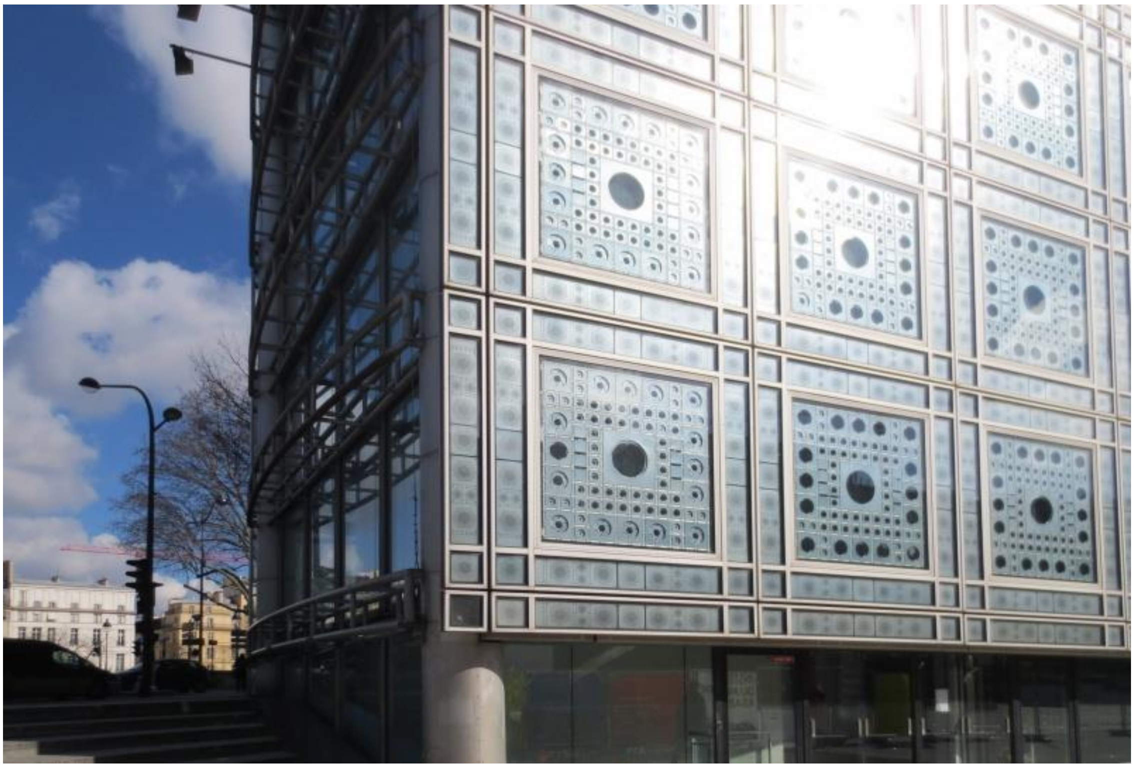
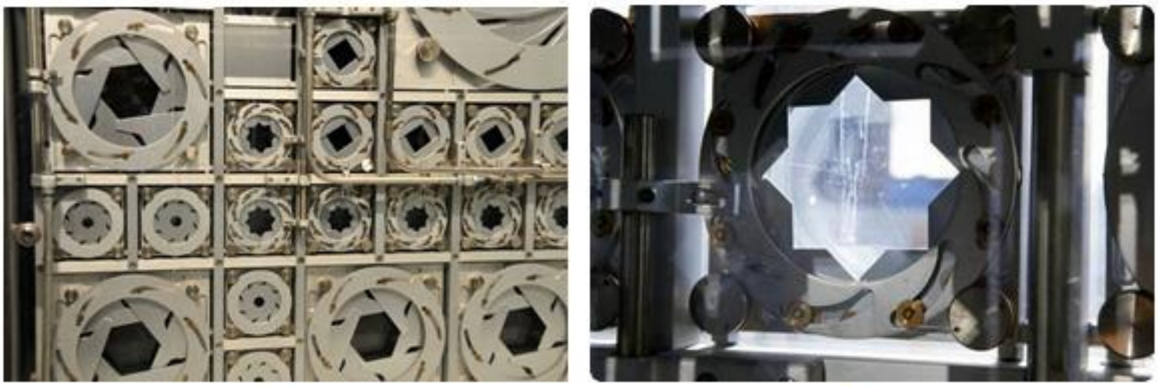
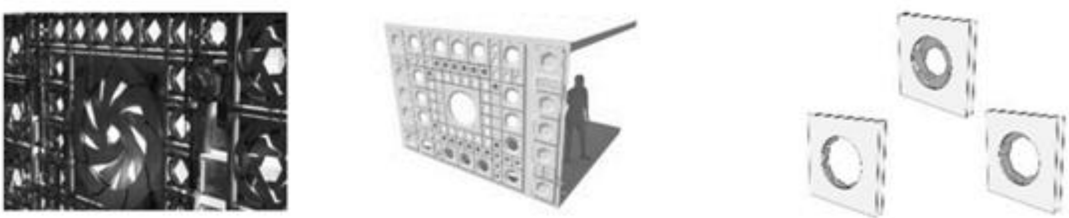


Figure 1-1: Façade of the Arab World Institute (Web A-01)



a) b)

Figure 1-2: Details (a-b) of the opening system (Web A-02)



a) b) c)

Figure 1-3: Diaphragm system: a) real design, b-c) virtual drawings (Velasco et al., 2015)

Museum of paper art

Name	Art paper museum
Location	Shizuoaka, Japan
Architect(s)	Shigeru Ban
Engineer(s)	Hoshino Architect & Engineer, Structural Chiku Engineering Consultants
Construction company	Obayashi Corporation
Year(s) of construction	2001-2002
Building Function	Museum of a paper manufacturer
Façade type	Curtain wall
Presence	South; west and east façade
Function	Thermal (solar control)
Climate zone	Subtropical
Classification	Movement: Mechanic based - Hybrid Control: Central - System-based

General situation

The building designed by the architect Shigeru Ban, tries to recreate the relation between the interior and the exterior spaces. The architect wants to create a flowing transition between the interior and the exterior by connecting the interior of the building with the surrounding landscape. The load-bearing structure of the building is a steel-frame construction that is combined with a glass pavilion on its roof. The concept for the façade has a spatial variety over the different sides of the building. The adaptive curtain wall façades are composed out of fibreglass reinforced panels. The north façade is a rigid double-skin façade made out of silica calcium boards and glass panels.

Adaptive system

The adaptive system on the south side differs from the system on the east and west façade. The panels on the south façade possess the opportunity on all floors to move and create a 'shitomido', which is a kind of awning that can go 5 m deep. The segments can fold upwards and outwards by using mechanical guide rails. By folding them to a horizontal position, they work as canopies that can provide shading to the interior spaces. In addition, they can slide sideways to provide less shading on moderate summer days. The panels are made out of lightweight plastic, which makes it easy to lift and open them. The system on the east and west side can open to a height of 10 meters, but is not capable of moving outwards. The movement on these façades is also executed by roller shutter doors. When fully opened, the interior of the building is completely exposed to the exterior environment.

Building physics and energy

The silica calcium boards on the north façade provide thermal insulation for the building. The opening and lifting of the panels on the other façades make it possible to create an efficient shading system for the interior of the building.

References:

(Jeska, 2008)

(Web A-03)

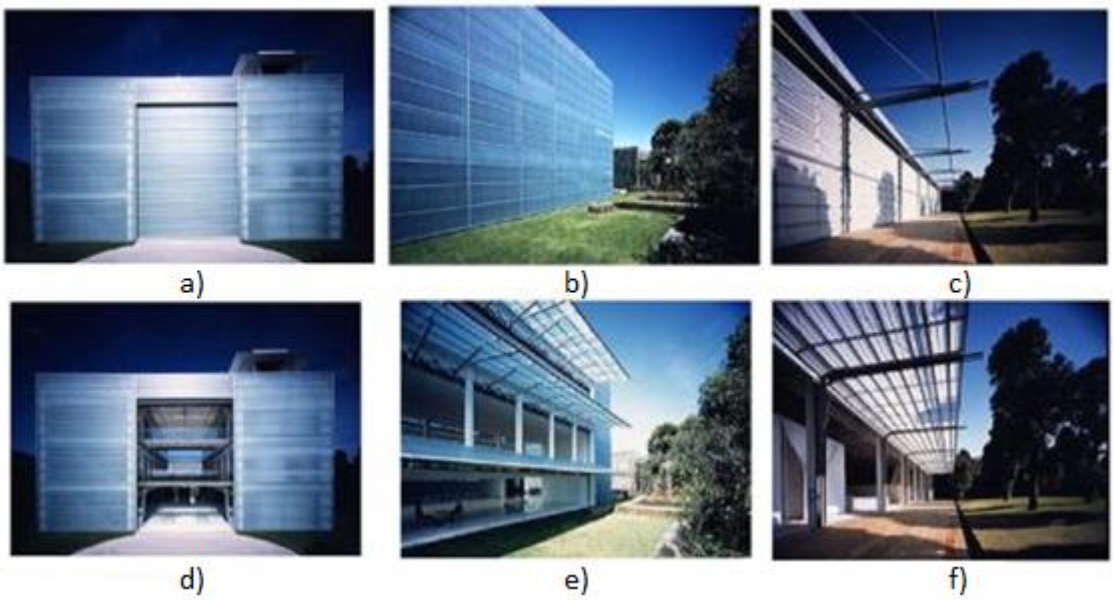


Figure 1-4: Museum of paper art: a-c) closed façades, d-f) opened façades (Web A-03)

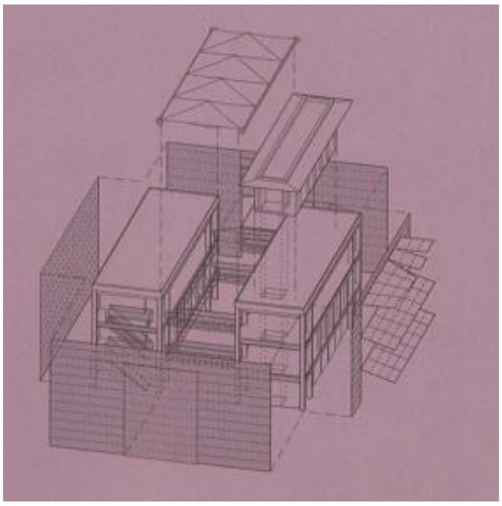


Figure 1-5: Overview of the different façades (Simone, 2005)

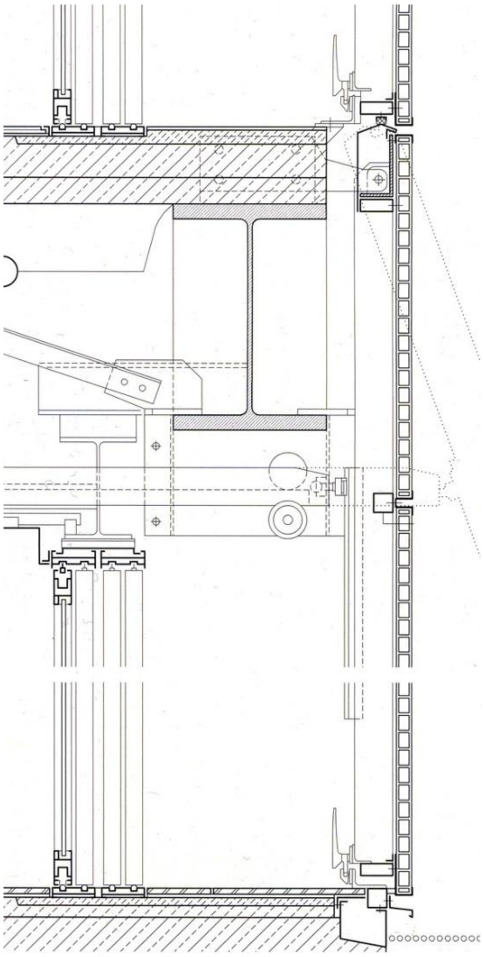


Figure 1-6: Detail of the system (Web A-03)

Agbar Tower Barcelona

Name	Torre Agbar Barcelona
Location	Barcelona, Spain
Architect(s)	Jean Nouvel and Fermín Vázquez
Structural engineer	Brufau & A. Obiol
Year(s) of construction	1991-2004
Construction company	Dragados
Building Function	Office and conference centre
Awards	International High-rise Award 2006
Façade type	Double-skin
Presence	All façades
Function	Thermal (solar control)
Climate Zone	Moderate (Subtropical)
Classification	Movement: Mechanic based - Rotation (Off plane)
	Control: Local - Direct (Sensor based)

General concept

The Agbar Tower in Barcelona was designed by the French architect Jean Nouvel for the Agbar Group, a holding company. The design for the tower was in association with the Spanish firm Fermín Arquitectos. The unusual form of the tower is inspired by the shape of a geyser that is rising into the air. The idea is based on the Montserrat mountain near Barcelona. In addition, inspiration was found in the towers of the Sagrada Familia. The structure is built with reinforced concrete and the cladding of the façade is done with glass. The height of the tower is more or less equal to 144 m. A special aesthetical effect is created at night by the 4500 LED (light-emitting diode) devices. This nocturnal illumination spectacle can create millions of colours. The tower itself is based on two concentric concrete oval cylinders of which the outer cylinder encases the inner cylinder.

Adaptive system

All sides of the Agbar Tower have a double-skin façade. The outer layer is composed of horizontal slats of glass. This glass is translucent and covers the whole building. The slats are a type of blinds and help to control the interior temperature. The control is done by an electronic mechanism that works with temperature sensors to regulate the opening and closing of the blinds. The louvers are moving according to a horizontal pivoting motion with a fixed pivoting axis.

Building physics and energy

The double-skin façade protects the tower from the solar radiation. The control of the opening and closing of the blinds helps to improve the interior temperature and results in a reduce of the tower's energy consumption. The inner layer of the double-skin façade is composed out of concrete (30-50 cm thick) and is thermally insulated on the inside. The outside of this inner concrete layer is cladded with an aluminium sheet.

References:

(Web A-04; Web A-05)


Figure 1-7: Nocturnal spectacle (Web A-04)


Figure 1-8: Detail of pivoting blinds (Web A-04)

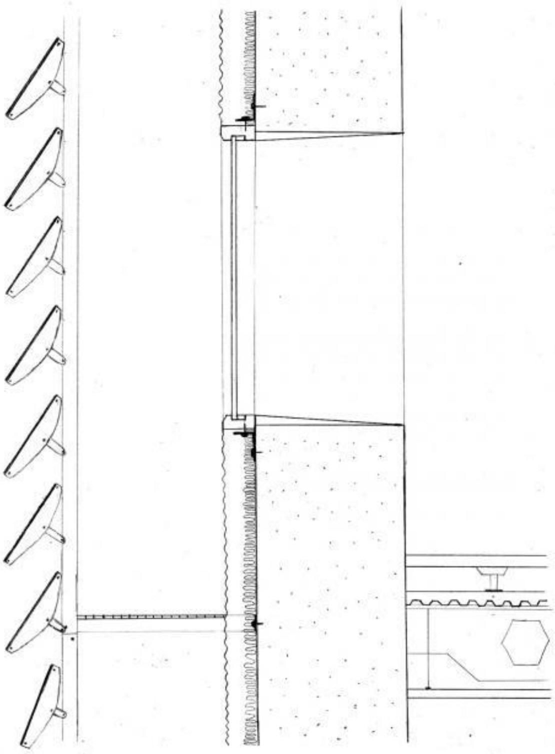


Figure 1-9: Detail of the double-skin façade (Web A-04)

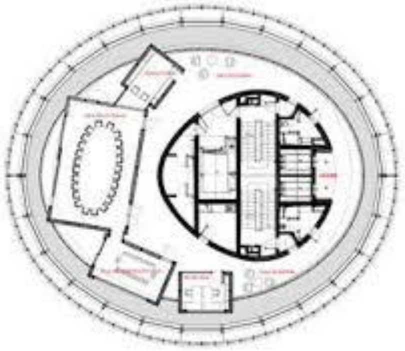


Figure 1-10: Ground plan (Web A-04)

EWE Arena

Name	EWE Arena
Location	Oldenburg, Germany
Architect(s)	Arat Siegel Schust (Architekten Stuttgart)
Engineer(s)	Colt, Höfker Ingenieure
Construction company	Colt, Denker, Mahlstedt
Year(s) of construction	2006
Building Function	Sports arena, concerts, stage-productions and exhibitions
Awards	Federal Photovoltaic Award in 2006, BDA Award Lower Saxony 2006, German Solar Award 2006, Cityscape Award of the City of Oldenburg 2006
Façade type	Curtain wall
Presence	South, west and east façade (200°)
Function	Thermal (solar control), Optical (daylight control), Electrical (energy)
Climate zone	Moderate
Classification	Movement: Mechanic based - Translation (In plane) Control: Central - Direct

General situation

The EWE Arena in Oldenburg is a sports- and multipurpose hall which makes part of the "Weser-Ems-Halle" exhibition centre, located in Oldenburg. The building exterior is completely glazed. To prevent overheating problems during the summer months, concrete overhangs were used to provide shading to the exterior glazing of the arena. In addition, a large movable shading system covers a 60° segment of the building.

Adaptive system

The shading screen of the arena consists of a curtain wall system foreseen of PV modules. The PV-sunscreen is 6.5 m high and 40 m wide and circulates 200° around the building according to the position of the sun. The construction has 18 separate segments that each contain 72 separate grey monocrystalline PV modules and 72 silk screen-printed glass elements. The PV modules are laminated into the glazing panels. They are interconnected in nine large groups, forming the strings. The screen follows the position of the sun by moving the complete unit every half hour in steps of 7.5°. Colt designed the control system that is responsible for the tracking of the sunscreen and installed the fixing system of the façade. The fixing system comprises a stainless steel roller that runs along the exterior of the building. The PV modules are individually clamp fixed to the rail. The construction is suspended from a lightweight concrete ring at the top. A lower ring at the bottom of the construction provides additional lateral support.

Building physics and energy

The EWE arena uses an innovative system that combines sun shading with the transformation of sunlight into electricity for the building. The screen provides shading and better daylighting performance for the interior of the building. The rotation makes it possible to capture maximum solar energy, which results in a maximised electrical output.

References:

(Web A-06; Web A-07)

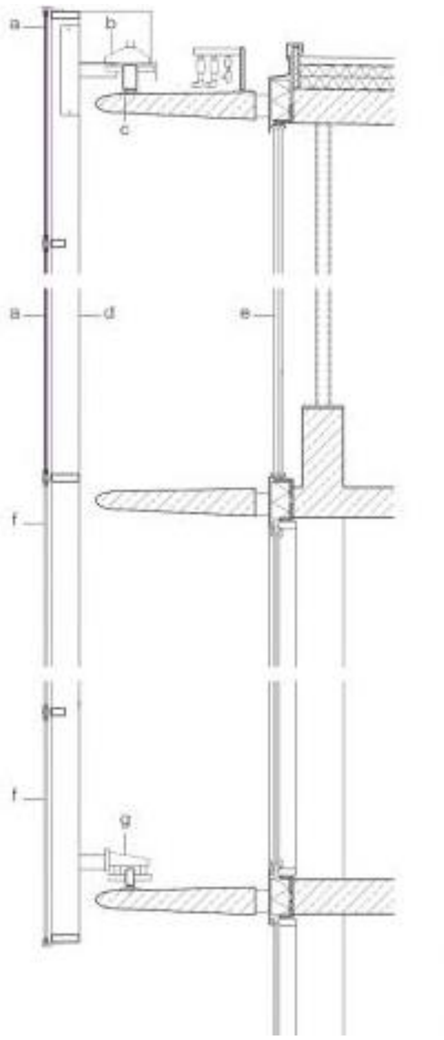


Figure 1-11: Detail of the system (Weller et al., 2010)

Figure 1-12: Details of photovoltaic panel (Web A-08)

Figure 1-13: Controllable solar shading (Web A-07)

Kiefer Technic Showroom

Name	Kiefer Technic Showroom
Location	Bad Gleichenberg, Austria
Architect(s)	Ernst Giselbrecht and Partner
Construction company	Harald Kiefer Metallbau GmbH
Year(s) of construction	2006-2007
Building Function	Office building and exhibition space
Awards	Austrian Architecture Award 2008
Façade type	Curtain wall
Presence	All façades (not the minor sides)
Function	Thermal (solar control)
Climate zone	Moderate
Classification	Movement: Mechanic based - Hybrid (folding)
	Control: Local - Direct

General concept

The Kiefer Technic Showroom in Austria has a dynamic façade foreseen of sunscreens that can open and close according to changing environmental conditions. When fully opened, a lot of daylight can enter as the exterior wall of the building is fully transparent.

Adaptive system

The façade of the showroom is an easy but very efficient curtain wall system. The frame exists of aluminium mullions and transoms. The sunscreen system is made of perforated aluminium panels. These shutters are electronically controlled.

Building physics and energy

The façade allows to control the solar gain by opening or closing the sunscreens. The electronical control of the system makes it possible to allow adaptation of the structure by the users according to their individual requirements to optimise the internal climate.

References:

(Web A-09; Web A-10)

Figure 1-14: Kiefer Technic Showroom (Web A-09)

Figure 1-15: Detail of the façade (Web A-11)

Pola Ginza Building Façade

Name	POLA Ginza Building Façade
Location	Ginza district, Tokyo, Japan
Architect(s)	Hoberman Associates, Yasuda Atelier, Nikken Sekkei
Year(s) of construction	2009
Building Function	Showroom building
Awards	Environment and Building Service System Design Award 2011
Façade type	Double-skin
Presence	Front façade
Function	Thermal (solar gain), Optical (daylight entering), Air flow (ventilation)
Climate zone	Moderate/Subtropical
Classification	Movement: Mechanic based - Rotation (Off plane) Control: Local - Direct

General concept

The façade of the new showroom building in the Ginza district in Tokyo was developed in 2009 by The Adaptive Building Initiative in collaboration with the design architect, Yasuda Atelier and the architect Nikken Sekkei. The request was done by POLA, a Japanese cosmetics manufacturer. The design is a shiny, adaptable skin that symbolises the important concepts of 'water' and 'light' in human life.

Adaptive system

The adaptive concept is inspired on plant concepts and is integrated in the double-skin façade of the building. The façade of the building exists of 185 individually controlled shutter mechanisms, with a dimension of one by three meters. The shutters are made out of curved acrylic panels. The panels are combined with LED lighting which can provide the building of various colours, which makes the building very attractive at night. The shutters are individually controlled in a motorised way.

Building physics and energy

The double-skin of the building's façade protects the shading system and allows natural ventilation by letting cooler air enter the building during night to reduce the cooling load. In addition, it maximises the natural daylight that enters the building during the whole year and it can increase the solar gain in the winter.

References:

(Web A-12; Web A-13)

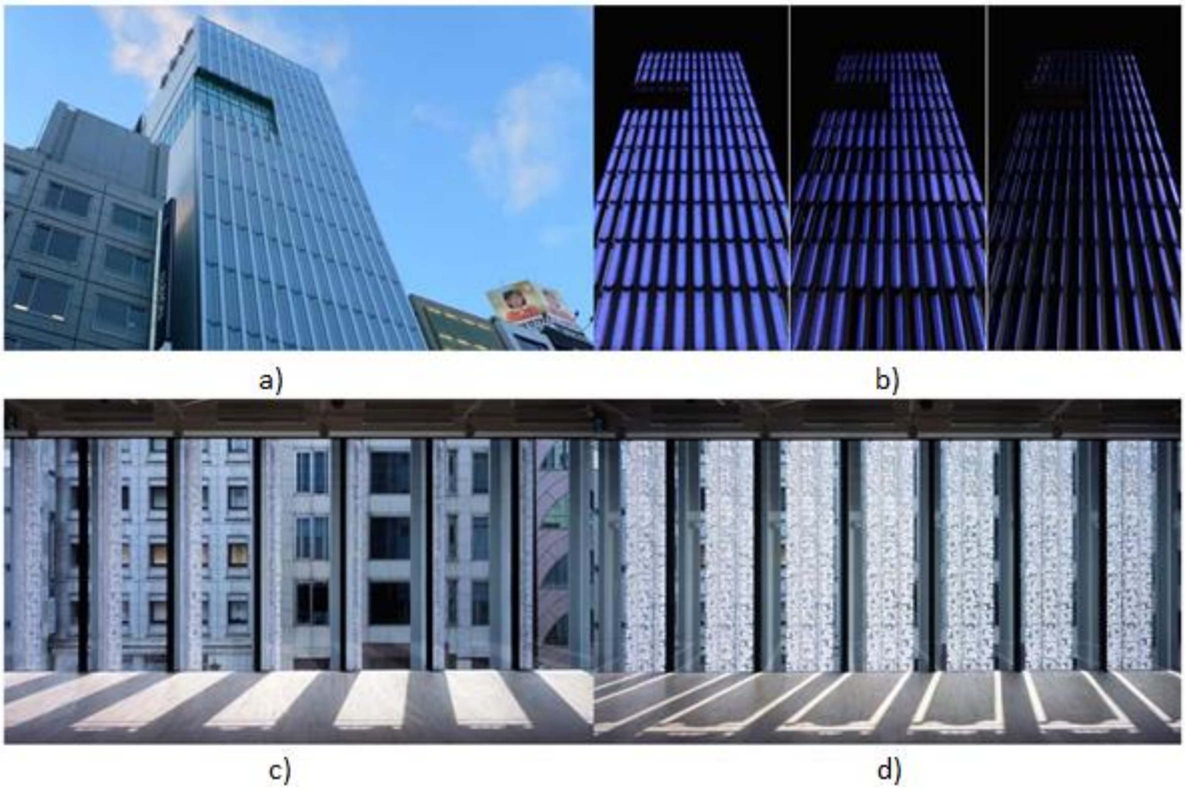


Figure 1-16: Façade of the Pola Ginza Building: a-b) outside view, c-d) inside view (Web A-14)

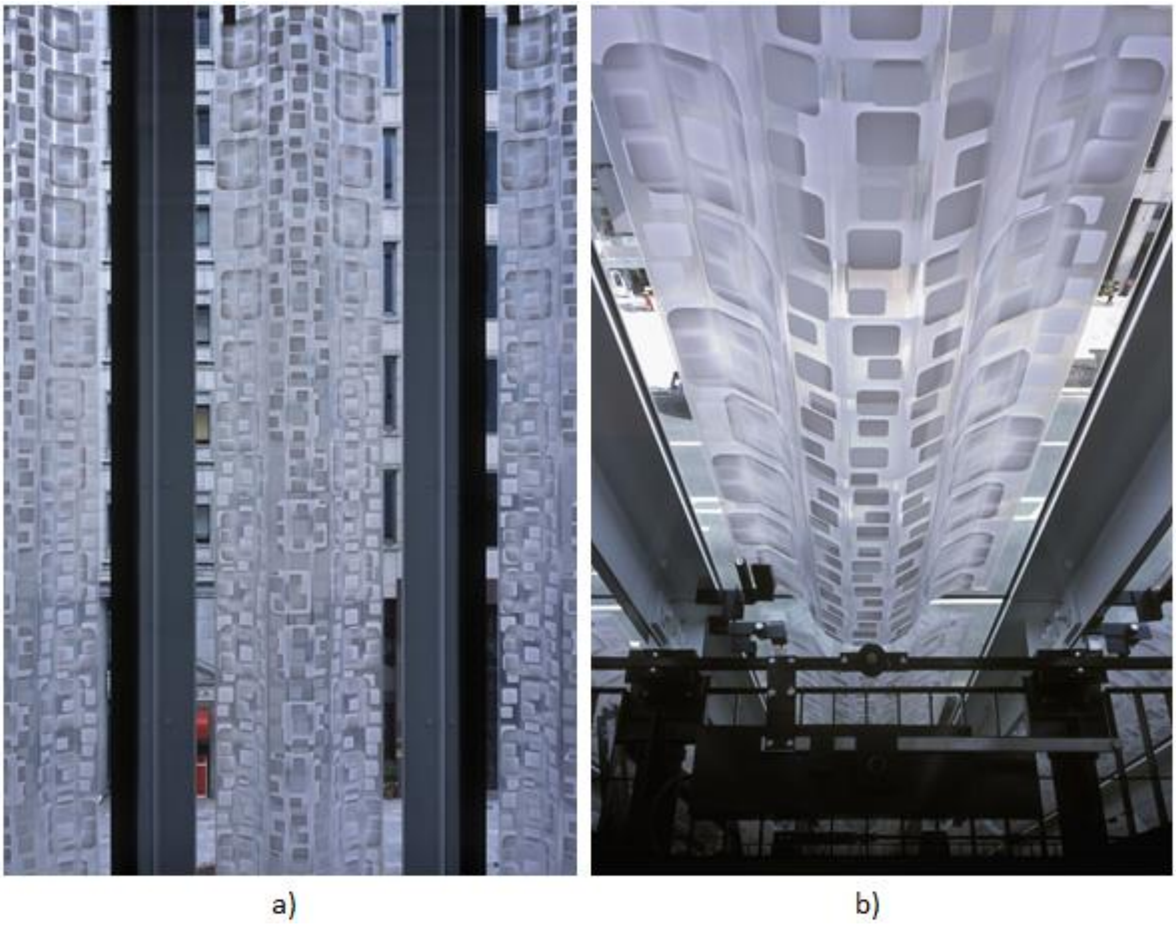


Figure 1-17: Rotating element: a) front view, b) upper view (Web A-15)

ThyssenKrupp Headquarters

Name	ThyssenKrupp Headquarters – Main building Q1
Location	Essen, Germany
Architect(s)	JSWD Architekten, Chaix & Morel et Associés
Engineer(s)	IDN Ingenieurbüro
Construction company	Frener and Reifer, Brixen/Bressanone
Year(s) of construction	2010
Building Function	Office building
Awards	Gold certificate by the German Society for Sustainable Building, BDA Essen Award, 2012 German Steel Construction Award, LEAF Award
Façade type	Curtain wall
Presence	All façades
Function	Thermal (solar control), Optical (daylight control)
Climate zone	Moderate
Classification	Movement: Mechanic based - Rotation (Off plane) Control: Central - Reactive

General situation

ThyssenKrupp created in Essen a group of buildings that is architecturally very powerful and in addition perfectly reflects the vision of the users. The Q1 building makes part of this ensemble of individual buildings, surrounded by trees, paths and small squares. The Q1 building forms the accent at the centre of the campus. The accent emphasises transparency, innovation and versatility. The sun protection system plays a key role in the overall appearance of the Q1. All the buildings on the campus are built following the "shell-core"- principle.

Adaptive system

The concept for the building exists of two parts. First of all, a constant horizontal overhang is foreseen, to provide protection against the sun. This overhang can also be used as a walking platform. In addition, the façade has a vertical set of twisting fins. The fins form the adaptive part of the sun shading system. The fins comprise a central stud to which horizontal cantilevered slats are connected. The twisting of the fins is possible between 0°, parallel to the façade (total blocking of direct radiation) and 90°, perpendicular to the façade (maximum daylight penetration). Moreover, an architectural accent was created by not making the fins in a rectangular way, but creating a special non-rectangular structure which has a pleasant effect during the rotation of the fins.

The flexible façade is composed out of 400 000 stainless steel slats in total, manufactured by ThyssenKrupp Nirosta. The steel sheets are covered with a zinc and magnesium coating, which makes the slats resistant to wind, corrosion, weather and UV radiation. In addition, the slats are grounded on one side and sandblasted on the other side. Depending on the point of view and the incidence of the light, the appearance of the slats will be different. An important aspect in the construction process was to keep the slats movable in the centre axis. This is necessary to react precisely to the signals of the electrical drive. The control system that steers the rotation of the slats is related to the seasonal sun position and the existing weather conditions. A weather station is placed on the roof, which sends signals to the computer.

Building physics and energy

The movable sunscreen reduces the solar gain. On the same time, it lets natural daylight enter the building. The façade system makes the need for an air conditioning system in the building unnecessary. In addition, the costs of the building are lowered by excluding the need for expensive aluminium profiles in the cladding of the façade.

References:

(Web A-16; Web A-17)

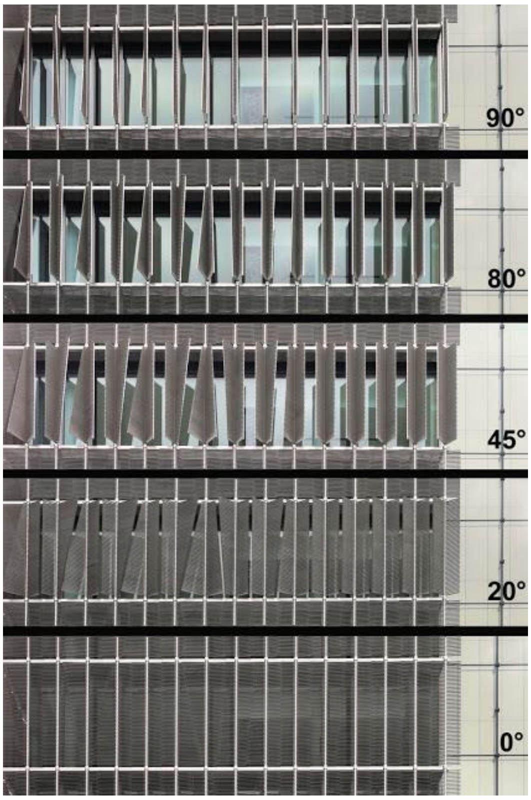


Figure 1-18: Twisting fins (Web A-16)

Figure 1-19: Façade view (Web A-17)

Figure 1-20: ThyssenKrupp Headquarters (Web A-17)

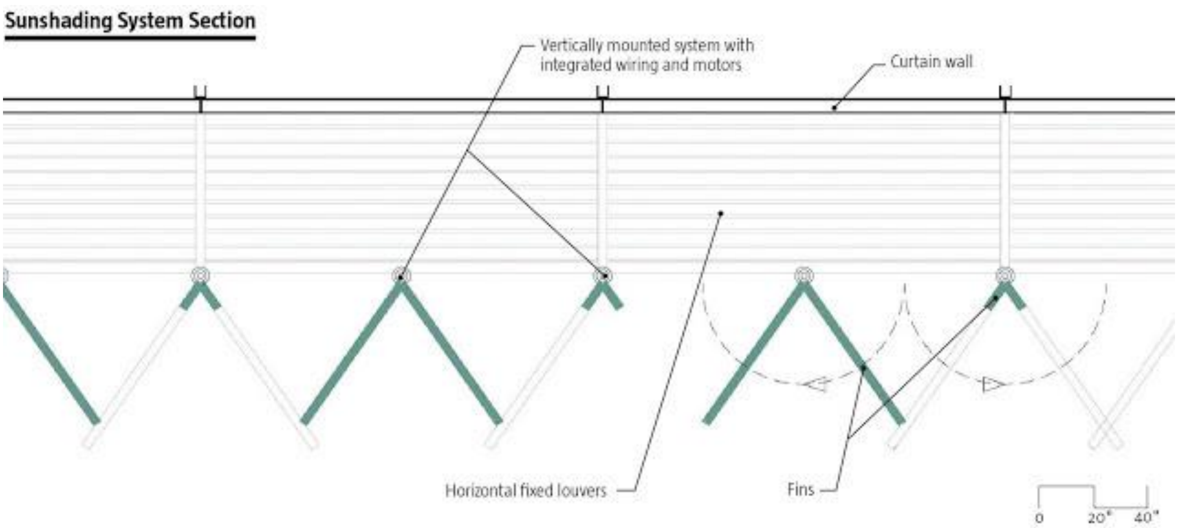


Figure 1-21: Detail of the movement of the fins (Web A-16)

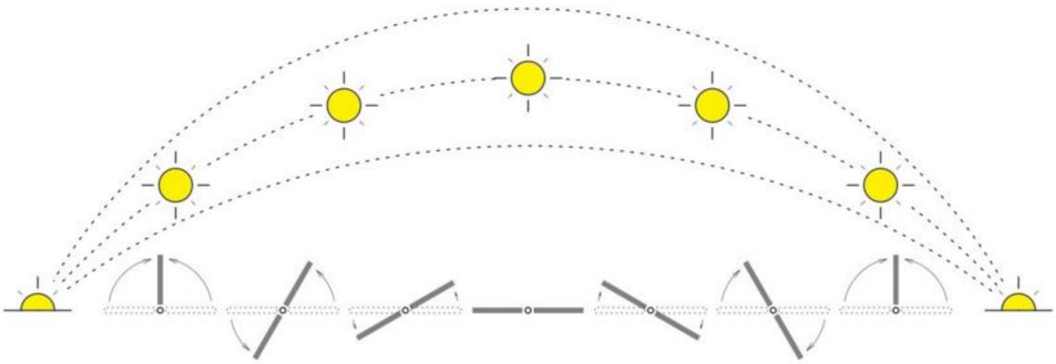


Figure 1-22: Turning according to position of the sun (Web A-17)

Sebrae Headquarters

Name	Sebrae Headquarters
Location	Brasilia Federal District, Brazil
Architect(s)	Groupsp - Alvaro Puntoni, Luciano Margotto, João Sodré, Jonathan Davies
Year(s) of construction	2010
Building Function	Office building
Awards	Award Architecture & Construction 'Best Architecture' 2011, International Award Architecture from Buenos Aires 2011
Façade type	Curtain wall
Presence	Inside atrium and outside (2 side faces not cladded)
Function	Thermal (solar control), Optical (glare, daylight entering)
Climate zone	(Sub)Tropical
Classification	Movement: Mechanic based - Rotation (Off plane) Control: Local - Reactive

General situation

The design of the envelope of the Sebrae Headquarters in Brazil takes the topographic characteristics of the building site as much as possible into consideration. The purpose of the architects was to integrate the building and his users with the natural landscape, including an optimal economic and environmental performance. The interior of the complex has a large spatiality. The sides of the buildings are foreseen of a cladding that protects against the sun. At the sides of the roof, a massive solar screen is placed.

Adaptive system

The cladding of the building is made of metal panels that are able to close and open individually. The panels protect the building against overheating and lower the use of expensive cooling features that are common in buildings in a warm climate. The fact that they can move independently, makes it possible to accommodate the occupants' individual demands. Moreover, the white metal colour is in perfect contrast with the natural colour of the other building materials, the blue colour of the sky and the green colour of the surrounding environment. The movement of the skin is complemented by a kinetic skin program.

Building physics and energy

The metal panels reduce the direct sun radiation and the glare that enters the building. The panels protect the occupants from too much heat gain from the sun. On the same time, the system allows natural daylight to enter the space, which reduces the need for artificial light. The massive solar screen that transcends the rooftop also allows the passing of light and acts as a shading system on the same time.

References:

(Web A-18)

Figure 1-23: Sebrae headquarters (Web A-18)

Figure 1-24: Inside atrium (Web A-19)

Figure 1-25: Brise-soleil cladding (Web A-20)

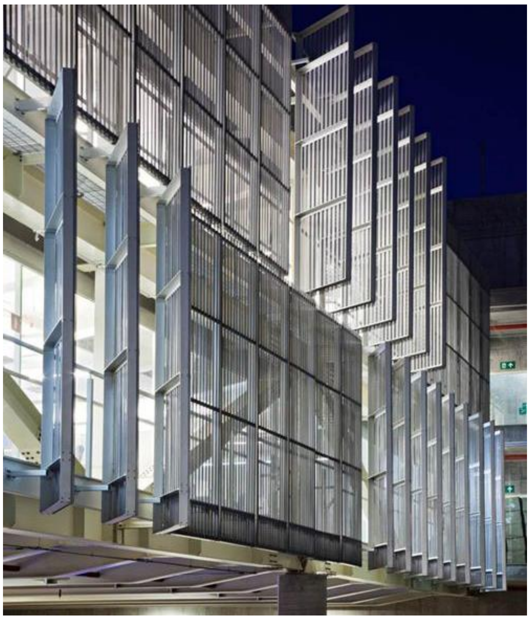


Figure 1-26: Brise-soleil cladding (from outside) (Web A-21)

Media-ICT Building

Name	Media-ICT Building
Location	Barcelona, Spain
Architect(s)	Enric Ruiz Geli, Cloud9 Architecture
Designer(s)	Vector Foiltec
Year(s) of construction	2010
Building Function	Building for science and technology companies, lobby for public exhibitions, workshops and events
Award	Best building in the world (WAF 2011)
Façade type	Curtain wall
Presence	South-west façade
Function	Air flow (air control), Optical (lighting), Thermal (shading system)
Climate zone	Moderate
Classification	Movement: Material based - External Input (Fluid) Control: Central - Reactive

General concept

The Media-ICT building, designed by architect Enric Ruiz Geli in cooperation with Cloud9 architecture, is situated in 22@, an experimental district. The south-west façade of this building in Barcelona is made out of plastic panels capable of transformation. The façade has a net-like steel structure which makes it able to integrate the public spaces to the building.

Adaptive system

The envelope of the building is a temperature-controlled skin that is capable of inflating and deflating. This system can be classified as a material based deformation principle triggered by an external input, more specific fluid. The inflatable segments have a triangular shape, inspired by nature. The membrane of the segments is a fluorine based plastic (ETFE: Ethylene tetrafluoroethylene). The segments are encased in a frame. The air chambers of the segments are centrally controlled by solar-powered sensors. The sensors are responsible for the contracting and inflating of the cushions according to the sunlight by differing the air pressures inside. The reaction of the sensors is based on the continuous calculation of the environmental changes (e.g. cloud cover). The system is not able to react quickly to the changing environmental conditions but needs on average about one hour to react.

Building physics and energy

The ETFE-membrane acts as a sunscreen and filters heat and UV-rays by inflating. The inflating chambers block the solar rays and create cooling shade. In winter, the solar rays are soaked up by the opening of the membrane to maximise the transmission of light and heat to the interior. Next to the adaptive façade, the building is equipped with a photovoltaic roof, a rainwater recycling system and district cooling as well. Al these measures contribute to an almost net zero building, the carbon emissions are reduced by 95%. In addition, the skin is anti-adherent and needs little cleaning.

References:

(Velasco et al., 2015)

(Web A-22)

Figure 1-27: Media ICT-building (Web A-22)

Figure 1-28: Air cushions (Web A-22)

Figure 1-29: Detail of the inflating cushions (Web A-22)

Roof Aldar Central Market

Name	Aldar Central Market
Location	Abu Dhabi, UAE
Architect(s)	Hoberman Associates, Foster and Partners
Engineer(s	Halvorson and Partners, BDSP Partnership
Year(s) of construction	2006-2011
Building Function	Market place
Awards	MAPIC EG Retail & Future Project Awards 2013, RIBA International Award 2013
Presence	Roof
Function	Thermal (solar control), Optical (glare, daylight control), Air flow (ventilation), dust and debris protection
Climate zone	Subtropical
Classification	Movement: Mechanic based - Translation (In plane) Control: Central - Reactive

General concept

The special concept that was used for the design of the Aldar Central Market is an adaptive roof system. In theory the concept can be applied to façades as well. The system was invented by Hoberman Associates and is an application of the Permea system.

Adaptive system

The kinetic design of the roof system is based on working with an operable grid. Permea is a system of panels that moves parallel to the building's surface. The roof shading of the Aldar Central Market belongs to the category of 'In Plane Translation' systems. The system is capable to change between completely covered and largely opened state. By adding seven layers into a sandwiched panel in each module, high apertures can be realised. The sandwiched structure results in a quite large thickness. The advantage of the system is that the different modules can be interconnected, which makes it possible to use less actuators. In the uncovered configuration, the panel profiles of the sandwich are aligned. This in contrast to the covered configuration in which the panel profiles have an offset relative to each other. The system is controlled in a reactive and central way by changing and responding to changing climatic conditions. The façade elements can retract and extend automatically, driven by sensors that collect environmental data.

Building physics and energy

The Permea system results in reduced solar gain and glare problems. It allows to control the shading and privacy in the building and is also capable to control ventilation, air flow, dust and debris protection.

References:

(Velasco et al., 2015)

(Web A-14)

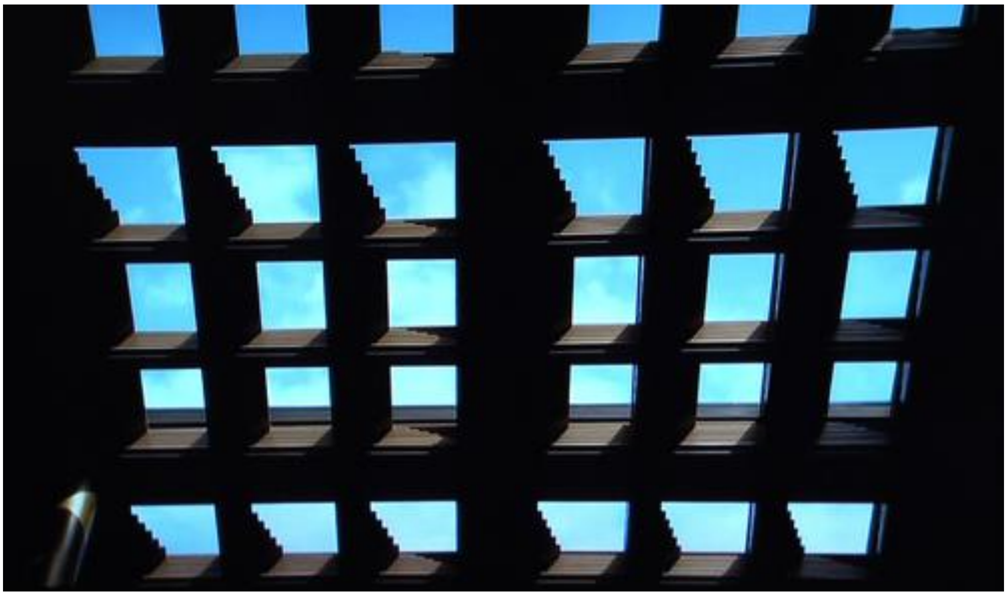


Figure 1-30: Roof structure (Web A-14)

Figure 1-31: Daylight control (Web A-14)

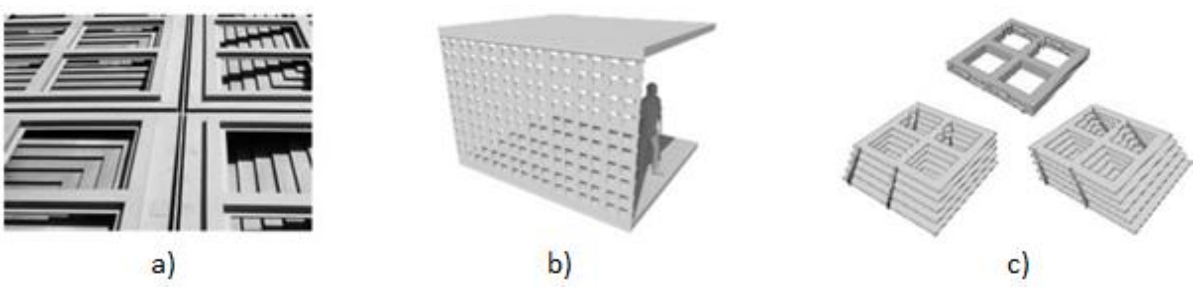


Figure 1-32: Planar kinetic system: a) real design, b-c) virtual drawings (Velasco et al., 2015)

Audiencia Provincial

Name	Audiencia Provincial
Location	Campus de la Justicia, Madrid, Spain
Architect(s)	Hoberman Associates, Foster and partners
Year(s) of construction	2011
Building Function	Campus of Justice
Presence	Roof
Function	Thermal (solar control), Optical (glare, daylight control), Air flow (ventilation)
Climate zone	Moderate
Classification	Movement: Mechanic based - Translation (In plane) Control: Local - Direct (Sensor-based)

General situation

Foster and Partners designed two distinct circular buildings for the new Campus of Justice in Madrid. The largest of the two, the Audiencia Provincial, consists of a roof over the atrium that exists of a triangulated grid. This grid is covered by an unique series of hexagonal shading cells. The shading system utilises the Strata system.

In the same Campus, Hoberman developed a shading system that consists of series of four-sided shading cells, based on the same Strata system. These are capable of covering the triangulated roof when extended and disappear into the structural grid of the roof when retracted. The inspiration is found in the dappled light that shines through the leaves of a tree.

Adaptive system

The Strata system is a system that can extend to a nearly continuous surface comprised of a series of slats in opened position. In retracted state, it forms a single slender profile, which is suitable to disappear into the building's structure. The shading system of the atrium is composed of perforated metal slats. These are attached to pivoting arms. This allows the slats to move laterally. The slats can retract in that way into a slender bundle which is aligned with the roof structure of the atrium. In retracted position, the slats do not obstruct the light. The movement can be classified as an 'In Plane Translation' system (sliding panels). An algorithm combines historic data about solar gain with real-time data that is gained by light sensors. This algorithm is capable of controlling the shading units. In addition, the control system is connected to a servomotor with custom-array control.

Building physics and energy

The shading system was developed to allow natural daylight to enter as much as possible, while minimising the penetration of direct sunlight on the same time. The Strata system is a useful shading control system to reduce solar gain and glare. On the same time, the system can control ventilation and air flow in an efficient way.

References:

(Lovel, 2013)

(Web A-14)

Figure 1-33: Audiencia Provincial atrium (Web A-14)

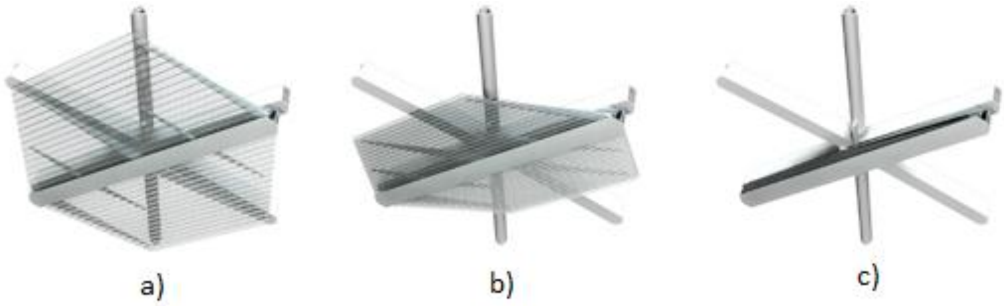


Figure 1-34: Strata system: a) opened slats, b) opening slats, c) retracted slats (Web A-14)

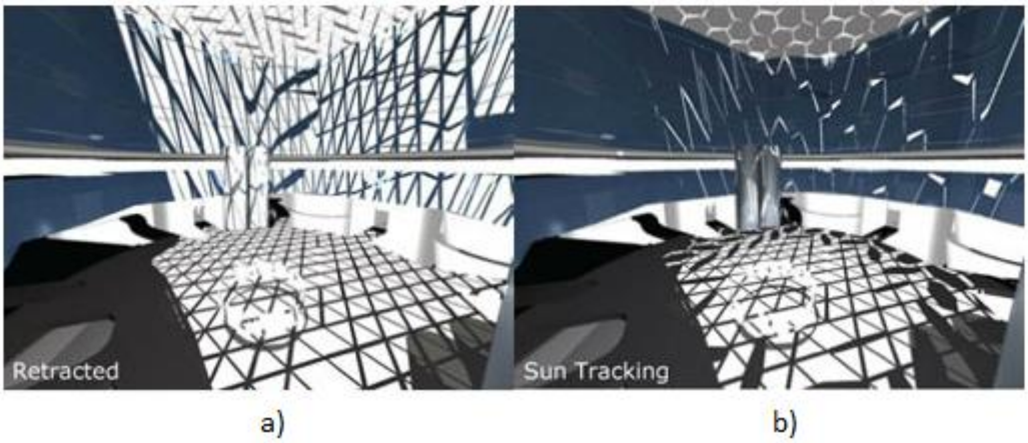


Figure 1-35: Roof position: a) retracted, b) sun tracking (Web A-14)

The Abu Dhabi Investment Council New Headquarters

Name	Al-Bahr Towers
Location	Abu Dhabi, UAE
Architect(s)	Aedas Architects, Abdulmajid Karanouh (Diar Consult)
Engineer(s)	Arup
Construction company	Al-Futtaim Carillion
Year(s) of construction	2009-2012
Building Function	Office building
Awards	CTBUH 'Innovation' award 2012, Tall Building Innovation Award 2012
Façade type	Curtain wall
Presence	South, west and east façade
Function	Thermal (solar control), Optical (daylight control, glare)
Climate zone	Subtropical
Classification	Movement: Mechanic based - Hybrid Control: Central - Reactive/(Direct)

General situation

The architectural firm AEDAS designed in 2008 the concept for the Abu Dhabi Investment Council Towers. The design for the towers was driven by the integration of environment, tradition and technology. The strength of the concept of AEDAS is the combination of inspiration from the past with looking forward into the future. Each tower is basically a curved cylindrical glass tower. The two towers are 150 m tall and the fluid form is inspired on a honeycomb. The building is located in a desert on the north shore of the island. The weather in the United Arab Emirates is characterised by intense heat and glare, requiring an innovative solution to create a comfortable indoor environment.

Adaptive system

The automated shading system is a curtain wall system. The screen of the façade is placed on an independent frame, two meter in front of the exterior of the building by applying the unitised method. Each unit of the screen exists of six triangular frames. The frames unfold through a centrally positioned actuator and piston. The cladding of the façade is placed on the south, west and east side. The north face of the building is only exposed to direct solar rays for a short time before and after working hours, which makes shading unnecessary. The geometric pattern (a triangular structure) for the design of the façade was based on the Islamic traditional Mashrabiya. The components of the system open and close as a reaction to the movement of the sun during the day and changing incidence angles during the different days of the year. In the night, the pattern is folded, which makes the exterior visible. In the morning, when direct sunlight is present, the pattern closes at the east-side and moves with the sun around the building during the day. The folding system is an example of a movement system that is a 'Hybrid In Plane Translation/Out-of-Plane Rotation System'. The dynamic movement of the panels recalls the opening and closing of flowers.

The façade consists of semi-transparent umbrella-like PTFE (polytetrafluoroethylene, a teflon-coated woven fiberglass membrane) panels, which form the movable components that react to the position of the sun by stretching. These panels are extremely durable and weather resistant. The fluid aerodynamic geometry of the panels helps to withstand the wind pressures effectively. In addition, the colour of the panels fits perfectly with the colour of the surrounding sand of the desert. The panels allow the sunlight to enter but block on the same time the strongest rays. This in order to prevent heat and glare gain in the building.

The frame for the cladding is made out of steel. Each tower comprises 1000 individual shading devices that are controlled by the 'Building Management System'. The actuation of the panels, based on parametric and algorithmic modelling, is done by control software in this management system. The mechanism of a unit is driven by an electric screw-jack actuator that is positioned centrally and uses a low amount of energy. The linear actuator responses to a pre-programmed calculated sequence which results in the opening and closing of the panel one time each day. In addition, the façade system includes some sensors which react to overcast conditions and high winds. These sensors will open the units in dangerous situations and provide live feedback to light, wind and rain. The Building Management System allows also manual intervention in emergency cases or for maintenance.

Building physics and energy

The system results in a huge increase of the use of alternative energy. It improves the comfort and light in the spaces. It reduces the entering of solar radiation in the building by 50%, which lowers the need for cooling. On the same time, the need for artificial lighting is reduced. The folding principle reduces solar glare combined with a better visibility by avoiding the distortion by internal blinds or the use of dark tinted glass. In addition, the towers are very high. This makes it possible to introduce a dynamic façade over a large area, which is more cost efficient. Moreover, the shading makes it possible to select more selective glass finishing for the façade that is behind the screen. More naturally tinted glass can reduce the need for artificial light by providing better views and less glare.

For the design, an integrated building model was used to view the project at any given time. This model creates the opportunity to facilitate performance optimisation. Moreover, it ensures proper coordination of the building elements. In addition, the overall form of the towers was optimised to complement the shading system as well. The towers are based on a circular plan, that becomes narrower at the base and the top and broader around the intermediate floors.

References:

(Premier, 2015)

(Karanouh & Kerber, 2015)

(Web A-23; Web A-24; Web A-25)

Figure 1-36: Abu Dhabi investment council (Web A-24)

a) b) c)

Figure 1-37: Unit in: a) closed position, b) opening position, c) opened position (Web A-23)

a) b)

Figure 1-38: Shading system Investment council Abu Dhabi (Karanouh & Kerber, 2015)

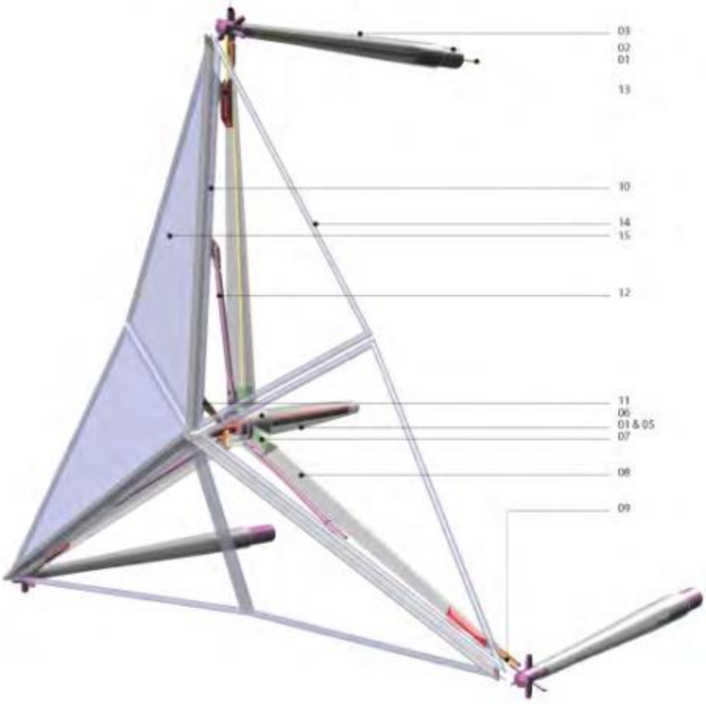


Figure 1-39: Construct detail (leaflet CTBUH Innovation Award, 2012)

Figure 1-40: Inside view of the curtain wall system (Karanouh & Kerber, 2015)

West 18th Street

Name	West 18th street
Location	Chelsea, New York
Architect(s)	ODA Architects
Year(s) of construction	2006-2012
Building Function	Residential building
Façade type	Curtain wall
Presence	All façades
Function	Optical (daylight control)
Climate zone	Subtropical (Moderate)
Classification	Movement: Mechanic based - Hybrid (folding)
	Control: Local - Reactive

General situation

To design the residential building in Chelsea, it was necessary to take a lot of restrictions into consideration. Regulations of the city asked for a continuous street wall, with a setback requirement at a certain height. Moreover, recesses in the façade were prevented by another building rule of the city. This resulted in the suggestion to use a metal operable screen as adaptive system for the façade.

Adaptive system

The metal operable screen makes it possible to encroach a certain amount of the floor area into the setback line. The gained space is used to create more residential outdoor space. The screen is a three dimensional structure that allows the occupants to adjust the screen to their individual needs. It forms a protection to the southern light. In contrast, the screen can be removed to allow daylight to enter.

Building physics and energy

The operable metal screen allows the user to control the entering of daylight in the building. In that way not only the use of natural light but also the interior heat can be controlled.

References:

(Web A-26)

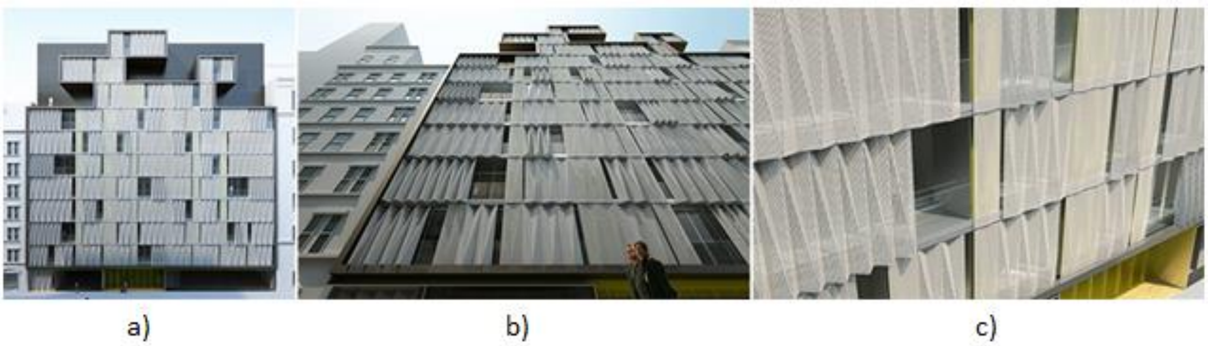


Figure 1-41: Different views (a-c) of the façade of West 18th Street (Web A-26)

CJ Research Centre's Kinetic Folding Façade

Name	CJ Research Centre
Location	Seoul, South Korea
Architect(s)	Yazdani Studio
Engineer(s	Matt Williams
Year(s) of construction	2011-2012
Building Function	Research and Development Centre
Façade type	Curtain wall
Presence	All façades
Function	Thermal (solar control), Optical (glare, daylight)
Climate zone	Subtropical
Classification	Movement: Mechanic based - Hybrid
	Control: Local - Direct

General concept

The CJ Research Centre in Seoul consists of three tear drop shaped towers. The towers have a glass atrium that allows the entering of a lot of solar radiation in the interior environment. The large quantity of glass stimulates the design of an adaptive shade system to make the energy use of the building more efficient.

Adaptive system

The kinetic façade system is made out of accordion folded window shading covers. The moving system exist of the automatically opening and closing of the metal steel strips. The strips are installed on scissor actuators . The opening system is inspired by an umbrella. To allow the bottom and top portions of the foldable system to move independently, two separate linear actuators are used.

Building physics and energy

The responsive façade adapts to changing solar radiation and user input. The system is able to maximise solar control. The façade allows proper natural light levels while reducing overheating and glare on the same time.

References:

(Web A-27; Web A-28)

Figure 1-42: CJ R&D centre (Web A-28)

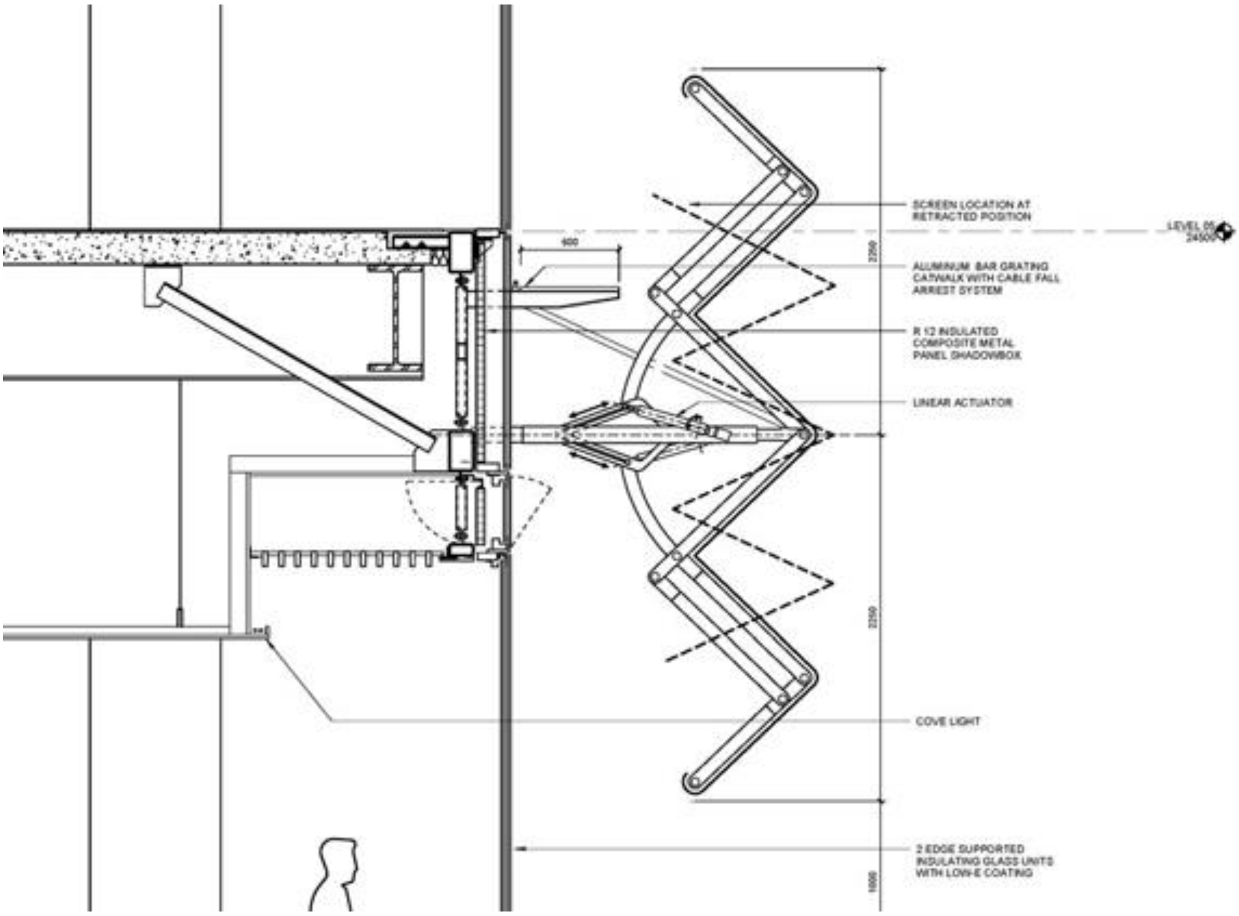


Figure 1-43: Folding system with scissors (Web A-28)

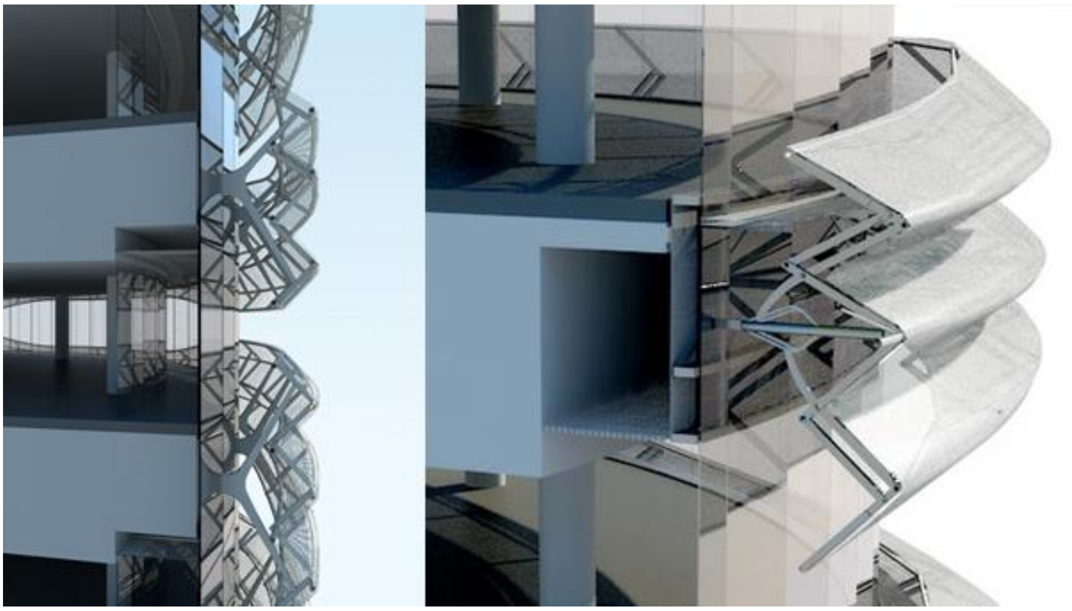


Figure 1-44: Kinetic folding façade (Web A-27)

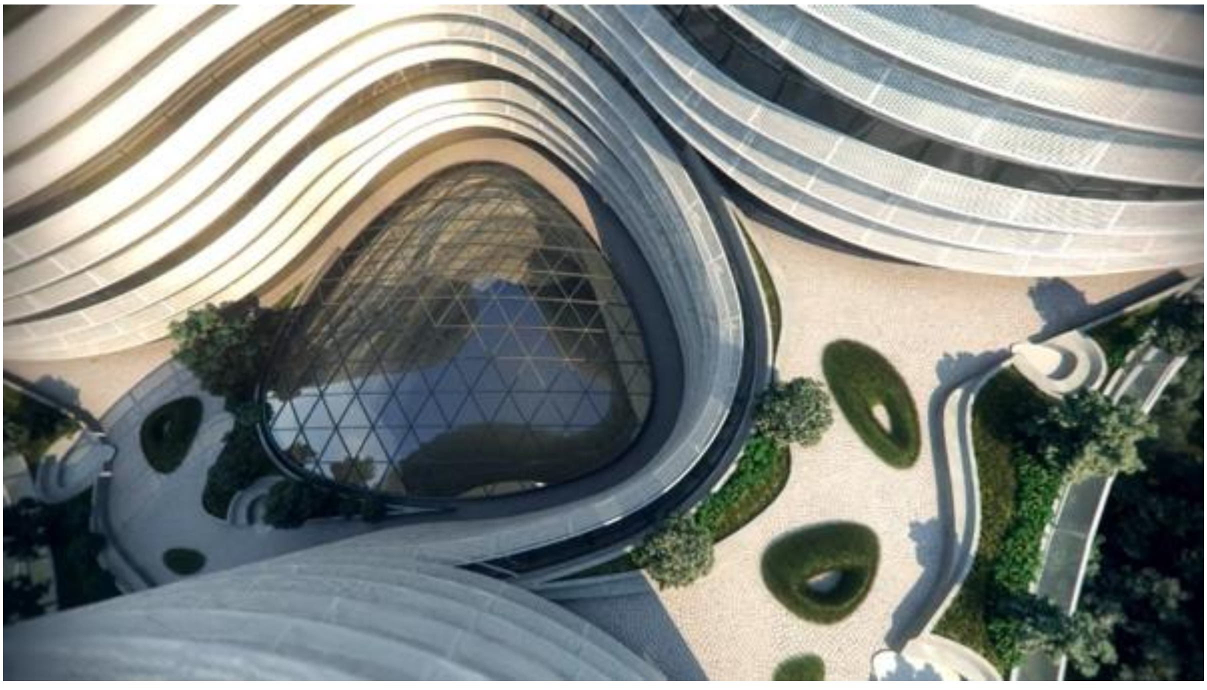


Figure 1-45: Top view of the research centre (Web A-27)

Thematic Pavilion

Name	Thematic Pavilion
Location	Yeosu, South Korea
Architect(s)	SOMA
Engineer(s)	Knippers Helbig Advanced Engineering
Year(s) of construction	2012
Building Function	Multimedia exhibition, space for innovations in research and technology
Award	Open international competition 2009
Façade type	Curtain wall
Function	Thermal (solar control)
Climate zone	Subtropical
Classification	Movement: Material based - External Input (External Force) Control: Central - Direct

General concept

This fish-like pavilion was built for the EXPO 2012 in Yeosu, South Korea along a new promenade in the former industrial harbour basin. The theme of the Expo was 'The Living Ocean and Coast'. The architects of SOMA (from Austria) had the intention to create a landmark that harmonises with its urban and natural context. The shape and design of the building create the experience of an ocean as an endless surface with a certain depth.

Adaptive system

The inspiration for the kinetic façade is based on the application of biological moving mechanisms in architecture (biomimetics). The façade has moveable lamellas that can control the entering of light in the building. The lamellas are individually controlled, and can open and close in succession which allows the creation of wave-like patterns over the length of the building. The lamellas are made out of glass fibre reinforced polymer. The material properties of the lamellas are the basis for the kinetic movement of the lamellas.

Building physics and energy

The façade of the building is foreseen of LEDs at the inner side of the lamellas. When the lamellas are in open position, the LEDs can illuminate the adjacent lamella. The size of the illuminated surface depends on the length of the lamella. The longer lamellas have a wider opening angle which results in a larger illuminated surface. The lamellas allow the control of solar energy. The system makes also use of renewable energy because the power for the operation of the moving lamellas is supplied by solar panels on the roof.

References:

(Velasco et al., 2015)

(Web A-29)

Figure 1-46: The kinetic light façade (Web A-29)

Figure 1-47: Movement of the lamellas (Web A-29)

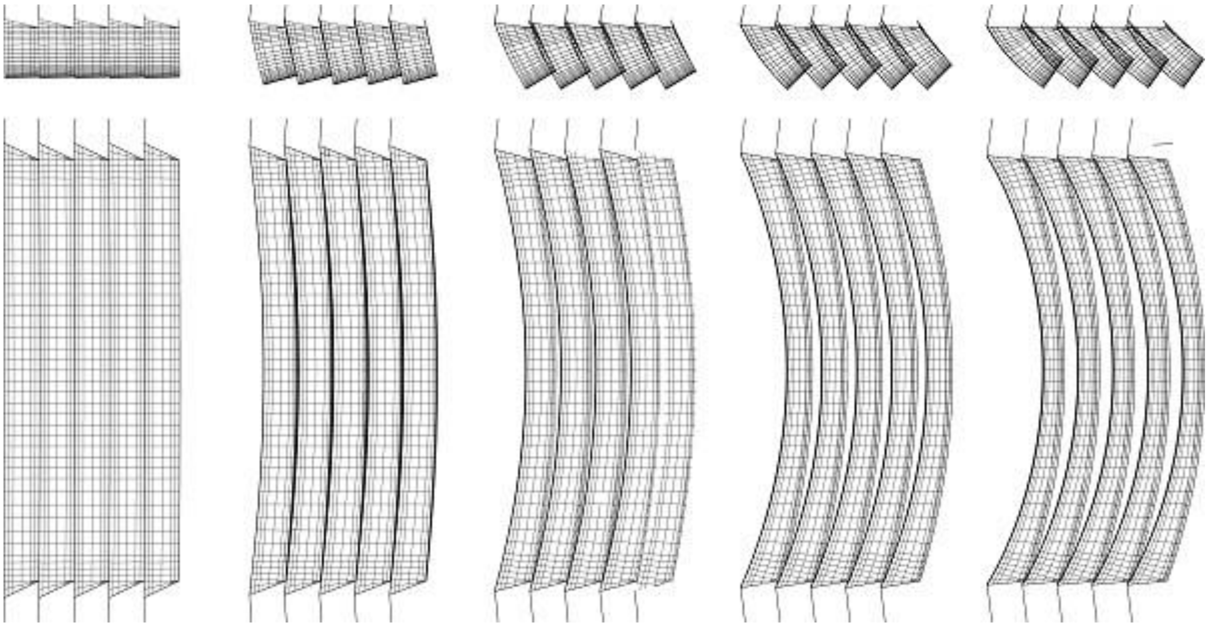


Figure 1-48: Opening of the lamellas (Web A-29)

Figure 1-49: Lamellas in the façade (Web A-29)

Media Headquarters building

Name	Conjoined Media Towers
Location	Doha, Qatar
Architect(s)	REX architects
Year(s) of construction	2013
Building Function	Office, studios and facilities for sister media companies
Awards	AR MIPIM Future Project Awards/Tall Buildings High Commendation 2015, Azure Magazine AZ Awards 2014, People's Choice Award 2014
Façade type	Curtain wall
Presence	West and east façade
Function	Solar control
Climate zone	Subtropical
Classification	Movement: Mechanic based - Hybrid Control: Central - Reactive

General concept

The two towers that form the Media Headquarters building were designed by REX for the two sister Middle Eastern Media Companies. The company wanted the headquarter to be in perfect relation with the traditional Arab iconography. REX designed ultra-thin, stone-clad towers combined with an array of retractable sunshades with a shape inspired by the Mashrabiya pattern. The towers form long, slender buildings with offices and other facilities for the two sister companies.

Adaptive system

The blossoming shading of the tower is created by deploying sunshades with a diameter of about 15 meter. The deploying of the sun shadings is executed from the cavities between the floors. The deployable umbrellas are retracted when the courtyards of the building are in the shadow and expanded when they are exposed to light. The opening and closing of the system is possible in a few minutes and follows the rotation of the sun. The sunshade elements are able to retract completely in the cavity, making the simple, stone-clad towers visible in an easy way. While the sun tracks across the sky, the entire façade transforms at one side, while it retracts in 60 seconds at the other side. This is done once a day at a specific moment according to the position of the sun.

Building physics and energy

The sunshade systems on the eastern and western façade protect the building from the sun in an efficient way. In the caps of the sunshade umbrellas on the east façades, LEDs are integrated. With this LEDs a light media spectacle can be created at night.

In addition, the sunscreens are effective for the adjoining surroundings. The courtyards are exposed if they are in the shadow and covered by the umbrella system when in sunlight.

References:

(Kolarevic & Parlac, 2015)

(Web A-30; Web A-31)

Figure 1-50: Overview of the building site (Web A-30)

Figure 1-51: Umbrella-like shading system (Web A-30)

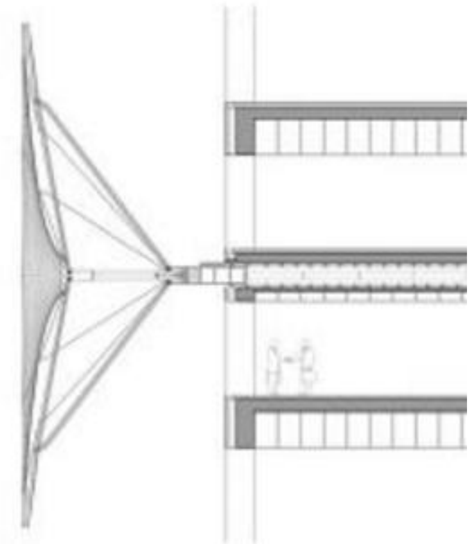


Figure 1-52: Umbrella in opened position (Web A-30)

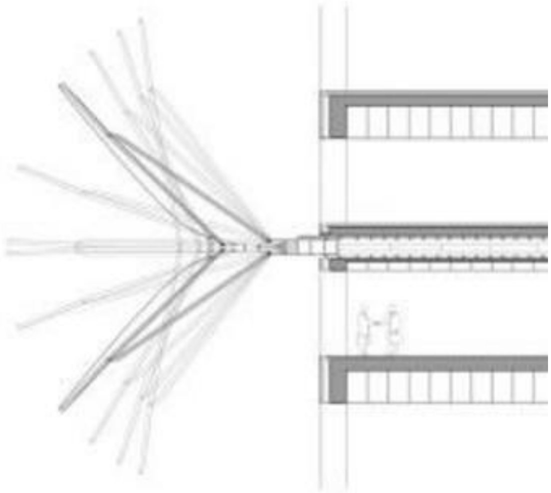


Figure 1-53: Opening of the umbrella (Web A-30)

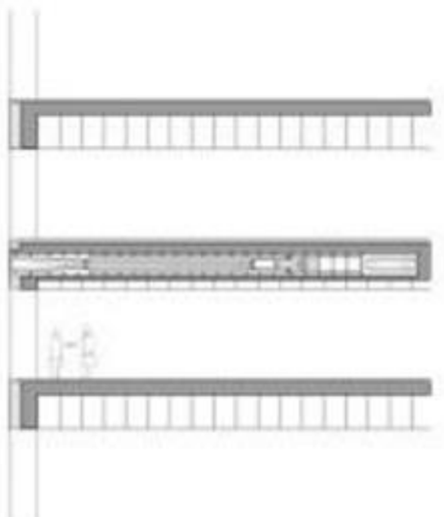


Figure 1-54: Umbrella completely retracted in the cavity (Web A-30)

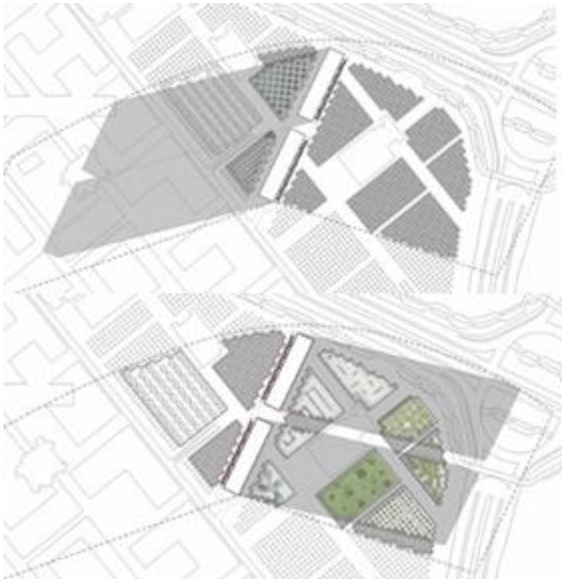


Figure 1-55: Covering of courtyards (Web A-30)

Solarleaf Bioreactor Façade

Name	Solarleaf
Location	Hamburg, Germany
Architect(s)	Splitterwerk Architects
Engineer(s)	SSC Strategic Science Consult GmbH
Year(s) of construction	2013
Construction company	Colt and Arup
Building Function	Experimental design
Awards	Zumtobel Group Award 2014
Façade type	Curtain wall
Presence	South façade
Function	Air flow (CO_2 balance), Thermal, Acoustic performance
Climate zone	Moderate

General concept

The Solarleaf façade uses algal biomass in combination with solar thermal heat to create a dynamic system. The system is a cooperation of the companies Colt and Arup. The algal biomass in the vertical glass louvres is created by conversion of daylight and CO_2 by the water in the louvres that contains nutrients. Furthermore, thermal effects from sun gain result in the heating up of the water inside the louvres. The biomass, which has a high energy content, and heat generation is exchanged and separated in a closed loop system.

Adaptive system

The Solarleaf façade works as a rainscreen system and forms the curtain wall of the building. The elements rotate according to the position of the sun. The photobioreactor, in which water circulates and algae grow, is on both sides foreseen of laminated safety glass. In addition, at the bottom part of the bioreactor, compressed air is introduced at several times. This stimulates the inflow of CO_2 and light by the algae. Moreover, it results in some natural maintenance: the compressed air creates a mixture of water and air that washes the inner surfaces of the panels. The transparency of the façades can be regulated by varying the cell density of the biomass. This density is regulated in a central building management system.

Building physics and energy

The bioreactor system helps to reduce the CO_2 emissions of the building. In addition, it increases the thermal and acoustic performance of the building. The system is an ideal application for high south faced façades. The fact that the system is based on biomass is advantageous over photovoltaic systems. For biomass no expensive storage is needed. Moreover, the efficiency of the solar thermal system is 60-65%, contrarily to the efficiency of photovoltaics, which have an efficiency of 12-20%. The biochemical process, the conversion of light to biomass, is facilitated by microalgae. The microalgae are responsible for the conversion of CO_2 because each single cell in the microalgae is capable of photosynthetics.

References:

(Colt et al., 2013)

a) b)

Figure 1-56: Solarleaf façade: a) front view, b) detail of two panels (Colt et al., 2013)

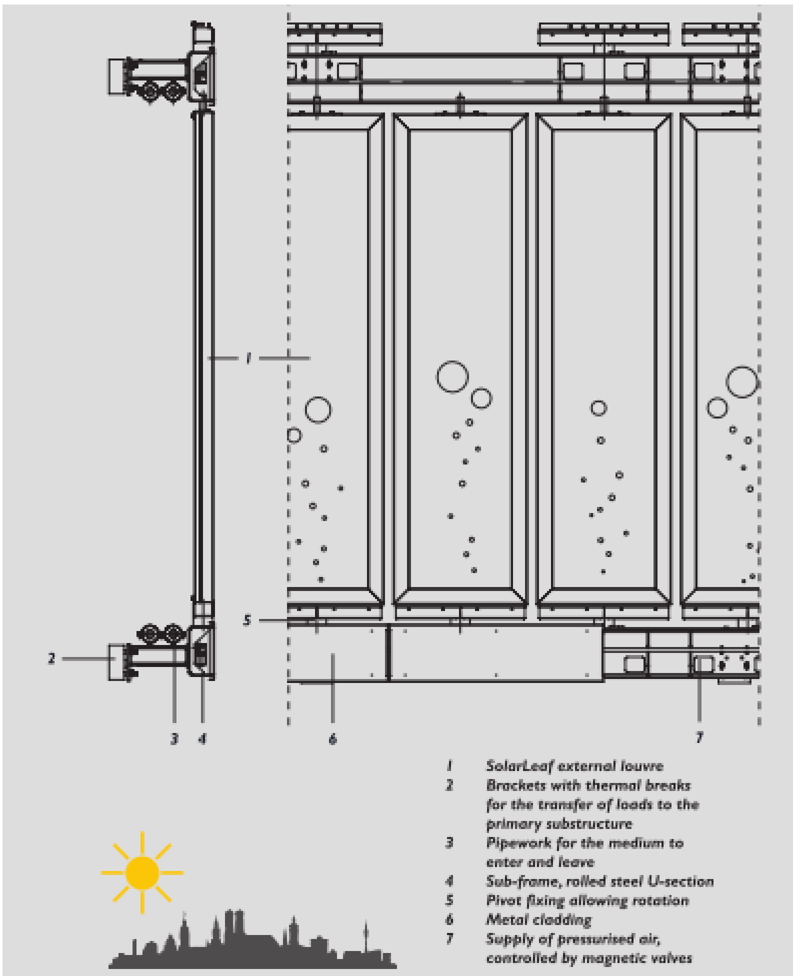


Figure 1-57: Detail of the solarleaf façade (Colt et al., 2013)

2 Prototypes

Adaptive Solar Façade

Name	Adaptive solar façade
Location	Chelsea, New York
Architect(s)	ODA Architects
Façade type	Curtain wall
Function	Thermal (solar control), Optical (daylight control), Electrical (Energy gain)
Classification	Movement: Mechanic based - Rotation (Off plane)
	Control: Central - System-based

General concept

The adaptive solar façade is a kind of dynamic façade based on the use of thin film photovoltaic modules. The dynamic façade makes part of the recent research to explore new methods for the integration of photovoltaic modules in building architecture.

Adaptive system

The photovoltaic modules are combined with the use of soft pneumatic actuators. These actuators can control the solar tracking and the enter of daylight. The modules rotate in response to environmental changes. In addition the occupants can rotate the elements to their personal needs. The control of the rotation is based on sensors, which react to environmental changes and occupant input. The modules are in addition improved by using adaptive algorithms that help the continuous adaptation of the behaviour of the modules.

Building physics and energy

The modules are able to control the visibility and the transparency of the façade. In addition, the system provides shading for the inner spaces and it can generate solar energy. By responding to the desires of the occupants, the system is able to increase the comfort. Moreover, the panels of the façade are lightweight and can be mounted almost everywhere on existing buildings.

References:

(Web A-32)

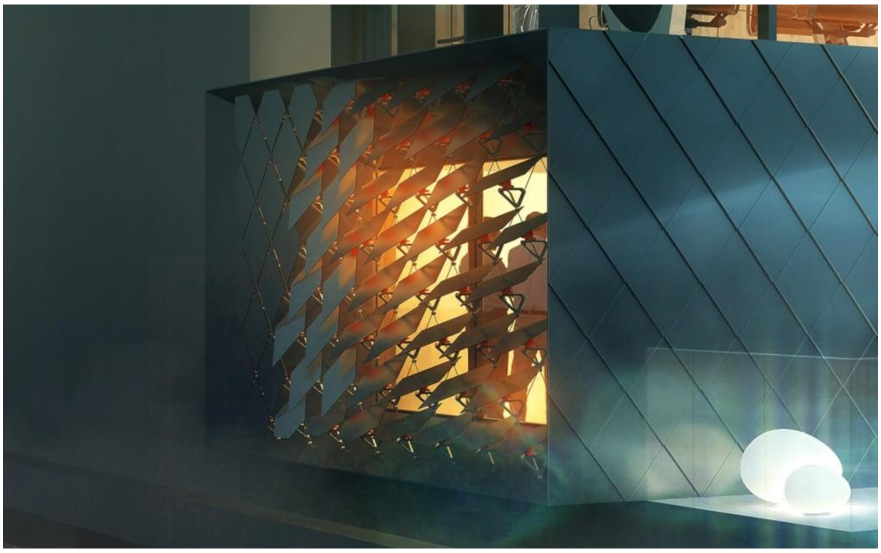


Figure 2-1: Prototype Solar Façade (Web A-32)

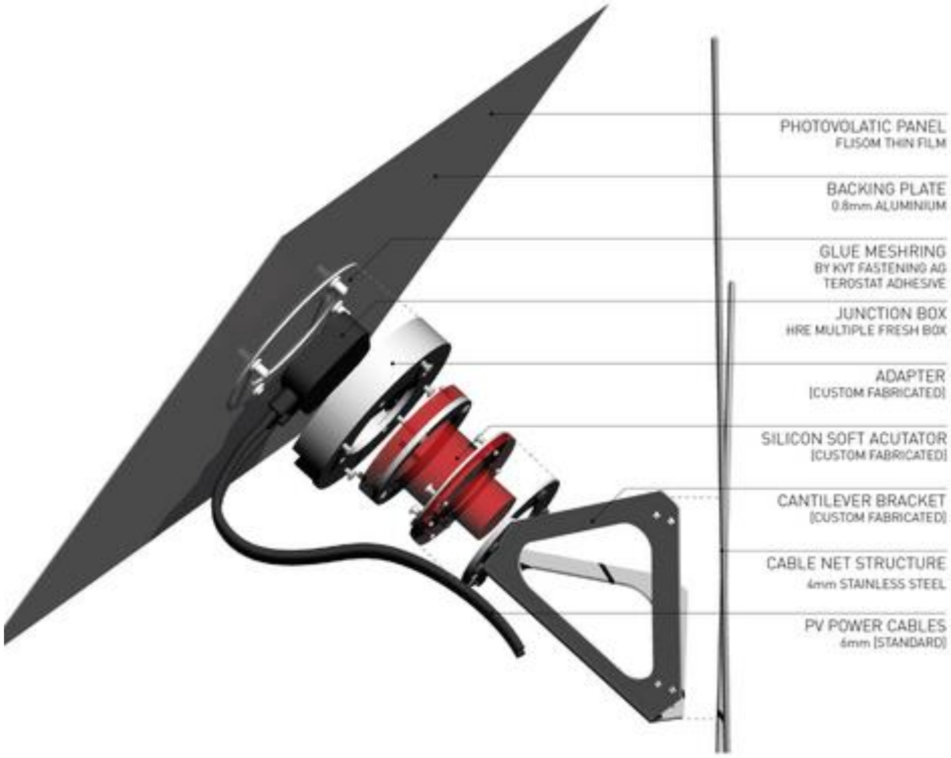


Figure 2-2: Basic module (Web A-32)

Figure 2-3: Prototype (Web A-32)

Kinetower

Name	Kinetower
Location	Damme, Belgium
Architect(s)	Kinetura (Barbara van Biervliet and Xaveer Claerhout)
Façade type	Double-skin
Function	Optical (daylight control), Electrical (regulation of energy)
Classification	Movement: Material based - Self-change
	Control: Local - Direct

General concept

The Belgian design team Kinetura recently created a new kinetic concept for buildings located in a green area on a distance of a city centre. The concept, called 'Kinetower', is made out of huge dynamic elements that are able to transform in a physical way.

Adaptive system

The movement is ensured by the use of flexible, shape memory materials. The flexibility of these materials is combined with motion-based technologies. The used flexible materials need to possess the property to be rigidified but on the same time flexibility is necessary to make it possible for the materials to bend. For the creation of the concept, the 'form follows function' approach was used. In the future, the movement and adaption of the panels should be further optimised to the specific application. Also the speed can be adapted according to more specific requirements.

Building physics and energy

When the Kinetower concept is used in the design of a high-rise building/tower, optimal use of daylight can be obtained and the possibility to capture or re-use energy. The Kinetower has a great illuminating power. This explains the fact that the Kinetower is sometimes called an energy-regulator. The regulation of the façade is based on the reaction to changes in the weather conditions and also changing needs of the users.

References:

(Premier, 2015)

(Web A-33)

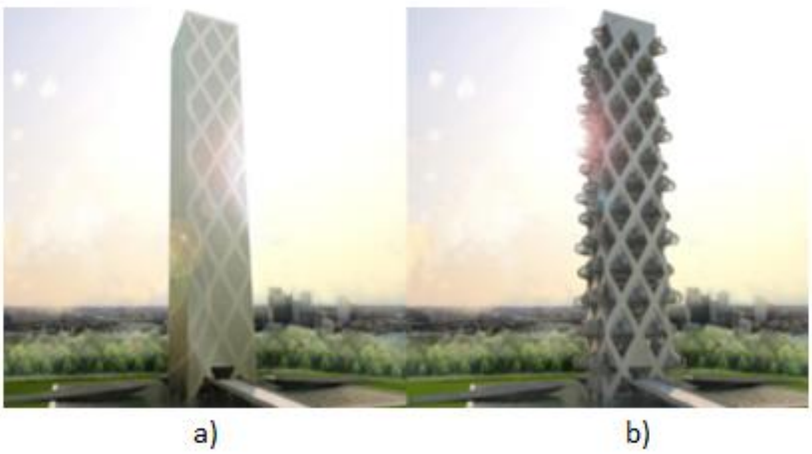


Figure 2-4: Kinetower: a) closed position, b) opened position (Premier, 2015)

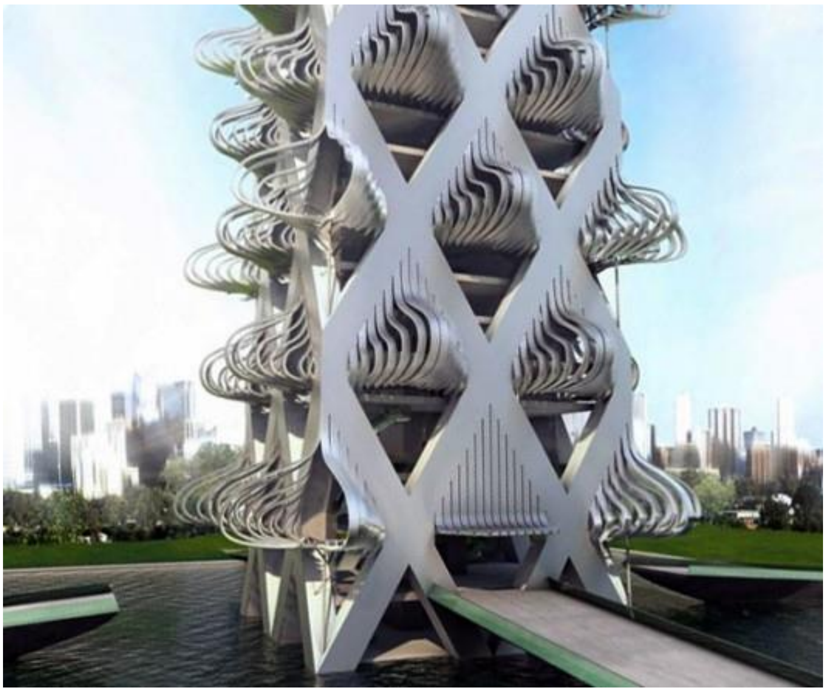


Figure 2-5: Close-up of the kinetic façade (Web A-34)

Figure 2-6: Detail of the flexibility of the used materials (Web A-33)

Adaptive Cellular Automata Façade

Name	Adaptive Cellular Automata Façade
Location	London, UK
Architect(s)	Marilena Skavara
Year(s) of construction	2009
Awards	MAPIC EG Retail & Future Project Awards 2013, RIBA International Award 2013
Façade type	Curtain wall
Function	Optical (daylight control)
Classification	Movement: Mechanic based - Rotation (Off plane) Control: Local - Direct

Adaptive system

This concept is an example of an 'Off Plane Rotating System'. The movement principle has one degree of freedom. The control of the system makes use of Cellular Automata, Genetic Algorithms and Artificial Neural Networks. It responds to different positions of the sun during the year. By generating cellular automated patterns, different shadow areas are provided during the year. However, the patterns need specific starts. The data is constantly updated by the use of GPS systems. Next to GPS systems, sensors are used as well to measure the light in the space. The system is adjusted according to shifts in the used patterns of cellular automata. A disadvantage of the concept is that is does not take the annoying reflections during the change of the geometry of the system into account.

Building physics and energy

By responding to the available light in the environment, different shadow areas are obtained. The kinetic system results in optimal light intensity in the internal space.

References:

(Velasco et al., 2015)

Figure 2-7: Cellular Automata Façade (Web A-35)

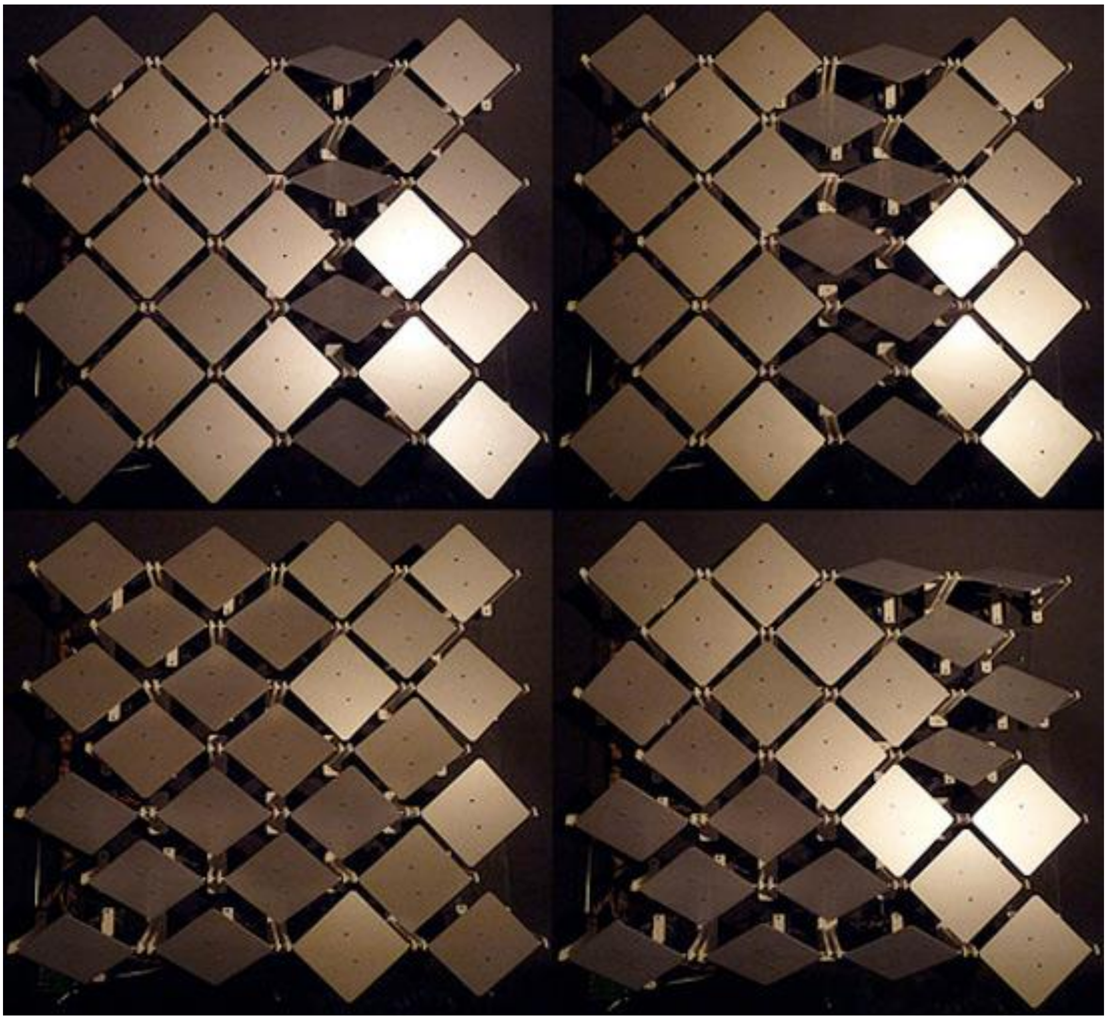


Figure 2-8: Kinetic movement (Web A-35)

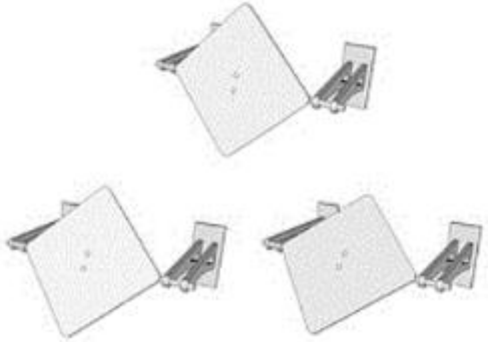


Figure 2-9: Detail of the kinetic unit (Velasco et al., 2015)

HelioTrace Façade System

Name	HelioTrace
Location	New York, USA
Architect(s)	Hoberman Associates (Adaptive Building Initiative), Permasteelisa Group
Engineer(s	Skidmore, Owings and Merril; Matt Williams
Year(s) of construction	2010
Awards	Citation of merit from the 2010 R+D Award
Façade type	Curtain wall
Function	Thermal (solar control)
Classification	Movement: Mechanic based - Translation (In plane) Control: Central - Reactive

General concept

The HelioTrace concept is a responsive kinetic curtain wall system made out of glass. For the façade the patented Strata system from the Adaptive Building Initiative is used. The constructability and performance were worked out by the Permasteelisa Group.

Adaptive system

The kinetic sunscreen consists of opaque panels perpendicular to the facets to project the façade from the mullions. Next to the perpendicular panels, also parallel panels are foreseen to the building's envelope. Instead of opaque glass panels, it is possible to use fritted, coated glass, composites or perforated metal as well. To respond to the solar movement and requirements of the occupants, the system is programmed. The segmented panels advance and retract according to the position of the sun.

Building physics and energy

The HelioTrace Façade system tries to find an innovative solution for minimising energy use and maximising user comfort. Tests on prototypes have shown that the system can reduce the solar gain by 81%.

References:

(Linn, 2014)

(Web A-14)

Figure 2-10: HelioTrace System (Web A-14)

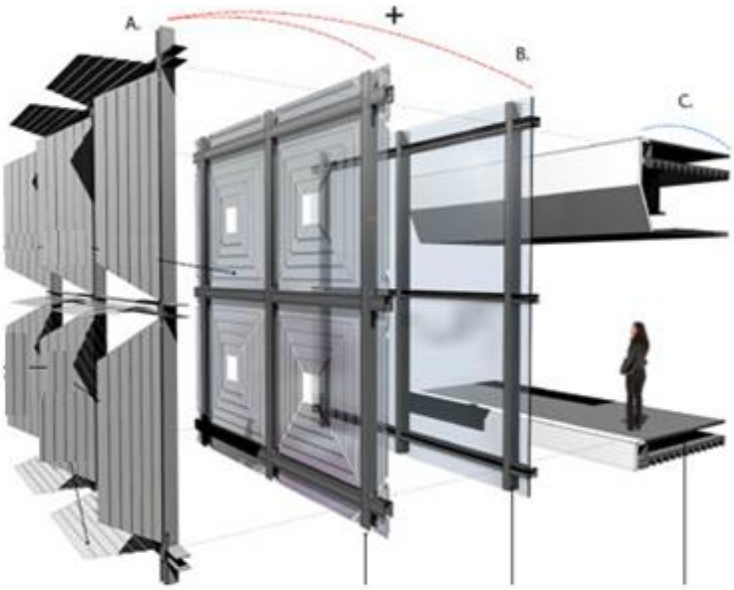


Figure 2-11: Construction parts of the system (Web A-14)

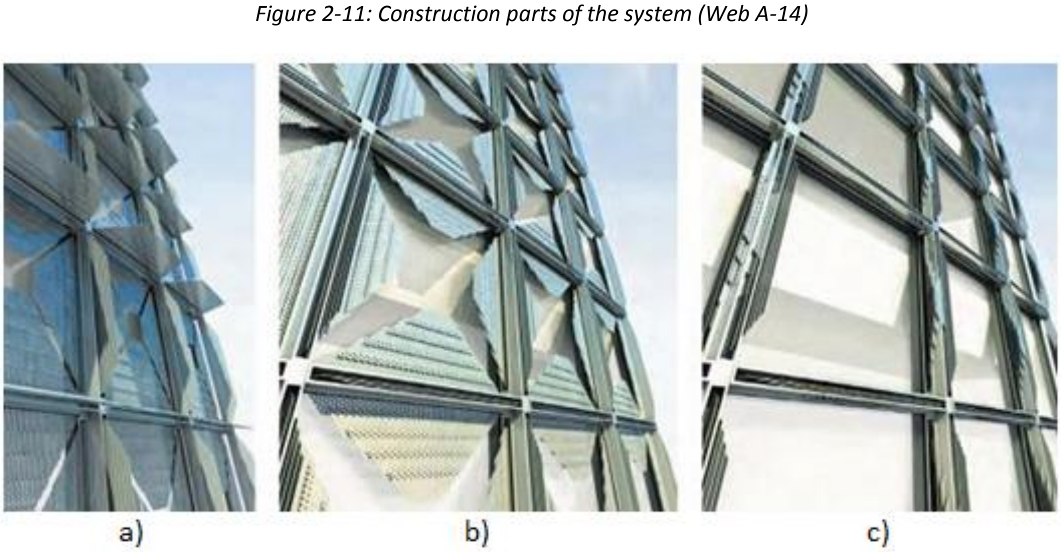


Figure 2-12: HelioTrace: a) perpendicular panels, b) parallel panels, c) retracted panels (Linn, 2014)

Glare Control Blade System

Name	Blade System
Location	Michigan, USA
Architect(s)	Mathew Schwartz, Robin Li, Mojtaba Navva
Year(s) of construction	2011
Building Function	Prototype
Façade type	Curtain wall
Function	Optical (glare control)
Classification	Movement: Mechanic based - Translation (Off plane)
	Control: Central - Direct

Adaptive system

The idea for a blade system to control glare by sunlight was a design proposal from Mathew Schwartz and Robin Li and dates from 2011. It is based on the translational movement of two separated layers. The movement is related to the differential position of the two layers to the direction of solar rays. According to the specific location and orientation of the blade system, the translation is chosen to be horizontal or vertical. The direct control of the system relies on the trajectory of the sun and the orientation of the building. To reduce the amount of actuators, different components can be connected in a mechanical way. This reduces the complexity but lowers the flexibility of the system. The control is done based on a developed algorithm that programmes an automated movement of the system.

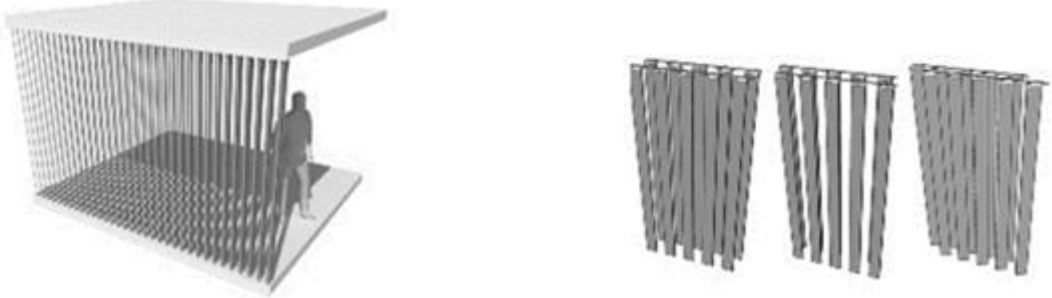
Building physics and energy

This system blocks part of the sun radiation while it allows natural light to enter the building and maintains a comfortable exterior view on the same time. It will reduce the energy consumption (cooling loads in summer and heating requirements in winter) of the building and enhance the interior quality. To further improve the system, photovoltaic cells can be integrated in the opaque and transparent materials that are used as blades.

References:

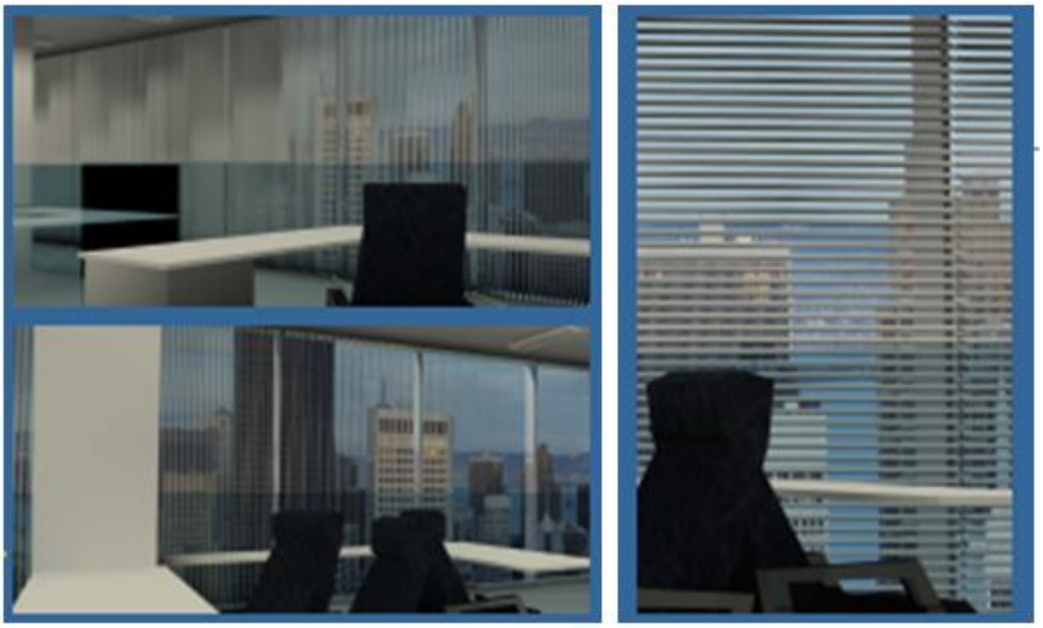
(Li & Schwartz, n.d.)

(Velasco et al., 2015)



a) b)

Figure 2-13: Glare control blade system: a) virtual prototype, b) detail of the opening blades (Velasco et al., 2015)



a) b)

Figure 2-14: Glare blinds: a) vertical, b) horizontal (Li & Schwartz, n.d.)

Bloom Installation

Name	Bloom installation
Location	San Diego, USA
Architect(s)	Doris Sung and Ingalill Wahlroos-Ritter (Woodbury School of Architecture)
Engineer(s)	Matthew Melnyk
Year(s) of construction	2011
Building Function	Installation
Function	Thermal (shading control, sun control)
Classification	Movement: Material based - Self-change (Temperature) Control: Local - Inner

General concept

The Bloom installation is a kind of shiny metal 'flower' with a height of about 6 m. The location of the installation is the Silver Lake Boulevard in San Diego. The skin is made of thousands pieces of laser cut, custom fabricated, metal sheets that make the 'flower' opening and closing according to the heat of the sun. In that way, the installation forms a towering shade structure.

Adaptive system

The bloom concept is a dynamic installation that uses thermal bimetal plates. The bimetal plates exist of two laminated metal panels with a different thermal expansion coefficient. The thermal responsive surface reacts to the change in temperature and direct solar radiation. This means that the system can be classified in the category of structures based on material deformation. The material deformation is caused by temperature changes.

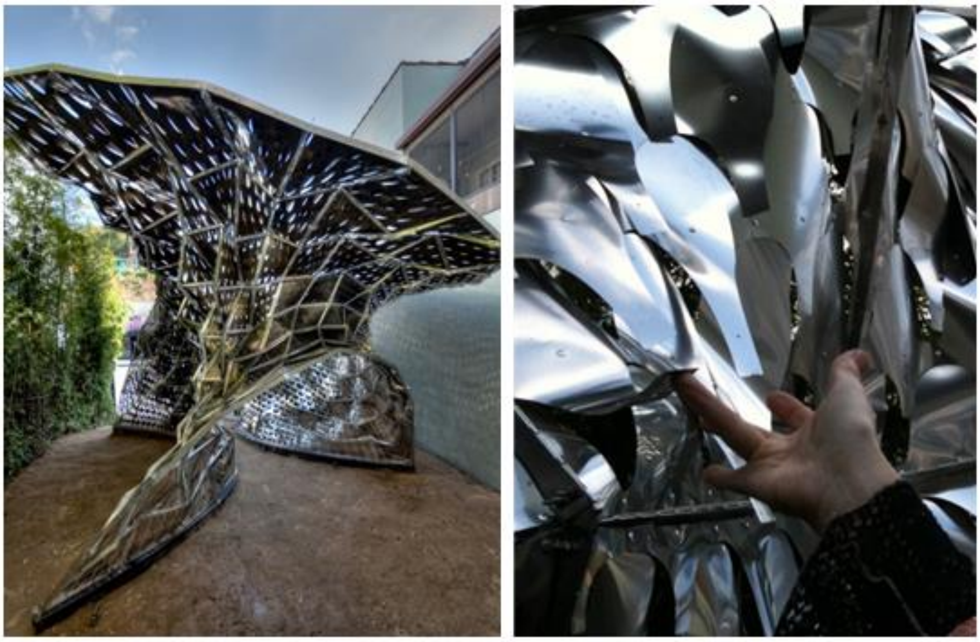
Building physics and energy

The surface of the building is a solid object when the temperature of the metal skin is cool. In contrast, when the metal is heated by the sun, the panels adjust and fan out. This makes an efficient air flow possible and increases the sunshade potential of the system. By using material properties for the kinetic deformation, the need for an external power source or mechanical parts is excluded.

References:

(Velasco et al., 2015)

(Web A-36)



a) b)

Figure 2-15: Bloom installation: a) global view, b) detail (Web A-36)

Figure 2-16: Material based deformation (Web A-30)

Figure 2-17: Visual effect from inside (Web A-37)

ShapeShift

Name	ShapeShift
Location	Starkart, Zürich
Architect(s)	Manuel Kretzer
Designer(s)	Dino Rossi and Sofia Georgakopoulou
Year(s) of construction	2011
Function	Air flow, Optical (lighting/shading system)
Classification	Movement: Material based - External Input (Electricity)
	Control: Local - Direct

General concept

The responsive concept designed by Manuel Kretzer is a new kind of building skin characterised by an extreme flexibility, thin dimensions and smooth actuation. The skin is supported by a light acrylic frame.

Adaptive system

The kinetic movement of this prototype is based on the use of Electro Active Polymers. These polymers can act as actuators by converting electricity into movement. By applying external power, the kinetic movement of the system starts up and is locally and directly controlled by the polymers. The components of the façade have typical three layers. The middle layer is a prestressed thin acrylic film painted with a conductive powder. This painting is foreseen on both sides and protected with a silicon layer. When electricity is applied, it is transmitted through the conductive coatings, which results in the expanding of the material to a flat shape. When no electricity is present, the double-curved prestressed shape is kept. The system is based on the application of voltage between two electrodes. By the attraction of opposing charges, the film is squeezed in the thickness direction. Contrarily, when equal charges are present, a linear expansion of the film is created, which makes the film thinner with an increased surface area.

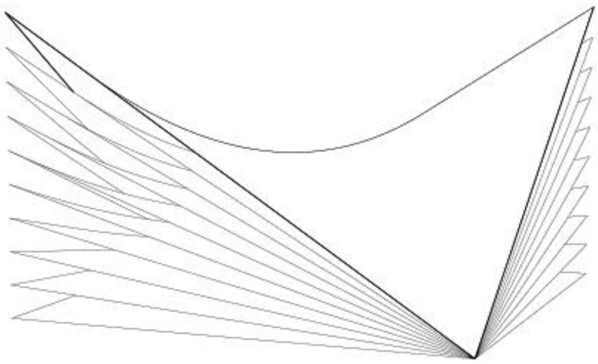
Building physics and energy

For the movement, energy is required, which is a drawback of the system. In addition the configuration is very unstable and fragile. However, the system does not need mechanical actuators. The concept results in a responsive façade that can control the air and lighting in the room. In addition, the façade is aesthetically pleasing. The system allows the reaction to responsive environments and human input by computer technology.

References:

(Velasco et al., 2015)

(Web A-38)



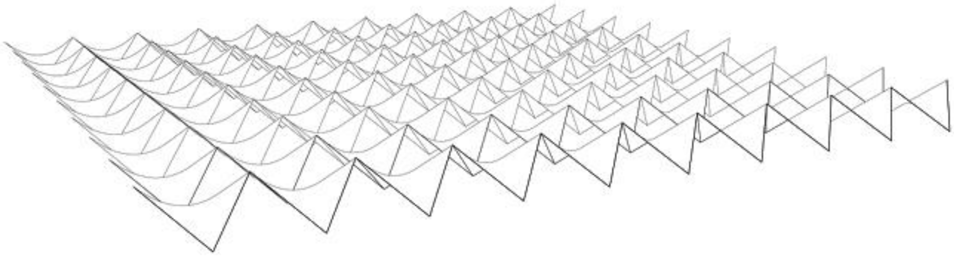


Figure 2-18: Principle of the Electro Active Polymers (Web A-38)

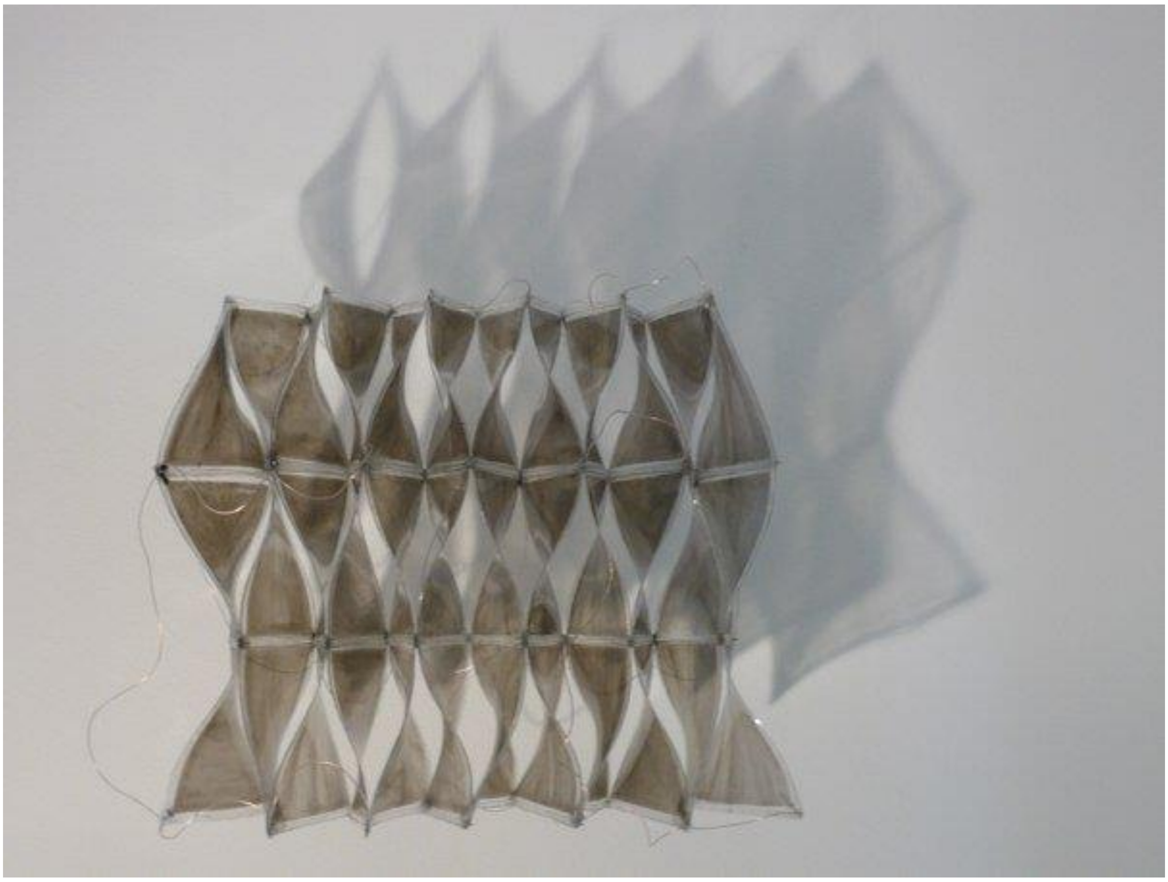


Figure 2-19: Prototype of the ShapeShift (Web A-38)

Pavilion

Name	HygroSkin-Meteorosensitive Pavilion
Location	Orleans, France
Architect(s)	Achim Menges, Oliver David Krieg, Steffen Reichert
Year(s) of construction	2011-2013
Building Function	Pavilion
Function	Optical (daylight control (illuminance))
Classification	Movement: Material based - Self-change (Humidity)
	Control: Local - Inner

General concept

Architect Achim Menges designed in cooperation with Oliver David Krieg and Steffen Reichert a pavilion in Orleans made of a thin plywood sheets skin. The skin can interact with the surrounding climate and is regulated by the moisture content.

Adaptive system

The concept for the adaptive behaviour of the pavilion is based on the responsive capacity of the used material. Wood is instable in relation to the moisture content. It possesses a hygroscopic quality which makes it able to take moisture from the atmosphere when the surface is dry and in contrast to yield moisture to the atmosphere in the wet case. This results in a sensitive skin that can open and close in response to humidity changes to keep the moisture content in equilibrium with the relative humidity of the environment. The movement of the skin is very simple and in constant interaction with the environment. In addition, the system provides constant feedback. The fact that the movement is based on material deformation, makes external energy unnecessary.

Building physics and energy

The humidity responsive apertures in the components can react to changes in humidity in the range from 30 to 90%. This is the humidity range from bright sunny to rainy weather conditions in moderate climates. By adapting to the existing humidity, the degree of openness and porosity of the pavilion is changed and as a consequence a different light transmission and visual permeability is obtained.

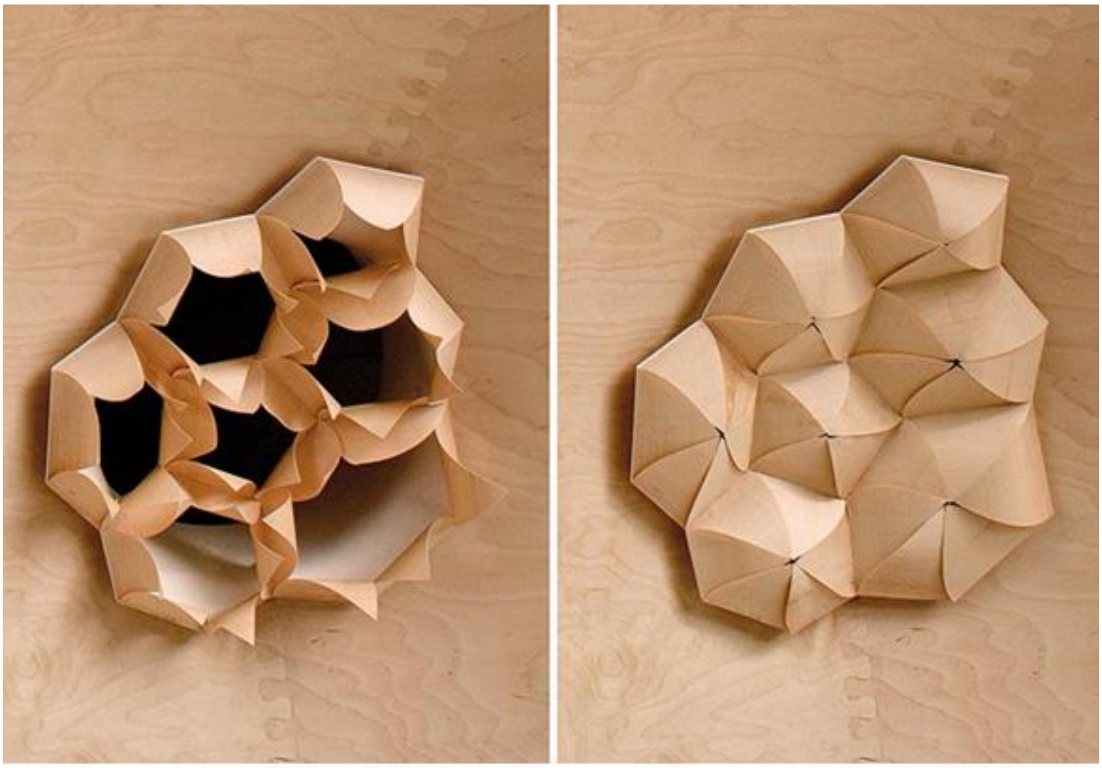
References:

(Velasco et al., 2015)
(Web A-38)

Figure 2-20: Pavilion in FRAC centre, Orleans (Web A-38)

a) b)

Figure 2-21: Daylight regulation: a) global inside view, b) detail inside view (Web A-38)



a) b)

Figure 2-22: Pavilion: a) open state at low relative humidity, b) closed state at high relative humidity (Web A-38)

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List of Figures

List of Tables