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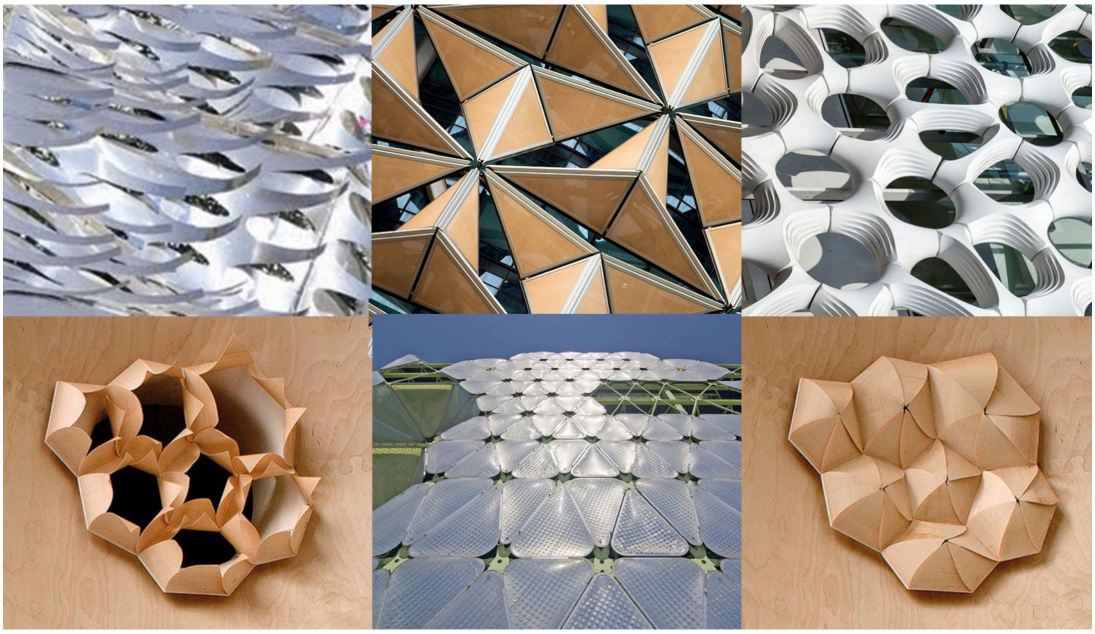

Adaptive building envelopes

Master of Science Thesis in the Master's Programme Architecture and Engineering

HANNA MODIN

Department of Civil and Environmental Engineering
Division of Building Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover:
Collage of examples of adaptive envelope solutions that are presented in the report

Department of Civil and Environmental Engineering Göteborg, Sweden 2014

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ABSTRACT

Striving for a more sustainable society improving the performance and reducing the energy consumption of buildings are important steps. Historically, buildings where designed based on the pre-conditions given by the surrounding environment and together with the available natural resources, creating comfortable spaces in relation to the climate. A long with technical development buildings have advanced into being less specified for a specific site and more and more dependent on technical systems to maintain interior comfort. In this thesis adaptive envelopes are studied, how they work, which materials that can be used for such systems and how they can improve the performance of the building. Adaptive envelopes, which can be divided into macro, micro or combined systems, intend to improve the comfort and energy performance of a building through using the energy available in the surrounding as a trigger for a change or alteration in the envelope configuration to work more efficiently under those specific circumstances. This can be done through an energy input that is controlled by a changed precondition and alters a mechanically controlled system or by the means of smart materials that react to changes depending on the material properties. Smart material systems are reliable and robust in the sense that they always react the same way and that they require less parts. But the mechanical systems have the advantage of being possible to control and to over-rule based on the desire of the occupants.

Results from the literature study shows that there are possibilities of reducing energy use through implementation of adaptive envelope solutions but that it still need to be further developed in order to be easily adopted to regular buildings. But as simulation tools are becoming better and better and more available adaptive envelopes is a viable solution for maintaining interior comfort without consuming large amounts of energy.

Key words: Adaptive envelopes, adaptive architecture, smart materials

Adaptiva klimatskal

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SAMMANFATTNING

I strävan mot ett mer hållbart samhälle så och minska energiförbrukningen i byggnader är ett stort steg. Historiskt sett så utformades byggnader utifrån de förutsättningar som gas av det omgivande klimatet tillsammans med de tillgängliga naturresurserna, för att skapa bekväma rum i samklang med klimatet. Men i takt med att den teknisk utveckling för byggnaders tekniska system har avancerat har byggnaderna i sig blivit mindre och mindre beroende av klimatet på deras specifika plats utan istället mer beroende av de tekniska systemen för att uppehålla en önskad innekomfort. I detta examensarbete studeras adaptiva klimatskal, hur de fungerar, vilka material som kan användas för sådana system och hur de kan bidra till byggnaden klimatsystem. Adaptiva klimatskal, som kan delas in i makro, mikro eller kombinerade system, har för avsikt att förbättra komforten och energiprestanda för en byggnad genom att använda den energi som finns i omgivningen som en utlösande faktor för en förändring klimatskalets så att det får egenskaper som är mer effektiva under dessa särskilda omständigheter. Detta kan göras genom en energitillförsel som styrs av en förändrad förutsättning och förändrar ett mekaniskt styrt system eller med hjälp av den smarta material som reagerar på förändringar beroende på materialets egenskaper. Dessa system är tillförlitlig och robusta i den meningen att de alltid reagerar på samma sätt och att de kräver färre delar. Men de mekaniska systemen har fördelen att vara möjligt att styra och reglera utifrån brukarnas önskemål.

Resultat från litteraturstudien visar att det finns möjligheter att minska energianvändningen genom adaptiva klimatskal, men att det behövs fortfarande forskning och utveckling av produkter för att på ett enkelt sätt kunna tillämpa adaptiva klimatskal i vanliga byggnader. Men alltefter som simuleringsverktyg blir allt bättre och mer tillgängliga blir adaptiva klimatskal en hållbar lösning för att upprätthålla god invändig komfort utan att förbruka stora mängder energi.

Nyckelord: Adaptiva klimatskal, adaptiv arkitektur, smarta material

Contents

Preface

In this study different examples of adaptive envelope solutions have been studied through a literature review. The master thesis was carried out from August 2013 to March 2014, at the Department of Civil and Environmental Engineering, Division of Building Technology, Sweden. The project was supervised by Prof. Carl-Eric Hagentoft and PhD student Axel Berge from the Building Physics research team and Maria Nordberg, environmental specialist at White Arkitekter AB.

One part of the project was done as a workshop for master students in the course *Building Design Lab* in collaboration with Axel Berge.

I would like to give a special thanks to Carl-Eric Hagentoft, Axel Berge and Maria Nordberg for supervising this project and for their valuable comments during the work with this thesis. Finally, I like to thank Magnus Persson for allowing us to borrow his students for the workshop and my opponents Staffan Sjöberg and Duncan Watt for valuable discussions throughout the entire process.

Göteborg, August 2014

Hanna Modin

1 Introduction

In order to achieve a more sustainable society the energy demand of buildings need to be reduced. According to the Intergovernmental Panel on Climate Change (IPCC) the energy consumptions in building are larger than the consumption for both the transport and the industrial sector, but they have also pointed it out to be the sector in which the largest energy savings can be done to the lowest cost. Improvements in insulation materials and mechanical system have contributed to increased energy efficiency but there are still opportunities to further enhancements when considering the entire building. The building envelope is one of the building elements where there are room for improvements.

1.1 Background

Our buildings main purpose and especially the purpose of the building envelopes are to protect us from the surrounding climate, but they also need to be able to provide good comfort. Throughout history this has been done with passive solutions such as solar insolation, thermal mass, shading and natural ventilation, thus the building itself was designed to deal with the fickle weather conditions. The building envelope did not only shelter but was also an active component in the system of the building.

The building envelope can be defined as an environmental filter. Elaborating that definition the envelope can be seen as a skin around the framed structure of the building manipulating the influence of the outdoor on the indoor environment, but that not necessarily is a part of the load-bearing structure itself. (Glass, 2002) It has several different functions to fulfil; it is not only a separating barrier between interior and exterior but also provides protection from cold, heat, light, It also plays a critical role in solar gain management, thermal load control, air infiltration and exfiltration, ventilation moisture management, noise control, air quality management and design.

A building envelope has according to Hutcheon (1963) eleven different functional requirements,

- Control:
  - Heat flow
  - Airflow
  - Water vapour flow
  - Rain penetration
  - Light, solar and other radiation
  - Noise
  - Fire
- Provide strength and rigidity
- Be durable
- Be aesthetically pleasing
- Be economical

This list of aspects of the building envelope is widely used and accepted but that does not make it simple to design. All of the aspects need to be considered and they are often affecting one another in both symbiotic and conflicting ways. Therefore the designer needs to trade of each category in order to reach the overall optimal result.

The development in building technology and building performance have led to a building envelope that designed so that the buildings are dependent on additional systems during large parts of the year. Because if left in a free running state it will lead to uncomfortable or even inhabitable circumstances. Enforcing the use of energy intensive HVAC and lighting systems to mitigate the unwanted conditions, which transform the indoor space in to a ‘manufactured’ rather than a 'mediated' environment (Addington & Schodek, 2005). Nowadays the comfort is maintained mainly by the use mechanical heat, ventilation and air conditioning systems that require not only energy input but requires advanced control systems in order to follow the changing conditions, while the envelope is left static acting mostly as a thermal and wind barrier. Conventional buildings have fixed thermophysical and optical properties thus the envelope cannot change along with the changes in weather, leaving an actual optimal performance only a few times a year. (Brand, 1994) As the buildings are constantly subjected to cyclic changes, day and night and seasonal changes in the external climate; different activities affect the internal climate, it only seems logic that the building envelopes should be used as a filter and use these change to benefit both the energy usage and the comfort.

All materials change with changing temperature and moisture content, some more and some less, the envelopes themselves can respond to the environment that they are in, reducing the need for additional control systems as the materials themself adapt to the present conditions.

Looking into the possibilities of adaptive materials and adaptive building envelopes could be one way to find a solution to problems with over-heating and to cool spaces without increasing the use of energy consuming HVAC systems.

In order to fully understand adaptive building envelopes some introducing sections will first explain some important factors; the historical background, the definition of adaptive envelopes, the climatic loads and the interior comfort.

1.1.1 History of the building envelopes

Historically buildings have not had the same shape and appearance in different places of the world. The function of the building and especially the building envelope to protect the inhabitants from the surrounding environment is the same no matter in which part of the world that you look. But as the climate vary as well as the available materials the solutions were many and place specific. The people built shelters suitable for their own climate and learnt how to use design and materials to improve the performance of the, often, simple shelters. When looking into vernacular architecture, often referred to as architecture without architects i.e. shelters built by the users and inhabitants, one can clearly see these differences. Where there existed large wood resources, like in Sweden, one built wooden buildings (an example can be seen in *Figure 1.1* while in other areas the supply of stone made it obvious to use stone instead. As the natural resources often reflect the climate in the region this also gave another benefit.

Figure 1.1 Traditional building in cold climate with unlimited access to timber

The wooden houses here in the northern parts of Europe are fast to heat and while the stone buildings in southern Europe instead remained cold during warm summer days, which was desired. Tent like structures with animal skins as protective layer were also common especially in cultures that move around a lot like the Sami people in northern parts of the Nordic countries, and Bedouins in the African deserts as seen in *Figure 1.2*.

Figure 1.2 Traditional Bedouin settlement in desert (Etan J. Tal)

You can find large amounts of old traditional buildings around that have very elaborated features, for example heat storage, shading and ventilation. One can say that there was knowledge about the surrounding climate that always influenced the design of the envelope. Architects used a number of different passive design concepts to achieve a good comfort in the buildings, ranging from surface finishes to light shelves, atriums to natural ventilation via thermal stacks. (Van der Aa, 2011)

The rise of the international style ideal during the 20th century which was made possible through the development of HVAC-systems enabled one united style all over the globe no matter where in the world a building was situated the building could follow the same aesthetics; a skyscraper in New York, Singapore or in Beijing could look exactly the same despite the very different climatic conditions. And the problems concerning heating, cooling and air quality where solved by mechanical heat and ventilation systems. This of course gave more people the possibilities to control their comfort, but at the cost of very large energy consumption. The use of HVAC systems not only consumes energy but is also known to create discomfort, like problems with draft and too dry air (de Boer, 2011). As the architectural design no longer is as strongly connected to the climatic nor the environmental factors, the building design became more of designing of a beautiful shape rather than something beneficial for the comfort. It was instead left to the HVAC engineers to solve the comfort problem. (Van der Aa, 2011) But in an endeavour to reduce energy demands looking back at the historic ways of solving protection and comfort through design is good starting point. The overall building design and the design of the building envelope could be more context and climatic specific than it is today, the more a building is adopted to a certain situation and the specific environmental loads that will affect it, the less time the mechanical system need to step in to maintain the comfort. To accomplish this, the designer not only has to understand the climate but how the envelope works as a filter between the exterior and interior conditions.

Trough out history the building envelope usually was a homogenous structure, constructed out of one single material or possibly two that worked together to form a solid, for example straw and clay or bricks and mortar. The properties of the envelopes were static and the entire thickness acted both as thermal insulation as well as structural and load carrying element. During the 1940's one started to add insulation when constructing brick walls in Sweden. (Abel & Elmroth, 2008) This was the start of layered construction of the building envelopes in Sweden. As the load carrying capacity of the buildings was moved from the external walls into the buildings the building envelope now functioned only as a climatic barrier. Development of the constitution of the envelope progressed, and in the 50's and 60's layered building envelopes in which one material fulfilled one specific function. Typical wall stratification can be seen in *Figure 1.3* where the different layers of the wall each fulfil one or possibly two of the functions of the entire envelope.

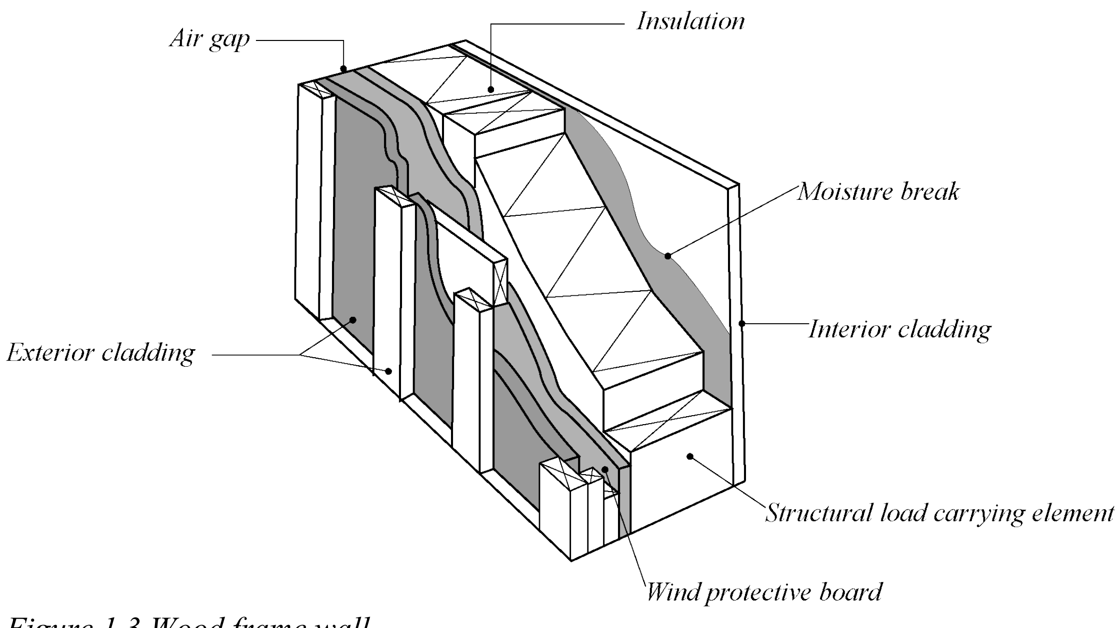


Figure 1.3 Wood frame wall

1.1.2 Adaptive building envelopes

An adaptive building envelope could be explained as an envelope that posses the abilities to change its properties and flexibly control the different parameters of a building envelope. These changes are made to answer to a change in the climatic loads or changed interior climate, in order to improve the interior comfort. The change can be accomplished in several different ways, by moving elements, by introducing air flows or through a chemical change in a material to mention a few. Altering the performance of the envelope depending on the surrounding climate and the desired interior climate is not a new idea. There was an example already in 1916; *'le mur neutralisant'* by Le Corbusier, that will be further explained in section 3.1.1. And later after the energy crisis a suggested wall build up called the '*the polyvalent wall'* by Mike Davies from 1981. The concept of adaptive building envelope also has close relations to the biomimicry, intelligent buildings, smart materials and nanotechnology.

In the literature the term used to describe building envelopes that change due to the surrounding climate and different demands are many, words as adaptive, responsive and intelligent are common but there are also more uncommon ones like polyvalent walls. In the literature one also find several definitions of an adaptive building envelopes, but for this thesis the following have been chosen.

"*A climate adaptive building shell (CABS) has the ability to repeatedly and reversibly change its functions, features or behaviour over time in response to changing performance requirements and variable boundary conditions. By doing this, the building shell effectively seeks to improve overall building performance in terms of primary energy consumption while maintaining acceptable thermal and visual comfort*"

(Loonen, 2010)

One can interpret this ability to change when influenced by a certain stimuli as a built in intelligence. Not the same kind of intelligence as we as humans possess but the envelope on the other hand does not have to perform as we do. This intelligence can take on different shapes and as it is a word often used as a buzzword, what actually is an intelligent envelope can be hard to distinguish. Adaptive properties are one example of an intelligent envelope solution, which through its intelligence is demanded to optimise the envelopes performance as an environmental filter. (Wyckmans, 2005) There are different levels of adaptivity, usually you distinguish between micro and macro responses, i.e. if the change is inside of a material or if it is on a large scale visible for the human eye. But there are also examples that go in between these two, where a micro response is transformed into a macro reaction. Micro responses are depending on the material properties and for that reasons they is harder to control, but as the are part of a larger system that can be solved if the system set up is done correctly. The differences between micro and macro will be further explained later in the thesis.

“ Form follows energy ” is an expression stated by Brian Cody, professor at Graz University of Technology, as a paraphrase to the well-established expression “*Form follows function* “ by Lois Sullivan, after he had been working both with research on energy efficiency in buildings and as an energy consultant for numerous architects in order to design more energy efficient building. He propose to take inspiration from the Asian martial arts and instead of blocking the energy in the attacking force, i.e. completely screen off the exterior environment instead using the energy in the attacking force and converting it into useful energy that can be utilized in order to reach the desired comfort demands. He state the possibilities of both energy production in the envelope but most prominent the envelope as an adaptable filter between internal and external conditions. (Cody, 2012) It sums up the entire idea behind adaptive envelopes, that through the means of design, materials and shape make use of the changes in energy in the surrounding in order to create more sustainable and comfortable interior spaces.

1.1.3 Human comfort

We construct buildings to provide ourselves with a comfortable and healthy environment in which we can dwell, work or relax. With buildings we create an indoor environment that is less severe than the outdoor environment. Buildings keep out precipitation, strong winds and excessive solar radiation and keep a comfortable indoor temperature and provide us with fresh air, they essentially provide for a comfortable space that answers to the occupants’ desires. As we spend more and more of our time inside the demands and standards on the interior comfort have become tougher and tougher. Human comfort is depending of the resulting effect of a number of factors:

- Thermal comfort
- Illumination
- Air quality
- Sound quality
- Sanitation

And can be defined as the absence of long-term extreme values of the different comfort parameters. The perception of comfort is also closely connected to the users possibility to alter and adapt the different aspects of comfort. Thus the overall comfort will be related both to the buildings response to the altering weather conditions, the buildings heating and cooling systems together with the freedom to change and the adaptive behaviour of the user. (Baker & Steemers, 2000)

Thermal comfort

The thermal comfort is depending on the air temperature, the operative temperature that is also dependent on the surface temperatures in the room, the humidity and the movement of the air. The thermal conditions that is perceived or considered comfortable is very individual, what one person might find to be a perfect temperature could be experienced as too cold or too warm for someone else. Obviously there is a difference in desired thermal properties depending on the type of activity that will take place in the space. Therefore a predicted correlation between the perceived thermal comfort and the actual thermal conditions is used. This correlation is based on laboratory studies preformed by prof. Povl Ole Fanger in the 1960s. This relation can be used to predict the number of dissatisfied people; this percentage (PPD, Predicted Percentage Dissatisfied) is the standard index to use when setting demands on thermal comfort. In order to maintain the desired level of thermal comfort no matter the fluctuations in weather outside of the building envelope most buildings rely on heating-, cooling- and ventilation systems demanding energy input is used.

Illumination

Illumination or daylight is crucial to the life within the building. But the strive to accomplish bright interior spaces can lead to problems with the thermal comfort as large glazed areas not only allows daylight but also solar radiation, which can result in problem with over heating. Large glazed areas are also problematic in the sense that they have a much higher U-value compared to a solid wall and therefore the need for heating increases and it can also lead to other comfort problems; draft and cold-draw. As the building envelope is the sole building element that can provide natural light, the design and materiality of it highly influences the comfort level both in terms of lighting and thermal comfort within the building.

1.1.4 Climatic conditions

A part from the comfort demands the surrounding climate and weather have a significant influence on the needed performance of the building envelope. The air temperature outdoors largely affects the thermal loss, as there is a linear relationship between the conduction through the building envelope and the temperature difference between inside and outside air temperature. It also influences the ventilation and infiltration as the changes in air pressure follows the changes in temperature. It is important to distinguish between climate and weather, where climate is the average over a long period of time whereas the weather is the short-term changes, minute-to-minute, day-to-day. The usual opinion of weather is in terms of temperature, humidity, precipitation, brightness, visibility, cloudiness, wind and differences in atmospheric pressure. (*Marshall Shepherd, Shindell, O'Carroll, 2002*) Simply put we can consider climate to be the history of the weather.

A building needs to be designed to cope with the climate that it is situated in i.e. cold, warm, dry or humid, or any combination of them. But it also needs to be designed to withstand the changes in weather in that specific climate. In climates as ours where we have large seasonal changes in weather the differences scenarios that the building is exposed to can vary from extremely cold and dry to warm and humid, but no matter the time of year or weather the building envelope need to ensure a comfortable interior climate. Meeting these changes are much more difficult as the fluctuations in weather is more unpredictable and have a much shorter timescale, but still affects the energy performance. Over the lifetime of a building there could also be changes in climate, generally much warmer, colder or humid weather. As the climatic changes are over fifty or hundreds of years they stand in relation to a normal lifetime of a building thus the climate can be considered more or less constant over the lifetime of the building, thus the extremes and the changes in weather is what have the greatest effect on the interior comfort. The weather is depending on different factors, such as solar radiation, air temperature, the pressure in the atmosphere, the wind, clouds and humidity in different forms to mention some examples. The buildings are exposed to changes in these different factors, with the main impact from changes in air temperature and humidity. Apart from the varying temperatures and the precipitation the wind directions and magnitudes are highly influential to the loads upon the building envelope as it induces pressure differences over it that results in driving forces for both moisture and thermal transport through the envelope.

1.1.4.1 The Swedish climate

The Swedish climate can be characterized as cold with an annual mean temperature below 10 degrees Celsius. It can also be considered as wet as the precipitation exceeds 200 mm in annual mean all over the country (SMHI, 2013), but the amount of varies with the highest amounts reached in the southwestern parts together with the mountain areas in the north. Despite the fact that Sweden have an annual mean temperature below 10° Celsius (SMHI,2013), the climate is classified as *temperate,* only the northernmost parts have a *subarctic climate*. The Gulf Stream largely affects the Swedish climate, leaving it both much warmer and much drier than other areas at similar latitudes. According to the climate definition by Köppen which is commonly used Sweden have three different climates, a part from the Subarctic climate in the north the central part has a humid continental climate while the southernmost parts has an oceanic climate. This also shows in the great temperature differences between the southern and the northern parts, where the southern parts have an annual mean of 8° Celsius while the northern parts only reaches – 3° Celsius (SMHI,2013).

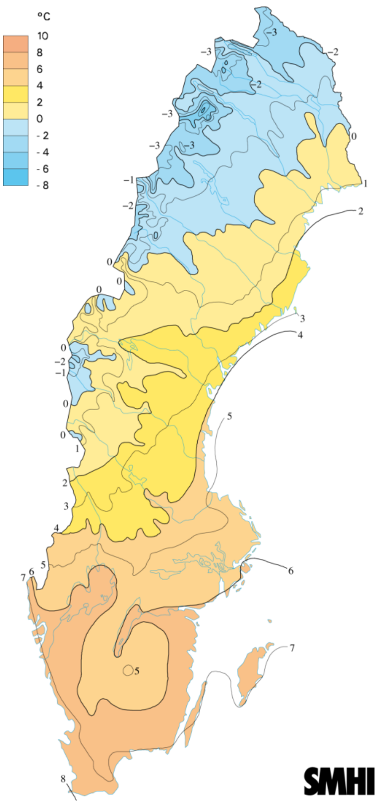


Figure 1.4 Annual mean temperatures 1961-1990, SMHI

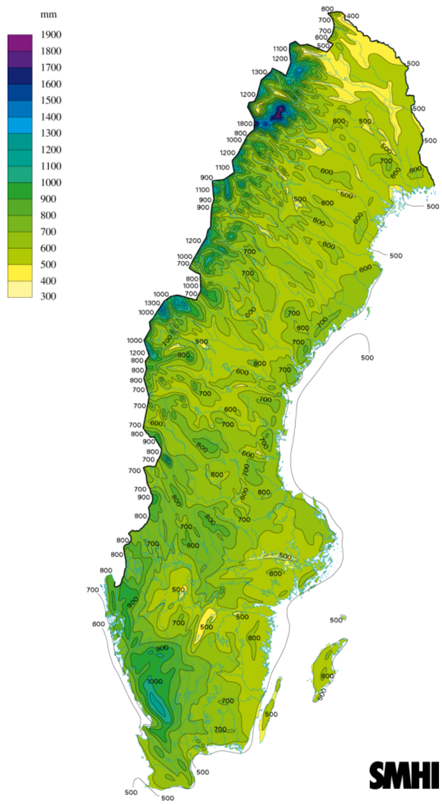


Figure 1.5 Annual mean precipitation 1961-1990, SMHI

Static building envelope can use this mean value in order to function well on a year basis. But an adaptive envelope can instead change depending on the weather, thus the small changes in temperature, wind and humidity, and achieve for that specific time an optimum envelope configuration in terms of insulation capacity, insolation, air tightness and other adaptive properties.

1.1.5 Phenomena

In order to be able to design an adaptive behaviour in for example a wall or a roof of a building one need to be aware of and understand the different phenomena that affects the building element and the materials that it is made out of. This knowledge can then be used to design building elements or entire buildings that respond to the surrounding.

1.1.5.1 Heat transfer

In order to be able to design an envelope that controls the thermal performance it is important to understand how heat is transferred through materials and in and out of a building. The heat flow through the building envelope could be divided into four parts; transmission through the solid part of the structure, ventilation, unintentional air leakages, heat gain from the solar radiation through the windows and the internal heat gains. To control the thermal comfort inside with help from the building envelope all of these factors need to be understood and considered. Simply put different types of heat transfer can be divided into three divers modes; conduction, convection and radiation, as illustrated in Figure 1.6. These three different modes will be further explained in the following section.

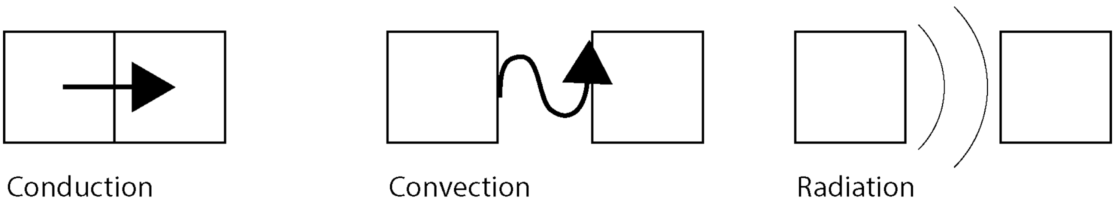


Figure 1.6 Primary modes of heat transfers

The transmission through the solid wall is directly related to the difference between indoors and outdoor temperature that both are dependent on time, thus the magnitude of the transmission also varies with time. The heat gradient over a material gives rise to heat conduction, which is a diffusive behaviour within the material on a microscopic level. The heat gradient can be seen as a change in heat within the particles (molecules and atoms) in the material, some are hotter and some are cooler and the diffusion is a natural transport phenomenon that is driven by a desired to balance the concentration of hot and cool particles in the entire material. This results in a microscopic movement within the material, as the particles collide they transfer kinetic and potential energy to each other, and through this process the heat is spreading in the material, particle to particle. Conduction only occurs in a material or in between two materials in contact with each other. Different material have different ability to transfer heat by means of conduction, the capacity is depending on the phase of the material, the density, type of chemical bond and the temperature. The conductive characteristic of a material is defined as thermal conductivity, λ (W/mK).

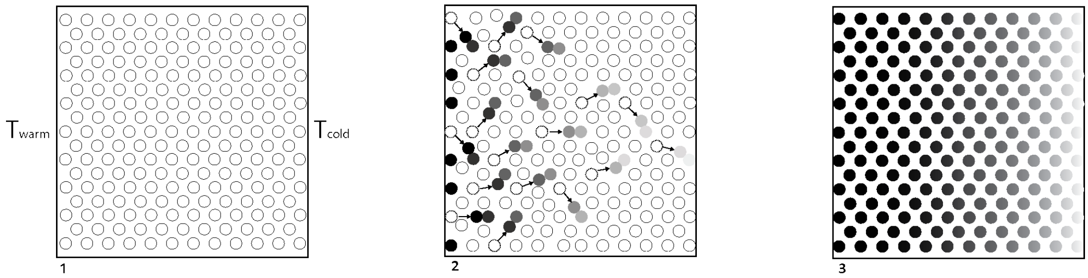


Figure 1.7 Principle of heat conduction

Heat transfer from one place to another by means of macroscopic movement in fluids is called convection. In building applications this fluid is usually air, which carries the heat on a macroscopic level, but the actual heat exchange between the different molecules is just as in the case of conduction a transfer of kinetic energy from one molecule to another (Addington & Schodek, 2005). Two different kind of convection can be distinguished, natural and forced. The differences lie in the underlying trigger to the motion of the air, in natural convection the air movement depends on the density difference between warm and cool air. While the flow in forced convection is assigned to the air by means of fans or the wind. As a consequence of the second law of thermodynamics the direction of heat transfer through convection is from an area with high pressure and high density to an area with lower pressure.

Heat can also be transferred by the means of electromagnetic wave, this kind of thermal transport is known as radiation and requires no medium, neither solid nor fluid in order to work. Radiation occurs between all surfaces with different temperatures, and the cold surfaces will radiate to the warmer. The level of radiation between two surfaces is dependent on the temperature difference, the angle and distance between the surfaces and the emissivity of the different materials. The emissivity is depending on the material properties, the characteristics of the surface and the surface temperature (Addington & Schodek, 2005). This type of heat transfer is dominant in the glazed areas of the building envelope. Otherwise the most prominent heat transfer mode through the building envelope is conduction and thereafter after convection.

1.1.5.2 Moisture transfer

The influence of moisture is also crucial for the building not only as it affects the building materials and causes them decay faster but also since the presence of water with in a material changes the thermal properties, lower insulation capacity but a better ability to store heat (Hagentoft, 2001). In order to design building envelops that cope with moisture we need to be aware of the mechanism behind moisture transfer. Similar to heat moisture can be transferred in different ways, through; diffusion, convection, capillary suction and be forced by a pressure difference or in combinations of the previously mentioned. Diffusion is induced by the desired to even out the differences in vapour concentration over a given layer of stagnant air or a material to reach a steady state.

The diffusive flux at steady-state in stagnant air is denoted g, and is defined as

$$g = -D\frac{dv}{dx} \tag{1.1}$$

Where dv is the change in vapour content in the different surfaces and dx is the distance between the two surfaces. The diffusion inside a material is depending on the material properties and can be said to be slower than that in stagnant air as the material induces a resistance.

The convective movement of moisture is analogue to that of heat, the moisture i.e. the water particles are carried by a flow of a medium; in the case of moisture this medium is air. The air have varying capacity to carry moisture depending on the temperature, simply put warm air can carry more moisture before it is saturated than cold air can. This phenomenon therefore can give rise to a phase change of the water as it is moved from an area with warm to cold air as the humidity will be condensed into water in order for the moisture in the air not to exceed the saturated level for that temperature.

As a small pipe is lowered into water the water level inside the pipe will be higher than the water level outside of it, this phenomenon is called capillary suction and is depending on the attraction between the walls of the pipe and the water molecules and the surface tension of the water. The height of the water level in the pipe is a direct result of need for nature to balance the negative pressure caused by the suction and the gravitational forces. The geometry of the pipe will also have influence on the final height that the water reaches, the smaller the radius of the pipe (r_2 *in* Figure 1.8*)* the higher the water goes (H_2). Moisture in a material is usually transported both by capillary suction as well as diffusion.

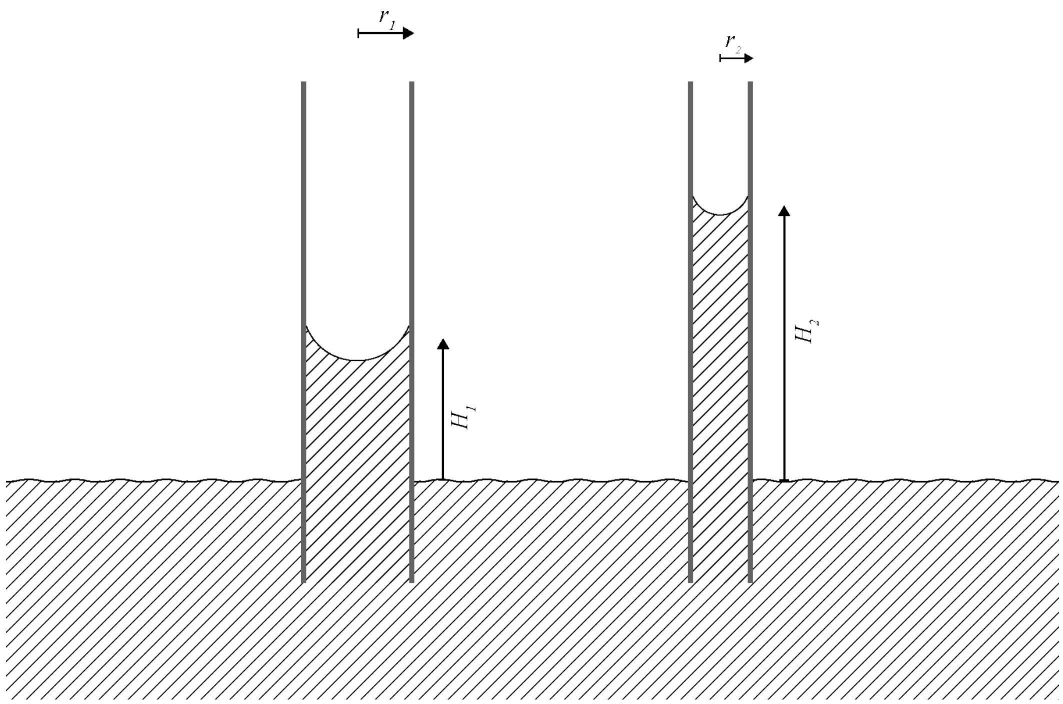


Figure 1.8 Principle of capillary suction

1.1.5.3 Responses in materials

To make use of these phenomena in the building envelopes and to understand the effects it has on a system of materials, response to different phenomena within a material need to be understood.

Thermal responses

Everything is reacting when exposed to different temperatures; the response is depending on the molecule configuration in a material or the connections between different materials in a combined structure. As heat increases in a material the atoms are excited by the heat energy and through the absorption of that energy their movement increase causing the material to expand. The magnitude of this expansion depends on the materials sensitivity to heat, i.e. its volumetric heat capacity. Heat can also trigger chemical reactions within the material transforming into new molecular configuration. This change within the structure of the material alter the properties of the material and can be both permanent or temporary; recovering to the initial state as the temperature returns to the starting point. Materials that permanently change after they are exposed to a temperature above a material specific boundary are usually called thermoset. Thermosetting properties are common among polymers. Heat can also change a materials state from solid to liquid and to gas with increasing temperature and return back again as the temperature decreases again. This process is termed phase change, and during the process energy is absorbed, stored and released. Colour change is another response to temperature this specific response is called thermochromic response. Thermochromic behaviour of a material occurs as the heat energy absorbed by the material induces a chemical reaction or a phase transformation causing it to alter its colour.

Light responses

Light can as well affect material in different ways as it contains large amounts of energy it can just as heat alter the chemical configuration in a material resulting in colour change or as in photovoltaic cells be converted into electric energy. Light can also cause materials to change shape that kind of reaction to light is called photomechanical.

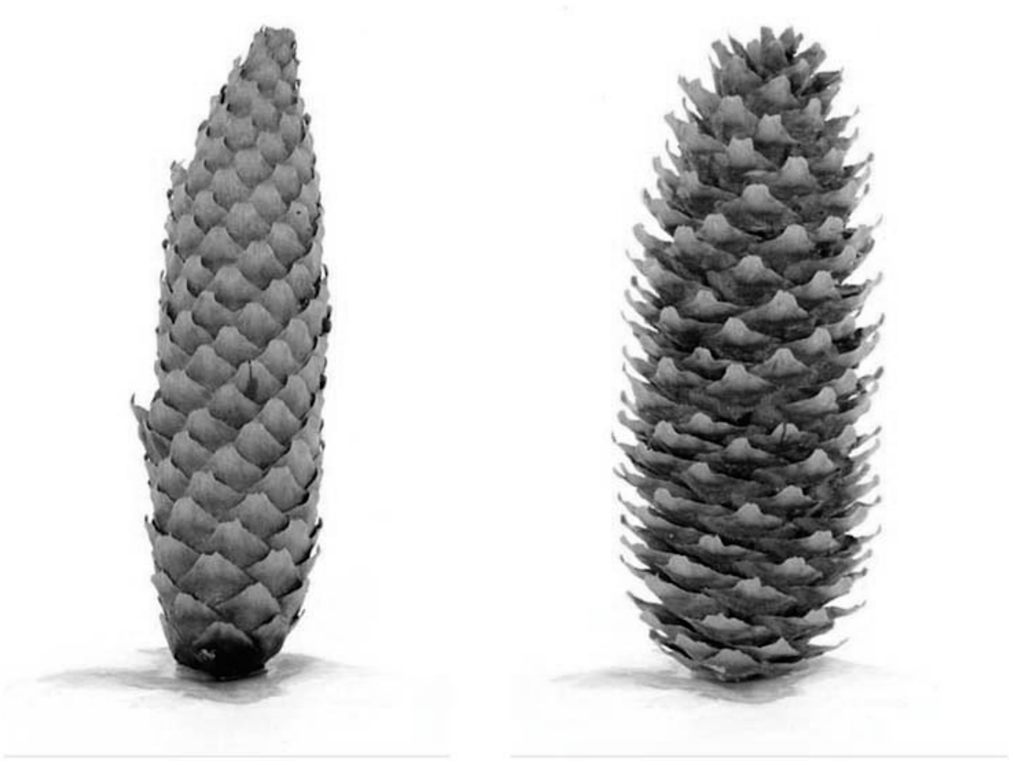


Figure 1.9 *A pinecone's reaction to humidity in the surrounding air (ICD for computational design, Stuttgart)*

Moisture responses

Moisture affects different materials in different ways. Materials based on plants or wood absorb water just as they did when their survival was dependent on the access of water, the presence of water within their cells cause them to swell and to become softer. One example of this are pine cones that after they have fell from a tree still reacts to different moisture contents, as seen in Figure 1.9. Other materials are not affected and altered themselves but can carry humidity within its pores that will change its performance and its properties. Other materials react chemically with water; this change could be both permanent and/or reversible by drying or heating of the material.

1.2 Purpose

The purpose of this master thesis is to find and discuss new; both existing and conceptual ways of designing building envelopes that respond to cyclic changes in the surrounding climate and how the use of such adaptive envelopes can help reduce the energy consumption of the building.

1.3 Limitations

The main scope of this thesis is the control of thermal capacities of the walls but moist as well as daylight will also be considered but to a smaller extent. This thesis will not cover the heat losses caused by eventual thermal bridges in the wall nor will in consider any acoustical advantages or disadvantages of the different concept designs.

1.4 Methodology

This master thesis will be executed mainly as a literature review but knowledge about the field will also be obtained through discussions with professionals and through workshops.

The aim of the literature survey is to study and evaluate existing examples and ideas of adaptive envelopes, gaining an overall understanding of the concept of adaptive building envelopes. And at the same time develop knowledge of the materials commonly used and how they perform. During the first part of this thesis the characteristics of a wall and it requirements when it comes to thermal, moist and daylight demands will be studied and evaluated.

The adaptive envelope design is the part of the thesis that discusses existing examples of adaptive and how one can approach the design problem. This problem will be targeted from two sides. Looking into both existing materials and how they can be incorporated in an adaptive design, as well as considering the problem from the other end; starting with the desired properties and mechanisms, and from that find suitable materials and configurations of materials.

The workshop intends to show how students from both the architecture program and civil engineering program answers to a task to design adaptive solutions.

2 Literature study

The results from the literature study within the context of this thesis will be presented in the following section. The chapter is divided into two distinct parts; adaptive building envelopes in which control system, mechanisms and different adaptive systems and simulation techniques are presented and a second part about materials that exhibits properties that could be used in responsive designs.

By studying research articles, academic thesis and various books along with videos on *YouTube* and *Vimeo*, knowledge about the two areas was acquired. Forums such as YouTube and Vimeo as the visual graphics provided for a good understanding both for microscopic adaptive movements and for large kinetic systems that were hard to grasp only through descriptions in text.

There are several recent papers and article discussing the possibilities of adaptive and/or responsive building envelopes. Research in the US, the Netherlands and Norway has shown promising results. (De Boer, Loonen, Wyckmans, *et al.*) The focus of theses studies have to a large extent been the glazed areas of a building envelope and how the alteration of them may help reduce the energy demand, through decreasing the heat gain from the sun when it is not desired.

2.1 Adaptive building envelopes

In this chapter the concept of adaptive building envelopes will be further elaborated in terms of control systems, mechanisms, systems and simulations.

2.1.1 Control systems

The control mechanisms of adaptive envelopes could be divided into two different system types, the *open loop system* (Figure 2.1) and the *closed loop system* (Figure 2.2).

Figure 2.1 Diagrammatic concept of open loop system

A sensor, a processor and an actuator build up an open loop system. (Addington & Schodek, 2005) The reaction of the sensor is read and interpreted by the processor, which in turn sends a signal to the actuator to preform according to a predefined logic. The sensors register the ambient conditions in their surrounding medium. They can be sensitive to changes in heat, moisture, pressure etc., and are classified following which one of these stimuli that they react upon. The actuator is the part of the system that converts the processed data into a mechanical, physical or chemical action.

The difference between the closed loop system and an open loop system is that the closed loop system also constitutes of a control unit that can measure the output action. The collected information could then be used as feedback to the processor (Addington & Schodek, 2005).

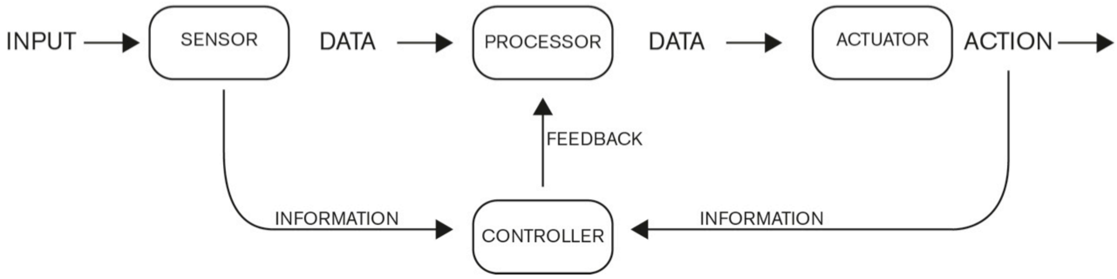


Figure 2.2 Diagrammatic concept of closed loop system loop system

The control unit is suitable if you wish to connect the adaptive envelope to a central building control system and if you want to allow users to interact with and influence its actions. As mentioned earlier, allowing the users to have some direct influence over a system that control for example thermal parameters could increased the experienced level of comfort. But it could also be used in a less complex feedback system in which control rules are incorporated in the processor allowing it to adjust the algorithm to change the output action following these rules, by comparing the action with the desired effect (Loonen, 2010). Some materials exhibit properties so that they can act both as sensors, processor and actuator. Then the processor is the material properties, which defines the rules for the reaction.

These different control systems can be implemented in different ways giving rise to different typologies of responsive architecture, which are stated below.

1. Material systems
   - The development of physical kinetic systems or the like are often developed within structural and mechanical engineering and material sciences.

2. Informational systems
   - The development of physical sensor systems, which to an increasing level can observe and send continuous information further to a processing system, which then actuate into behaviours passing information back to the environment.

3. Processing systems
   - The development of physical processing systems, which filter and decide from large amounts of sensor information and stored information. These are often associated and developed within computational science.

4. Behavioural systems
   - The development of logic and behavioural gestures, patterns and systems, often associated with artificial intelligence sciences based upon computational and neurological sciences.

   (Kirkegaard, 2011)

2.1.2 Mechanisms

There are two levels of mechanisms that drive the adaptive behaviour; micro level and macro level but combinations are also seen.

Macro-level

In short this mechanism can be seen with the naked eye and it is often associated with motion of various kinds like folding, sliding, rolling, hinging, etc. The driving principal behind a macro-level adaptive mechanism is usually an electromotor, which is triggered by an input from a sensor and driven with external energy input. There are examples of adaptive envelopes with macro-level mechanisms that neither acquires additional energy nor an external sensor. Because of their scale they also tend to be more mechanical than the micro-level, which could be a disadvantage when it comes to maintenance, as the use of a large number of parts, can be problematic when something breaks. An example of a macro-level adaptive concept is mechanically controlled venetian blinds, but they could come in all different shapes and transformation patterns.

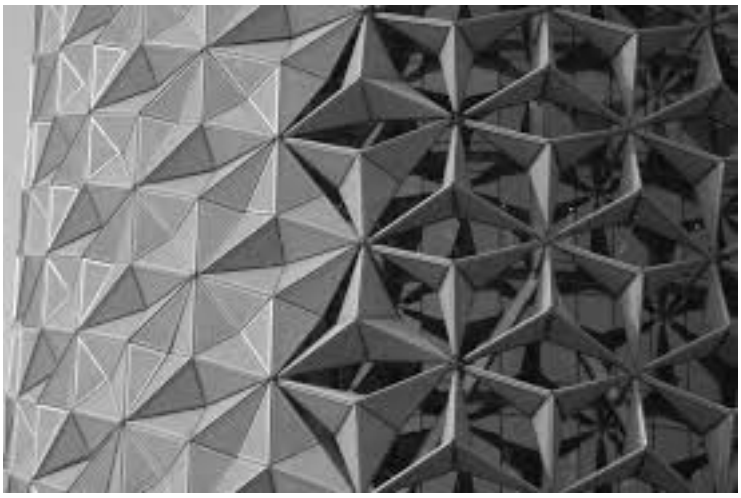


Figure 2.3 Example of a macro- level adaptive system at Al Bahar towers, where the panels fold or unfold to act as solar shading.

Micro-level

As the name implies, micro-level changes occur in a smaller scale. The change occurs within the material it self, for example the arrangement of water molecules when the water transits from the fluid phase to the solid phase (ice) as seen in Figure 2.4. This change in a material's properties could be applied as an invisible change in the envelope that alters for example the thermal properties or it can be used as a motor to drive a larger system, for example wax pistons or photovoltaic cells. In wax pistons wax expands when the temperature is increased, this in turn induce a pressure in the piston, which can be used to create movement of for example blinds.

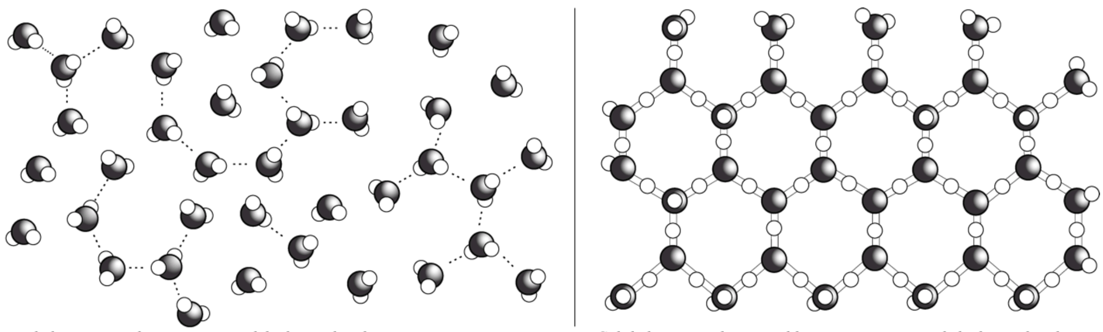


Figure 2.4 Molecule configuration of water as fluid and ice.

2.2 Adaptive systems

There are several existing examples of systems for adaptive building envelopes and facades. Most falls into the macro level of mechanisms, exhibiting large changes that usually are governed by computerized control systems. The most seen example is different types of adaptive solar shading systems, with shutters, venetian blinds or other systems that control the solar gain in the interior. But there are examples where the macro level effect is controlled and driven by a micro mechanism rather than pure external input. The examples of micro mechanism in which the system only is based on that change in properties are not as many, but there are several examples of glazing with coating that change depending on temperature or light intensity. In the following three sub-chapters systems that are adaptive to different environmental parameters will be presented and explained.

2.2.1 Responding to solar radiation

Adaptive systems that react to different levels of solar radiation is by far the most seen adaptive façade solution. There are examples of micro, macro and combined systems, but computer controlled macro systems are the most common. The adaptive solar shading systems can take on many different shapes and forms, there are external and internal systems, different kinds of blinds and shutters (Weston, 2010) but also more innovative examples both when it comes to shape and appearance but also in terms of driving mechanism.

A common way to reduce the solar heat gain is to use windows that have an additional coating. These coating can be of different kinds but with one thing in common, they can under influence of high levels of radiation, (Addington & Schodek, 2005) high temperature or an electric current (Mehrabian *et al.*, 2013) change their transparency and thus reflect the heat radiation, not allowing it to enter into the room. This is an example of a micro level system that is commonly used, but today it has the drawback of not being able to over rule. There are systems currently being developed for which the occupants through the introduction of a small electrical current can overrule the reaction in the glass coating, these systems can not yet be found on the market but show a possible solution (PEER+, 2009).

Whether it is macro or micro, based on natural reactions or computed algorithms, it is especially important to consider the trade off between solar heat gain and daylight, obviously as they have the same original source the use of shading systems also affects the amount of daylight, that are let into the building.

2.2.2 Responding to thermal loads - Variable U-values

Another adaptive solution is to allow the U-value of the wall to alter according to the heat loads from the surroundings. This could be achieved in a number of different ways, for example by introducing a controlled airflow in the wall stratification (Hagentoft, 2013) or by the use of deployable insulation panels that can be moved to a configuration that is suitable for the current surrounding conditions (Guttfield, 2012).

Airflows within the wall

Already early examples of adaptive walls exhibits ideas of air flowing in the building envelops. *Le Mur Neutralisant* (Harvey, 1991) is the first example of what later gets the name double skin façades. The concept in it self is not adaptive if the air in the space is stagnant, but it has been used as a starting point for adaptive solutions where the air in the in between space is heated by solar radiation and could be evacuated or kept in the space depending on the need for insulation at that specific time. Or the heated air could be used even more direct as pre-heated air that could be transported to be used for heating of the interior. The concept of 'le mur neutralisant' will be further developed in section 3.1.1. Moving air can also be used to decrease the U-value of a wall build up. By incorporating air channels within the wall and allow air to flow within them the convection give rise to an increased U-value. The convection could be either natural or forced. In a steady-state simulation the U-value for a wall with forced convection in the air channels have increased 4.7 times to be compared with 3 times for a natural induce convection. Similar results have been found for a simplified dynamical model (Hagentoft, 2013). The use of air within the build up of the envelope whether being pre-heated air to reduce the U-value when desired or introducing convection within to increase the U-value to reduce the insulation level of a space, can be a powerful tool when designing responsive building elements as it enables both completely automatic responses by natural convection or controlled responses if decided to use forced convection.

2.2.3 Responding to moisture contents

There are several different concepts that use the response to water as mechanism for change. Material similar to that of the well-known fabric Gore-Tex does not change per say but behaves differently depending on the phase of the water. It allows vapour to exist and enter but block liquids from passing through material. And others that instead grants liquids unlimited access while refuse to let vapour through the membrane, so called hygrodiodes. While Gore-Tex is a polytetraflourethylene (PTFE) based polymer the hygrodiodes is a layered construction that allows water to pass through the means of capillary suction in a felt material. (Hagentoft, 2013) There are also material that change depending on the relative humidity in the surrounding, like the smart retarder developed by Hartwig Künzel (1999) at the Fraunhofer-Institute of Building Physics. The smart retarder is essentially a 2 mm nylon film that has a permeability that varies from 1 perm at a relative humidity below 50% to a value of 36 perm when the relative humidity reaches 90 %, diagram over the change can be seen in Figure 2.5. This material was discovered after specifications were defined based on heat and moisture calculations and computer simulations together with in-situ testing (Künzel, 1999).

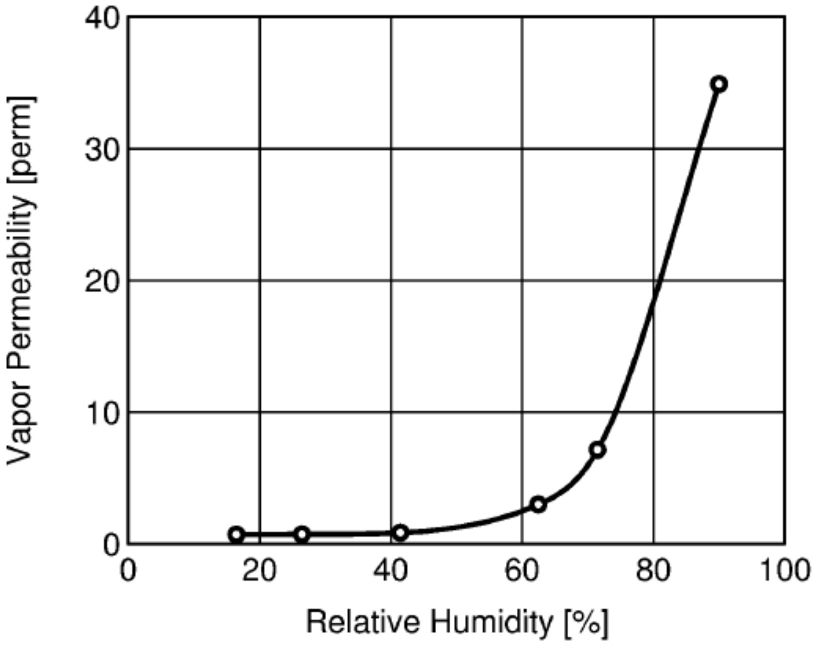


Figure 2.5 Variations of the vapour permeability of the smart retarder with the ambient relative humidity, determined by cup tests. (Künzel, 1999)

2.2.4 Simulations of adaptive building systems

The development in computer technology have improved capacity of handling complex simulation models have enabled more accurate calculations of the energy performance. This can hopefully be used as a design tool already at an early stage, making it possible to design an optimal envelope, adopted for specific conditions and context. This goes for both static and adaptive building envelopes. Simulation programs used for energy calculations of building and especially on building envelopes are in the best case dynamic and can be used to optimize the behaviour of the envelope. However, the optimization tends to be lame as the many of the input values, for example insulation value that you might want to alter to find an optimum are fixed to one value. Therefore the software cannot truly consider an adaptive envelope but rather optimize the relationship between otherwise static parameters (De Boer *et al.*, 2011).

In order to find a way around this problem the research group FACET (a Dutch acronym of 'Adaptive façade technology for increased comfort and lower energy use in the future') at the Energy research Centre of the Netherlands (ECN) and the Unit Building physics and systems at Eindhoven University of Technology, have developed an inversed modelling method. This means that they search for ideal hypothetical envelope parameters for different climatic conditions as well as different building types, that will maximize the interior comfort simultaneously as they minimize the amount of energy used for heating, cooling, ventilation and lighting. The key focus is to clarify the theoretical potential of adaptive architecture rather than starting of with the performance of existing examples (De Boer *et al.*, 2011).

Preliminary results from the FACET projects shows that an optimal adaptive building envelope can reduce the total heating and cooling demand for an office by a factor 10 compared to a newly built state of the art office. In this simulation an optimal thermal behaviour and optimal daylight characteristics were optimized using a multi-objective optimization technic (De Boer *et al.*, 2011).

Pareto is a simplified simulation method of a static building envelope compared to a simulation of a long-term adaptive building envelope, optimizing for thermal comfort and energy demand. Instead of simulating the actual conditions for every moment over for example a year, the simulation period is the simulation divided into suitable sub time spans that get set conditions. For Pareto simulation performed by FACET (De Boer *et al.*, 2011, Loonen *et al.*, 2011) optimal properties for a static envelope for the entire year was found, as a reference, while twelve different optimums where found for the adaptive envelope each corresponding to one sub time span, in this case corresponding to a month. The received outcome indicates that the optimized solution for a static envelope at best is a good compromise for the whole year. The adaptive envelope on the other hand was shown to preform better in mid-winter and mid-summer, while the it in the in between months becomes a trade-off problem between the two parameters simulated. This example together with an excepted level of over-heating of 200 hours / year the adaptive envelope reduces the energy demand for heating and cooling with 50 % compared to that of the optimized static envelope. (Loonen *et al*, 2011). Introducing more parameters will of course alter the result but it gives a clear indication of the possibilities.

2.3 Materials

One important factors when speaking about envelope design is to use materials in such a way that it contributes to the climate in the building. And above all use the materials to their full potential. This can only been done if the properties of a certain material is well known and with the knowledge of how that material reacts and answers to changing conditions in its surrounding. The envelope is nothing without the materials that it is made up by, they are the boundaries and their properties open up for adaptive solutions as all materials adapt to be in balance with the environment, whether it is on a molecule level or through a change in shape. But the way that materials are used in envelops today most of these changes in properties can be neglected and assumed to be static. New systems for envelops can use materials both existing and new materials in such a way that these changing properties are exploited and used to benefit the climate in the building.

The relationship between the buildings, architecture, and materials has changed throughout history, starting out with a quite straightforward one. Before the industrial revolution materials for a construction were chosen for two different reasons; either because they were locally available and useable for the desired purpose, a pragmatic reasoning, or they were chosen based on their appearance and the ability to shape them into ornamentations. It was at this time crucial to have knowledge of how the materials reacted in order to design with them; this intuitive understanding was acquired through a process of trial and error. (Addington & Schodek, 2005) This can be seen in vernacular buildings where the available materials have been used in such a way so that they contribute to the comfort and the overall performance of the building. After the industrial revolution the materials are to a larger extent seen as just a separating surface without none or little influence on the building system. The separation between the structural, thermal and visual aspects of a façade gave rise to buildings in which the materials on the exterior and interior surface becomes the important ones but they mostly fulfil a visual and aesthetic function rather than being a contributing element in the building performance. (Addington & Schodek, 2005) The actual performance of the envelope is to a large extent depending on what is in between these layers.

Today a lot of the intuitive knowledge of different materials has been lost and resulting in a material use that is not optimal for that specific material. Introduction of new construction materials have always been slow, and as the background knowledge for obvious reasons are less extensive the way they have been initially used have not been optimal. As new types of materials were introduced and replaced a previously used material in a specific structure they where initially used in the same way as the previously used materials. The first cast iron bridges where designed in the same way as stone and wooden bridges had been designed. As steel stone and wood have different structural properties the same structural system was likely not the optimal use of both all of them. Later another structural system was developed in which the steel worked in a more optimal way in both tension and compression. The same can be seen when reinforced concrete started to replace wooden industrial buildings in the early 20th century, they where designed as if they would have been made out of wood still. But after some time a system that better suited the properties of concrete was refined.

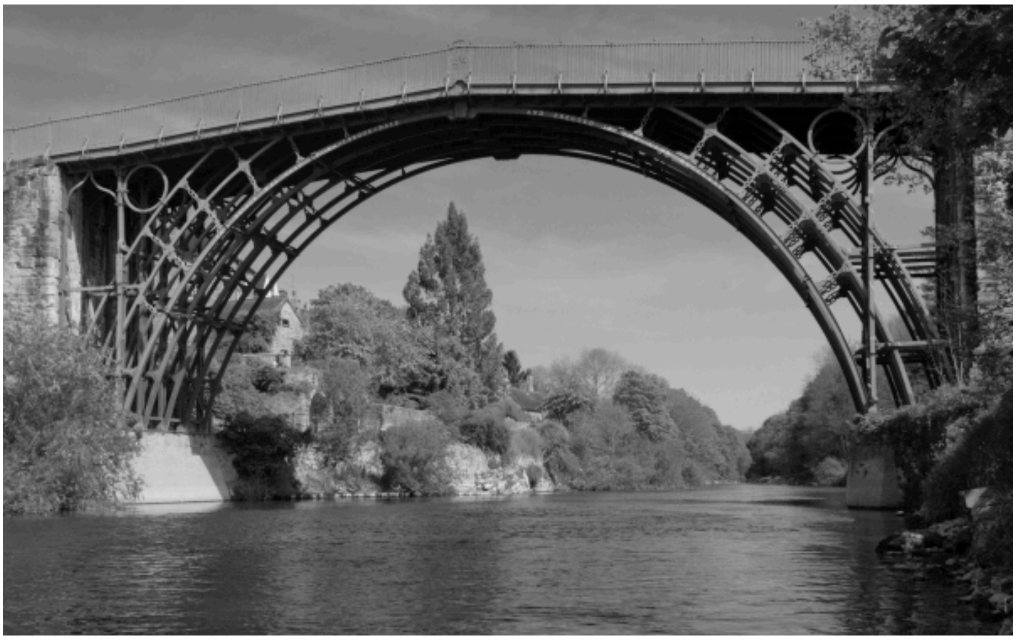


Figure 2.6 The Iron Bridge, England, the world's first cast iron bridge, design inspired wood bridge building techniques.

The same can be seen today, new types of materials exhibits properties both thermal and structurally different from the materials commonly used today. But still they are incorporated as replacement for existing materials rather than being used in their optimum sense. Materials commonly used in building are static, i.e. they do not respond to the changes in the surrounding environment. If the building have an adaptive envelope or moving parts, these are in most cases made up by mechanical systems driven by extra input energy. One group of material that can be considered to be new in the building industry today is so called smart materials, that not only can withstand the forces that the building is exposed to but also respond to changes in these forces, to operate at their full potential.

2.3.1 Smart materials

Smart materials have several definitions but in this thesis the definition from the *Encyclopedia of Chemical Technology* (Kroschwitz, 1992) is used:

"Smart materials and structures are those objects that sense environmental events, process that sensory information, and then act on the environment. "

There are three primary material classes: metals, ceramics, polymers and composites the later being combinations and variations of the three first. Smart materials can be found within all of these, either as molecules, pure materials or composites (Addington & Schodek, 2005).

A material are considered to be smart if it exhibits the following characteristics:

- Immediacy - thus the response is immediate and in real-time
- Transiency - they respond to several environmental states
- Self-actuation - the intelligence is in the material it self
- Selectivity - their response is predictable and discrete
- Directness - the response is local, i.e. it occurs in close proximity to the activating event

Smart material can be divided into two different groups, depending on how they react to the energy (stimuli):

- Type 1: the material absorbs the energy and undergoes a change

- Type 2: the materials that remain the same but have the ability to convert energy from one type to another, for example from kinetic to electric.

(Addington & Schodek, 2005)

It can be hard to understand the possibilities that can be found in the material properties of the smart materials through these theoretical definitions, therefore the following chapter will present and explain some smart materials that could be implemented in the design of building envelopes.

2.3.2 Metals

Metals are a common material used in construction of buildings and in building components. All metals share their main properties being opaque, electrically and thermally conductive. But the different metal also exhibit different other properties. Their electric and thermal properties make them especially suitable for adaptive elements. Two metal-based smart materials will be presented in this section

Thermo-bimetals

A thermo-bimetal is constructed from two different metals with different thermal expansion coefficients, by attaching them together by welding, brazing or riveting the difference causes the metal to bend, principal shown in Figure 2.7, when exposed to heat. This can be used to transfer a change in temperature into a mechanic change, thus it is a type 2 smart material.

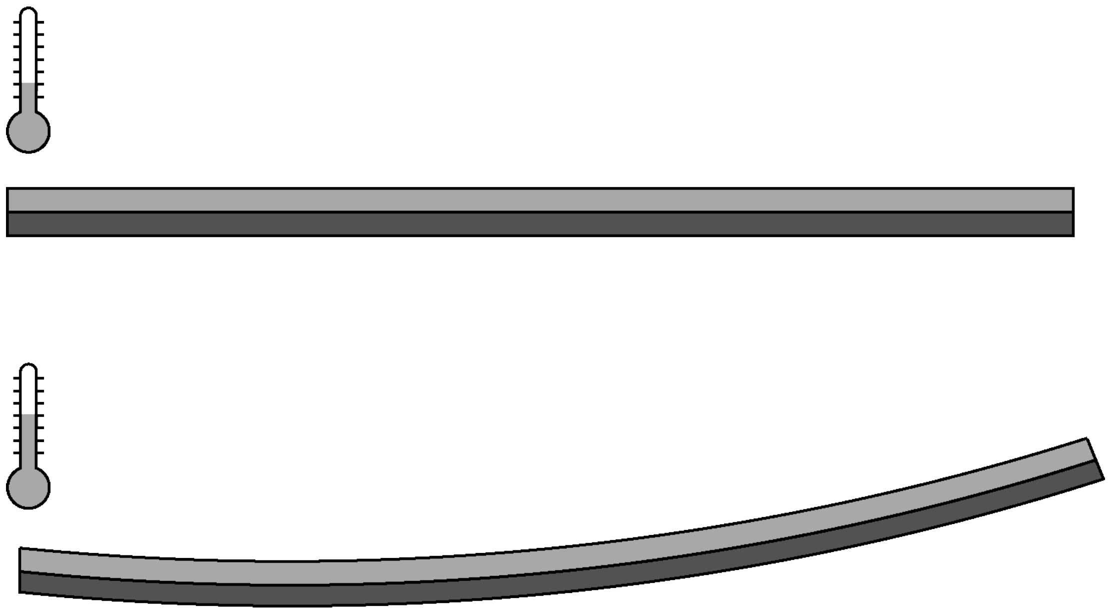


Figure 2.7 Principle illustration of thermo-bimetal

Thermo-bimetals have been used a long time in clocks, thermostats, and thermometers and as circuit breakers in electrical devices. Architect and biologist Doris Kim Sung (2014) has at her office in Los Angeles been carrying out new interesting tests using thermo-bimetals for self-regulating ventilation as well as test for automatic blinds. She designed a pavilion called BLOOM as a proof of concepts; the bimetallic strips open when the temperature on their surface is high, and return to the initial position as it cools down again.

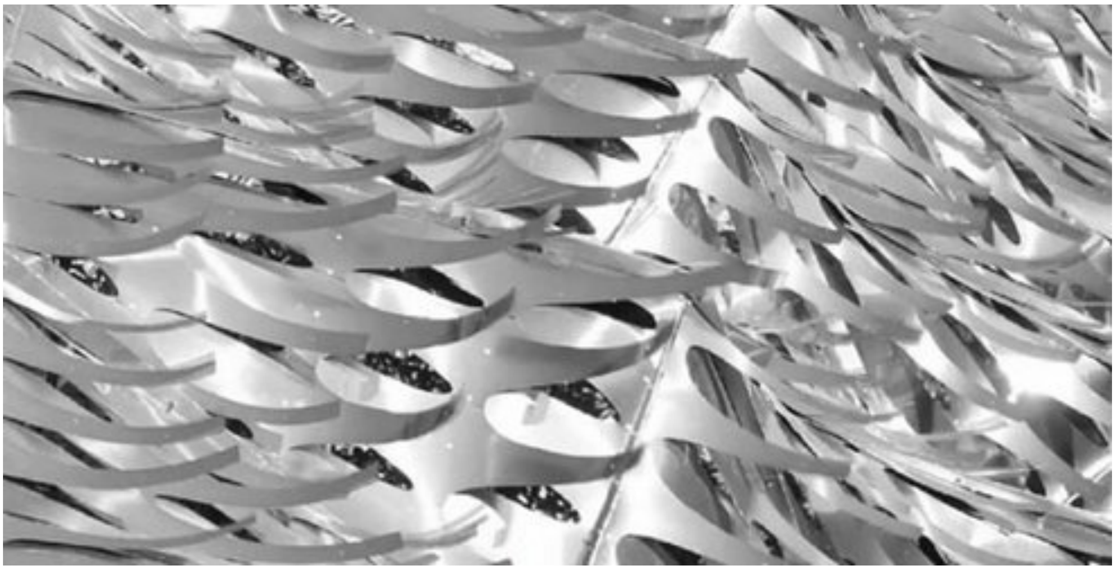


Figure 2.8 Self-regulating ventilation, proof of concept (Doris Kim Sung)

The curvature (*K*) of the bimetal is given from the elasticity of the two materials and the thickness and the misfit strain (E), which is given by the difference in thermal expansion and the temperature difference from the reference temperature i.e. when the metal has no flexure.

$$\kappa = \frac{6E_1E_2(h_1+h_2)h_1h_2\epsilon}{{E_1}^2{h_1}^4 + 4E_1E_2{h_1}^3h_2 + 6E_1E_2{h_1}^2{h_2}^2 + 4E_1E_2{h_2}^3h_1 + {E_2}^2{h_2}^4}$$

Where

$$\epsilon = (\alpha_1 - \alpha_2)\Delta T$$

The bending is predefined by the different metals used, as the curvature *K,* is directly related to the Young's modulus of the material. So the curvature is always the same and can therefore easily be modelled. The active material (with the larger coefficient of thermal expansion) is usually an alloy of iron-nickel-manganese or manganese-nickel-copper, while the passive component usually is alloys of iron-nickel or nickel-cobalt-iron, known as invar and super invar materials i.e. their coefficient of thermal expansion is very small. (Peters, 2011)

Shape memory alloys

The behaviour of shape memory alloys can be very similar to that of thermo-bimetals, the change their shape because of a shift in temperature, but the shape change is not pre-defined by the differences in properties of two separate materials. Instead, the rules for how and when a change occurs are stored in the molecular structure of the alloy. The temperature boundary depends on the properties of each alloy but commercially available products usually react to temperature between – 35 °C to 90 °C. Two different types of shape memory alloys can be distinguished, one-way memory and two-way memory. Where one-way memory means that the alloy can return to its initial shape once after being heated and when cooled again the shape is retained while two-way memory refers to the memory alloys that exhibits so called multi-shape return, i.e. it can take on several shapes and go back and fourth between them.. Some of the shape memory also exhibits special elastic properties, so called super-elasticity or mechanical memory effect, which give the alloy up to twenty times higher elastic properties than for normal materials at constant temperature (Peters, 2011).

The shape memory alloys or memory metals as they often are called are the type smart material that already is widely used. There are examples of use in space engineering, medical technology as well as in fashion design and in load-bearing architectural structures. The memory metals have also shown to be very fatigue resistant. There are cases where memory metals have transferred large loads for over 100,000 cycles without resulting fatigue. (Peters, 2011)

Nickel-Titanium is a specific shape memory alloy which above previously mentioned properties also exhibits very good corrosion resistances together with high tensile strength and consequently, better ductile fracture properties along with being biocompatible (Peters, 2011). For what seem obvious reasons this is the most implemented shape memory alloy, but there are also others common ones like copper-zinc, copper-zinc-aluminium gold-cadmium amongst a few.

2.3.3 Polymers

A lot of the materials around us today are polymers of some kind, our clothes, paints, food containers, glues, bottles and much more. But all of them are far from every day materials, and there are a lot of possibilities for adaptiveness hidden in the properties of some of them. There are also great research possibilities to design polymers that have properties chosen for a specific purpose. In order to get a better understanding of the possibilities some existing polymers that respond to different stimuli will be presented in this section.

Shape memory polymers

Shape memory polymers have the possibility to change shape depending on exposure to different stimuli. The most common stimulus is thermal changes but there are also other examples that will be discussed further on. Shape memory polymers are always thermoset, which means that after they are cured at production they cannot be melted and remoulded. But on the other hand this makes them more rigid.

Exposed to thermal stimuli, thermally activated shape memory polymers change from one shape to another. If the shape memory polymer is constrained when cooled down from it’s elastic state, it is reshaped and that shape will then hold until it is heated above the threshold value again, then it will return to the shape in which it was cured initially. This can occur over and over again with little effect on the material properties. The threshold temperature at which the polymer changes can be almost any in between -26 °C to 260 °C. (Brownell, 2008) The high upper limit is due to the fact that shape memory polymers are thermosets, they can be exposed to high temperatures without being destroyed.

There are products that exhibits more dramatically changes, from a rigid material to a very elastic state as the temperature increases and then back to rigid again as cooled down. (Peters, 2011, Brownell, 2008) There also exist shape memory polymers, which also have thermocromatic properties, as the temperature changes it does not only change shape but also colour (Peters, 2011).

Photosensitive memory polymers are another example of a type of polymer that changes shape when exposed to a external stimuli. In this case the wavelength of light is the triggering quantity, and the polymer can be designed to answer to a particular wavelength. (Peters, 2011)

Usually shape memory polymers are derived from petroleum, and as they then are thermoset they are hard to recycle. But there are alternatives, a polylactic acid polymer; with raw material from corn developed by NEC have thermal shape memory properties. Once heated it can be shaped, and when it cools that shape remains until the next time that the material is heated above a temperature around 60°C when it returns to its initial shape, but if it is heated above a typical molding temperature of around 160 °C the material will melt, unlike the thermoset material. And thereby it can be recycled easier (Brownell, 2008).

Electro active polymers

Electro active polymers or EAPs are polymers that change their volume when subjected to an electrical charge, they expand and contract based on electrical impulses, just as our own muscles are doing.

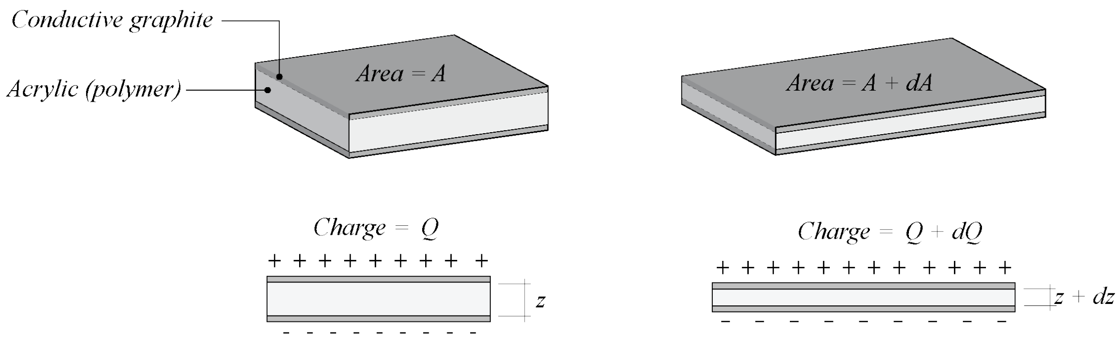


Figure 2.9 Principal of dielectric elastomer

One example of electro active polymers (EAP) are dielectric elastomers, which are normally made out of a layer of either acrylic or silicon, coated with conductive graphite on each side. As an electric current is applied, an electrostatic pressure is generated between the graphite layers and the size of the dielectric elastomer is changed due to condensation of the polymer layer. The virtual efficiency between inputted electric energy and the output in mechanical energy is 70 % (Peters, 2011). This effect can be used for example as an actuator or as in Decker Yeadon's (2013) suggestion to solar shading where a pattern of dielectric elastomers between window panes provide for shade as the dielectric elastomers unfolds shown in

Figure 2.10. They call their system the homeostatic façade and it will be further explained in section 3.1.3.

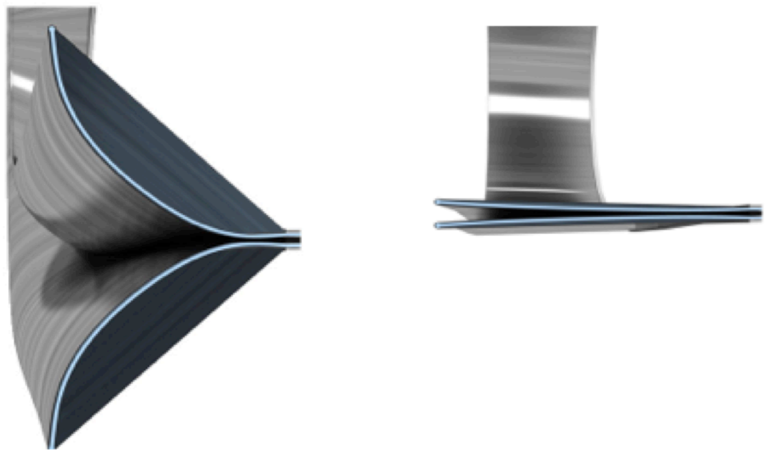


Figure 2.10 EAP as solar shading, principle (Decker Yeadon architects)

Another type of electro active polymers is ionic polymers metal composites (IPMC). When a current is applied to this kind of EAP, instead of a change in size of the polymer, it curves. This curvature can be achieved at a very low voltage, only 2-3 W. The principle can be seen in *Figure 2.11*. The IPMC is made up by two electrode made out of a highly conductive metal and between these two layers there is an ionomer, a type of polymer. This is a very strong electro active polymer often referred to as an artificial muscle; some examples of it have the capacity to lift 20 times its own weight (Peters, 2011).

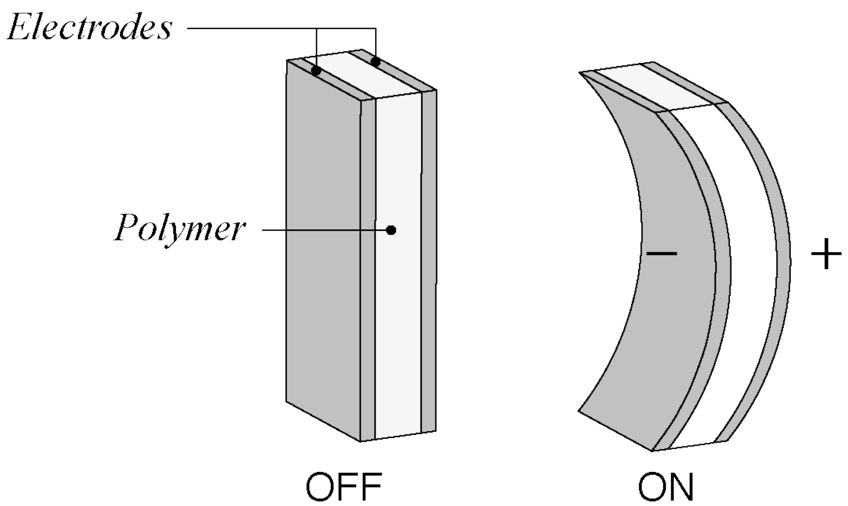


Figure 2.11 Principal of ionic polymer metal composites

Photochromic materials

Photochromic materials have the ability to reversibly change their absorption characteristics in response to the wavelengths of radiation (especially ultraviolet light). This capacity can be used to absorb or reject energy of different wavelengths at the surfaces of a building, i.e. the roof or in windows. The molecules that are used appear colourless before it is excited by the electromagnetic energy in the light. The energy input causes the molecules to alter their molecular build up, resulting in a reflection of longer wavelengths in the visible spectra. (Addington & Schodek, 2005)

Photochromic coating

Starting off in the 60s and 70s, when colouring was used to reduce thermal losses through large glass surfaces, the development in glass and window design has come a long way. There are great numbers of concepts and products with varying solutions to decrease the thermal losses or reduce solar gains by adding a polymer or metal coating to the glass. In windows, photochromic behaviour can be obtained by using iron oxide with fluorides (or chlorides) of silver or copper. This can be used to make windows go darker as the radiation from the sun increases and then return to the initial state if the exposure vanishes, as illustrated in *Figure 2.12*. The initial state is characterized by a light transmission in the visible spectra of about 80-90%, which can decrease progressively down to 10-15% as the solar radiation increase (Peters, 2011).

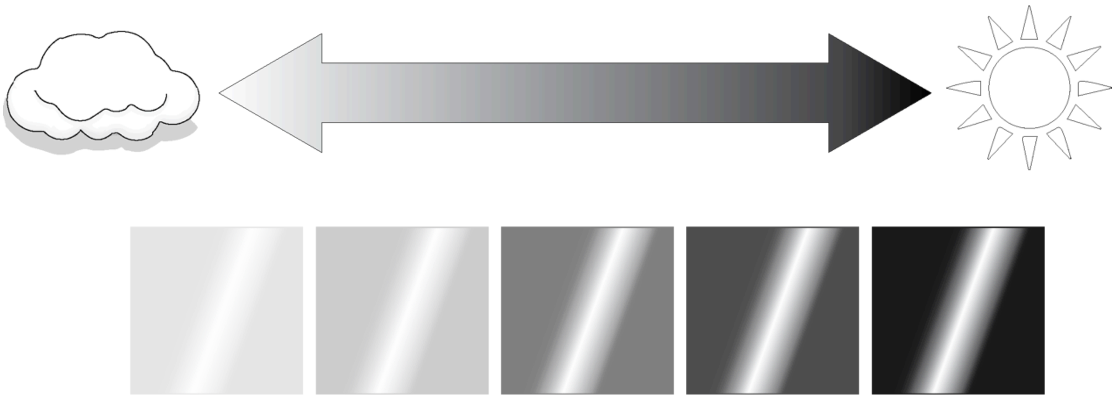


Figure 2.12 Principal of photochromic coating on glass

Thermochromic coating

This type of coating, commonly made out of vanadium dioxide, will reflect all infrared light if the temperature reaches a threshold value (29˚C) but the temperature change will not affect the visible light. This property is suitable in many cases as the infrared light will be allowed to enter into the space when the temperature is low, for example during winter time, which also is when the heat obtained from the sun is a welcome contribution to the interior comfort. (Mehrabian *et al.* 2013) There are also electrochromic glasses where the transparency is change by introducing an electric current which alter the colour of a thin layer from transparent to blue (Mehrabian *et al.,* 2013). By reversing the voltage the glass turns lighter again. The colour change is caused by a chemically induced molecular change at the surface of the material. (Addington & Schodek, 2005)

Phase change materials

All existing materials are affected by heat. As heat is applied to a material the molecules also start to move and the different kinds of bonds between the molecules are affected as the heat increases they eventually breaks. This event is what causes a material to change phase, from solid to liquid and eventually to gas as the heat energy increases. The distance between the molecules also increases as the bond breaks, which can be seen in the principle diagram *Figure 2.13*. This process occurs at different temperatures for different materials, as everybody knows for water these boundary temperatures is 0° C and 100° C. The heat absorbed by the material when transiting from a lower phase to a higher is stored in the material as latent heat and as the surrounding temperature cools down the molecules once again slows down and inter-molecular bonds is created once again. As this happens the latent heat is release into the surrounding.

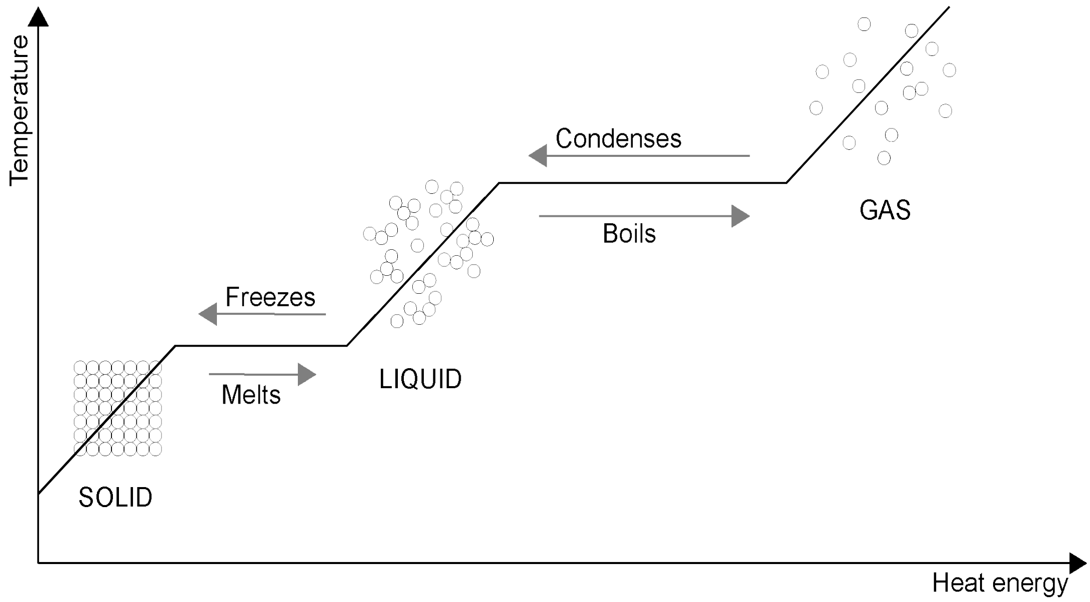


Figure 2.13 Different phases of a material exposed to heat

As 0° C and 100° C never is within the desired interior temperature range, water is not a suitable phase change material (PCM) for that purpose. But there are other materials that melt at around 20 - 50 ° C, thus they are very well suited for implementations in interior environments. When one of these materials is used in a room and the temperature reaches the melting point of that specific material, heat is stored inside the material and the temperature is kept constant, thus the use of phase changing material prevent the room temperature to reach above the melting point of the material. The use of PCM's helps to reduce the fluctuations in the interior climate, reducing the peaks, increasing the thermal capacity of the building, similar to the effect of a heavy weight construction.

The materials most commonly used for applications in buildings are paraffin and salts, which have suitable melting points. They can be divided into organic and inorganic, as illustrated in Figure 2.14, where paraffin is an organic compound while the salts are inorganic compounds. Eutectic phase change materials are mixtures of different compounds, which could be both organic and/or inorganic. It is then the relation between the two compounds that give the final melting point. (Aschehoug & Perino, 2009)

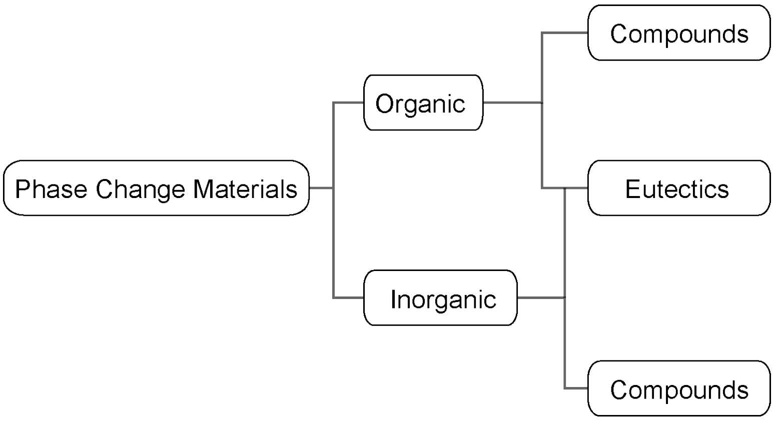


Figure 2.14 Different types of PCM's suitable for use in buildings

The different types of PCMs have different properties in terms of flammability; corrosion, price and density to mention a few, these properties have to be checked against desired properties and effects in building applications. (Aschehoug & Perino, 2009)

Usage of PCM in buildings

The material is encapsulated in a container or inside another building material like gypsum or ceramics to make it easier to handle and incorporate into a building. One can say that a PCM material have the purposes to fulfil when implemented into a design, first to enable usage of natural heat sources and secondly to increase the thermal inertia of the building. Both of these scopes can reduce the energy demand for cooling and heating of the building. PCM are usually used in building in one of three different techniques; in the walls, in another building component like ceiling or floor, or in a separate heat storage system. Focusing here on the implementations in walls the PCM systems can be divided into the ones used in opaque wall and the ones used in the transparent walls.

Opaque walls

The PCM is as previously stated used to increase the thermal inertia of the building element in this case the wall. In the wall stratification, they can be placed either towards the exterior or the interior. Where to place the PCM is depending on the desired effect.

A PCM layer placed close to the interior will be affected by the changes in the interior temperature and will melt as the room temperature increases, this process will reduce the surface temperature along with the air temperature in the space and thus improving the comfort and reducing the fluctuations in the interior climate. The PCM will still be affected by the solar gain on the exterior and that together with the internal gains. Because of these gains the PCM in this case will be constantly be close to the melting point. This solution is suitable in areas where the exterior temperature is not extremely hot but there still could be problem with over-heating inside.

The other solution, placing the PCM close to the exterior surface is on the other hand more suitable in warm countries where it is desired to reduce as much of the solar heat gain as possible. In this case the PCM layer collects and stores the heat energy from the outdoor environment rather than from the interior, i.e. absorbing the energy before it enters into the spaces. PCM in walls can be coupled with ventilation to further increase their effect on the interior comfort in terms of operative temperature as the ventilation can cool down the PCM and redistribute the heat. (Aschehoug & Perino, 2009)

Transparent walls

In the transparent parts of the building walls, PCM solar walls could be one solution. They are a kind of modified solar walls, which uses PCMs to reduce the size and weight of the building element without loosing the capacity to store heat. A traditional solar wall is made up by a transparent layer towards the outdoor environment and then and air gap followed by an opaque wall that absorbs the solar radiation on its outer surface. The heat is then transported through the opaque wall by means of conduction and is then released into the interior space by radiation and to some extent also convection at the surface, the principle can be further studied from *Figure 2.15*.

In order to make this work the opaque wall needs to have high thermal inertia, thus it have been common to use heavyweight materials such as masonry, concrete or stone. The best performance have been found when the non-transparent layer has a frontal weight of 350- 400 kg/m2 and a thickness of 0,30- 0,35 meters, this reduces the possible applications of the solar wall as not all structures can manage such a load. By replacing the heavy material with a layer of PCM the same energy storage capacity could be maintained with a much lower weight (Aschehoug & Perino, 2009).

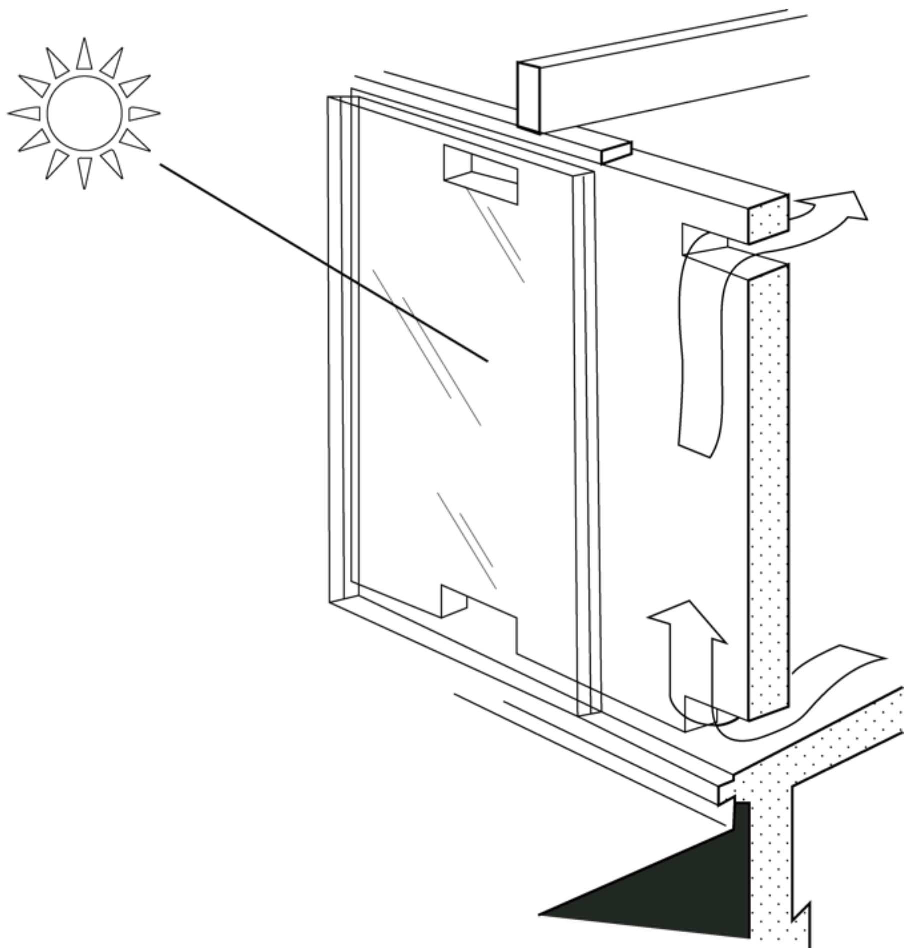


Figure 2.15 *Principal of traditional solar wall*

To achieve the best performance the PCM should be placed next to the air gap and have an insulating layer inside that will help control the heat loss through the element. As the PCM works both as a heat accumulator and as a heat source depending on the thermal conditions in the surrounding they allows for a smoothing of the fluctuations in the interior climate (Aschehoug & Perino, 2009). All PCM are not completely opaque and therefore it is possible to let diffuse daylight to enter into the room through such an element. An example of a solar wall with PCM is the GLASSX-system that will be further explained in section 3.1.2.

2.3.4 Adaptivity through fabrication

Not all smart materials need to be high tech and rely on complicated chemistry and/or physics to work. Rather it is more about exploiting the full potential of a material through knowledge about how it reacts to a certain stimuli. As all materials do react in some way to the environment they are in, it is all about using the changes as an advantages rather than a problem in a static solution. As Bart de Boer states (2011), not all material that meet the requirements to be used as a part of an adaptive building envelopes have to be high-tech or futuristic but could also be very down-to- earth. With help from existing technologies such as parametric modelling tools and digital production methods such as laser cutting, CNC-milling and 3D printing. Through clever use of these technologies every day materials as metal sheets or wood veneer, could be transformed into responsive, memory materials. Mark Weston (2010) discusses these possibilities in his paper on memory mesh; a material sheet that through parametrically controlled cutting patterns can respond to increased tension and the spring back as the tension is released. This response is caused by deliberately making the material anisotropic in a dimension in which it before the alteration was stable. This process could be done on several different composites such as carbon fibres, wood veneers, metals, paper, fabrics or any material that posses some kind of plastic deformation. Further development of these thoughts is being researched; for example how to create memory mesh concept from materials that already are naturally anisotropic with respect to a given environmental stimuli (Weston, 2010). One example of such a material is wood, which expands to different extents along and perpendicular to the fibres. This specific property is used when developing a passive-active building skin that would work as a humidity gate, using the evaporation as a cooling system for buildings in warmer climates. As the wood absorbs moisture it swells and the cutting pattern governs a shape change in the entire building skin. (Weston, 2010) The possibilities in material production is offering opportunities to increase the performance of each material used in a structure so that it works in its best possible way and that it contributes to the overall performance of the building envelope.

2.3.5 The use of smart materials

Smart materials can be applied in a number of different areas. In some cases they can just replace a conventional material but through its smart properties give additional benefits, on example of this is paint with nano-particles of titanium oxide, which not only protect the surface but also reduce pollution in the surrounding air through photo catalytic behaviour. (Peters, 2011) Some smart materials have been a part of daily life for a long time, an analogue thermometer is a liquid with suitable expansion properties when exposed to increasing temperature or it is a rolled bimetal strip that when subjected to higher temperatures unfolds and moves a pointer over a circular indicator panel.

The smart materials are still not exploited as much as they could have been. Smart materials have been applied in architecture, but rarely so that the responses give a global effect on the performance of the entire structure. (Badarnah & Knaack, 2008) They have rather been incorporated as show offs having nothing or very little to do with the rest of the building. Despite that there are examples of adaptive envelopes and building components that make use of the specific properties of smart materials, they are few and most are still under development. The connection between the possibilities with smart materials and sustainable design could be explored much more. Smart materials and there abilities to respond to stimuli should act as inspiration for adaptive designs.

3 Design of adaptive envelopes

An adaptive envelope could come in any shape or expression. Some base their design on the usage and benefits that a smart material may offer; others start of with a problem in the interior environment that could be improved by changing the way to think about a building envelope. No matter in which end you start the design of an adaptive envelope is a complex task and lots of knowledge, understanding and cooperation are needed to achieve a feasible solution.

In this chapter different examples of adaptive building envelopes and adaptive building components that can be used in the envelope will be presented. The later part of the chapter will discuss design of adaptive building envelope based on a workshop that was held for younger students.

3.1 Examples of adaptive building envelopes and components

In this section a selection of adaptive building envelopes will be presented and discussed. The examples will span from traditional building methods to high tech concepts of today. Both entire envelope concepts along with adaptive components suitable for implementations in buildings will be discussed.

3.1.1 Early examples

Le Mur Neutralisant

Le Corbusier's concept *Le Mur Neutralisant* from the early 20^{th} century was based on the idea that by pumping heated air through a space between large glazed areas the U-value of the wall would increase, and thus the overall building would acquire less heating. But as the fans needed to force the air through the space as well as the heating of it required a lot of energy, little or no energy was actually saved. But the U-value was nonetheless changed, as the temperature at the exterior surface was higher than without the heated airflow. But what actually is done is an addition of a tiny extra heated room, i.e. increasing the heated space. The idea was only implemented in one building *Villa Schwob*, Switzerland, in 1916, it was suggested for several bigger projects as well but where never realised as Le Corbusier was informed of the drawbacks of the concept. Later research of the concept has proven that it could be an energy saving concept if it would be combined with solar heating of the air (Harvey, 1991).

US Pavillion world expo montreal

Richard Buckminster Fuller used one of the very early examples of an adaptive envelope system in his design of the US Pavilion for the World expo in Montreal in 1967. The pavilion was design as a gigantic geodesic dome, 76 meters in diameter and 62 meters high. The dome was constructed from a lattice steel structure with transparent acrylic sheets as façade material. In order to keep the comfort within reasonable levels a computer controlled shading system was used that retracted screens in accordance with the direction of the incoming solar radiation. (Stanton, 1997)

Polyvalent wall

Mike Davies himself described his concept as follows:

'What is needed is an environmental diode, a progressive thermal and spectral switching device, a dynamic interactive multi-capability processor acting as a building skin. The diode is logically based on the remarkable physical properties of glass, but will have to incorporate a greater range of thermal and visual adaptive performance capabilities in one polyvalent product. This environmental diode, a polyvalent wall as the envelope of a building, will remove the distinction between solid and transparent' (Davies, 1981)

To achieve this he suggests a layer wall build up, shown in *Figure 3.1* where each layer fulfils a specific function.

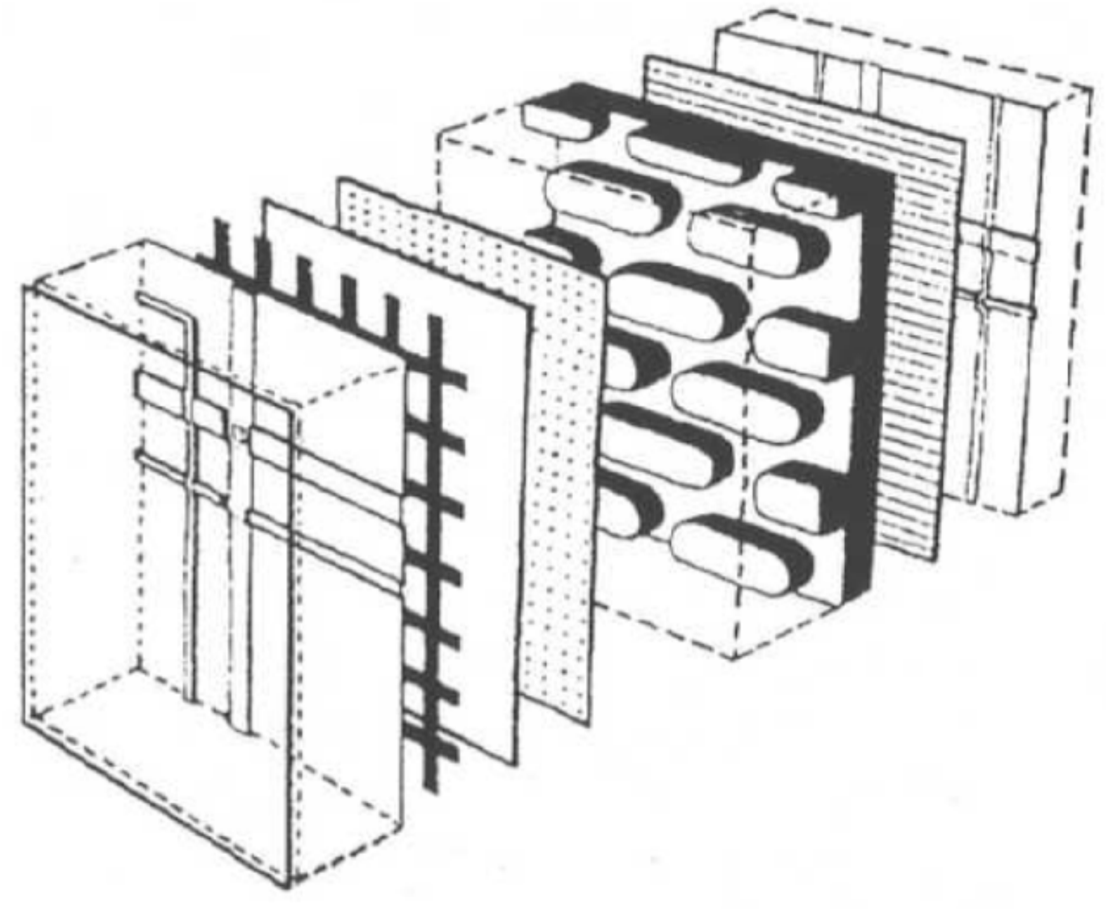


Figure 3.1 Principle sketch of polyvalent wall (Davies, 1981). Interior to the right

The idea of the different functional layers within the glass element is to provide sun and heat protection, and to regulate the functions of the envelope automatically according to current conditions. The wall itself also generates the necessary energy. The idea has not yet been realized but the concept have served as inspiration for many more recent examples for new facade technologies and engaged many researchers.

3.1.2 Contemporary examples

In this section some more recent examples will be presented shortly.

Institute du monde Arab

The southern wall of Institute du monde Arab in Paris is possibly the most well known example of an adaptive building envelope. It was designed by Jean Nouvel and Architecture studio and completed in 1989 and is made out of 240 photosensitive shutters that work as a sun-shading device for the otherwise glazed wall. It is a closed loop system in which the level of radiation on a certain part of the façade is collected and the information interpreted and fed to the actuators cause small motors to open or close the shutters. There is no chance to overrule the system for a user. The shutter is crucial for the interior climate of the building but this kind of highly mechanical solutions tends to break easily and the different parts are not easy to replace when that happens (Coehlo & Maes, 2009). There have been a lot of problems with the façade, especially with fatigue in the moving parts of the system.

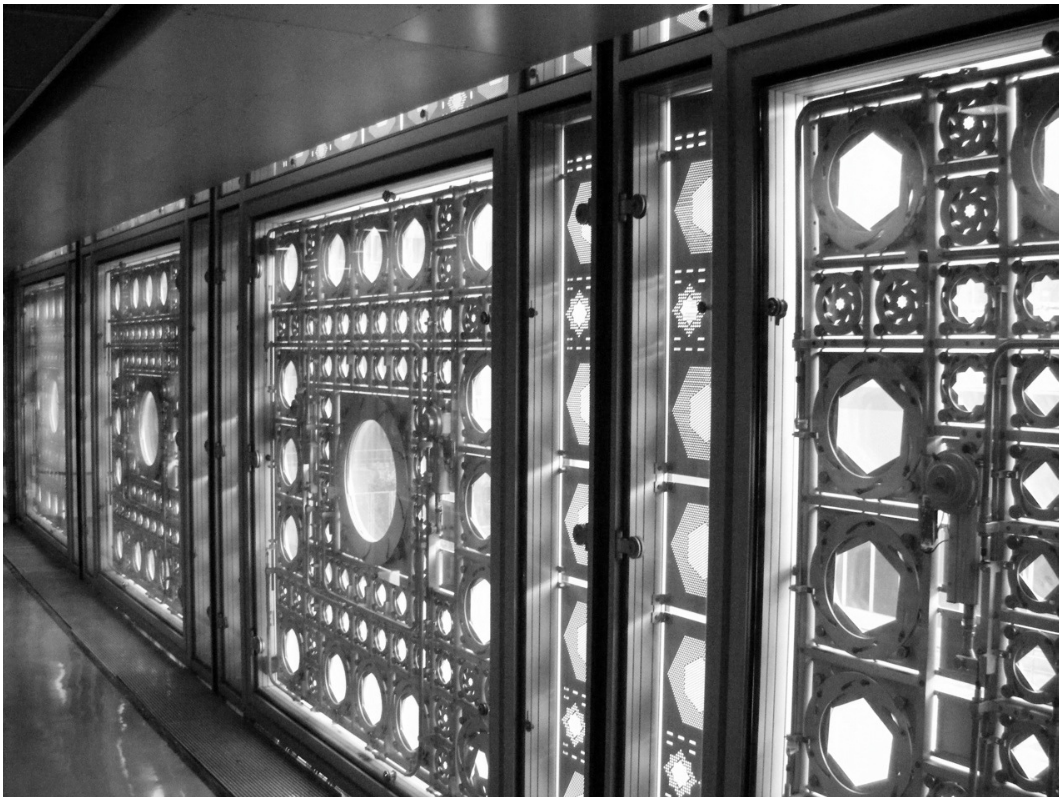


Figure 3.2 Detail of the sunscreen elements

Al Bahar towers

The Al Bahar towers were recently completed in Abu Dhabi it is designed by the architecture office Aedas. It has an adaptive outer skin to reduce the solar radiation into the spaces. The sunscreen is a triangulated pattern similar to that of traditional Arabic sunscreen, *Masharabiya*. It is made from metal frames and fibreglass panels. The panels programmed to open and close according to the movement of the sun. This macro-system is estimated to reduce the solar gain with 50%, which in turn reduces the need for air conditioning. The solar screen also gave another advantages as the solar gain is reduced the glass in the windows do not have to be highly reflective and that improves the interior daylight conditions significantly. Learning from the problems with The Arabic institute in Paris all the elements and components in the sunscreen have been tested, both in wind tunnels and for fatigue, to ensure that they will have the same life time as the building. The system is also constructed in such a way that if a part is damaged it is easy replaceable. (Aedas, CNN, 2012)

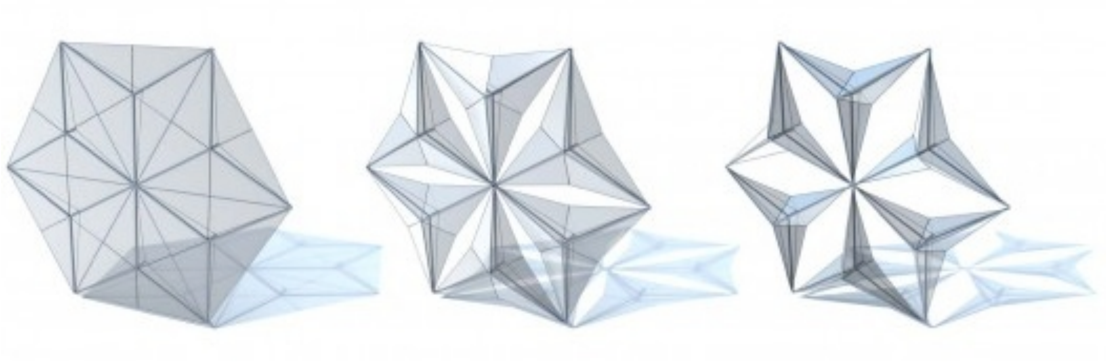


Figure 3.3 Detail of of the sunscreen elements (Aedas)

Media ICT

Media ICT by Cloud 9, was inaugurated in 2010 and in 2011 it was awarded *World building of the year* (World Buildings Directory, 2013) but apart from this it have been in focus due to its high performance and innovative solutions when it comes to energy efficiency and carbon di-oxide reduction. To achieve it high goals that was set early in the design process. Several different adaptive concepts have been developed along side the architectural design, the most striking element being the solar shading system on the south façade. The ETFE–cushions that are used as a transparent envelope are filled with nitrogen gas, as the heat from the sun increases and the need for solar shading advents a vegetable oil will melt and pour into the cushions where it will stick to the nitrogen gas molecule creating a fog. The system is driven mechanically and is triggered by the temperature change of the ETFE surface. This system was developed together with researchers at Fraunhofer institute (Ruiz-Geli *et al.*, 2010).

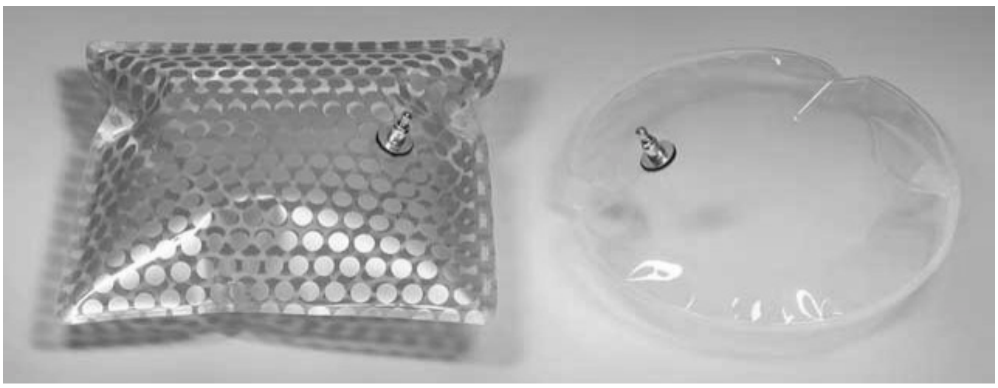


Figure 3.4 *ETFE cushions from Media ICT (RobAid)*

GLASS X

A product already available on the market is GLASSX; it is a PCM solar wall that uses a salt hydrate encapsulated in a polycarbonate container as an opaque layer. The polycarbonate is also painted grey to further improve the absorption. In the GLASSX system a prismatic polycarbonate layer is added in front of the PCM layer, the shape of the prisms are such that they allow solar radiation to reach the PCM in winter time when the solar angle is small but and the extra solar heat is needed indoors but blocks most of the radiation during summer time when the heating demand is smaller, see *Figure 3.5*. (Aschehoug & Perino, 2009, GLASSX, 2013)

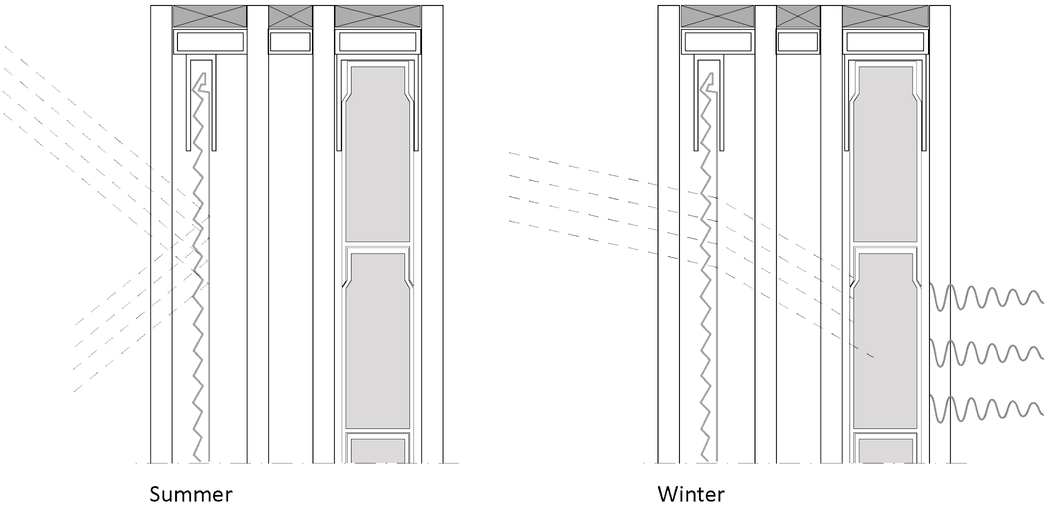


Figure 3.5 *Working principle of GLASSX wall, with a prismatic polycarbonate layer*

Figure 3.6 GLASSX, solar wall with PCM

Solar balloons

One interesting example, which unfortunately was not permanent, but only an art installation, was the Solar Balloons by Spridd at Bonniers Konsthall in Stockholm. The installation was created by Spridd architects together with Peter Kjaerboe a researcher at the Department of energy technology at KTH Royal Institute of Technology and a sail maker; Peter Håkansson (Ruin, 2011). The system is a mixture of a micro and macro mechanism with a solar cell at the exterior façade, which generate electric power, used to power a fan that inflates the large balloons. Thus as the sun shines and electricity is produced, the balloons work as solar shading, without demanding extra energy input or advanced control systems. The only necessary adjustment is the calibration of the fan in relation to the size of the balloons and the amount of electric power that is retrieved from the photovoltaic cell. The balloons do not only block the solar heat gains but it also alters the entire ambience of the space.

Figure 3.7 Solar Balloons by Spridd (Photo by Mattias Givell)

3.1.3 Examples under development

There are numerous of examples of concepts for adaptive building envelopes under development around the world. A selection from them will be presented in this following section.

Homeostatic façade

The homeostatic facade system is a sun shading system developed by the architecture firm Decker Yeadon. It was inspired by the phenomena of homeostasis in biological systems, the system that our bodies use to adapt to the environment. The idea is that it could regulate the climate within the building automatically and without using large amounts of energy. It uses dielectric elastomers, chosen for their low need of energy input and flexibility in shape. The dielectric elastomers can as described in section 2.3.3, transform electric energy into mechanical work. In this conceptual façade design ribbons of dielectric elastomers are placed in between the two glazed layers in a double façade. The dielectric elastomers are the capacitors and by wrapping them over a polymer core that works as the actuator of the system, the entire ribbon can open and close like wings, depending on the environmental conditions in the surrounding. Using the surface of the material as the motor enables a local control over the reaction in the façade with high precision. The flexibility provided by the dieletric elastomers and the polymer core also enables freedom of patterning (Decker Yeadon Architects, 2013).

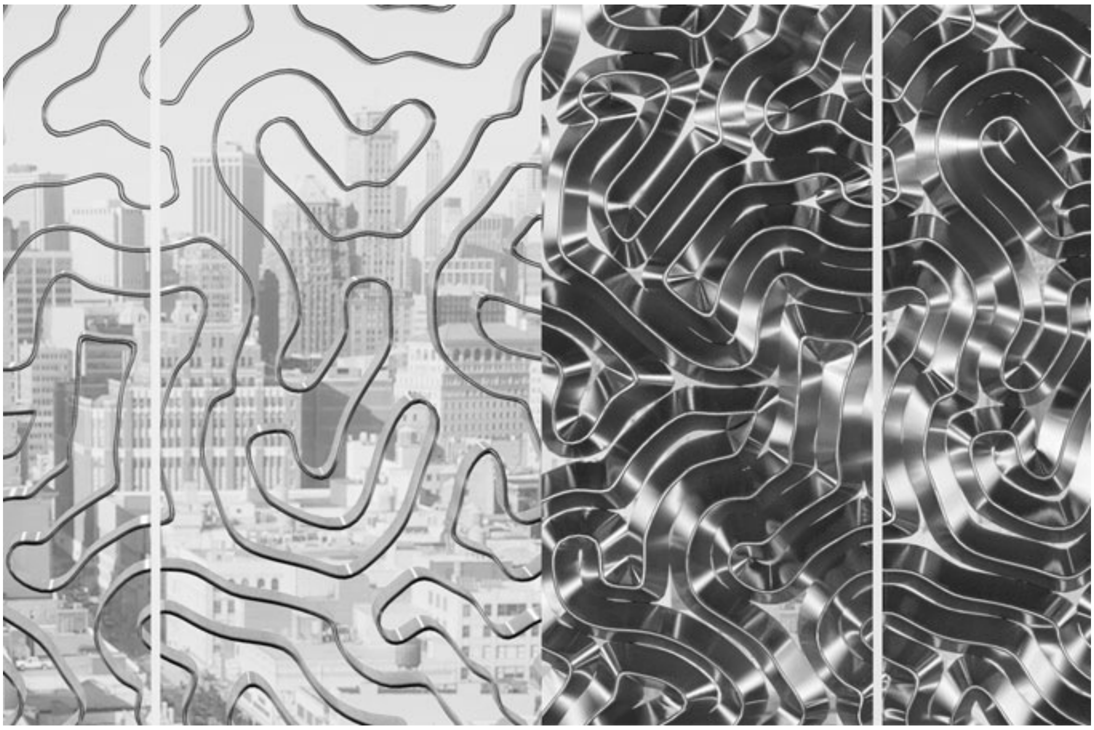


Figure 3.8 *Example of pattern for homeostatic façade, in open and closed configuration. (Decker Yeadon Architects, 2013)*

Smart energy window

Smart energy window is a pilot project currently being tested in the Netherlands. The concept is that by introducing a small electric current, the g-value of the window can be altered, and thus controlling the solar radiation that enters into a space. But, the special feature is not the change in transparency per se but the fact that the glass surface produces electricity from the solar radiation that hits the surface and that the produced is related to the level of transparency. The darker the glass the more energy is produced (PEER+, 2009). There are little information of how these properties are achieved but one can guess that some kind of liquid crystals are used as one of the founder is an expert in that field of chemistry. The different g-values and the corresponding generated power could be seen it *Figure 3.9*.

Figure 3.9 *Different stages of the Smart energy glass and a principle indication of the generated electric power (PEER +)*

Bionic breathing building skin

Investigating the existing concepts of adaptive building envelopes whether realized or only conceptual, a lot of them have been inspired from phenomena in nature. Knaack and Badarnah (2008) were inspired from the different types of respiratory systems that you can find in nature when creating the concept of a bionic breathing skin for buildings. Through research and analysis of these different systems they found that the surface area where the exchange take place actually is divided into many, many small parts. The building skin was therefore designed out of small components that by acting together can create a global behaviour, by either inhaling or exhaling, illustrated in *Figure 3.10* (Knaack & Badarnah, 2008).

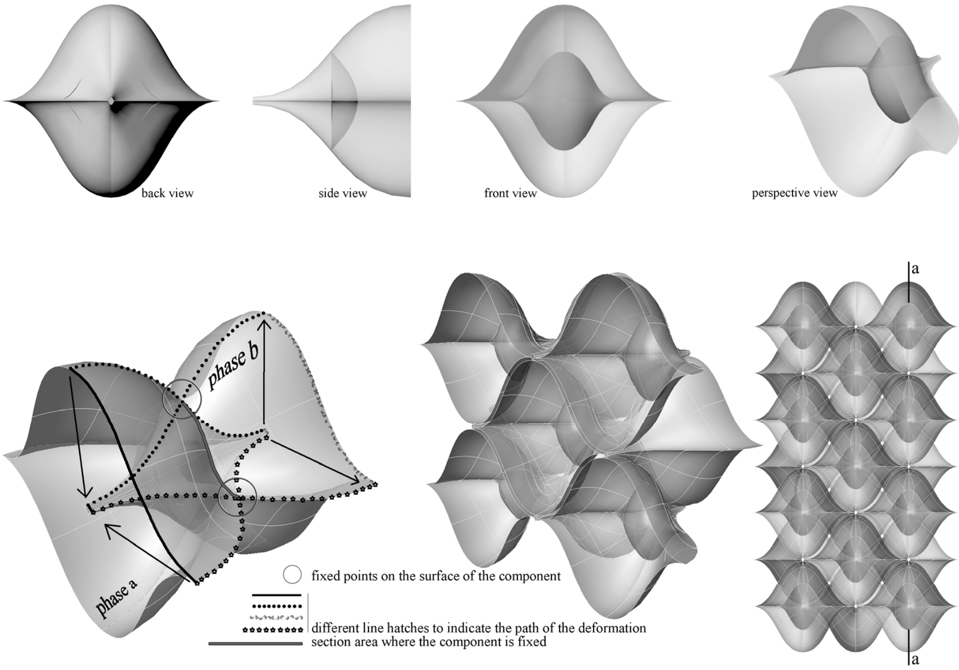


Figure 3.10 Principal of bionic breathing building skin (Knaack & Badarnah, 2008)

Active thermally insulated windows

Active thermally insulated (ATI) windows are a concept and a closed loop system that can control the thermal insulation value of a window through the use of thermoelectric units. This kind of unit can transfer heat in the opposite direction of the naturally induced heat flow. The units is installed in between the panes in a multi-pane window and by applying a voltage they can help with heat transfer and control, to further enhance their performance they can be coupled with fans. In order for the thermoelectric units to respond to the varying weather conditions in the environment around a building both sensors and thermostats are used to dynamically control the power supply and the effect of the fans. CFD (Computational Fluid Dynamics) modelling of the heat transfers in the window have been performed on a smaller selection of weather cases, the results from these tests are then used to create a surrogate model which holds for every possible case and use that as a governing control model.

The TE (Thermoelectric) units perform in two directions when the interior temperature exceeds the exterior the window system need to reduce the heat transfer to the outside while when the temperature inside is lower than outside the they instead reduce the heat transfer from the outside and in.

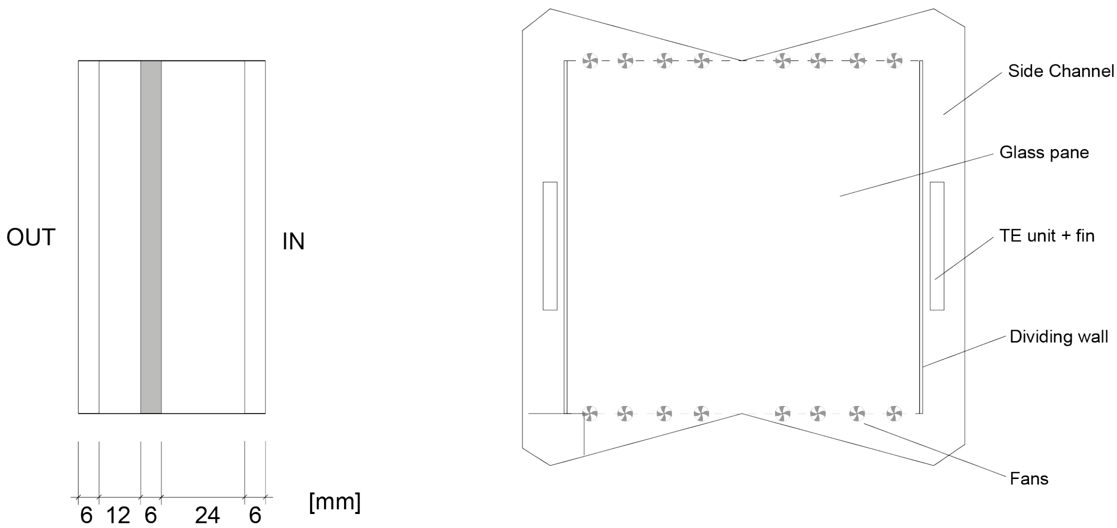


Figure 3.11 Principle design of Active Thermally Insulated windows

As you can see in *Figure 3.11*, the system is built up by three panes with air gaps in between, two channels, the TE units, two fins, fans, a heat sink, sensors and a thermostat. The fins are attached to the TE units in order to increase the heat transfer from the TE units to the surrounding air; this subsystem is located in the side channels. The heat sink is used to reduce the thermal resistance between the exterior climate and the TE units. The fans, which can be found in both the top and the bottom of the air gap that are bounded by the interior and the middle pane, are there to support the convection.

The reduction of heat loss through the windowpane is achieved by introducing electric power. In order to see the relation to the energy efficiency of a normal window with the same build up as the ATI-window the same measure as for HVAC-units are used. The Coefficient of Performance (COP) is the relationship between the amounts of heat, *Q*, transferred in the system for a given electric input, *P*.

$$\mathbf{COP} = \frac{\boldsymbol{Q}}{\boldsymbol{P}} \tag{3.1}$$

The COP for an ATI window is calculated as the difference in heat transfer between a normal window and an ATI window over the electric input used by the TE units.

$$\mathbf{COP}_{\boldsymbol{ATI}} = \frac{\boldsymbol{Q}_{\boldsymbol{normal}} - \boldsymbol{Q}_{\boldsymbol{ATI}}}{\boldsymbol{P}_{\boldsymbol{TE}}} \tag{3.2}$$

(Zhang & Messac et al., 2010)

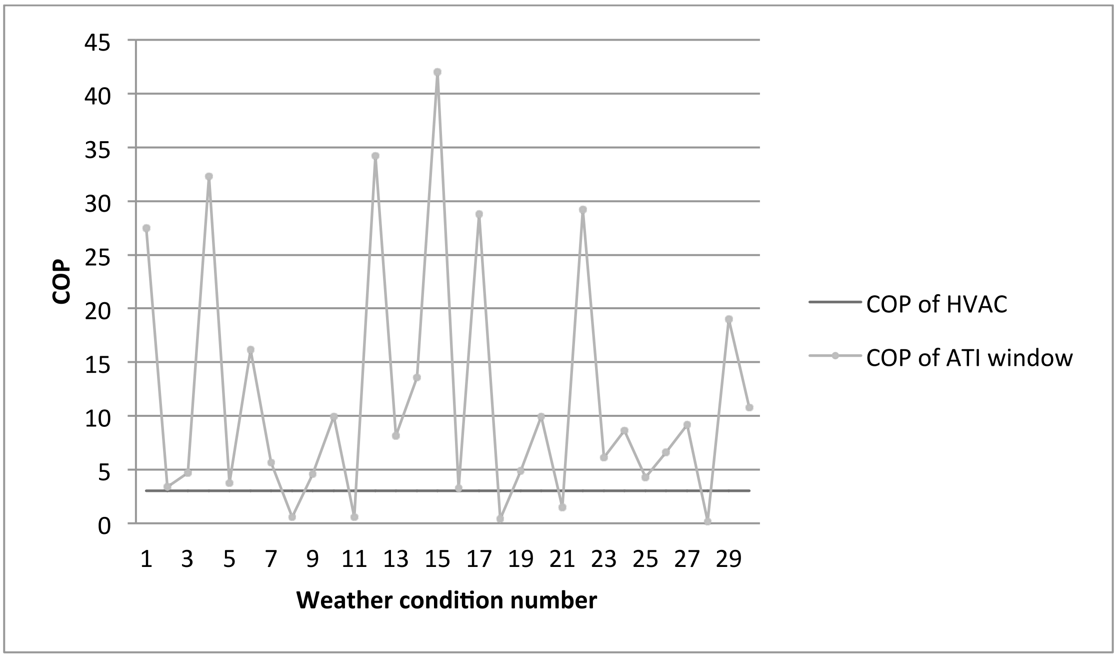


Figure 3.12 Values of COP for different weather conditions (Zhang & Messac, et al.)

From *Figure 3.12* we can conclude that the COP for the ATI window in almost all weather scenarios exceeds that of an ordinary HVAC system that usually reaches a COP of 3. (Zhang & Messac et al., 2010)

3.2 Workshop

In order to learn from how others think when it comes to possible solutions for adaptive building envelopes, a workshop was organized for the students in master year 1 and 2 within the course *Building design lab*. The course is open for both master students from both the master program of architecture and urban design and the master program of Structural engineering and building technology. The aim of the course is to through design and knowledge and use of energy simulation software design a façade for an office building.

3.2.1 Method

The workshop was divided into two major parts a *top down* and a *bottom up* assignment. Each of the assignments was introduced by a short lecture. The initial task; assignment 1, was started off through a general introduction to heat transfer mechanism and phenomena that affect the boundary conditions and a problem introduction. The assignment was formulated as;

"Formulate a variation of weather situations for which the optimal properties of the building envelope varies. Analyze which indicators that could be used to create the responses that will change the properties."

The objective of the assignment was to formulate a set of boundary condition combinations on a wall. The types were created from assumed combinations of phenomena that affect the climate. The phenomenon were grouped into three categories; weather, internal gains and comfort expectations.

For each set of boundary conditions the optimal properties of the building envelope was determined. The combination of various phenomenon and optimal properties could then be used to find good indicators for the response in adaptive building components. The first assignment was then concluded through a brief discussion and an exchange of ideas.

From the parameters found in the top-down part (assignment 1) of the workshop together with knowledge gained from an inspirational lecture about existing materials that respond to different kinds of stimuli, the assignment was to sketch concepts and ideas for adaptive building components and discuss how they could be implemented into a building design and what benefits it would give. The students were told to think outside the box and that there were no boundaries in material properties; the desired material properties were assumed to be possible to achieve by advances in material research. There was no limitations to how many steps the response was achieved or how many materials that were used.

3.2.2 Aim of workshop

The aim of the workshop was to get the students to start reflecting on the role of the envelope in the building performance. And how the design of the envelope can contribute to the energy performance on the building but at the same time act as a strong architectural component.

3.2.3 Results from the workshop

The workshop resulted in several different suggestions for adaptive envelope elements and also entire envelopes. A few of them will be presented and discussed here, the remaining can be found in appendix A. All illustrations in this section are used with permit from the students.

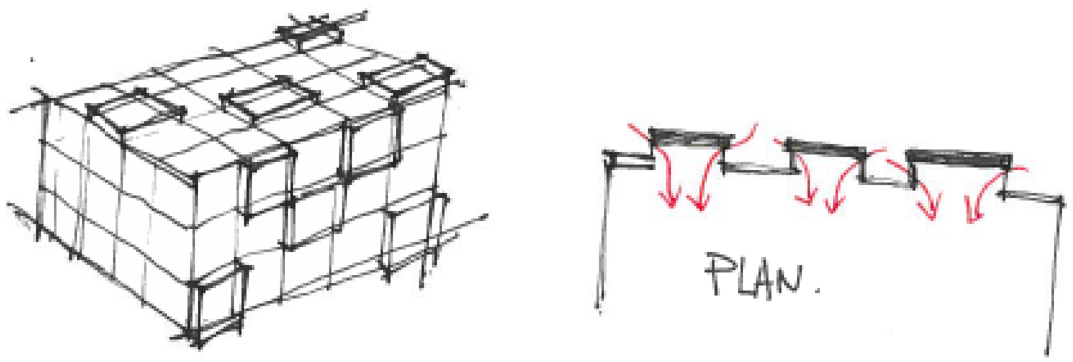


Figure 3.13 Illustration of retractable windows

One of the ideas that were presented during the workshop was the principle of retractable walls sections (principle seen in *Figure 3.13*) with translucent part that could be placed both in the façades and the roof providing daylight for the interior space, but only where and when it is needed. The layout also considered reducing the amount of direct sunlight into the rooms by only having window surface on the sides of the box, but by doing that you would also loose valuable views to the exterior. One of the larger benefits with this concept is that the boxes as they are pulled back flushed to the wall, contribute as if they would have been part of a solid wall. They might increase the insulation of the entire building envelope, assuming that the joints are well executed.

Another concepts that also deals with providing views out and daylight, only where occupants are present, the concept it suggest dielectric sheets to be used as a responsive solar shading and piezo-electric tiles on the floor are used to detect user presences. Piezo-electric materials generate an electric current when exposed to pressure. The footsteps of a person entering a room create a current that in turn causes the dielectric sheets to curl and open. Principle of the concept and design suggestion can be seen *Figure 3.14*.

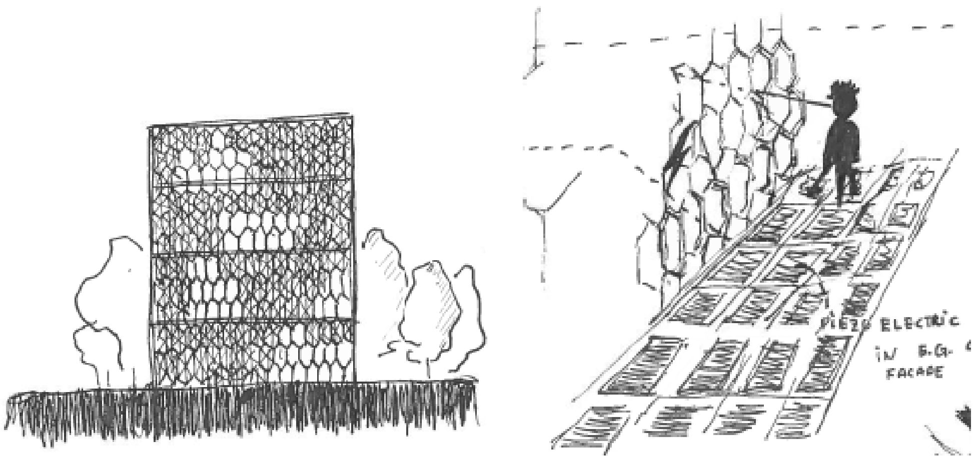


Figure 3.14 Dielectric solar shades

Other concepts focused more on the solid parts of the wall, like introducing adjustable airtightness in the wall to allow air to infiltrate or color changing paint that can reflect or absorb energy depending on the temperature or on the wavelength of the incident light. Color changing paint is a concept that is easy to grasp and is used on buildings already today in some parts of the world. The variable airtightness is more complicated to understand, you will need to simulate it to fully understand the consequences of such a concept and how all the other features and parts of the wall assembly should be designed to achieve the best performance of it.

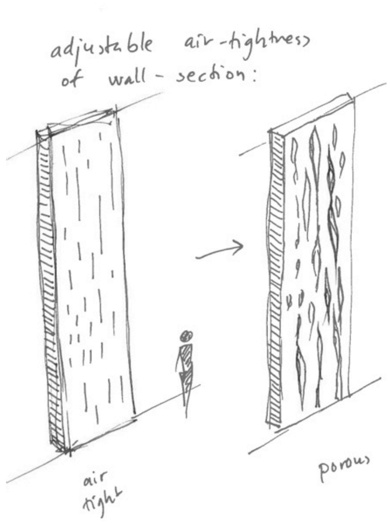


Figure 3.15 Adjustable airtightness

The groups of students that managed reach the most well considered and thought through resulting concept were the ones that were a mix between architecture and engineering students. This could of course be a mere coincidence as the number of group was small. You could on the other hand relate that to the fact that the knowledge base was wider as the students form two different fields cooperated. Those groups had time to also consider the materials or systems that actuated the desired change in the envelope.

4 Reflections

Our modern buildings are becoming more and more airtight and have higher insulation values and that, together with the need for daylight, often result in overheating problems that actually is depending mostly on the building design. It is a problem that has been created through the choice of envelope structure. But as the seasonal differences are that large here in Sweden, we can not go back to thinner walls with less insulation and glazed areas with higher U-values, because over a year we need it in order to keep the comfort. At the same time the building sector is predicted to be the sector in which most energy savings could be done. Adaptive envelopes are one answer to that question. The complexity of the envelope in terms of properties and acquirements reflect on the intricacy of the design of adaptive envelopes. Even if it might be easy to intuitively come up with a concept answering to one part of the problem like for example solar insolation. The relation and influence of that concept on the rest of the parameters that make up the functions of the building envelope making it hard or near impossible to visualize the overall resulting impact. This is because of the broad knowledge that is needed to be able to keep it all in mind when searching for suitable design concepts. It is hard to predict how trade offs between the different parameters will affect the overall performance of a wall without simulating each of the iterations and variations and then compare them. But I believe that there are great opportunities to both save energy and improve interior comfort through adaptive building envelopes.

Both the micro and the macro mechanism offers great possibilities for creating adaptive envelopes, which mechanisms to choose is as for every design decision dependent on the location and pre-conditions for that specific project. Micro systems are the systems in which the reaction is occurring on an atomic level and therefore cannot be seen with the human eye. These types of systems are reliable as the material properties once understood and used stay the same, but they lack in control. Thermochromic glass treatments will go dark if the temperature is high without considering the daylight levels inside a space and can therefore despite the good intention, cause discomfort. Macro systems on the other hand suffer from their need for external energy input and the size of the elements. Not all building envelopes can have moving part externally. In order to resolve the problems with control for the micro systems and decrease size of elements in macro systems a combination of the two levels is a closed loop system, where smart materials can be used as sensors, creating for examples electric energy that can be used to alter the shape of a dielectric elastomer that through its shape shift fulfils a new function in the envelope system.

Adaptive solar shading could really be the key to solving problems with overheating. If the heat gain from the sun could be eliminated, then HVAC cooling systems would not have to be used to the same extent as they are today in our climate. Different solutions for adaptive solar shading are by far the most seen example of adaptive envelope solutions. It is rather easy to calculate the effects and benefits from an adaptive solar shading system whether it is being done as a mechanical system or based on material properties. Simply put; the more you reduce the heat gain from the sun the less you have to cool. This is a simple relation, but it only considers one of the factors that a building envelope has to provide for. In office buildings for example, which usually have large cooling demands, automatic solar shading is becoming more and more of a standard. But there are still possibilities for improvement; the development of solar shading systems seems to have stagnated. Examples like the sunscreen at Al Bahar towers and the dielectric system currently under development shows that we can go further both in terms of coherence between the design and the building service function and in implementing smart material creating solutions that are less dependent on input energy.

The complexity of the envelope function also makes it close to impossible to prove by the means of simple calculation that the energy or comfort benefits will compare to the investment cost. But as simulation and calculation software rapidly advances it will soon be possible to motivate adaptive solutions even for projects that do not fall into the category of research or showcase projects. But the research needs to be made available to building industry on a broader level, in order for it to become more than just research. It goes for both different simulation techniques and software, the more used they get and the more widespread they become the more the building design can win from it.

Most adaptive envelopes react to radiant heat and heat transfers by means of convection, but adaptive solutions for conductive transfer also offers possibilities to alter the performance of a wall over time. Paying closer attention to the impact of the thermal inertia in a building and how that affects the comfort and energy production is another solution that would be interesting to develop. Adaptive access to heat storage could be one way to even out the effects from different weather scenarios within the same season. Phase change materials incorporated into common construction materials like plasterboards are already on the market and only need to find its proper place, same as for the reinforced concrete when it replaced wooden beams and pillars. Alterations to the U-value of the wall by introducing air flows or by the means of smart materials that change shape to increase insulation thickness would be a solution that would be perfect for situations where the changes in weather from extreme warm to extreme cold are occurring within small time periods, one extreme during the day and another during the night for example, like in the desert areas close to the equator.

It is interesting to see the similarities between the concepts suggested by the students in the workshop that was held and those that currently are being researched. Brian Cody (2012) is currently researching a project with deploying movable elements, which can be used to vary the transparency level of the façade, from 0% in spaces that are currently not in use whereas more light can be let into used spaces, but the elements can also be controlled by exterior and/or interior conditions, allowing them to adopt not only to the activity in the spaces but also the environment (Cody, 2012). Very similar to several of the concepts suggested by the students, meaning that the ideas are valid but in order to be realized they need to be more developed and researched.

The view of materials in the building industry today have resulted in a separation between the design of the envelope from a energy performance perspective and the design of the exposed surfaces, not only in terms of a mind set but actually divided into two different professions, the building performance engineers design the inside of the envelope while the architects are responsible for the interior and exterior cladding. The building envelope is the boundary between interior and exterior conditions, but it is often considered as a two-dimensional surface rather than a three-dimensional often layered building component. This view constrains the design of building envelopes as it dismiss the possibilities to use the design of the build up within the depth of the wall to improve the performance of the overall envelope. In envelope design materials can be exploited to a greater extent, instead of simplifying their material properties in calculations and simulation their natural adaptive properties can be used in adaptive envelopes. The different properties at different conditions just need to be analysed so that they might be used in the most efficient way.

The use of smart materials in the building envelope could be one possible way to approach the problem. Phase change materials can through their ability to store heat reduce the peaks in interior climate so that cooling and heating requirements will be minimized. Shape changing polymers and alloys can be used to alter the geometry of the wall thickening the insulation or introducing air gaps to allow convection through the envelope. Thermo-bimetals can be used as self controlling ventilation vaults opening and closing depending on the surrounding temperature much a like the Bloom pavilion by Doris Kim Sung (2014). There are many possibilities but the designs with smart materials need to be as robust and reliable as the mechanical and conventional systems. Based on that the use of smart material is often questioned when compared to existing systems that can perform the same result, but with a need for energy input. This is because new systems are more expensive and that they have not been tested in real situation to the same extent as the conventional systems. Mechanically controlled translucent blinds that are programmed to be used when an indicator thermometer reaches a threshold values might work just as well as a glazing with a thermochromic surface treatment in terms of reduction of heat gain from the sun and resulting daylight conditions in the room. But the smart material has the advantage to be independent of a large system and can instead act directly upon the threshold temperature, thus reducing the risk of failure somewhere along the process from sensor to action. As material research is developing fast the possibilities, as a building performance engineer or an architect, to ask for or develop materials suitable for a specific task are many. It have been done in other fields for a long time, but in building technology research have been more focused on developing structural elements or single building components rather than finding something that can affect the entire envelopes performance as its properties are perfect for its specific task.

From discussions with my supervisor Axel Berge, brainstorming about concepts for adaptive building envelopes I discovered that there is a problem of insecurity around the design questions that addresses the questions that is on the border between the field of architecture and building performance design. I believe that this insecurity is all over the construction sector, resulting in solutions that are accepted based on lack of courage and knowledge outside your own field. The same situation occurred in during the workshop, engineering student feel less secure on commenting on the aesthetics and the architecture students are instead afraid of speaking their minds when it comes to the building physics. In order to design coherent solutions where space and performance informs one another, the different groups within a design team need to understand each other's problems better. As a building performance engineer you need to understand the impact that, for example, that a solar shading will have on a buildings appearance and raise the design questions concerning not only aesthetical aspects but also system design and influence on interior climate and comfort on a broader level. As an architect it is crucial to understand how the choices you make on form and appearance will have a direct influence on the performance of the building. But with that said, it is important to be able to think outside the box and instead of assuming that you know the best solutions, really test them. If only through simple simulations, the knowledge gained could largely affect the resulting project. A good communication about this question and design teams including both engineers and architects are needed in order to properly design adaptive building envelopes and concepts.

The design of adaptive envelopes offers yet another possibility for the designing architects and engineers. The visual actions in an adaptive façades advertise changes in the environmental loads acting on the buildings. This enables unique design possibilities. Not only do the envelope or façade itself need to be aesthetically appealing and suit in the context. But it could also be designed as an event in the daily life of the city that could help raise awareness of the different scenarios present in a building and the energy needed to cope with them in order for the interior spaces to remain comfortable. The opening of shutters or a colour change of the façade triggers questions from the spectators like; why is the façade changing and when is the altering its appearance. These changes in the exterior or an interior surface of a building help to make the connection between changing environmental load and its relation to the interior climate, and the reaction visible and interesting for everyone. The building envelope can, by displaying the environmental impact on the building and the energy use act as a gigantic billboard for sustainable buildings. But with that said it is utterly important that the use, of smart material an adaptive building components does not stay as only billboards. They need to be true and not only added to promote a sustainable image without truly being a part of the buildings performance.

4.1 Further studies / work

Considering the amount of current research in adaptive building components I believe that more and more solutions will pop up. The FACET group is currently working on developing prototypes that will answer to their simulated façade set-up. Solar responsive structures have been highly overrepresented and even though there still are more to be done there, I believe that we will see an increased number of examples of concepts that are more integrated within the walls.

As continuation of this thesis I would suggest looking closer into how to properly simulate adaptive behaviour. And also look into how different priority order, between different parameters affect the interior comfort and energy efficiency.

5 Conclusions

The sustainable buildings of today have been optimized element by element, the wall stratification and insulation level, the windows are as good as they may possibly get and the ventilation system, fans and heat exchanger are getting better and more energy efficient all the time. But in order to reach even further, the building have to be seen more as one optimized system rather than a collection of small pieces. It is not enough to have well-insulated and airtight walls that cope with most of the climatic situations when you during hot periods need to cool the building, and then something is substantially wrong. The need for a performance-based architecture is therefore rising. Shape, placement and building systems need to work together to improve the energy performance. The building needs to be in closer relation to the climatic context, and as the building envelope is the border between the surrounding climate and the interior the envelope design is becoming a crucial parameter in sustainable and energy efficient building design. As Mark Weston (2010) puts it '*building sustainable is simply good design and it always have been'*. And from this thesis it is clear that there are great possibilities with adaptive envelopes of different kinds but that there still lack commercially available solutions and development. The envelope design is dependent on so many parameters and has so many possible solutions that it soon turn into a very complex problem. But despite that there are great possibilities to save energy as shown in the studies performed by the FACET group.

Based on my studies I believe that despite the complex design problem the use of adaptive envelope solutions can improve both energy efficiency and comfort. And be the future for building performance design.

6 References

Abel E., Elmroth A., 2008 *Byggnaden som system*, Studentlitteratur, Lund

Addington M., Schodek, D., 2005: *Smart materials and technologies in architecture*, Architectural press, Oxford

Aedas, 2012, *Al Bahar towers,* www.aedas.com, 2013-10-12

Aschehoug, Ø. and Perino M., editors, 2009: Annex 44 - *Integrating Environmentally Responsive Elements in Buildings , Expert Guide – Part 2 Responsive Building Elements,* IEA - ECBCS.

Boer B.d., Ruijg. G. J. *et al.,* 2011: *Energy saving potential of climate adaptive building shells- Inverse modelling of optimal thermal and visual behaviour*, Proceedings of the International Adaptive Architecture Conference, London, 3-5 march, pp.16

Brand S., 1994: *How buildings learn: What happens after they're being built,* New York: Viking Press.

Brownell B., 2008, *Transmaterial 2: A Catalog of Materials That Redefine Our Physical Environment*, Princeton Architectural Press

CNN, 2012: *Cooling buildings in Abu Dhabi heat*, http://www.youtube.com/watch?v=GSbJIlpv4Dc

Cody B., 2012: *Form follows energy,* xia-international-online, http://www.xia-international-online.com/, 2013- 11-23

Coehlo M. & Maes P., 2009: *Shutters: A permeable surface for environmental control and communication*, MIT Media Lab, Cambridge, Massachusetts,US

Davies M., 1981: *A wall for all seasons,* RIBA Journal, 88(2), p 55–57.

Decker Yeadon architects, *Homeostatic façade system* http://www.deckeryeadon.com/projects/HomeostaticFacadeSystem.html

Fred Guttfield, 2012: *Deployable External insulation*, http://vimeo.com/41924777

http://guttfieldarchitecture.co.uk/project-view.php?project=10,

Glass J., 2002: *Encyclopedia of Architectural Technology*, Chichester: Wiley-Academy

GLASS X: http://www.glassxpcm.com, 2013-11-14

Hagentoft C-E., 2001, *Introduction to building physics*, Studentlitteratur, Lund

Hagentoft C-E. (2012) *Potential impact on innovative and active building envelope components and materials*. 5th International Building Physics Conference, Kyoto, Japan, May 2012.

Hagentoft, C-E. (2013): *Dynamical U-value of a wall structure by using controlled interior forced or natural convection*. Abstract 2nd Central European Symposium on Building Physics – CESBP 2013, Vienna, Austria, September 9-11

Harvey B., 1991: *Le Corbusier and the "Mur Neutralisant": An Early Experiment in Double Envelope Construction*. Proceedings of the Ninth International PLEA Conference. pp. 257–62.

Hutcheon, N.B, 1963: *Requirements for Exterior Walls*, Canadian Building Digests, CBD-48.

Badarnah L. & Knaack U., 2008: *Bionic breathing skin for buildings,* Proceedings of SB07 Portugal: Sustainable Construction, Materials and Practices: Challenge of the Industry for the New Millenium, Department of Building Technology, Delft University of Technology, Delft, The Netherlands

ICD (Reichert S., Menges A.), 2006: *Biomimetic Responsive Surface structures*, icd.uni-stuttgart.de/?p=5655, 2013-10-02

Jeffrey Stanton, 1997: *EXPO 67 – Architecture,* http://www.westland.net/expo67/map-docs/architecture.htm, 2014-02-23

Kim Sung D., 2014: *Bloom pavilion,* http://www.dosu-arch.com, 2014-02-25

https://www.ted.com/talks/doris_kim_sung_metal_that_breathes

Kirkegaard P. H., 2011: *Development and evaluation of a responsive building envelope*, International Adaptive Architecture Conference, Building center, London

Kroschwitz, J. (ed.), 1992: *Encyclopedia of chemical technology*, New York, John Wiley & Sons

Künzel H.M. (1999): *Flexible vapor Control Solves Moisture Problems of Building Assemblies – Smart retarder to replace the Conventional PE-film, J. Thermal Envelope & Building Science*, Vol. 23, July 1999, pp. 95-102

Loonen R., 2010: *Climate adaptive building shells- What can we simulate?,* Technische Universiteit Eindhoven,

Media ICT : www.worldbuildingsdirectory.com, 2014-02-24

Mehrabian S., Younesi,G., Rasoulzadeh F., 2013: *Creation Sustainable Building shells using smart materials,* Advanced materials Research vol. 685, 2013, pp. 240-244

Nicol J. F. & Humphreys M. A., 2002 : *Adaptive thermal comfort and sustainable thermal standards for buildings* ,Energy and Buildings, Vol. 34,2002, pp. 562-572, Oxford, UK

PEER +, 2009: *Smart energy glass*, http://www.peerplus.nl, 2014-02-23

Peters S., 2011: *Material revolution Sustainable and multi-purpose materials for design and architecture*, Birkhäuser, Basel

RobAid, 2010: *Etfe-material-research-made-plastic-facades-more-practicable-*

and-affordable, http://www.robaid.com/tech/etfe-material-research-made-plastic-facades-more-practicable-and-affordable.htm, 2014-02-23

Ruin K., 2011: *Soldrivna ballonger på Bonniers konsthall,* Newsletter 1-11, IEA Task 41

Ruiz-Geli E. *et al.,* 2010: *Media-ICT*, Actar Illustrated

Shepherd J., Shindell D., O'Carroll C., 2002: *What's the Difference Between Weather and Climate?,*NASA

SMHI, 2013: *Climate data for Sweden*, www.smhi.se/klimatdata, 2014-02-23

Van der Aa A. Co-authors: Heiselberg P., Perino M., 2011: Annex 44- *Designing with responsive building components, IEA- ECBCS*

Weston M., 2010: *Memory Mesh: Conformationally Adaptive Solar Shading*, Proceedings of the 14th Congress of the Iberoamerican Society of Digital Graphics, pp. Bogotá, Colombia, November 17-19, 2010, pp. 412-414

Wyckmans A., 2005: Doctoral thesis, Intelligent building envelopes, *Architectural concept & applications for daylighting quality*, Norwegian University of science and technology, faculty of architecture and fine art,Trondheim

Zhang J., Messac A. et al., 2010, *Adaptive Optimal Design of active Thermally Insulated Windows using surrogate modeling,*

Appendix A

Summary of the results from the workshop

Adaptive Building Components

The optimal properties of a building envelope changes depending on the outdoor climate and the desired indoor climate and the effect of various heat sources. With a traditional static approach, a set of constant properties is chosen for the building envelope. Variations in the climate are handled by technical systems that add or remove heat, like radiators or chilled beams. Both adding and removing heat demands energy. If the building envelope can adapt to variable climate conditions, the desired indoor climate can be maintained over the year, with less need for heating and cooling.

The aim of the workshop was to create new concepts for climate adaptive building components. The discussion was held from two different perspectives; a top down perspective and a bottom up perspective. With the **top down** perspective the students looked at the current climate situation and speculated freely around the kind of properties that are desirable in the building envelope. A **bottom up** perspective on the other hand is based on available technology and the students combined known materials to form components with the appropriate adaptable properties.

The work was divided into two assignments based on the two perspectives:

Assignment 1: Top down

The assignment started with a presentation of heat transfer mechanisms and the various phenomena affecting the boundary conditions.

The assignment was formulated as;

> *"Formulate a variation of weather situations for which the optimal properties of the building envelope varies.*
>
> *Analyze which indicators that could be used to create the responses that will change the properties."*

The objective of the assignment was to formulate a set of boundary condition combinations on a wall. The types were created from assumed combinations of phenomena that affect the climate. The phenomenon were grouped into three categories; weather, internal gains and comfort expectations.

For each set of boundary conditions the optimal properties of the building envelope was determined. The combination of various phenomenon and optimal properties could then be used to find good indicators for the response in adaptive building components.

Assignment 2: Bottom Up

From the parameters found in the top-down part of the workshop together with knowledge gained from an inspirational lecture about existing materials that respond to different kinds of stimuli, the assignment was to sketch concepts and ideas for adaptive building components and discuss how they could be implemented into a building design and what benefits it would give. The students were told to think outside the box and that there were no boundaries in material properties; the desired material properties were assumed to be possible to achieve by advances in material research. There was no limitations to in how many steps the response was achieved or how many materials that were allowed to be used.

How we will use the material in our research

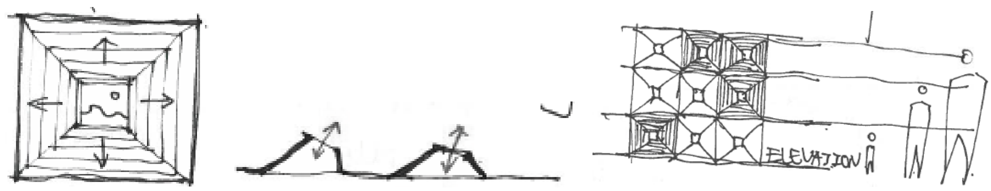
Our next step will be to organize the different concepts into groups dependent on which properties they affect. From this structure we will have a basis for analysis of the workshop outcome. Some ideas from each group will be analyzed more in detail. The analysis will focus on energy performance through basic simulations of heat transfer, day lighting and energy balance. If there are obvious moisture risks those will be analyzed as well, either through simulations or through a discussion.

Some of the analysis will be part of the Master's thesis *'Adaptive Building Envelopes'* and some will be part of the article *'Concept Development for Building Materials and Components of Tomorrow'* which will be presented at the Nordic symposium of building physics 2014 in Lund.

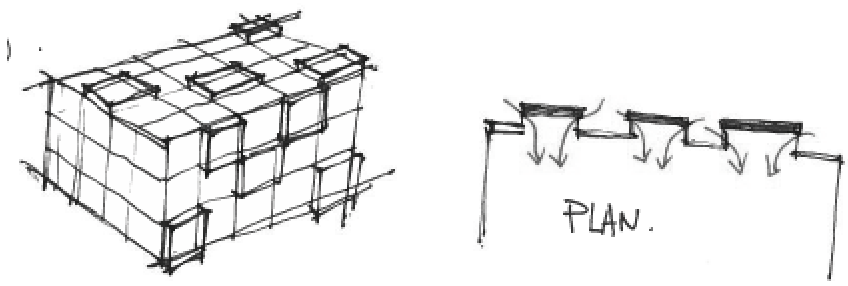
Resulting concepts for Adaptive Building Components

Following is a summary of the concepts suggested by the students.

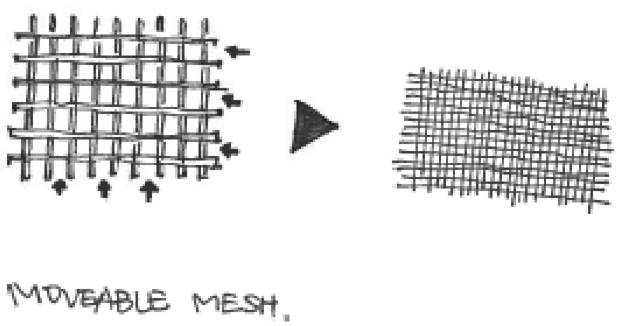
1. **Moveable window**
   Windows which can be moved within and thus let the occupants chose their own view and also shield the direct sunlight in favor for diffuse light.



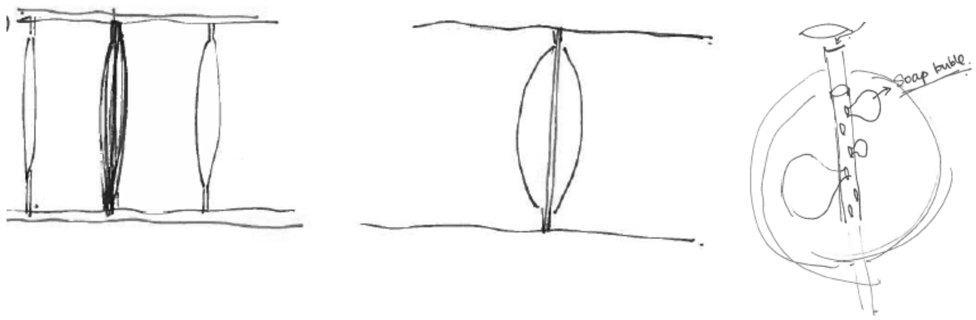
2. **Retractable windows**
   Windows on the sides of retractable squares on the façade. Will reduce the direct sunlight and the direct sunlight will hit the walls instead of reaching into the room.



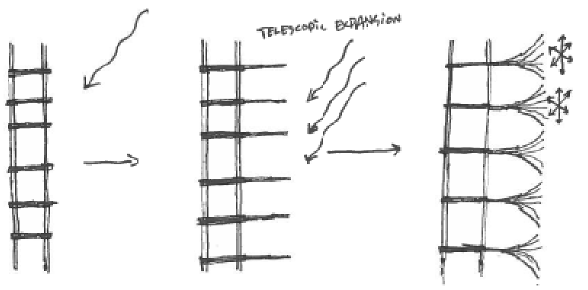
3. **Moveable mesh**
   A solar shading in the form of two layers of mesh. By moving one of the layers and thus changing the overlap, the transparency of the surface can be varied.



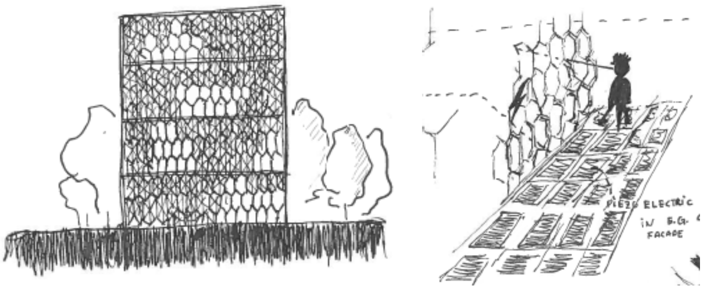
4. **Inflating spheres with bubbles inside**
   Spheres in the walls that can be filled with soap bubbles through small holes in a pipe going through the spheres. The soap bubbles will stop air movement in the wall and thus increase the thermal resistance of the wall.



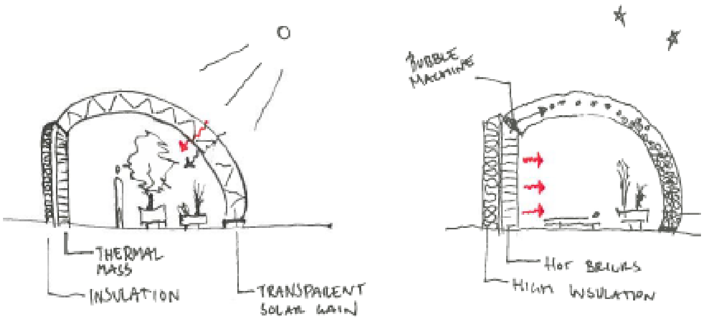
5. **Retracting memory metals as sunshades which also can "bloom"**
   Telescopic expansion of bars in the surface. First step gives extra shading from the bars. In the second step the end of the bars spread out like flowers and shades a larger part of the building surface. Could be responding to temperature through bimetals or memory metals.



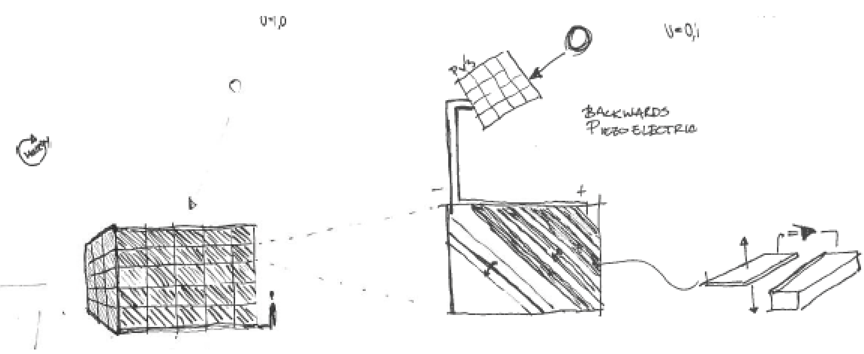
6. **Di-electric sheets that open up to allow view where persons are present**
   Window shades which react to people moving through the building so that the windows are covered when no one can see out but let the light in when there are people in the rooms. The occupancy detection could be governed by piezo-electrics and the shades could be made of dielectric elastomers.



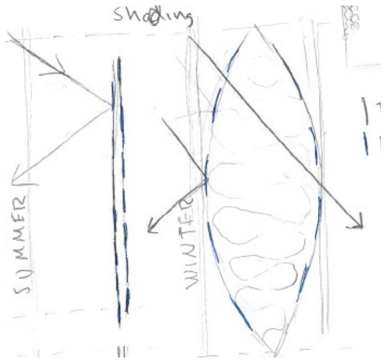
7. **Day/Night soap cycle wall**
   Transparent wall that fills with soap bubbles to enhance insulation during the night by reducing convection.



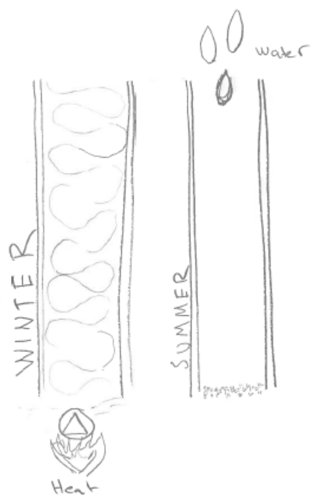
8. **Adaptive panels from transparent to shading absorbing heat**
   Increased shading of windows when the sun is shining by coupling PV cells to material that thickens when a voltage is applied (inverse piezo electric). The material could also be used to store the heat.



9. **"Bubblegum" increasing insulation, varying transparency**
   Insulating bubbles which blocks sun and have thin insulation during summer but gets blown up to get thick insulation and partial transparency during winter.

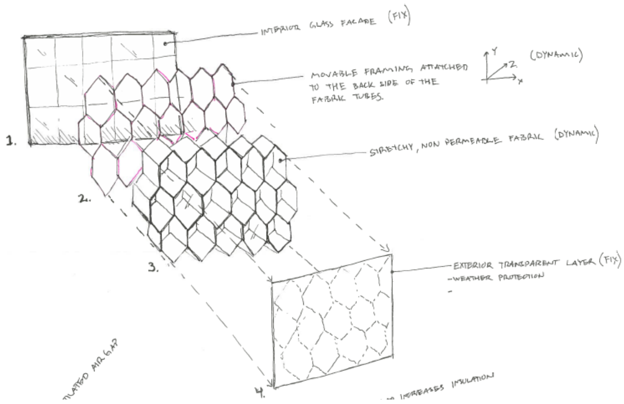


10. **The "cotton candy wall"**
   A wall with cotton candy as insulation, which can be removed during summer with some drops of water. An example of consumable insulation.



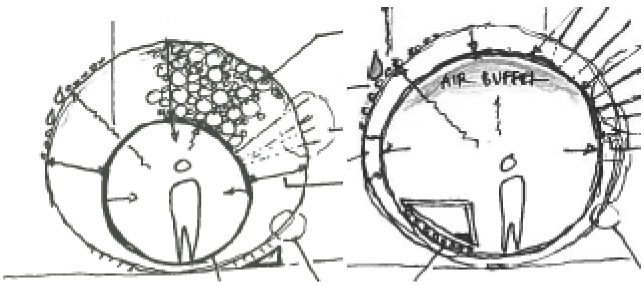
11. 3D moving hexagonal pattern

Two layers of honeycomb pattern grids with some stretchy and flexible material in between. By moving one of the layers in response to the sun, the amount of direct sunlight can be controlled. One of the grids could also be moved normal to the wall to create a ventilated air gap in the façade to remove excess heat.

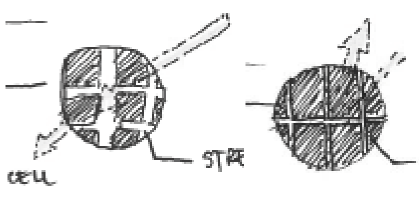


12. "Bubble fish"

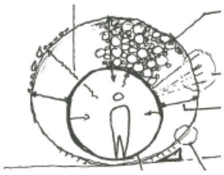
An indoor room that can change size to smaller during winter and larger during summer.



a. When the walls get thicker the transparency increase in several parts by moving shading apart.

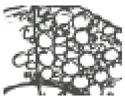


b. Smaller rooms means a smaller volume to heat.



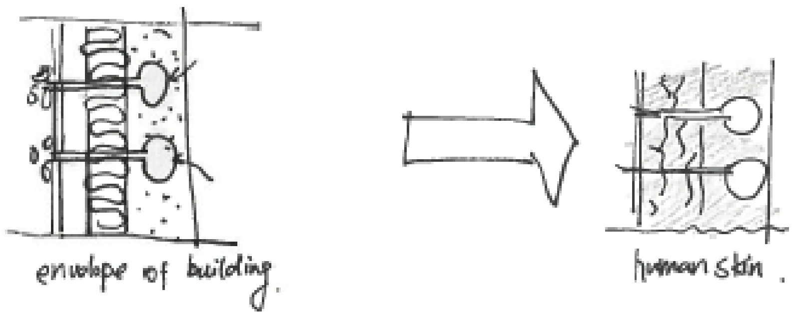
c. A higher ceiling height creates a heat buffer.

d. The thicker walls could contain compressible or consumable insulation. To lower U-value.



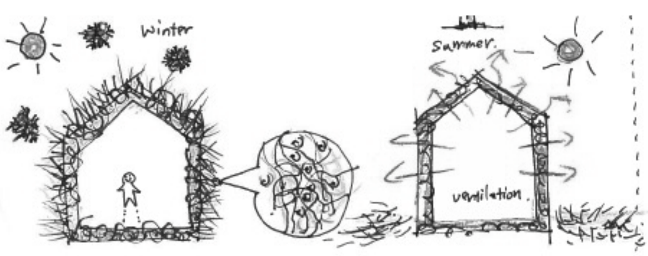
13. Mimicking the human skin

Sweating buildings. Liquid containers connected to the surface which can make the building sweat for evaporative cooling during hot days.



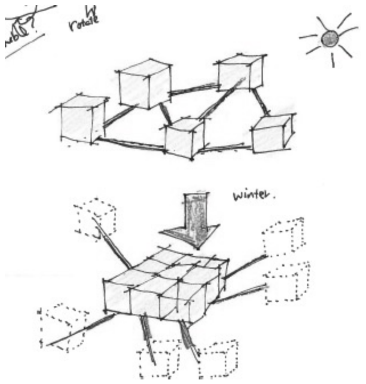
14. Reversed seasons

Insulation growing on the outside of the building over the winter and reduced/removed during summer to adapt the insulation properties.



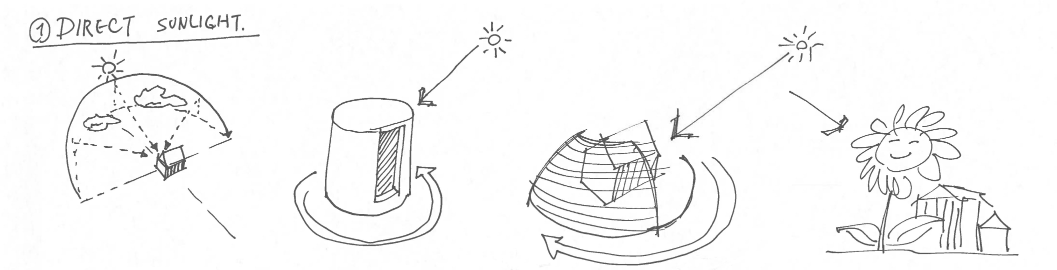
15. Self-assembling house(s)

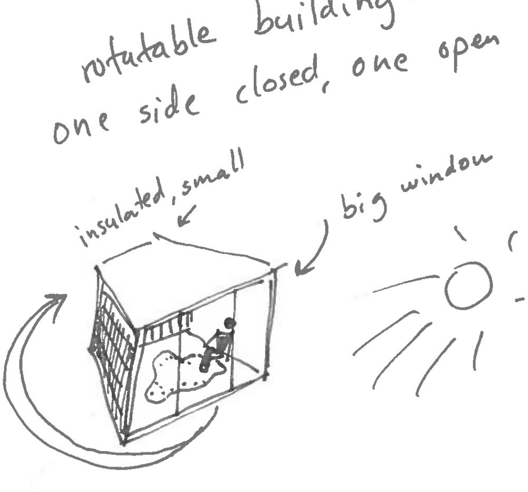
Movable buildings which stand separate during summer but moves together during winter to reduce the external surface area.



16. Rotatable building one side closed and one side open

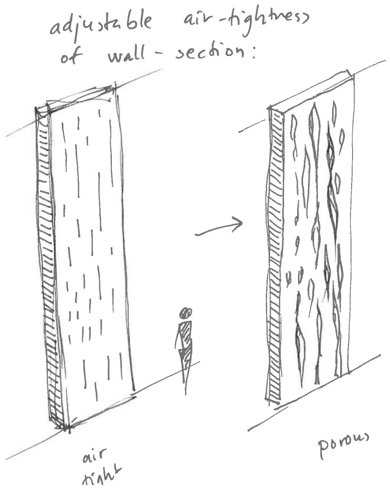
By allowing the entire building to rotate, the orientation of the building can be optimized following the solar path.





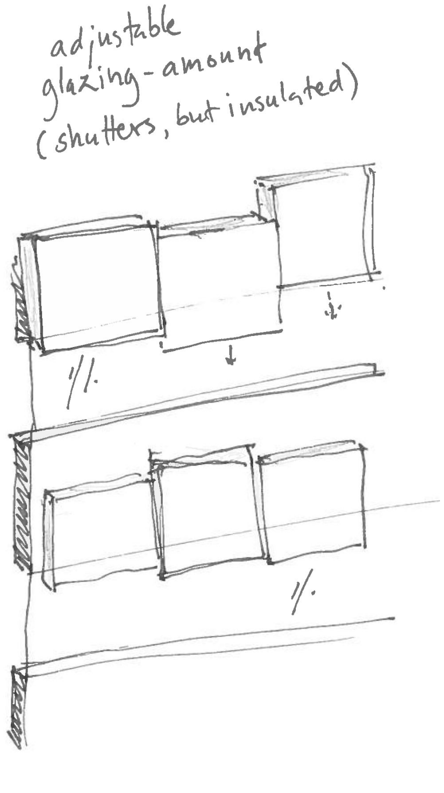
17. Adjustable air-tightness

Changing the air-tightness in the wall to allow fresh air to infiltrate through the wall, instead of using a HVAC system.

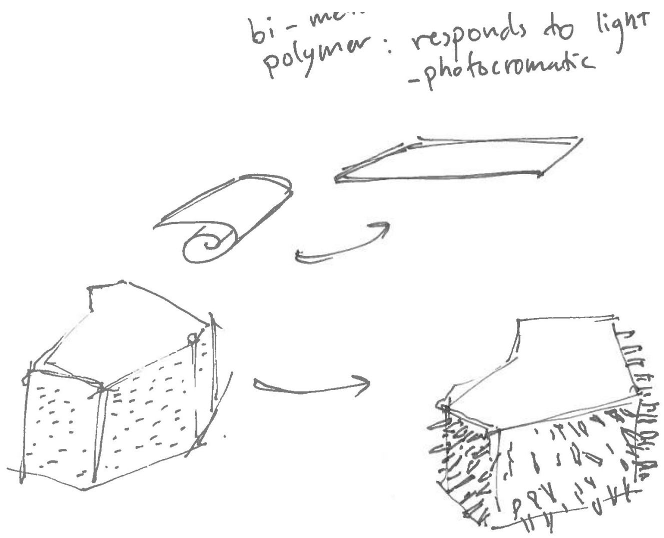


18. Adjustable glazing amount, insulated shutters

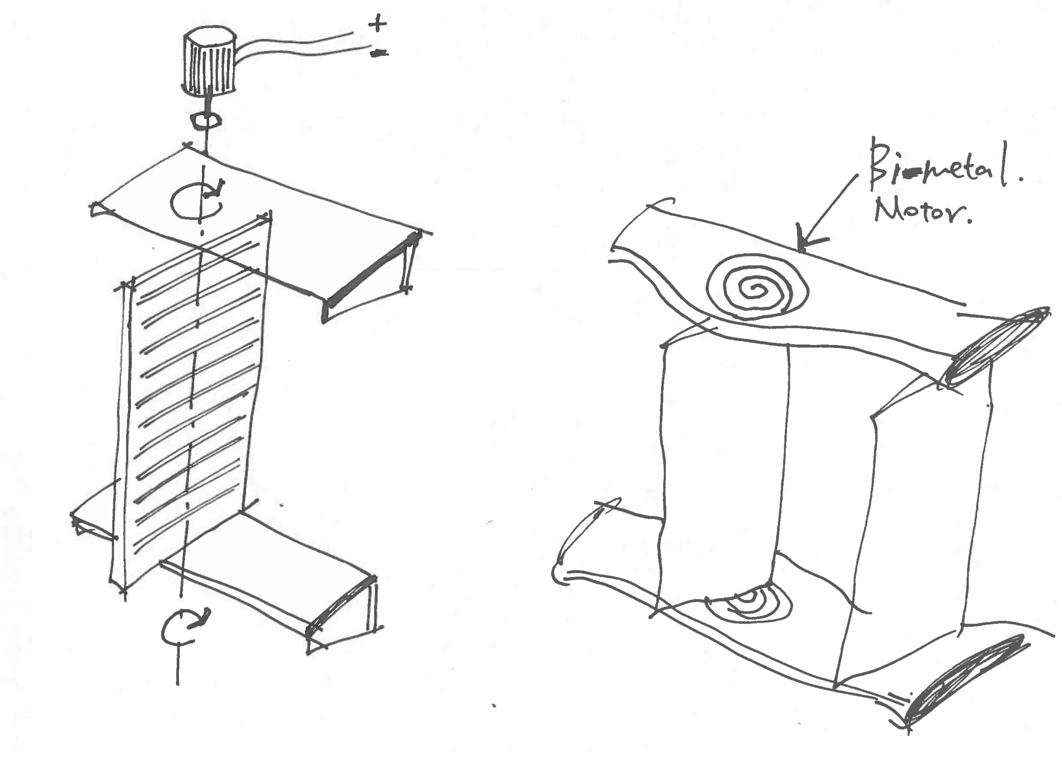
Insulating shutters can be used to vary the amount of glazing in a façade as well as being used as extra night insulation and decreasing night radiation to the sky.



19. Bi-metal or SMP solar shading system
Using bi-metals or shape memory alloys to create a shading system consisting of smaller individual pieces.

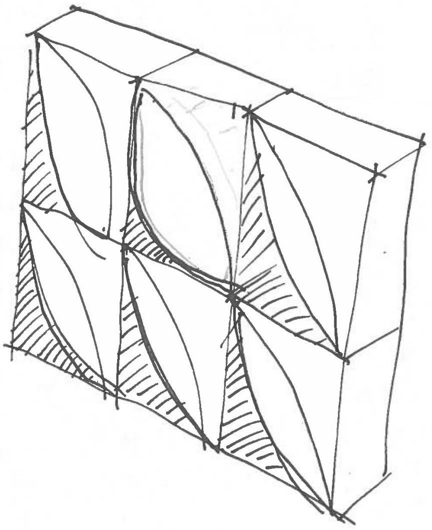


20. Bi-metal as motor for shading fins
By using bi-metals as a motor for rotating vertical shading the amount of parts used can be decreased. This can also reduce the need for maintenance.



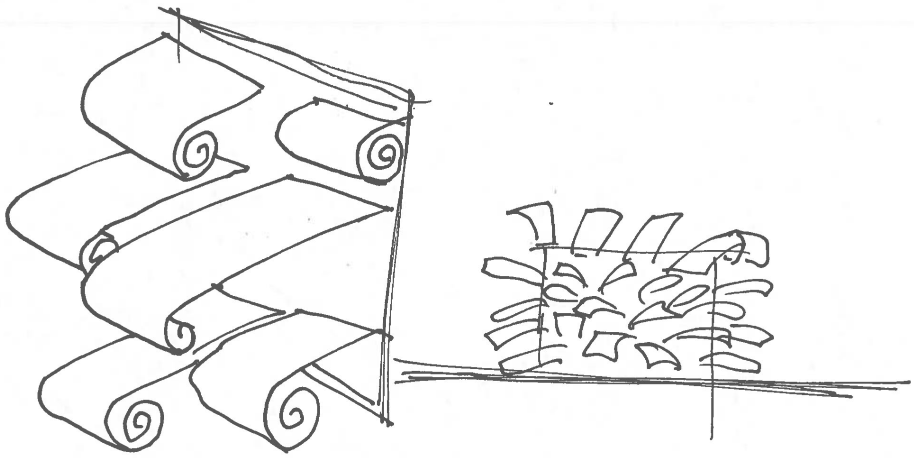
21. "Eyes" that open through bimetals

Using bi-metal strings as opening mechanism for an exterior layer creating openings in the façade similar to eyelids.

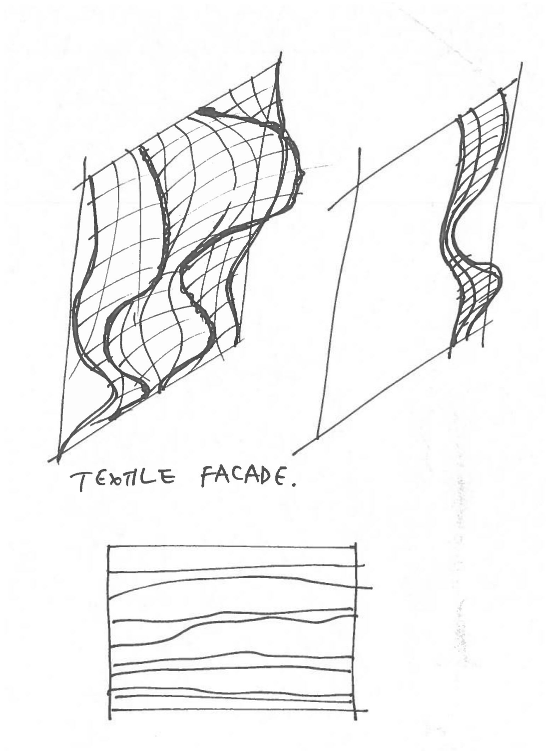


22. Bi-metal shading

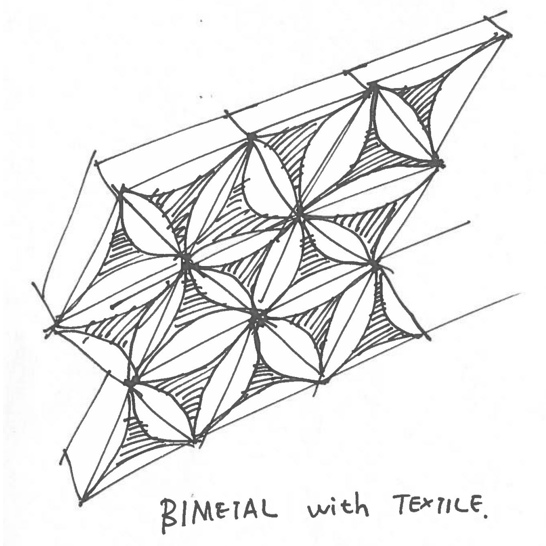
Similar to 22 this concept used bi-metal sheets for shading, but this time in a larger scale.



23. **Textile façade with integrated SMA that control the shape of the façade**
    Similar to 25 but instead of bi-metals using shape memory alloys ,which have a higher flexibility in shape.

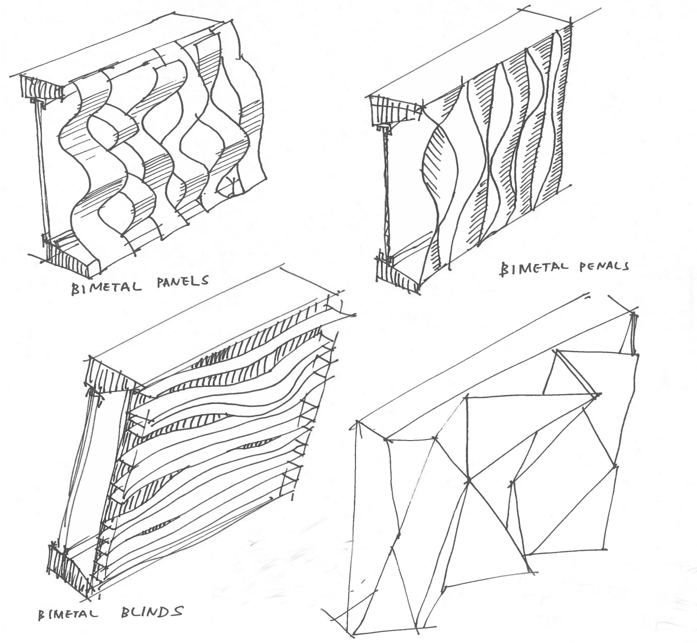


24. **Bi-metals and textiles**
    Additionally concepts that use bi-metals strings to move and control a shading fabric.



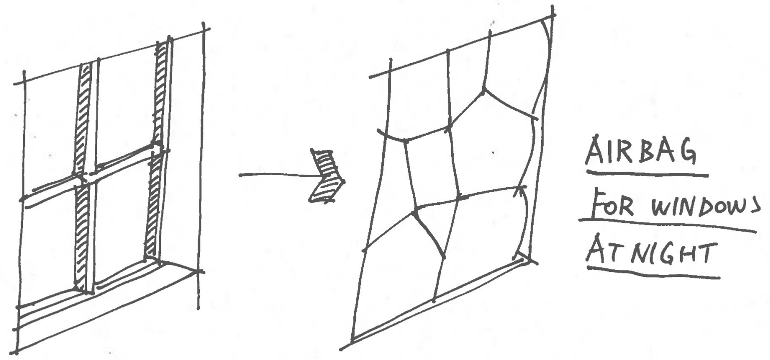
25. Different strategies for bi-metal solar shading systems

Additional concepts that use bi-metals in different shapes as a passive adaptive solar shading that responds to high temperatures.



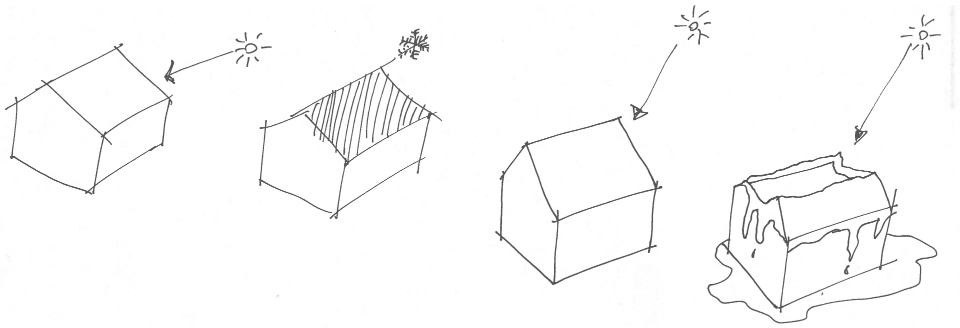
26. Air-bags for windows

Inflating bags over windows that can both increase the insulation and decrease night radiation.



27. Colour changing roof

Applying colour changing paint (photochromic) on the roof of building can by the current colour either reflect or absorb heat.



Concluding thoughts

From the different concepts three trends can be found, there are on group of concepts that focuses on consumable insulation (7,9,10,14), that allow the insulation value to differ over the year. Another group is that of different solutions for passive solar shading system, which uses bi-metal or shape memory alloys as actuators.

(5, 19, 21, 22, 23, 24, 25) The last group is moveable windows, or rather moveable views where the view out is present only where people are present. Allowing areas where the need for views out and daylight is small at a given time instead can be insulated further, and then be opened when needed. (1, 2, 3, 6) One can also conclude that most of the suggested components have a direct response with only one material acting as both actuators, driving the response and as a sensor to the environmental changes.

Thank you!

The workshop was very successful from our point of view resulting in many interesting concepts for adaptive building components that already have triggered our brains to start working and investigating the possibilities. Therefore we like to thank all the students participating for inspiring us and forcing us to once again think outside the box ourselves!