“Adaptables”
An Adaptive Façade for the Future Faculty of Architecture at Delft University of Technology

Research Building Technology [AR5AB010]
Rosalie van Dijk [1140647]
Semester I, 2008-2009
Main tutor: Dipl. Ing. T. Klein
2nd tutor: Ir. E.J.G.C. van Dooren
Lab coordinator: Ir. F.R. Schnater
Preface

The building technological research and design that has been done in the first semester of 2008-2009, focuses on issues in the field of sustainability that have been recognized by many academics as not yet thoroughly implemented in today’s architecture. This research will focus on the design for an adaptive façade for the future faculty of Architecture in Delft. An adaptive façade has the ability to respond to changing internal and/or external climatic conditions.

Sustainability, as an integral aspect of both the future educational program and the faculty premises, forms a theme of considerable urgency in the design for a new faculty of Architecture at Delft University of Technology. A large gain can be obtained in the design of the façade since this makes up a considerable area of the building and the façade is the most significant contributor to the energy budget as well as the comfort parameters of a building. Moreover, adaption of the façade can contribute to a flexible use of the interior spaces. The assignment is approached from the interior by setting up requirements for the internal spaces and the adjacent façade. Instead of focusing only on a comfortable internal environment – still intrinsically related to installation systems - the façade should also address the user influence: an office façade will be used differently from a studio façade. Since many different people will make use of the building and its different rooms, an adaptable envelope could contribute to the answer to the problem of a well-suited yet flexible building.

The research is part of the graduation project for architecture students in the SADD2 studio. To implement this research into the architectural design for the future faculty of Architecture, three typical spaces related to educational buildings and their façades will be researched: a studio space, an office space and a meeting room, see Figure 1. These three spaces have different demands from the user perspective. Ultimately, one façade concept should be able to serve all spaces.

Furthermore, the interior and exterior influences on the façade need to be established in order to understand its fundamental functions and their interdependence from each other; they form the foundation for taking decisions during the design of a façade. Thirdly, a façade’s functionality can be met in many different ways. Looking at current possibilities will give a good view on what is available nowadays, but will also show what functionalities of the façade are missing or not yet developed thoroughly. This can generate ideas for new components in a façade.

The starting point for the design of the façade in the coming semester of the SADD graduation project is an adaptable façade concept. The analysis of adaptive components will result in a toolbox with adaptive components, which is organized by its functionality in a diagram. The components will be organized alphabetically and their potential as an adaptive component will be explained. Many different concepts for an adaptive façade can be generated using this diagram. However, only three concepts are worked out and will be discussed. In the end one concept will be chosen to be worked out into a final façade design.

1 http://www.buildingforbouwkunde.nl/CompetitionBrief/tabid/90/Default.aspx
2 Strategic Architectural Design Development
1. Analysis roomtypology

![Diagram of Design Studio, Office space, Meeting room]

2. Finding the problem // looking at examples

![Diagram showing internal influences and external influences]

3. Solutions // concepts

![Diagram of adaptive components]

Figure 1: Research scheme
# Contents

Summary ................................................................................................................................. 6  
Adaptiveness .......................................................................................................................... 7  
  Introduction ......................................................................................................................... 7  
  Research Question ............................................................................................................. 8  
  Levels of adaptivity ......................................................................................................... 8  
  Room typology ................................................................................................................. 9  
Comfort .................................................................................................................................... 11  
  Visual requirements ........................................................................................................ 11  
  Thermal & hygienic requirements .................................................................................... 12  
  Acoustic requirements .................................................................................................... 13  
  Conclusion ....................................................................................................................... 14  
Climatic conditions ............................................................................................................... 15  
  Internal factors ................................................................................................................ 15  
  External factors ............................................................................................................... 16  
Amount of adaptivity .......................................................................................................... 22  
  Adaptivity per function ................................................................................................... 22  
  Adaptivity analysis .......................................................................................................... 27  
  Conclusion ........................................................................................................................ 30  
Adaptive façade components .............................................................................................. 32  
  Adaptive functions .......................................................................................................... 36  
  Diagram adaptive components ...................................................................................... 39  
  Glossary of adaptive components ............................................................................... 42  
Façade concepts .................................................................................................................. 54  
  Design Concept: Manual façade .................................................................................... 54  
  Design Concept: Mechanic-façade ................................................................................ 57  
  Design Concept: Smart-façade ..................................................................................... 61  
Design .................................................................................................................................... 65  
  Studio façade design ....................................................................................................... 66  
  Office façade design ...................................................................................................... 67  
Conclusion ............................................................................................................................ 69  
  Recommendations ............................................................................................................ 70
Bibliography .......................................................................................................................... 71

Appendices ........................................................................................................................................ 73

- Design drawings faculty of Architecture (P4 presentation 2010-03-18)
- Syllabus
- Analysis adaptivity per orientation
- Climate data for the Netherlands in 2008
- Product data
- Calculations of heat and cool loads studios & offices
Summary

The aim of this research is to study the possibilities of adaptation in a façade in order to be able to design an adaptive façade for the future faculty of Architecture at TU Delft. In general, an adaptive façade has the ability to change, responding to changing internal and/or external climatic conditions influencing room comfort. It was evident from the beginning of the research that an adaptive façade can have a positive effect on a building’s energy consumption and comfort. The idea that an adaptive façade can contribute to a flexible building and usage of space as well, is quite new; it assumes that this type of façade is necessary to fulfill the different requirements per room type placed on the internal climate. To verify this, three room typologies – a design studio, an office and a meeting room – have been researched on their user and climate requirements. An understanding of the difference in use of both the room and its façade (for instance practicability of the façade), and the related comfort requirements per room typology is necessary to comprehend the effects on the façade. The study on comfort shows that light and ventilation need to be adaptive because every room type has different comfort requirements. The usable floor area per person is different per room type and the reverberation time varies as well, but this difference is solved cleverly by using materials with different absorption qualities in the room itself.

A difference in temperature, light, ventilation and sound all have influence on the design of the façade and the internal climate. The relevant internal factors influencing room comfort are people, electrical devices and lighting. Their effect on the internal climate differs per room typology since the amount of people and the surface area vary. The external conditions – solar radiation, outside air temperature, humidity, precipitation and wind – are dependent on location and orientation and cannot be influenced by design; however, an adaptable façade must make best use of these conditions.

The amount of adaptation needed in a façade is analyzed in the adaptivity analysis. The analysis takes into account the different functions, day and night differences, the seasons and the façade’s orientation. Different profiles have been defined to study the effects of the different adaptive functions in relation to each other. Furthermore, different levels of adaptivity have been quantified to research what function needs what amount of adaptation, the levels being: minute-to-minute, day and night, season and years. These levels are necessary to limit down the choice for certain components even more.

To be able to actually design a façade with adaptive components, one needs to know what is there and what is not. An overview has been made for façade components that can adapt manually, mechanically and on a material level – so-called ‘smart’ materials. Of course, this overview is not complete and probably never will be, but within the timeframe of this research, it does tell what the potential of the component is and its advantages and disadvantages. The components have been organized per function into a diagram. In combination with the defined profiles for designers it’s a useful tool to create new façade concepts. Three different concepts have been worked out with the help of the profiles and the diagram with adaptive components. These adaptive concepts show the possibilities, effects and restraints for the future façade with adaptive components. The last chapter shows the result for an adaptive façade design as a result of the graduation assignment in both architecture and building technology.

In conclusion, adaptivity in a façade is dependent on a lot of different factors: the user profile and practicability of the façade; its effectiveness in time, meaning the different levels of adaptivity; its climate profile; its costs and architectural choices. It is also a direct outcome of what components are available at the time of making the concept and design. The future façade will potentially take in more and more functionality, with a better integration of building services and integration with a building's structure.
Adaptiveness

Introduction

According to Ulrich Knaack, professor Design of Constructions at TU Delft, it makes more sense to make use of the environment instead of shutting it out because making use of the environment will have a positive impact on the comfort level of the occupants as well as on the energy consumption (Knaack, Façades, 2007). Buildings that are able to adapt to changing climatic conditions throughout the year are often called intelligent buildings. Since the term intelligent can be misleading, the phrase adaptive will be used instead (Knaack, Façades, 2007, p. 85). Adaptiveness is the (cap)ability to adapt. In building it is the capacity to respond to changing exterior conditions in order to effectively influence the interior conditions.

Since the façade is one of the most significant contributors to the energy budget as well as the comfort parameters of a building it has become inevitable to make a design concept for an adaptive façade. The façade of a building forms the interface between the outside climate and the user inside. In winter it must ensure a comfortable interior climate, in summer it must prevent the entry of too much direct sunlight. It should provide natural light penetrating far into the building and a high degree of natural ventilation.

These requirements lead to a conflict of objectives. On the one hand, sun shading is needed to keep the cooling capacity as low as possible yet it reduces the amount of natural daylight entering the building. In winter, an optimum use of natural light and the desired amount of direct sunlight are often accompanied by glare. Predominantly natural ventilation in a location near a highway – as is the case for the Faculty of Architecture - is connected with an undesirable entry of noise and polluted air. The aim in devising an adaptable façade concept is to find for each location and intended use an optimum compromise between the various requirements.

Normally, facades are designed for one function only. In this research, adaptivity is more than being able to adapt to the external environment related to location and typical use. It is also concerned with the possibility of creating multiple functions behind the façade. This can be interpreted in different ways. The first interpretation is that of three different room typologies with separate façades that have a variation in adaptivity, see Figure 2a. This means for example that an office occupant is able to regulate or make more changes to the façade than occupants of the studio spaces. Another interpretation is that of a 100% adaptable façade, see Figure 2b. The starting point here is a room with a façade that can serve different room typologies and uses. The façade is made up of different components which should all be separately adaptable. Combinations of different components are related to the specific room typologies, such as a studio space or an office. This challenges the façade design in a way that different degrees of adaptivity might have to be incorporated within one component. If for instance an office needs different sun shading than a studio space, this would automatically mean that two types of sun shading are needed; this would be ineffective and nondurable.
Starting point for the development of the façade is the room typology per function. The adjacent façade is adaptable. It’s like a chameleon skin adapting itself to provide best possible interior conditions. It should be able to adapt to the different functions or uses according to the needs of the building’s occupants and without a reduction of indoor comfort levels and waste of energy. It also assumes that there is a significant difference in internal climate between the different room types. The adaptive façade can contribute to a reduction in energy use and have a positive effect on the comfort levels inside as well as contribute to the flexible use of the interior spaces behind it. To be able to verify these requirements, the following research question has been set up. The key questions below specify the contents of the research for an adaptive façade for the future faculty of Architecture.

**Research Question**

How can adaptivity contribute to the façade design of the future faculty of Architecture at Delft University of Technology?

**Key questions**

*Room typology*

What are the different room typologies?
What schematic layout can be made per room typology?
What are the typical requirements per typology?

*Façade*

What are the interior influences on the façade?
What are the exterior influences on the façade?
How much adaptivity is necessary for the façade to function?

*Adaptive components*

What adaptive components are there in the façade?
Are there adaptation techniques from other fields that could be useful?
What adaptive components in a façade do not yet exist yet are useful?

*Levels of adaptivity*

A façade that facilitates multiple functions and usage is challenged by the problem of having to adapt different components in different ways and at different times in order to be effective. Different degrees of adaptiveness need to be defined because of this.
In Figure 3 below, four levels of adaptivity have been defined. The first level represents sudden changes. It is called minute-to-minute because it needs to be able to react immediately. Some functions in the façade have to take care of rapid changes and need the ability to do this. External sun shading is a perfect example. When it starts to storm, the shading device needs to be taken up immediately.

The next level is the day and night level. Of course, a change in – for example – temperature can be taken care of by a thick layer of thermal insulation. However, it would be smarter if this layer is able to adapt itself to benefit from the external conditions available. The third level is that of the seasons. In summer, sun shading or blinds against overheating control are necessary. In winter however; the sun’s energy is desirable to heat up the room, so shading is unwanted. Nevertheless, it might be necessary due to blinding effects (glare).

The last level of adaptivity is based on years. This level is more concerned with replacing components or upgrading them. If it would be possible to take out the adaptive components in the façade, then the broken of deteriorated components could be replaced by new or better ones.

Room typology

Below, three typical spaces related to educational buildings and their façades will be researched: a design studio, an office space and a meeting room. These three spaces will be studied and worked out into room typologies. Their layout and function will be explained from the user perspective. Ultimately, one façade concept should be able to serve all typologies.

Design studio

The layout of the design studio is based on the current layout that is used at the temporary faculty of Architecture. Here, a studio has room for a maximum number of 20 students, scattered over two large tables. In between the tables there is room for model making. The ceiling height of 4 meters is based on the general building height applied in the design for the faculty of Architecture, see the appendices.

The practicability of the façade in a design studio is ambivalent. On the one hand, you want the user – who spends a lot of time in this space – to regulate the functions itself. On the other hand, if the façade can regulate its own or by sensors, this will probably let the user feel more comfortable more often because the sensor or façade will intervene more quickly than the user does. Furthermore, it is easier to agree on the internal climate with four people than with 20 people.
**Office**

The office design is based on four people who need to work on approximately 32 m². Assuming a standard grid of 2.700 mm, the room is less deep than a design studio, namely 5.400 mm. The room height is similar to that of a design studio; this is done because of flexibility reasons. The façade’s practicability is important in this case because the user of the offices will want to be able to regulate their room comfort in some way. This can for example be solved by the possibility of openable windows.

**Meeting room**

The meeting room has a similar surface as an office space. However, a lot more people need to fit in and gather around a central table. From the user perspective, the façade should be able to regulate itself. Nevertheless it is desirable that some components can be regulated by the room’s users to enable them to change the room’s conditions quickly.

![Figure 4: Room typologies for a studio, office and meeting room 1:200](image)

Up till now, it has become clear that an adaptable façade can contribute to room comfort and the building’s energy consumption. Moreover, it can give the user a feeling of being in control of its internal climate. What has not become clear yet is what effect the user has on the indoor climate and the façade and if there are other aspects as well that influence the façade’s functionality. Furthermore, it will be important to develop the tools that are able to design an adaptive façade. The next chapter will go into more detail on the effects and the requirements on the indoor climate and the differences per room typology.
Comfort

The requirements placed on the interior climate are essentially determined by the term 'comfort'. The demand for comfort and its levels have increased since the invention of the refrigerator and the development of building installations ever since. However, comfort is still determined by many different factors, including gender, health, nutrition, age, season and type of work (Daniels, 2003, p. 26). Moreover, it is culturally dependant. For instance, a person coming from the tropic climate region would find an interior climate of 27 °C and a relative humidity of 70% more acceptable than someone from the cold regions.

In general, comfort requirements should have minimal fluctuations in order to create a comfortable indoor climate. The ranges in which these values should fall are called comfort zones. In Figure 6 one can find the comfort zones according to the ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers) standards. The requirements on comfort can be subdivided into visual, thermal, hygienic and acoustic aspects. The requirements are based on Dutch building regulations (NEN, 1996) (NEN, 2003) (NEN, 2007), ASHRAE standards (ASHRAE) and Neufert data (Neufert, 2006) and are elaborated below.

Visual requirements

For good lighting practice it is essential that in addition to the required illuminance, qualitative and quantitative needs are satisfied. Lighting requirements are determined by the satisfaction of three basic human needs:

- visual comfort, where the workers have a feeling of well-being; in an indirect way also contributing to a high productivity level;
- visual performance, where the workers are able to perform their visual tasks, even under difficult circumstances and during longer periods;
- safety.

Natural daylight is preferable in all spaces and can be achieved by a window-room depth ratio of 2:3.

![Figure 5: Rule of thumb daylight entry (Source: Neufert, p. 346)](image)

In Table 1 the lighting requirements according to the NEN-EN 12464-1 from the Dutch Normalisation Standard are summarized for office and educational work.

The illuminance for most tasks lies around 500 lux with a maximum of 750 lux for technical drawing work. For the design for the future faculty this would mean that 500 lux has to be achieved in most room by natural daylight. The extra 250 lux can be arranged by artificial lighting.
### Table 1: Lighting requirements for office and educational interiors, tasks and activities (Source: NEN 12464-1)

<table>
<thead>
<tr>
<th>Task</th>
<th>Illuminance [lux]</th>
<th>Footnotes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Office</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Writing, typing, reading, data processing</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>Filing, copying, etc.</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>Technical drawing</td>
<td>700</td>
<td></td>
</tr>
<tr>
<td>CAD work stations</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>Conference and meeting rooms</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>Educational facility</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Classrooms, tutorial rooms</td>
<td>300</td>
<td>Lighting should be controllable</td>
</tr>
<tr>
<td>Classroom for evening classes and adults education</td>
<td>500</td>
<td>Lighting should be controllable</td>
</tr>
<tr>
<td>Technical drawing rooms</td>
<td>750</td>
<td></td>
</tr>
<tr>
<td>Teaching workshop</td>
<td>500</td>
<td></td>
</tr>
</tbody>
</table>

### Thermal & hygienic requirements

A difference can be made between a comfortable environment and an acceptable environment, see Figure 6.

The minimum acceptable temperature is 18 °C, whereas a comfortable temperature would be 20 °C. The same accounts for the maximum value of the temperature. As a maximum, 27 °C would hold as acceptable, whereas 25 °C is still comfortable, see Figure 6.

The relative humidity will vary between 30 and 65% - see Figure 6 - and the vapor production will be around 30 to 60 grams per hour (NEN, 1996, p. 9). The air movement around the body will vary from 0 to 20 cm/s (Herzog, 2004, p. 22).
The indoor air quality is mainly determined by the ventilation of the room. To protect people's health, the minimum of ventilation needed is 30 m³/h. This value is based on the CO₂-concentration in the air inside the room, which is a measure of the amount of pollution in the air. A good quality of air contains less than 0.1 volume percent CO₂ (1000*10⁻⁶). As a limit, 0.12 volume (1200*10⁻⁶) percent is employed (NEN, 2002, p. 5). However, the applied minimum of ventilation nowadays is 50 m³/h. In Table 2 below, the ventilation requirements per room type are shown.

<table>
<thead>
<tr>
<th>Room Type</th>
<th>Air stream [dm³/s/person]</th>
<th>Ventilation [m³/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Office</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>Meeting room</td>
<td>15</td>
<td>50</td>
</tr>
<tr>
<td>Classrooms</td>
<td>5.5</td>
<td>55</td>
</tr>
</tbody>
</table>

*Table 2: Ventilation requirements according to NEN 1089*

The aim is to ventilate the future faculty of Architecture mostly by natural ventilation. Mechanical ventilation is still needed in order to facilitate sudden changes in ventilation capacity, for instance in auditoria. It is recommended to introduce at least 55-60 m³/h of fresh air into mixed-use rooms and in large, open-plan areas at least 75 m³/h per person. This helps to extract formaldehyde from interior furnishings and insulating materials, nitrous oxide (heating) and solvent vapors (Daniels, 2003, p. 31).

**Acoustic requirements**

Disturbance by noise is experienced by different people in different ways. The level at which people lose concentration is dependent on the type of work. Routine work is less sensitive than brainwork. For individuals the correlation between noise level and the annoyance experienced is much lower than non-acoustic factors of a social, psychological or economic nature. For example, in a car the noise level can be 70 dB(A) at which one can concentrate on driving the car. In an office with a noise level of 70 dB(A) work will be stated as virtually impossible (NEN, 2007, p. 7).

According to the NPR 3438 from the Dutch Normalisation Standard (NEN, 2007, p. 18), both design work and teaching work have a target sound level of 35 dB(A). This value should not exceed 45 dB(A). Values alike are also stated in *Advanced Building Systems*. In Table 3 one can find the sound pressure level and the reverberation time for different educational functions by Klaus Daniels. The reverberation time in an office is ideally 0.8 second. For lecture halls this value is 0.9 second. In Table 3 the reverberation time is weighted slightly different and averaged to 1 second for the same functions.

<table>
<thead>
<tr>
<th>Type of area</th>
<th>Sound pressure level [dB(A)]</th>
<th>Reverberation time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Halls, corridors</td>
<td>40</td>
<td>2</td>
</tr>
<tr>
<td>Auditorium, reading room</td>
<td>35</td>
<td>1</td>
</tr>
<tr>
<td>Offices: Meeting room</td>
<td>35</td>
<td>1</td>
</tr>
<tr>
<td>Small office area</td>
<td>40</td>
<td>1.5</td>
</tr>
<tr>
<td>Large office area</td>
<td>45</td>
<td>0.5</td>
</tr>
<tr>
<td>Reading room, class room</td>
<td>35/40</td>
<td>1</td>
</tr>
</tbody>
</table>

*Table 3: Guideline values for sound in different areas according to Klaus Daniels*
Conclusion

In Table 4 below, a summary of all comfort requirements has been made. The biggest difference in the different room typologies can be found on the amount of space available per person. However, this has no direct influence on the design of the façade. The difference in temperature, light, ventilation and acoustic absorption do have influence on the design of the façade and the interior. Especially the aspects light and ventilation need adaptable components, since large differences can be expected here. There is also a considerable difference between the reverberation time of a design studio and a meeting room. This means that the amount of absorption material in the façade (and in the room behind it) need to be higher in a design studio than in a meeting room.

<table>
<thead>
<tr>
<th></th>
<th>Design Studio</th>
<th>Office</th>
<th>Meeting Room</th>
</tr>
</thead>
<tbody>
<tr>
<td>User</td>
<td>Student/teacher</td>
<td>Staff/PhD</td>
<td>Student/staff</td>
</tr>
<tr>
<td>Usable Floor area [m²/person]³</td>
<td>5</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>Temperature [°C]</td>
<td>20-26</td>
<td>20-26</td>
<td>18-24</td>
</tr>
<tr>
<td>ΔTmin-max [°C]</td>
<td>8</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Light [lux]</td>
<td>500-700</td>
<td>300-700</td>
<td>500</td>
</tr>
<tr>
<td>Ventilation [m³/h]</td>
<td>55</td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>Reverberation time [s]</td>
<td>0.6</td>
<td>0.8</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 4: Summary of comfort requirements per room typology

³ The usable floor area per room typology is based on NEN 1824-2001 from the Dutch Normalisation Standard. The calculation is explained in §4.2.
Climatic conditions

The primary reason for creating a barrier between inside and outside is the desire for protection against a hostile outside world and inclement weather. Several other reasons have been added to these protective functions, such as light in the interior, sufficient natural ventilation, a visual relationship with the surroundings but, at the same time, a boundary between the private sphere and public areas.

The requirements placed on the façade from inside and outside are protective, regulatory and communication functions. These functions need to be regulated and controlled. A comprehensive understanding of these fundamentals and their interdependence form the foundation for taking decisions during the design of a façade.

Internal factors

The requirements placed on the interior climate are essentially determined by the term ‘comfort’ and should have minimal fluctuations in order to create a comfortable indoor climate.

![Figure 7: Factors influencing thermal comfort](image)

The relevant influencing factors related to the construction of the façade are air temperature, relative humidity, surface temperature of the building components and airflow across the body, see Figure 7. These quantifiable variables are considered to be external influences and determine the level of thermal comfort. The number of people and their activities, electrical equipment and lighting in the room also have a direct effect on the heat load, humidity and sound levels of the room and thus influence the comfort levels; these factors are internal influences.

In Table 6, the basic properties per room type are given. The amount of people inside a room is a rough estimation based on the usable floor area. The calculation of the heat production is based on values shown in Table 5. These values have been determined from the reader *Klimaatinstallaties* (Schalkoort, 2003), and are based on normative standards. For lighting, a heat load of 7 W/m² can be used to calculate the average heat load. Daylight concepts and application of presence sensors optimized this value to 3 W/m². For the calculation of the heat load through lighting 5 W/m² will be used. In general, the current average heat load varies between 15 and 23 W/m² – depending on the use and the amount of daylight (Haartsen, Brouwer, & Mihl, 2005, p. 30).

<table>
<thead>
<tr>
<th>People</th>
<th>100 W/person</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical devices</td>
<td>12 W/m²</td>
</tr>
<tr>
<td>Lighting</td>
<td>5 W/m²</td>
</tr>
</tbody>
</table>

*Table 5: Internal heat load*
## Table 6: Basic properties of the different room typologies

<table>
<thead>
<tr>
<th></th>
<th>Design Studio</th>
<th>Office</th>
<th>Meeting Room</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of people</td>
<td>10</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Usable Floor area [m²/person]</td>
<td>5</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>Total [m²]</td>
<td>50</td>
<td>16</td>
<td>12</td>
</tr>
<tr>
<td>Heat production [W]</td>
<td>People 1000</td>
<td>People 200</td>
<td>People 600</td>
</tr>
<tr>
<td></td>
<td>Electrical devices 600</td>
<td>Electrical devices 192</td>
<td>Electrical devices 144</td>
</tr>
<tr>
<td></td>
<td>Lighting 250</td>
<td>Lighting 80</td>
<td>Lighting 60</td>
</tr>
<tr>
<td>Total heat load [W]</td>
<td>1850</td>
<td>472</td>
<td>804</td>
</tr>
<tr>
<td>Ratio heat load vs. floor surface [W/m²]</td>
<td>37</td>
<td>29,5</td>
<td>67</td>
</tr>
</tbody>
</table>

At the bottom end of the Table 6, a ratio has been drawn up between the heat load per room type and its floor surface. This ratio (total heat load divided by surface) tells something about the heat load per m² and is derived from the total heat load for people, electrical equipment and lighting. For this research, it is more interesting to know how much heat can transfer through the façade. The heat transfer through the façade can be estimated in a ratio per m² where the heat load is divided by the façade surface. Its calculation for the different room typologies can be found in Table 7. A conclusion that can be drawn from these calculations is that the internal influences differ per room type, resulting in different a heat balance per room typology.

## Table 7: Heat transfer through the façade

<table>
<thead>
<tr>
<th></th>
<th>Design Studio</th>
<th>Office</th>
<th>Meeting Room</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total heat load [W]</td>
<td>1850 W</td>
<td>472 W</td>
<td>804 W</td>
</tr>
<tr>
<td>Façade surface [m²]</td>
<td>43,2</td>
<td>21,6</td>
<td>21,6</td>
</tr>
<tr>
<td>Ratio heat load vs. façade surface [W/m²]</td>
<td>42,8</td>
<td>21,9</td>
<td>37,2</td>
</tr>
</tbody>
</table>

### External factors

Solar radiation, outside temperature, humidity, precipitation and wind are external influences that can have severe fluctuations in the external climate. As a rule, the external influences on a façade cannot be influenced by design, however, an adaptable façade must make best use of all the ever changing climatic conditions. They represent a primary criterion even at the stage of choosing a plot of land. Specific external conditions require careful analysis because their nature and intensity varies according to district, region, country and continent. Besides the climatic specific to the location, other factors (e.g. a neighboring highway with higher levels of noise and polluted air) call for special measures in the design for a façade. This section focuses on the climatic conditions that affect a façade in general, but will also look at the site-specific conditions for the future faculty of Architecture.
Outside air temperature

Of all external factors affecting the façade design, the outside air temperature plays an important role because it has a large effect on heat balance of the façade. Deducted from the extensive data that has been collected for more than 50 years by meteorological institutes, a distinction between 5 climatic zones can be made, see Table 8. Delft is part of the Netherlands and can be sorted in climate zone three, a moderate climate.

<table>
<thead>
<tr>
<th>Climate zone</th>
<th>T_{\text{average}} (°C)</th>
<th>Precipitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. warm and humid (Paramaribo)</td>
<td>26</td>
<td>27, 25, 2800</td>
</tr>
<tr>
<td>2. warm and dry (Cairo)</td>
<td>19,5</td>
<td>24, 15, 80</td>
</tr>
<tr>
<td>3. moderate (Netherlands)</td>
<td>13</td>
<td>23, 4, 800</td>
</tr>
<tr>
<td>4. boreal (Siberia)</td>
<td>1,3</td>
<td>20, -14, 500</td>
</tr>
<tr>
<td>5. ice climate (Greenland)</td>
<td>-8</td>
<td>4, -20, 580</td>
</tr>
</tbody>
</table>

Table 8: Overview of climate zones

Figure 8 shows the temperature measured for every month in the Netherlands. It shows the mean temperature, the mean daily minimums and maximums and the absolute minimums and maximums.

Figure 8: Average temperature curve (30 years) for the Netherlands, measured in De Bilt
Sun
The Sun plays a key role in terms of site specific, external conditions. Its influence is ambiguous: on the one hand the sun’s radiation is perceived as pleasant and wanted when it lights and heats up a room; on the other hand the sun’s lasting emission in summer can lead to an extreme room temperature, see Figure 9.

It is important to consider the intensity and duration of radiation in conjunction with the orientation and inclination of the façade. In Figure 10 one can see the effects of the sun’s radiation on a typical day in July in the Netherlands. It’s measured on horizontal and vertical surfaces with different orientations and on a plane perpendicular to the sun (standard plane).

From Figure 10 can be concluded that the solar radiation on the East façade is as high as the radiation on a West façade. However, the period when the maximum radiation on the façade occurs, differs. On the East orientated façade, the maximal radiation occurs at 8 a.m., whereas for the West façade this occurs at 5 p.m.

Another fact that can be deducted from the diagram is that the surface radiation on a South façade is much less than on a West façade due to the sun’s high altitude in July.
**Water**

Air can absorb water vapor until it reaches its saturation point, which depends on the temperature. We therefore speak of the ‘relative humidity’ (of the air). In winter, the relative humidity (φ) is on average 80% at an outside air temperature of -10 °C. In summer, the humidity varies more but on average is 50%. Moist air is fractionally lighter than dry air at the same temperature.

Water of precipitation that can penetrate through a wall must be able to diffuse out again. Furthermore, moist penetration and leakage cannot occur. Water vapor flows from the side with the higher vapor pressure (partial pressure) to the side with the lower pressure. If there is a simultaneous severe temperature gradient, the temperature drops below the dew point and the water condenses out of the air (and hence leads to the risk of condensation collecting on surfaces and mould growth).

The vapor diffusion resistance of the layers should generally decrease from inside to outside in order to combat the formation of condensation water within the component (avoidance of vapor trap). Condensation water that accumulates within the façade construction during the heating period must be able to evaporate completely during warmer months.

**Wind**

Wind is for the indoor climate mainly of influence on the amount of outdoor air that can infiltrate through slits. This infiltration causes natural ventilation inside a building. In principle, all buildings should be designed for natural ventilation unless extraordinary hygiene requirements indicate otherwise. Even when a building is located in an environment with less than ideal conditions and is subjected to high emission rates (sound, air pollution, dust, strong winds etc.) natural ventilation is still the most desirable solution (Daniels, 2003, p. 15).

Wind-force is registered by wind speed in m/s. The most occurring wind speed in the Netherlands is 4 m/s. The wind direction is next to wind speed also of importance. In the Netherlands south-west is the dominating wind direction, whereas south-east wind occurs seldom, see Figure 11. Air permeability due to a blast of wind plays a huge role in the design of the façade. The amount of rain that can enter is closely connected with it.

![Figure 11: Compass card de Bilt, the Netherlands](image-url)
Sound

The requirements to be met by the façade with respect to sound insulation to protect against external noise depend on the prevailing external noise level and the permissible and actual noise levels within the building, see Figure 12. Since the location of the faculty of Architecture is situated close by a roadway which also allows heavy goods traffic, see Figure 13, sound levels up to 90 dB can be expected.
The sound insulating effect of facades, also junctions with floors and partitions can be improved, mainly by employing the following constructional measures:

- Increasing the weight of the components;
- Increasing the number of successive, separate leaves, e.g. double leaves, preferably with different material thicknesses;
- Increasing the elasticity of the components;
- Increasing the asymmetry of the assembly in terms of the weight of successive layers;
- Increasing the distance between surfaces forming the boundary to an air layer;
- Increasing the degree of absorption.
Amount of adaptivity

The initial analysis in the chapter on Climatic conditions, which presupposes that a design studio, an office and a meeting room need different amounts and sorts of adaptivity in the façade, resulted in a difference in heat load and heat transfer through the façade. However, it does not inform us about the amount of adaptivity that is necessary per room type. This has lead to the following type of analysis, based on a scheme by Mike Davies, published in his article *A Wall for all Seasons* (Davies, 1981). Davies made an analysis of what functions a low glare neutral façade should use on different moments during a sunny spring day (and night). This type of analysis will be used in this research as well to find out what functions the future façade should have, when located in a moderate climate such as Delft. It takes into consideration the weather, the seasons and the building’s orientation. The tilted rectangle in the figures below visualizes the future faculty. The analysis is different from Davies’ scheme in that it only looks at daytime (2 PM) and nighttime (2 AM), however, it does look at the different seasons. An emphasis is put on season since every façade has to deal with this influence, albeit in a different way per climate region. The information is based on climate data for the Netherlands in 2008, which is recorded in the appendices.

Because all the different functions of a façade are quite complicated to gather in a scheme at once, the analysis is split up in different categories: thermal insulation, building mass (heat storage), (de)humidification, natural ventilation and daylight. Other adaptive functions, for example acoustics, will be discussed briefly afterwards because they are not influenced by the seasons but more by location. This will already raise discussion on whether the façade should be able to adapt minute to minute, on a daily basis, a few times a year when the seasons change or on a yearly basis. The separate schemes per function will then be combined to one per season and per day or night.

Adaptivity per function

Thermal insulation

Looking at thermal insulation and combining this factor with extreme climate conditions for the different seasons, this provides the following scheme. On a hot summer day, little thermal insulation is applied to keep the heat out of the building. During the night, the insulation should be gone, enabling the building to get rid of the heat that was built up during the day. In winter, a lot of thermal insulation is needed to keep the heat produced inside.

![Figure 14: Analysis thermal insulation future faculty](image-url)
Heat storage

Ideally, the heat storage capacity of a building is flexible. In winter, although much insulation is needed, the building mass should be as small as possible to let the sun’s radiation inside and heat up the building. During a spring (or autumn) day, the heat storage capacity should be most flexible: either building mass is wanted or not, depending on the weather. In summer, a lot of heat needs to be stored in building mass so the building won’t overheat. During the night, this built-up heat will cool off.

(De)humidification

Moisture does not need much adaptivity in the façade, however, there is a difference between the seasons. In summer, the relative air humidity is generally the highest causing moist air. This can feel uncomfortable with high temperatures. In winter, there is need for humidifiers since heating causes the air to become dry.
Natural ventilation

The need for natural ventilation during the day is evident for all seasons. In spring (and in autumn), natural ventilation is generally needed, however, there are days that the outside temperature can be very low. In that case, it is wise to reduce the amount of natural ventilation. During a cold winter night, it is necessary to close the ventilation so as not to lose too much heat. In summertime, on the contrary, ventilation is even needed during the night to cool off the building.

Daylight

Daylight has two aspects to it: visible light and radiation. Visible light can cause glare so an analysis is made of what can be expected, see Figure 18. Radiation, on the other hand, is concerned with infrared (IR) and ultraviolet (UV) radiation which can cause overheating. The aspect of overheating is analyzed in Figure 19.

Infrared and UV radiation contain a lot of energy which causes a rise in temperature when trapped inside a room (the greenhouse effect). In winter this effect is wanted to
warm up the building, however, in summer it is not. During daytime, some sort of adaptive shade is needed to keep different amounts of radiation out per façade.

Other factors influencing the façade design are vision, wind and water barriers and acoustics. These factors are not dependant of the seasons and only slightly dependant on the day and night cycle. In Table 9 below, the levels of adaptvity per function have been organized. Here, a typical west façade is taken as an example, and will be scored per function on its level of adaptvity.

<table>
<thead>
<tr>
<th>Function</th>
<th>Minute-to-minute</th>
<th>Day/Night</th>
<th>Seasonal</th>
<th>Yearly (upgrade)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal insulation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat storage</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(De)Humidification</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural ventilation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daylight</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overheating control</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vision</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind &amp; Water</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acoustics</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 9: Levels of adaptivity per function for a west façade*
The level of adaptivity for thermal insulation is mainly dependant on seasons. However, it is also very effective when the insulation layer can change during the day and night. The score for a change in adaptivity on a yearly basis is based on the upgrading aspect of the façade; when even better insulation values can be achieved, it might be necessary to replace the component.

The component for heat storage has to be effective on different levels as well. The effect of adaptivity on the minute-to-minute level will not be so great since the heat accumulating effect needs hours to take place. On a daily basis and during the different seasons, an adaptive storage capacity is desirable.

The amount of moisture will differ mostly between summer and winter. However, if we take into consideration the change in room humidity due to a changing amount of people – which is especially the case in a design studio – it can be convenient if the amount of moisture in the room can be regulated minute-to-minute.

The amount of natural ventilation can change on all four levels. The minute-to-minute and the daily adaptivity level are mainly influenced by the amount of people; the seasons and the related temperature influence how much ventilation is necessary, see Figure 17; and since the standards on ventilation are expected to increase with the years, it might even be necessary to replace the component within (a few) years.

Daylight will need to be regulated on a minute-to-minute basis, depending on the sun’s influence on the daylight level in the interior. The sun’s energy and its heat accumulating effect on the interior will need to be regulated on all four levels. Of course, it’s dependant on the season, but its positive effect on the building’s energy consumption is great when the component is also able to react to changes during the day (and night). As for vision, this component needs to be regulated on a minute-to-minute basis and during the day.

The wind and water component has different levels of adaptivity: this can change from minute-to-minute, from day to day and per season. Looking at the moderate climate the building is situated in, it is not necessary to change the level of adaptivity during the years, only when it is necessary to replace the component(s).

The component that regulates the amount of sound coming is needs to be very flexible: this can change per minute and is not dependant on the seasons at all.

In general, the level of adaptivity is different per function. This difference needs to be taken into account when designing façade concepts. If a component is able to fulfill multiple functions, it might be that the difference in adaptivity level makes the component unsuitable to serve all functions.
Adaptivity analysis

Spring/Autumn

Thermal insulation is needed during a spring or autumn day to keep the heat produced inside and to keep the cold outside the building, see Figure 20a. Heat storage is wanted on sunny days, however, on cold days the building mass needs to be reduced to nil to allow the sun’s energy – and thus heat – into the interior. Some of the excessive moisture could be absorbed but this will reduce the feeling of comfort since the air temperature will drop as well. Ventilation is wanted when the outside temperature is lower than the inside temperature as long as the minimum temperature inside still is acceptable (higher than 18°C). For daylight, screens are needed to reduce glare caused by the sun’s low angle. Since the sun’s intensity is not as high as in summer, protection against overheating is only necessary on warm days.

During spring (or autumn) nights, the need for thermal insulation increases in comparison to the day situation. The heat storage capacity needs to be able to decrease because the nights are colder than the days and there is no possibility to store heat during the night. The amount of moisture is similar to the day situation, see Figure 20, so the amount of absorption can stay the same. Generally, natural ventilation needs to decrease because colder nights can be expected; ventilating the interior would mean a decline in temperature. There is no need for glare protection or overheating control.

A comparison between the day and night situation, provides information on the needed response time of the adaptive components. It's necessary for the insulation layer to adapt during day and night; the same holds for the façade's heat storage capacity and for natural ventilation. In spring and autumn it might be necessary to ventilate, however, there are also situations in which ventilation is unwanted. The components influencing daylight (glare) and overheating need to be adaptable on a daily basis as well.
Summer

On a hot summer day a lot of building mass is wanted to absorb the heat caused by a large amount of solar energy. The amount of thermal insulation is just needed to keep some of the heat out. This conflicts with the natural ventilation which could be used to cool down the rooms inside the building. For moisture, some sort of absorption is needed to extract moisture from the interior. This will help people feel more comfortable since a low relative humidity and a high room temperature feels much better than a high relative humidity and a high room temperature, see Thermal & hygienic requirements. As for daylight, light is desirable yet the solar energy that accompanies it is not. In order to combat this phenomenon, overheating control is needed. However, this overheating control should let the visible light through and keep the energy out.

During the night, there is no need for insulation since the heat that was built up during the day needs to be able to get out. The building mass needs to be reduced to slowly release its heat during the night. In combination with natural ventilation, the room temperatures will drop and stored heat will be released more quickly since the difference in temperature will force the heat inside the building mass to evaporate on the surface. Moisture still needs to be absorbed, although the amount of absorption can be less at night than during the day when the urge is higher to reduce the room temperatures. There is no need for glare protection or overheating control.

Comparing the day and night situation in summer, it becomes clear that – as can be expected – the components against glare and overheating need to be adaptive on a daily basis; they are only needed during the day. The amount of natural ventilation needs to be adaptable on a daily basis as well because the need for it differs between day and night. The component for moisture does not need to adapt daily, however, severe swings in temperature will have an effect on the relative humidity and thus on comfort. An adaptive component that reacts in itself to these changes would be ideal. The building mass (heat storage capacity) of the façade does not need to change every day, whereas the thermal insulation does. The insulation needs to be able to reduce itself to non-insulating.

Figure 21: Façade functions during a summer day (a) and night (b)
It is wise to choose either for a building with a large heat storage capacity without (natural) ventilation (Figure 22a), or for a lightweight building with a large natural ventilation capacity, see Figure 22b. In the first case, the building mass will absorb the heat trapped inside the building. This is a passive way of cooling and will only need extra ventilation when the outside temperature is higher than the inside temperature. In the case where there is no mass but a lightweight construction is used instead, ventilation is needed to cool the building. This type of construction can get rid of the heat much quicker.

**Winter**

During a cold winter day, see Figure 23a, thermal insulation is obviously needed to reduce heat loss through the façade. The capacity to store heat, on the contrary, is unwanted since it will restrict heat (radiation) from the sun to enter the building. The absorption of moisture is undesirable as well because heating of the interior causes the air inside to become dry; instead of dehumidifying, it’s necessary to supply extra moisture inside the rooms. Natural ventilation is desirable from the point of ventilation, however, the cold that accompanies the natural fresh air is not. In the winter situation, the sun has the lowest angle which means that direct daylight can penetrate furthest into the rooms. The accompanying heat is desirable but glare is not so protection is needed.

On a winter night, there is no need for overheating and glare control. Natural ventilation is non-desirable since the low temperatures that accompany the fresh air will severely cool down the building. It’s then wiser to ventilate mechanically with pre-heated air. Similar as for the day situation, moisture needs to be added to the interior during the night to increase the room temperatures and humidify the air. Building mass is undesirable during the night as well, because it would only store cold. Maximum insulation is needed to keep the heat produced during the day inside the building.
By comparison, the day and night situation in winter do not differ so much from each other. During the night, more thermal insulation is needed and less natural ventilation. The heat storage capacity stays the same in both situations, and the protection against glare and overheating does not differ from the spring and summer situation: the component needs to be adaptable on a daily basis. Instead of extracting moisture from the rooms (as has been the case in spring and summer), it is necessary in winter to add moisture to the rooms.

**Conclusion**

In Table 10 below, the different adaptive functions that are needed in the façade to contribute to a comfortable interior have been quantified for the day and night situations and for every orientation. At the right end of the table, the level of adaptation per season is specified. In appendix 3 this table is made per orientation, taking into account the seasons more elaborately. The amount of adaptivity is reflected in plusses and minuses since it is interesting for this research to know how much the façade should be able to adapt. However, it is not feasible within the timeframe of the research to specify the amount of adaptability in exact values. Of course, there is a lot of potential to answer this question more specifically but for now it goes beyond the scope of the research.

As can be seen in Figure 14 and derived from Table 10, the component for thermal insulation needs to be extremely adaptive. In summer it must be able to reduce itself to non-insulating, whereas on a cold winter night it needs to be as insulating as possible. Comparing the necessary insulation for the different seasons and between day and night, shows that within a season itself the matter of adaptivity is not as great as between the different seasons. This could imply that instead of searching for one extremely adaptable insulation component, one could apply two components with differing insulation properties to compensate one extreme component.

The heat storage component is most useful during summer, and least useful in winter when it’s unwanted to store heat. From Table 10, one can see that this component needs to be available in summer when it’s most effective, and in spring and autumn, albeit not as necessary as in summer. Considered needs to be whether this component can be taken off the façade in winter or whether it can stay on if it’s capacity to store heat can
be reduced to nil. This decision cannot only be based on the matter of adaptability within
the component but is also dependant on the design for and the use of the façade.

Although Table 10 reads that the absolute value ranges from -- to ++, moisture does not
necessarily need an adaptive component in the façade, since the effect of adaptable
humidification on room comfort is much smaller than for instance thermal insulation;
moreover, it’s more effective to (de)humidify through HVAC (air conditioning) because a
HVAC system will most likely be installed anyway.

The component for (natural) ventilation needs to be 100% adaptive. In summer, it needs
to be able to naturally ventilate the complete building; in winter it needs to be closed
down or only operate at 25% of its capacity (see Table 10). A traditional register seems
to be the most obvious solution. However, this only solves the ventilation component and
does not deal with a decline in temperature in winter or a temperature rise in summer.
So, it is necessary to not only look at solutions per façade function, but also look at its
effect on the other functions.

The two aspects related to daylight – glare and overheating – will be discussed
separately, although both only need protective components during the day. To allow
visible light into the interior while preventing glare, components offering protection
against glare are necessary all year round. Although the sun’s intensity is much higher in
summer, its blinding effect is bigger in winter when the sun’s angle is lowest.

The chance of overheating is obviously highest in summer. As the sun’s intensity
decreases from summer to winter, the amount for protection necessary against
overheating decreases as well from summer to winter. The ambivalence in protective
components against overheating lies in the fact that most components developed up till
now also prevent visible light entering the interior. This has a negative effect on room
comfort in winter when daylight and the sun’s heat are desirable. In summer, light is still
wanted whereas radiation (overheating) is not. In the chapter on Adaptive Façade
Components, components will be searched for with both qualities, so as to prevent
ambivalent reactions.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal insulation</td>
<td>--</td>
<td>++</td>
<td>--</td>
<td>++</td>
<td>--</td>
<td>++</td>
<td>--</td>
<td>++</td>
<td>Similar for every orientation</td>
</tr>
<tr>
<td>Heat storage</td>
<td>--</td>
<td>+</td>
<td>--</td>
<td>++</td>
<td>--</td>
<td>++</td>
<td>--</td>
<td>++</td>
<td>North façade is different</td>
</tr>
<tr>
<td>Dehumidification</td>
<td>--</td>
<td>++</td>
<td>--</td>
<td>++</td>
<td>--</td>
<td>++</td>
<td>--</td>
<td>++</td>
<td>Similar for every orientation</td>
</tr>
<tr>
<td>Natural ventilation</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>++</td>
<td>--</td>
<td>+</td>
<td>--</td>
<td>+</td>
<td>North façade is different</td>
</tr>
<tr>
<td>Daylight</td>
<td>--</td>
<td>o</td>
<td>--</td>
<td>++</td>
<td>--</td>
<td>+</td>
<td>--</td>
<td>+</td>
<td>North façade is different</td>
</tr>
<tr>
<td>Overheating control</td>
<td>--</td>
<td>-</td>
<td>--</td>
<td>++</td>
<td>--</td>
<td>+</td>
<td>--</td>
<td>+</td>
<td>North façade is different</td>
</tr>
</tbody>
</table>

Table 10: Matter of adaptivity per function, season and orientation
Adaptive façade components

- Thermal insulation, gradually
- Accumulation, gradually
- Reflection of internal heat radiation
- Allow diffuse daylight, controlled
- Allow direct sunlight, controlled
- Allow UV-radiation, controlled
- Light reflection and absorption, gradually
- Visual connection, controlled
- Ventilation, inlet of summer breeze
- Exclude contaminated air
- Wind tightness/Draft tightness
- Water tightness
- Humidification/Damp diffusion
- Protection of the wall against vapor openings by precipitation or water for cleaning
- Sound insulation
- Sound reduction (absorption or reflection), gradually

*Figure 24: Adaptive functions of a façade (Christoph Feldtkeller, 1989)*
The requirements to a façade have not always been as extended as is the case nowadays. In the past and to some degree even today, façade requirements were defined exclusively by the architect. However, the façades of the future should be intelligently designed to satisfy all requirements of future users while ensuring optimum use of the environmental resources available. Designers should bear in mind that this can be done as long as it is compatible with the overall building program. The notion that a well designed façade can contribute to a reduction in energy use has made the application of adaptable façade concepts more widely accepted and used.

In Figure 24 all functions that could be adaptive within a façade are listed. However, a façade must fulfill a multitude of differing functions, some static and some adaptable. The principal factors defining a comfortable interior are:

- Visual contact between interior and exterior
- Daylight penetration into interior
- Natural ventilation
- Optimal insulation
- Optimal sun protection
- Comfortable surface temperatures
- Adequate glare control

In a traditional façade, see Figure 25, visual contact and natural ventilation are solved by a window that is openable. The window also takes care of the daylight penetration into the interior. Either curtains (blinds) or external shading devices are used to regulate the amount of daylight and the accompanying energy that can heat up the room inside. The thermal insulation is solved by a brick cavity construction and the brickwork also has a positive effect on the surface temperature of the façade.

In the coming text, all functions in the facade will be determined and discussed on their possibility to adapt. From then on, an inventory will be made on the components that will be able to fulfill an adaptive function.

---

Within the functions of a façade that can contribute to acceptable comfort levels inside a room, a distinction can be made between static functions and adaptable functions. Static functions are for example burglary prevention and fire protection. There is no need to adapt these functions in order to improve the energy levels of the building or to improve the flexible usage of the interior rooms. Adaptable functions in a façade are able to contribute to these aspects and can be listed as following:

- **Temperature control**
  - Thermal insulation, gradually
  - Heat accumulation, gradually
  - Reflection of internal heat radiation

- **Ventilation**
  - Ventilation, inlet of summer breeze
  - Humidification

- **Daylight regulation**
  - Allow diffuse daylight, controlled
  - Allow direct sunlight, controlled
  - Allow UV-radiation, controlled
  - Light reflection and absorption, gradually
  - Visual connection, controlled

- **Wind reduction**
  - Wind tightness
  - Draft tightness

- **Water barrier**
  - Water tightness
  - Damp diffusion
  - Protection of the wall against vapor openings by precipitation or cleaning water

- **Acoustic performance**
  - Sound insulation
  - Sound reduction (absorption or reflection), gradually

- **Architectural adaptiveness**
  - Color
  - Texture
  - Shape

In the following chapter on Adaptive functions the adaptive possibilities of façade functions will be explained more thoroughly. The adaptive components related to these functions can be organized into different categories. This organization will become visible in a diagram, which can be found in the next chapter. The scheme will offer designers and architects an overview of the adaptable components that have been developed up till now. The adaptive components in the diagram are organized alphabetically in a glossary and elaborated on function and potential per adaptable component.
An initial idea on what criteria can be used to organize these components will help the research to become more specialized. Important to state is that all installation components that could be put into a façade to contribute to comfort will be left out of the research. Incorporating this element would make the research even more complex; so it is necessary to demarcate what type of components will be looked at. Adaptive components regarding heat, ventilation, daylight, et cetera, will be organized into three aspects of adaptation: manual adaptation, mechanical adaptation and adaptation on the level of the material. The reason for this type of organization lays in the fact that there will be different room types with different users. For some room types it is convenient to use manual adaptation components; other room types might be more in need of materials that can adapt in themselves.

The term ‘smart materials’ from now on will be used to indicate materials that adapt on material level. Common uses of the term ‘smart materials’ suggest materials that have intrinsic or embedded quick response capabilities. They can be applied selectively and strategically and perform in a direct or local role, although this idea is quite new to architecture.

In this research, smart materials will be used in a passive manner, meaning that the material is able to change in itself. They can either be environmentally activated (external influences) or electrically activated. The major drawback in environmentally activated materials lays in the fact that the response might not coincide with the interior needs. Light, heat and view must cross the glazed façade, and the optimization of a single environmental factor is unlikely to coincide with the desired response to the other environmental conditions. For this reason, much more development has devoted to electrically activated chromic materials. These materials do, however, have disadvantages as well.

A so-called smart material needs energy input – electrical, mechanical, et cetera – in order to be able to change property. A distinction is made in Smart Materials and Technologies between materials that absorb input energy and undergo a change (Type 1), and materials that stay the same but their energy changes (Type 2). An overview of common smart materials is given in Table 11. Extensive information on smart materials can be found in Smart Materials and Technologies.

<table>
<thead>
<tr>
<th>Type of smart material</th>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1 Property-changing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermochromics</td>
<td>Temperature difference</td>
<td>Color change</td>
</tr>
<tr>
<td>Photochromics</td>
<td>Radiation (Light)</td>
<td>Color change</td>
</tr>
<tr>
<td>Mechanochromics</td>
<td>Deformation</td>
<td>Color change</td>
</tr>
<tr>
<td>Chemochromics</td>
<td>Chemical concentration</td>
<td>Color change</td>
</tr>
<tr>
<td>Electrochromics</td>
<td>Electric potential difference</td>
<td>Color change</td>
</tr>
<tr>
<td>Liquid crystals</td>
<td>Electric potential difference</td>
<td>Color change</td>
</tr>
<tr>
<td>Suspended particle</td>
<td>Electric potential difference</td>
<td>Color change</td>
</tr>
<tr>
<td>Electrorheological</td>
<td>Electric potential difference</td>
<td>Stiffness/ viscosity change</td>
</tr>
<tr>
<td>Magnetorheological</td>
<td>Electric potential difference</td>
<td>Stiffness/ viscosity change</td>
</tr>
</tbody>
</table>
Type 2 Energy-exchanging

<table>
<thead>
<tr>
<th>Material</th>
<th>Source</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electroluminescents</td>
<td>Electric potential difference</td>
<td>Light</td>
</tr>
<tr>
<td>Photoluminescents</td>
<td>Radiation</td>
<td>Light</td>
</tr>
<tr>
<td>Chemoluminescents</td>
<td>Chemical concentration</td>
<td>Light</td>
</tr>
<tr>
<td>Thermoluminescents</td>
<td>Temperature difference</td>
<td>Light</td>
</tr>
<tr>
<td>Light-emitting diodes</td>
<td>Electric potential difference</td>
<td>Light</td>
</tr>
<tr>
<td>Photovoltaics</td>
<td>Radiation (Light)</td>
<td>Electric potential difference</td>
</tr>
</tbody>
</table>

Type 2 Energy-exchanging (reversible)

<table>
<thead>
<tr>
<th>Material</th>
<th>Source</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piezoelectric</td>
<td>Deformation</td>
<td>Electric potential difference</td>
</tr>
<tr>
<td>Pyroelectric</td>
<td>Temperature difference</td>
<td>Electric potential difference</td>
</tr>
<tr>
<td>Thermoelectric</td>
<td>Temperature difference</td>
<td>Electric potential difference</td>
</tr>
<tr>
<td>Electrorestrictive</td>
<td>Electric potential difference</td>
<td>Deformation</td>
</tr>
<tr>
<td>Magnetorestrictive</td>
<td>Magnetic field</td>
<td>Deformation</td>
</tr>
</tbody>
</table>

Table 11: Basic characteristics of common smart materials (Addington, 2005)

Adaptive functions

In this chapter, an analysis is made of the different functions that need to be regulated in the façade. Problems concerning temperature, ventilation, light, water, wind and acoustics cannot be solved at once and need to be solved by façade components. A suggestion is given on what functions in the façade could be adaptive and in that way contribute to room comfort and a reduction in energy use. The aspect of flexible space usage which also is an advantage as opposed to static façade components will be taken into the account at the stage of designing the concepts.

Temperature

Good thermal insulation increases the surface temperatures on the inside of the façade, which improves the level of comfort near the façade, reduces the maximum heating requirement and hence lowers the capital outlay. Furthermore, it shortens the operating time of the heating system, which cuts the consumption of heating energy and operating costs (Herzog, 2004, p. 55).
Adaptables: An Adaptive Façade for the Future Faculty of Architecture

Adaptive thermal insulation and storage capacity will improve the feeling of comfort all year round since the range in which a comfortable feeling can be achieved will be wider. Moisture can make people feel uncomfortable when the relative room humidity is below 30% and the temperature is below 18 °C, or when the relative humidity is above 70% and the room temperature is 24 °C or higher. An adaptable (de)humidifier can contribute to room comfort.

Fresh air

In addition to all other positive aspects of minimizing heating energy consumption through the form and orientation of buildings, special attention should be given to their suitability for natural ventilation (Daniels, 2003, p. 17). Fresh air, wind flow and the inherent energy potential they contain are essential parameters for future integrated planning concepts and should be used accordingly.

Air movement in a room strongly influences comfort; in general, increased air movement is still experienced as comfortable as room temperatures rises, and vice versa (Daniels, 2003, p. 29). The possibility to decrease or increase air movement (through an adaptable air in- and/or outlet) inside a room and natural ventilation thus increases the comfort levels.

Daylight & Visual comfort

The daylight availability can be specifically exploited by means of intelligent day lighting concepts. Besides the targeted distribution of the solar radiation entering the interior by means of suitable shading systems, there is a second approach which is based on the fact that only the visible part of the solar spectrum can be used for illuminating the interior. As the infrared component in particular increases the thermal load in the interior, systems with specially coated glasses are desirable. These coatings are selective, that is, they are designed to admit the wavelengths of visible light within the spectrum (Herzog, 2004, p. 58). However, these coatings are static solutions; people are not able to apply them in summer (when there is a large amount of infrared radiation causing overheating), and leave them out of the façade in winter (when there is the need to heat up the room; this could be done with infrared radiation). Components which can control the ingress of (direct) daylight and control the problem of overheating at the same time are desirable.
Visual comfort exists when the perceptive faculties in the human brain can operate without interference. Incorrect distribution of light density in a room, glare, poor color matching and inappropriate interior design all inhibit perception (Daniels, 2003, p. 33). In summer, the Sun will be high in the sky causing short shadows. In spring and fall the Sun will be situated lower and cause a much more direct ingress of (sun)light (with long shadows). This will have a negative effect on visual comfort when no means are used to filter this light. The possibility to control

**Wind/Water barrier**

The possibilities for adaptable wind and water barriers may at first seem unnecessary. The whole point of making these sort of barriers is to actually keep out wind and precipitation. However, if it would be possible to pass wind through an adaptive barrier, you could use it in combination with ventilation. On a windy summer day this would mean that higher air velocities could be reached, cooling the interior behind the façade.

An adaptable water barrier could be used outside in combination with sun shading, to create a barrier during a rain shower; this could reduce maintenance costs on the façade.

**Acoustics**

Adaptable sound insulation could be useful in such a way that the insulation in a façade nearby a roadway should be much greater than the sound insulation in a façade adjacent to a park. It might be interesting to be able to change the insulation according to a room occupant’s likes. Completely soundless and sound-absorbing rooms, on the other hand, are perceived as uncomfortable.

**Architectural components**

Adaptive architectural components mainly have an aesthetic reasoning behind them but they could have positive side effects on other functions in the façade as well. Adaptive architectural components could be color-changing, texture-changing or adapting shape.
### Diagram adaptive components

<table>
<thead>
<tr>
<th></th>
<th>Manual</th>
<th>Mechanical</th>
<th>Smart material</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thermal insulation</strong></td>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
<td><img src="image3" alt="Diagram" /></td>
</tr>
<tr>
<td></td>
<td><img src="image4" alt="Diagram" /></td>
<td><img src="image5" alt="Diagram" /></td>
<td><img src="image6" alt="Diagram" /></td>
</tr>
<tr>
<td><strong>Heat storage</strong></td>
<td><img src="image7" alt="Diagram" /></td>
<td><img src="image8" alt="Diagram" /></td>
<td><img src="image9" alt="Diagram" /></td>
</tr>
<tr>
<td></td>
<td><img src="image10" alt="Diagram" /></td>
<td><img src="image11" alt="Diagram" /></td>
<td><img src="image12" alt="Diagram" /></td>
</tr>
<tr>
<td><strong>(De)humidification</strong></td>
<td><img src="image13" alt="Diagram" /></td>
<td><img src="image14" alt="Diagram" /></td>
<td><img src="image15" alt="Diagram" /></td>
</tr>
<tr>
<td></td>
<td><img src="image16" alt="Diagram" /></td>
<td><img src="image17" alt="Diagram" /></td>
<td><img src="image18" alt="Diagram" /></td>
</tr>
<tr>
<td><strong>Natural Ventilation</strong></td>
<td><img src="image19" alt="Diagram" /></td>
<td><img src="image20" alt="Diagram" /></td>
<td><img src="image21" alt="Diagram" /></td>
</tr>
<tr>
<td></td>
<td><img src="image22" alt="Diagram" /></td>
<td><img src="image23" alt="Diagram" /></td>
<td><img src="image24" alt="Diagram" /></td>
</tr>
<tr>
<td><strong>Ingress of daylight</strong></td>
<td><img src="image25" alt="Diagram" /></td>
<td><img src="image26" alt="Diagram" /></td>
<td><img src="image27" alt="Diagram" /></td>
</tr>
<tr>
<td></td>
<td><img src="image28" alt="Diagram" /></td>
<td><img src="image29" alt="Diagram" /></td>
<td><img src="image30" alt="Diagram" /></td>
</tr>
</tbody>
</table>
### Overheating control

- **Manual**
  - Sun shading
- **Mechanical**
  - Heat pipe
  - Sun shading
- **Smart material**
  - Electrochromic
  - Photochromic
  - Phase Change Material
  - Thermochromic
  - Vegetation

### Vision

- **Manual**
  - Sun shading
- **Mechanical**
  - Blind
  - Diaphragm
- **Smart material**
  - Electrochromic
  - Chemochromic
  - Liquid crystal
  - Polymer film
  - Thermotropic
  - Vegetation

### Wind & Water

- **Manual**
  - Sun shielding
- **Mechanical**
  - Diaphragm
- **Smart material**
  - Fabric
  - Silica gel
  - Vegetation

### Acoustics

- **Manual**
  - Register
  - Window
- **Mechanical**
  - Register
  - Vacuum
- **Smart material**
  - Piezoelectric

**Legend:**
- **Manual**
- **Mechanical**
- **Smart material**
<table>
<thead>
<tr>
<th>Architectural Component</th>
<th>Manual</th>
<th>Mechanical</th>
<th>Smart material</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Color</td>
<td><img src="LED_light.png" alt="LED Light" /></td>
<td><img src="glow.png" alt="Glow-in-the-dark" /> <img src="mechanochromic.png" alt="Mechanochromic" /> <img src="photochromic.png" alt="Photochromic" /> <img src="polymer.png" alt="Polymer film" /> <img src="thermochromic.png" alt="Thermochromic" /></td>
<td></td>
</tr>
<tr>
<td>- Texture</td>
<td><img src="LED_light.png" alt="LED Light" /></td>
<td><img src="vegetation.png" alt="Vegetation" /></td>
<td></td>
</tr>
<tr>
<td>- Shape</td>
<td><img src="sun_shading.png" alt="Sun shading" /> <img src="0_pa.png" alt="0 Pa" /> <img src="vacuum.png" alt="Vacuum" /></td>
<td><img src="vegetation.png" alt="Vegetation" /></td>
<td></td>
</tr>
</tbody>
</table>

*Table 12: Components for an adaptive façade*
Glossary of adaptive components

<table>
<thead>
<tr>
<th>Component + Description</th>
</tr>
</thead>
</table>

### Air cavity

An air cavity in a multi-layered façade can contribute to lowering the radiant surface temperature of the internal layer. If it’s possible to close down the cavity, it can contribute to an adaptive thermal insulation.

Applications of multi-leaved façades with air cavities are mostly found in Germany, where banks and large offices want to be associated with the ecological image and the ideal workplace with which these types of facades are praised for. Yet, the energy reduction is not as great as expected and the possibility to use natural ventilation through the façade is ‘only’ possible for two-third of the year. Nevertheless, this type of construction offers interesting possibilities that need further examining.

### Blind

The primary function of a blind is prevention against glare. Blinds often appear as a type of sun shading; the G-value lies around 0.3. The available systems exist mostly of horizontal or vertical venetian blinds of fabric or aluminum and roller blinds.

Blinds are protected from external weather influences and cleaning and have low maintenance. Nevertheless, it’s least effective in blocking out the sun’s heat because the absorbed radiation is given off to the interior in the shape of heat through convection and radiation.

### Chemochromic material

A material that changes color when exposed to specific chemical environments.

Chemochromic materials need a change in chemical concentration to change color. A good example of a chemochromic is ancient litmus paper; this type of paper is used in chemistry lessons as a pH-indicator. Philips Research Laboratory has developed a chemochromic optical switch based on metal hydrates similar to a electrochemical switch. It is shown that lanthanide hydride thin films can be switched from absorbing to transparent with a NaBH4 solution. The reverse reaction can be accomplished with an aqueous H2O2 solution (CNRS, 2009). Its application is best suited for adaptable vision.

### Cloud gel (Thermotropic)

Cloud gel is a thin plastic film that responds to a change in temperature.

The response temperature is adjustable to need and location. The application in glazing is best suited for skylights rather than windows. In addition to automatically changing from clear to diffused in response to heat, cloud gel glazing also turns white and reflective, reducing the transmission of solar heat and air conditioning costs (See “Thermochromic material”).
Diaphragm

A diaphragm is a component based on the principle of a camera shutter. In the façade, it can regulate the amount of daylight entering the interior. It can be adapted manually or mechanically.

A famous example of a design with diaphragms is the Institut du Monde Arabe by Jean Nouvel from 1987. Here, multiple openings operating on the principle of a camera shutter mechanically control the amount of daylight. The mechanisms and controls are left exposed, however, the mechanism itself is delicate and requires considerable maintenance. Furthermore, the effectiveness of such sun shading systems can vary according to the position of the sun or the position of the shading mechanism itself; typical G-values lie between 0.2 and 0.5.

Electro chromic material

A material that changes color when a voltage is applied (see "OVS").

Potential uses for electrochromic technology include daylighting control, glare control, solar heat control, and fading protection in windows and skylights (Toolbase Services, 2008). The relative transparency and color tint of electrochromic windows can be electrically controlled. It is necessary, however, for the voltage to remain on for the window to remain in a darkened state. The colored state of electrochromic glazing tends to be bluish, nevertheless, this type of glazing has become most recommended for building façades since it’s able to maintain view (spectral transmission) from the bleached to the colored states.
Fabric (or Textile)

Teflon, a high performance fabric, is more or less waterproof, but still allows moisture vapor permeability. The breathable material is stretched into a porous form to form the ‘breathable’ membranes also known as Gore-Tex.

Its application is wide since it’s an engineered material; characteristics such as liquid entry pressure, biocompatibility, chemical stability and other factors can be predetermined. This allows a range of industrial applications such as filters and vents (Addington, 2005).

Glow-in-the-dark

Phosphorescence is the mechanism used for glow-in-the-dark, and is a specific type of photoluminescence related to fluorescence. Glow-in-the-dark material finds its application in paints and lighting.

Unlike fluorescence, a phosphorescent material does not immediately re-emit the radiation it absorbs. In simple terms, phosphorescence is a process in which energy absorbed by a substance is released relatively slowly in the form of light. Unlike the relatively swift reactions in a common fluorescent tube, phosphorescent materials used for these materials absorb the energy and "store" it for a longer time as the processes required to re-emit the light occur less often (Wikipedia - Phosphorescence, 2009).

Heat engine

A heat engine converts thermal energy to a mechanical output and essentially cycles between a low temperature and high temperature reservoir.

A heat engine can be established across a junction in a semiconductor, producing an enormous temperature difference (thermoelectric). This temperature difference can be used as a sink (for cooling) or as a source (for heating) (Addington, 2005, p. 140). In the latter, the heat produced could be used to dehumidify the room if necessary.

Heat pipe

A heat pipe is a heat transfer mechanism that can transport large quantities of heat with a very small difference in temperature between the hotter and colder interfaces (Wikipedia, 2009).

In modern PV cells, heat pipes are often used. Their application is ideal because the radiant heat of a large surface can easily be concentrated to a small surface. The accumulated heat can be transported to water or another medium that needs to be heated. In comparison to other systems, for instance a water pipe, a heat pipe has a lot of advantages. A useful façade application for a heat pipe would be inside building mass to extract surplus heat.

Heat pipes must be tuned to particular cooling conditions. The choice of pipe material, size and coolant all have an effect on the optimal temperatures in which heat pipes work. Most manufacturers cannot make a traditional heat pipe smaller than 3 mm in diameter due to material limitations (though 1.6mm thin sheets can be fabricated) (Wikipedia, 2009).
Light

Lighting in buildings has primarily been for the illumination of space and objects. However, lighting can be used as an adaptive component as well. We already see LED lighting being applied in ‘mood’ installations or in bars looking to differentiate themselves from their competitors. LEDs are particularly suited for pattern making and color variability (see the image of the Agbar Tower in Barcelona (Spain) by Jean Nouvel), since both effects can be produced by incandescent systems with color wheels.

Although inorganic LEDs have drawn the majority of efforts in the developments of new solid state lighting technologies, there is a considerable speculation regarding the entry of organic materials. Organic LEDs or OLEDs are based on thin film technology. The thin films can provide any type of color and light distribution, regardless of how the individual pixels are arrayed. Perhaps the most provocative aspect of OLEDs is that the films are flexible, able to be molded around curves, and transparent, which allows almost any substrate (Addington, 2005, p. 178).

Liquid crystals

The liquid crystal suspended particle device (SPD), contains molecular particles suspended in a solution between plates of glass. In their natural state, the particles move randomly and collide, blocking the direct passage of light. When energized, the particles align rapidly and the glazing becomes transparent. This type of switchable glazing can block up to about 90 percent of light (Toolbase Services, 2008).

Liquid crystal glazing came into the architectural market fully tested and refined. Issues regarding their durability, maintenance, sizing, mounting and packaging has been partially resolved. Major disadvantages are the change in specularity – which does not contribute to a reduction in infrared radiation, the continuous requirement for power in their transparent state and the reduced view from oblique angles.

Mechanochromic material

A material that changes color due to imposed stresses and/or deformations (see "OVS"). Mechanochromic materials are mostly used in the aerospace industry in a paint to model aerodynamic flows. Some examples can be found in the automotive sector as well (Resource Efficiency Network, 2009).

Application in the building industry is not as useful because a mechanochromic material will change color when force is exerted on it. In a façade only wind force will have an effect.
Optical Variable Systems

Optical variable system is the collective term for a class of smart materials which includes photochromics, thermochromics, mechanochromics, chemochromics and electrochromics. Related technologies to electrochromics include liquid crystals and suspended particles devices that change color or transparencies when electrically activated.

The term ‘color-changing’ can be misleading since the material does not actually change color. The change in an external energy source produces a property change in the optical properties of a material – its absorbance, reflectance, or scattering. The so called 'color-changing' material group is invariably fascinating to any designer. Table 13 summarizes the design features of the various chromogenics.

<table>
<thead>
<tr>
<th>System type</th>
<th>Spectral response</th>
<th>Interior result view</th>
<th>Interior result thermal</th>
<th>Input energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photochromic</td>
<td>Specular to specular transmission at high UV levels</td>
<td>Reduction in intensity but still transparent</td>
<td>Reduction in transmitted radiation</td>
<td>UV radiation</td>
</tr>
<tr>
<td>Thermochromic</td>
<td>Specular to specular transmission at high IR levels</td>
<td>Reduction in intensity but still transparent</td>
<td>Reduction in transmitted radiation</td>
<td>Heat (high surface temperature)</td>
</tr>
<tr>
<td>Thermotropic</td>
<td>Specular to diffuse transmission at high and low temperatures</td>
<td>Reduction in intensity and visibility, becomes diffuse</td>
<td>Reduction in transmitted radiation, emitted radiation, and conductivity.</td>
<td>Heat (high and/or low surface temperature)</td>
</tr>
<tr>
<td>Electrochromic</td>
<td>Specular to specular transmission toward short wavelength region (blue)</td>
<td>Reduction in intensity</td>
<td>Proportional reduction in transmitted radiation</td>
<td>Voltage or current pulse</td>
</tr>
<tr>
<td>Liquid crystals</td>
<td>Specular to diffuse transmission</td>
<td>Minimal reduction in intensity, reduction in visibility, becomes diffuse</td>
<td>Minimal impact on transmitted radiation</td>
<td>Voltage</td>
</tr>
<tr>
<td>Suspended particle</td>
<td>Specular to diffuse transmission</td>
<td>Reduction in intensity and visibility, becomes diffuse</td>
<td>Minimal impact on transmitted radiation</td>
<td>Current</td>
</tr>
</tbody>
</table>

*Table 13: Comparison of smart window features (Addington, 2005)*
**Phase Change Material**

PCM are microcapsules made from paraffin and salt hydrates. Phase changing materials seek to take advantage of a change in temperature or pressure level, causing the material to change state at a precise temperature or pressure level. This phase change can be predicted based on the composition of the material and is reversible. PCM can simulate a non-existent thermal mass and can balance out variations of the indoor environment, reducing peak temperatures.

In architecture, the material has mainly been explored for helping the thermal environment inside a building. PCM has an additive form which makes it very suitable to incorporate in many forms and materials. Paraffin and fatty acids have been incorporated in wallboards and plastic pellets. Of particular interest is that successful applications occurred when phase-changing materials were encapsulated in one form or another. PCM’s have successfully been incorporated into textiles via the use of micro-encapsulation technologies. They have also been encapsulated in pellets to be used as radiant floor or wall heating. Their major advantage over hot water pipes in concrete is their quick response time. Moreover, they can be taken up in a light framing system as opposed to the heavy mass systems (Addington, 2005).

**Photochromic material**

A material that changes its color in response to a change in the amount of ultraviolet radiation on its surface (see "OVS").

In architecture, photochromic materials have been applied in various façades, albeit with varying amounts of success, to control solar gain and reduce glare. These applications have not proven effectively because of the slowness of response and heat gain problems (Addington, 2005, p. 86). Applications inducing color change can be found in printing with photochromic inks. These so-called smart inks are widespread since they can be used with most printing processes, including offset, lithography, and so on.

**Piezoelectric material**

Piezoelectric materials convert mechanical energy into electrical energy and vice versa. Most piezoelectrics are bi-directional in that the inputs can be switched and an applied electrical current will produce a deformation (strain).

A piezoelectric film – a thin, lightweight film that can be glued to surfaces – can be applied as a sensor to detect micro-deformations within a surface. Paints that contain piezoelectric materials can detect and assess damage.

An interesting application lies in the reduction of the amplitude of acoustic vibrations where the elastic energy contained in sound is converted to electricity. Researchers at TU Darmstadt in Germany have been investigating ways to reduce vibrations by attaching piezo elements. When the material is bent by a vibration in one direction, the system responds to the bend and sends electric power to the piezo element to bend in the other direction. The research team sees future applications in cars and houses to reduce noise (Wikipedia - Piezoelectricity, 2009).
Polymer film

Polarizing film

Polarizing films are inexpensive and have adhesive backings that allow them to be applied to glass substrates. They can reduce glare.

![Figure 27: Radiant color film (a) and radiant mirror film (b)](image)

Radiant color and mirror film

Radiant color film is transparent and possesses remarkable reflective and transmissive qualities. The color of the reflection perceived depends on the angle that light strikes it. It’s possible to create different kinds of optical properties.

Radiant mirror film reflects 98% of visible light. The opaque mirror film can be embossed, cut, coated to be UV resistant, and given an adhesive backing or laminated to other surfaces. It’s metal free and thermally stable. It consists of multiple layers, so it is possible to create different kinds of film with different optical properties.

View directional film

This polymeric material is embossed with very small specially shaped grooves or micro-louvers. This film can be used effectively to control light coming in through it, reducing glare.
Register (or ventilation slot)

A register is often part of a window and can contribute to natural ventilation in the façade. The modern windows typically no longer permit gap ventilation since they are well sealed. Some models however, do have small operable flaps to provide ventilation even when the window is closed. Another component that could be placed in the façade with adaptable ventilation is a sound baffle, which also has the function of reducing the airborne sound coming in. This is especially effective along highways.

A sound baffle today can be designed to be as high as 10 cm so that it does not have an extreme effect on the façade’s esthetics.

Silica gel

Silica gel is a granular, vitreous, highly porous form of silica made synthetically from sodium silicate. Despite its name, silica gel is a solid.

Silica gel is most commonly encountered in everyday life as beads packed in a semi-permeable plastic to control local humidity in order to avoid spoilage or degradation of some goods (Wikipedia - Silica gel, 2009). In a façade, it could be applied to dehumidify the air coming in to optimize room comfort. However, its chemical structure needs further analysis and development in order for it to be save to use in façades. Furthermore, if it would be save to use, a solution still needs to be found for the problem of heating the gel to 120°C in order for the material to release its contained water.

Sun Shading

Sun shading is applied to façades to stop augmented radiation from solar heat and blinding from direct sunlight. A distinction can be made between internal and external shading devices. The internal shading devices and their effects can be found under ‘Blinds’. A third type of shading is sun shading inside the façade, which will be discussed here as well.

External sun shading is very effective because the in the shading collected and converted radiation is given to the outside air through convection. In this way it does not aggravate the internal climate, which is the case with internal sun shading. Within external sun shading, a distinction can be made between permanent and adaptive sun shading.

Permanent sun shading can have a G-value of about 0,1. A major disadvantage is that this type of sun shading hinders light entering a room even when there is no sun.

Adaptive sun shading comes in different shapes: roller blinds, venetian blinds, awning blinds, canopies or lamellae systems. This type of shading has the advantage that it can be taken up or in when the sun is not shining or when the sun is not disturbing comfort. But although it’s better protected against weather influences than permanent sun shading, its moving parts are vulnerable and need maintenance quite often.

Another type of sun shading is the shading in between insulating glazing. Again, a distinction can be made between permanent and adaptive shading. An example of permanent shading in an air cavity is the system from Oka-Solar, in which permanent, triangular plastic profiles are redirecting the light. An adaptive system is for example the façade for the Institut du Monde Arabe, which is explained under ‘Diaphragm’ in this chapter. In general, G-values of 0,2 and 0,5 can be expected with this type of shading.
**Suspended particle device**

In suspended particle devices (SPDs), a thin film laminate of rod-like particles suspended in a fluid is placed between two glass or plastic layers, or attached to one layer. When no voltage is applied, the suspended particles are arranged in random orientations and tend to absorb light, so that the glass panel looks dark (or opaque), blue or, in more recent developments, grey or black color. When voltage is applied, the suspended particles align and let light pass. SPDs can be dimmed, and allow instant control of the amount of light and heat passing through. A small but constant electrical current is required for keeping the SPD smart window in its transparent stage (Wikipedia - Smart Glass, 2009).

Suspended particle devices are an alternative to liquid crystals for privacy applications, with similar drawbacks. They, too, are not effective for reducing infrared transmission, and they also require continuous power to remain transparent. In addition, they have even less ability for their spectral profile to be tweaked toward one color or another. Their primary advantage over liquid crystals is their ability to permit much more oblique viewing angles (Addington, 2005, p. 171).

**Thermochromic material**

An input of thermal energy (heat) to the material alters its molecular structure. The new molecular structure has a different spectral reflectivity than does the original structure; as a result, the material’s color – its reflected radiation in the visible range of the electromagnetic spectrum – changes (see “OVS”).

In architecture and furniture design, thermochromic materials can be used to show the past presence of a person. Color change can be achieved by printing thermochromic inks on surfaces. The image fades with time, see Figure 29.

![Figure 29: Memories of touch through the use of thermochromic materials (Courtesy Juergen Mayer)](image)

The use of thermochromic materials on the exterior of a building is not yet perfect. Problem with the use of current available thermochromic paints on the exterior is that exposure to ultraviolet wavelengths in the sun’s light may cause the material to degrade and lose its color-changing capabilities (Addington, 2005, p. 87). Moreover, its low transmissivity in the visual part of the spectrum, which currently ranges from 27 to 35%, makes the thermochromics little used in the development of smart windows. Several thermochromic technologies are being explored, but gel-based coatings seem to be the most promising, see Cloud Gel (California Energy Emmission, 2006).
Thermotropic material

An input of thermal energy (or radiation for a phototropic, electricity for electrotropic and so on) to the material alters its micro-structure through a phase change (see "OVS"). In a different phase, most materials demonstrate different properties, including conductivity, transmissivity, volumetric expansion, and solubility.

Thermotropics respond to the same environmental input as do thermochromics, but the difference in the internal mechanism has given thermotropics broader potential application. Thermotropics undergo a change in specularity, resulting in the ability to provide diffuse daylight even as the view is diminished (Addington, 2005, p. 169). A smart application of thermotropic materials would be in skylights where light rather than view is paramount.

Another application would lay in heat absorption. Thermal energy can be absorbed and inertial swings dampened by material property changes (Addington, 2005, p. 140).

Vacuum

Vacuum is a volume of space that is essentially empty of matter, such that its gaseous pressure is much less than the atmospheric pressure (Wikipedia, 2009). Within vacuum, different ranges of vacuum can be achieved; the lower the pressure, the higher the level of vacuum.

In building technology, vacuum can bring a lot of advantages: it’s lightweight and therefore saves materials, but more importantly, it has high insulation values and the potential for freeform design. Below, some ideas are illustrated using vacuum. Difficulties in achieving vacuum in a façade lie mostly in the sealing of the vacuum and preventing the outer surfaces from touching each other, reducing the insulation values dramatically.

Figure 30: Ideas for vacuum applications in a façade
Vegetation

Vegetation on buildings has long been used for a decorative and thermal effect. There are however more possibilities. Plants on walls can assist in cooling buildings in summer as they provide shading that reduces solar gains to the building. The effect of transpiration by plants can also extract heat from the surrounding air (Durabuild, 2006).

A list of vegetation suitable on buildings is given in the case study report: Vegetation on Building Façades (Durabuild, 2006, pp. 14-19).

Ventilation

Within the term ‘ventilation’, a distinction can be made between natural and mechanical ventilation. Mechanical ventilation is usually employed if continuous ventilation is required. In this research, the installation components that are able to do this will not be looked at. So, the term ‘ventilation’ refers to components in the façade that can contribute to natural ventilation which can be regulated.

The most common method of natural ventilation is window ventilation whereby different types of hardware and fittings have an impact on the efficiency of the ventilation (Knaack, Façades, 2007, p. 75). In Figure 31 below, different types of ventilation openings are shown.

Figure 31: Different types of ventilation openings (Knaack, 2007)
Water pipes

Water pipes are used today in floor radiant systems. In concrete, they can regulate the surface temperature, influencing room comfort. A good example where water pipes are used for adaptive insulation is in the Zollverein School of Design and Management in Essen from SANAA. Here, Transsolar – the building services advisor – introduced mining water of approximately 30°C in water pipes within a massive concrete shell to regulate temperature and room comfort. Due to this active thermal insulation, which during winter heats the building through its shell, there was no need for a multi-layered shell structure with traditional thermal insulation. A disadvantage to water pipes as opposed to heat pipes, is that water pipes are not as effective.

Window (openable)

A window is in the first place permeable to light, giving us the possibility to link the exterior with the interior environment. A window can provide ventilation and regulate the transfer of humidity and sound. The first translucent or transparent windows were generally immovable items. Today, there are many ways in which to open a window and to control daylight, ventilation and sound. In the figure below, different types of standard openings are shown.

Figure 32: Overview of the different types of window openings (Knaack, 2007)
Façade concepts

This chapter will offer three concepts for the future façade for the faculty of Architecture in Delft. The adaptive components in the last chapter are used to create several strategies for an adaptive façade. These components have been scored on their functionality (light, storage capacity, sound, et cetera) and on their effectiveness in time. These aspects will determine for a large part what components are suitable for what concept and their functions.

Design Concept: Manual façade

The idea behind this concept is a façade that preferably uses manual components only for adaptivity. The main advantage of this type of façade in comparison to a façade with mechanical components is that the input needed for the façade once build is low: it needs the user of the room behind it to adapt it. A comment to this concept is that it requires an active contribution of the room’s occupant. The user must act upon the façade in order to influence the internal climate of the room. If the user does not changes components at the right time, the comfort levels might change in a negative way. Below, the manual components that have been analyzed up till now are given.

An initial approach for this concept is that the façade only uses the components that can be adapted manually. However, as can be concluded from Table 14, the manual components are not able to serve all functions in the façade and when they do, they might not be adaptive sufficiently. Mechanically adaptive components will be used as well to solve the deficiencies. For thermal insulation, heat storage and the wind and water barrier, mechanical components will be applied.

<table>
<thead>
<tr>
<th>Function</th>
<th>Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal insulation</td>
<td>-</td>
</tr>
<tr>
<td>Heat storage</td>
<td>-</td>
</tr>
<tr>
<td>(De)Humidification</td>
<td>Ventilation</td>
</tr>
<tr>
<td>Natural ventilation</td>
<td>Air cavity / Register / Window / Ventilation</td>
</tr>
<tr>
<td>Daylight</td>
<td>Blind / Diaphragm / Fabric (curtain)</td>
</tr>
<tr>
<td>Overheating control</td>
<td>Sun shading</td>
</tr>
<tr>
<td>Vision</td>
<td>Blind / Diaphragm / Sun shading</td>
</tr>
<tr>
<td>Wind &amp; Water</td>
<td>-</td>
</tr>
<tr>
<td>Acoustics</td>
<td>Register / Window</td>
</tr>
</tbody>
</table>

Table 14: Possible materials for a manually adaptive façade
**Concept development**

The application of a heat engine for insulation and storage is quite logic when we look at the diagram in Table 12. Here, one could apply vacuum or a water pipe as well to solve the thermal insulation, but the heat engine component is also useful for heat storage whereas the other two components are not. For natural ventilation, four different components can be applied. When looking at other functions as well, it’s convenient to either choose for a register, a window or a ventilation component. Regulating daylight can be done by blinds and/or sun shading or a diaphragm. Decisions need to be made what materials have the best properties per function in the façade. In Figure 33, a proposal for the façade is given.

![Figure 33: Conceptual proposal for a manual façade](image)

**Light**

To solve the daylight issue, one could apply blinds, sun shading or a diaphragm. If we want to tackle the problem of overheating, at least external sun shading is needed. A blind or a diaphragm can be applied to solve the daylight regulation, but this decision will be based on the architectural viewpoint, practicability and costs.
**Thermal insulation & storage**

A heat engine can be used for insulation in a similar way as has been done in the Zollverein School by SANAA; its storage capacity lies hidden in its sink function. Electricity can generate a temperature difference in the engine making it possible to store heat. The process also works vice versa: stored heat can be converted to electricity. It must be said that theoretically, vacuum will keep out all heat in the shape of convection and conduction. So in summer, it’s not necessary to store as much heat during the day in the façade with vacuum as would be necessary in the façade with a heat engine. Still, the heat engine component is more attractive.

**Wind & water**

The window and ventilation component are quite similar in that they both can contribute to natural ventilation. The ventilation component actually comes in the shape of a window opening. Therefore, the decision is made to use an openable window in combination with a register to control the amount of fresh air, moisture and sound.

**Sound**

To control the sound coming inside, a register is applied. It has the advantage over a window that a register – or acoustic baffle – still has the capacity to ventilate the room while blocking airborne sound, whereas a window can only be closed to block out sounds.

**Conclusion**

In conclusion, this concept seems to be a traditional façade. A heat engine is used to make adaptive insulation and storage capacity possible. The solutions for daylight regulation are not different from the ones used up to today but they have proven to be effective. The option of the diaphragm is interesting, but also a matter of taste. As for ventilation, a traditional window will function good. In combination with a register, it can have a positive effect on acoustic comfort and natural ventilation. Furthermore, there is no adaptive wind and/or water barrier that can be operated manually or mechanically. For this, traditional foil can be applied or smart materials such as silica gel or breathable fabric.
**Design Concept: Mechanic-façade**

The idea behind this concept is not very innovative: the façade is able to adapt itself by components that are driven by electricity; it does not need any interaction with the user of the façade. The façade is intelligent in that it can adapt itself, but for this it will need sensors and mechanical components to act upon internal or external changes; room comfort is programmed in advance. The components usable for this concept are:

![Image of components](image)

In Table 15 below, all components are organized to their function. The (LED)light component cannot be retrieved from the table because it has been sorted under the architectural component. However, it could be used as a daylight component as well, but it's less effective in the façade than in a ceiling. Furthermore, all façade functions seem to be able to be solved by mechanical components. In the coming paragraph a comparative assessment will be made on what components might have more than one functions and for that reason are smart to use for this façade concept.

<table>
<thead>
<tr>
<th>Function</th>
<th>Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal insulation</td>
<td>Air cavity / Heat Engine / Vacuum / Water pipe</td>
</tr>
<tr>
<td>Heat storage</td>
<td>Heat Engine / Heat pipe</td>
</tr>
<tr>
<td>(De)Humidification</td>
<td>Heat Engine / Ventilation</td>
</tr>
<tr>
<td>Natural ventilation</td>
<td>Air cavity / Register / Window / Ventilation</td>
</tr>
<tr>
<td>Daylight</td>
<td>Blind / Diaphragm / Fabric (curtain)</td>
</tr>
<tr>
<td>Overheating control</td>
<td>Heat pipe / Sun shading</td>
</tr>
<tr>
<td>Vision</td>
<td>Blind / Diaphragm / Sun shading</td>
</tr>
<tr>
<td>Wind &amp; Water</td>
<td>-</td>
</tr>
<tr>
<td>Acoustics</td>
<td>Register / Vacuum / Window</td>
</tr>
</tbody>
</table>

*Table 15: Possible materials for a mechanic-façade*

**Concept development**

When looking at the table above, the application of a heat engine again seems attractive since it can control the thermal insulation, the heat storage capacity and the moisture. A heat pipe also could be very interesting, because although it might not contribute to the (de)humidification function, it can contribute to overheating control.
Daylight regulation and vision are well solved by blinds, diaphragms or sun shading. A window or register have the function of both a ventilation component and sound barrier. Vacuum on the other hand also has a positive effect on blocking out sound and can be used as thermal insulation. In the coming text, a consideration needs to be made on function and multi-functionality.

**Light**

Within the daylight concept, there are two possibilities. The first one is the traditional solution in which blinds control the daylight coming in and external sun shading controls the possibility of overheating in summer. The second approach is more innovative. Here, internal blinds take care again of vision and daylight, but now a heat pipe controls the problem of overheating by extracting surplus heat from the room if necessary. The first option is the saver one, since this solution has proven to be very effective in a lot of façades. However, external sun shading has the disadvantage that it needs maintenance often. Application of a heat pipe in the façade seems very attractive although more research needs to be done on its effectiveness; it will need a large surface where the heat will cling to in order to be able to extract heat from the room.

![Figure 34: Possible components in a mechanic façade concept](image)
**Thermal insulation & storage**

Thermal insulation can be solved by two components with multiple functions in the façade: vacuum or a heat engine. Vacuum can achieve very high insulating values when executed properly, whereas a heat engine can perform three different functions within a façade: it can insulate, store heat and dehumidify a room, although this hasn’t been tested yet. A heat engine can produce an enormous temperature difference, giving it the possibility to store heat (sink function) or as a source for heating. The storage capacity can also be solved by a heat pipe, which also can tackle the problem of overheating in summer.

**Wind & water**

Natural ventilation can be resolved a ventilation component, a window or a register. Again, the ventilation component and window component are quite similar. The ventilation component could be used for fresh air and to dehumidify the room. However, opening the ventilation component will bring along airborne sound from outside and it is questionable whether the fresh air will ventilate the moisture away from the room or bring new moisture inside. A register can solve the acoustic problems that natural ventilation can bring. A window is then necessary for views in and outside, and if it’s openable, it can contribute to natural ventilation.

**Sound**

The sound component in the façade can be solved by vacuum, a register or a window. A window is the most primitive solution in that it can either be opened or closed. When the user closes the window to exclude sound, it automatically shuts down natural ventilation. With an acoustic baffle (register), the aspect of natural ventilation is not completely excluded. However, this component does have an effect on how the façade (or window) is going to look like since it will be placed above the window. Using vacuum as sound protection is a more preventive approach. Here, sound is blocked anyway from the interior by high insulation values. When a window is put in, this will automatically form an acoustic bridge for sound to enter the room, just as the gaps that will appear between the different components.

**Conclusion**

From the analysis, it becomes clear that there are actually two separate concepts within the main concept of the mechanic façade. The first one, see Figure 35, uses the heat pipe for storage and overheating control, the vacuum for thermal and acoustic insulation, blinds to control vision and daylight and a ventilation component for fresh air and to dehumidify the internal climate when necessary.

The second sub concept, see Figure 36, has incorporated a heat engine in the façade for thermal insulation, heat storage and dehumidification. The window in combination with an acoustic baffle enables natural ventilation while insulating acoustically. Internal blinds control vision and daylight whereas external sun shading keeps the problem of overheating in summer under control.
Comparing the two sub concepts has not led to a definite choice. All components have something going for them. However, if a choice has to be made, then the first concept seems most promising. When the heat engine and the heat pipe are compared, the heat pipe has already been developed much further making its application in a façade more feasible. Furthermore, the use of vacuum in façades is to be encouraged more because although there are problems regarding sealing and the costs involved are still considerable, its insulating effect is enormous resulting in a lowering or annihilating of the installation costs and energy consumption.
Design Concept: Smart-façade

The ‘smart-façade’ concept assumes a façade that is (completely) built up by ‘smart’ adaptive components. In this concept, it is not necessary for the user or the facility management to change or replace anything within or on the façade; no components will be interchanged. The façade can adapt itself to create the best comfort inside. The adaptive components that could be used for this concept are:

As a starting point, all ‘smart’ components from the diagram with the adaptive components (Table 12) have been sorted by function and collected in Table 16. A preliminary conclusion that can be drawn from this table – and concept – is that thermal insulation and natural ventilation cannot be solved by smart components, or at least, a smart component that can do this has not been found during this research. Both functions need to be solved in another way, either manually or mechanically. All other functions in the façade seem to be able to be solved by smart components. Research still needs to be done to find the right combination of components that can fulfill the façade’s needs. The decision is amongst others based on the Adaptivity analysis and the glossary.

<table>
<thead>
<tr>
<th>Function</th>
<th>Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal insulation</td>
<td>-</td>
</tr>
<tr>
<td>Heat storage</td>
<td>PCM / Thermo tropic</td>
</tr>
<tr>
<td>(De)Humidification</td>
<td>Silica gel / Breathable fabric</td>
</tr>
<tr>
<td>Natural ventilation</td>
<td>-</td>
</tr>
<tr>
<td>Daylight</td>
<td>Electro chromic / Liquid crystal / Photo chromic / Suspended particle / Thermo chromic / Thermo tropic / Vegetation</td>
</tr>
<tr>
<td>Overheating control</td>
<td>Electro chromic / (PCM) / Photo chromic / Thermo chromic / Thermo tropic / Vegetation</td>
</tr>
<tr>
<td>Vision</td>
<td>Electro chromic / Liquid crystal / Radiant color/mirror film / Thermo tropic / Vegetation</td>
</tr>
<tr>
<td>Wind &amp; Water</td>
<td>Breathable fabric / Vegetation</td>
</tr>
<tr>
<td>Acoustics</td>
<td>Piezoelectric effect</td>
</tr>
</tbody>
</table>

*Table 16: Possible materials for the smart-façade*
Concept development

The application of electrochromic materials in the façade seems smart as the material appears several times for different functions in the table above. Thermotropic materials and vegetation can be used as well for similar functions. Furthermore, PCM seem a logic material to use for heat storage and overheating control, however, thermotropic material can also fulfill the storage function. With this information, the following concept can be made, see Figure 37. Within this concept, decisions need to be made what materials have the best properties per function in the façade.

Light

Electrochromics can tackle the problem of regulating daylight, glare protection and adaptable vision. A disadvantage of an electrochromic window is the need to keep electricity on in order to keep the window in a darkened state, an advantage is that the window stays transparent at all times. A thermotropic window has the same abilities, however, the interior result – after a rise in temperature instead of applying a current – is a reduction in intensity and visibility and diffuseness. A disadvantage of this type of window is the impracticability to be able to switch the window on or off; something that is possible in an electrochromic window.
Another material that has the potential to reduce glare and solar gains, as well as regulating daylight in summer is vegetation. On buildings, it has a decorative effect and the effect of transpiration helps the plants to extract heat from the surrounding air. The decision to choose for this type of ‘smart’ material however, is not solely based on technical reasoning, it is also based on esthetics and an architectural point of view.

**Thermal insulation & storage**

For the adaptive insulation function, there are no smart materials that can be applied. For this function, a manual or mechanical component needs to be used, for example an air cavity or vacuum. To solve the heat storage capacity one could automatically choose for PCM but thermotropics also have the capacity to absorb thermal energy. More research needs to be done on the storage capacity of thermotropics in comparison to PCM. At first glance, it seems as if PCM can store more heat. Nevertheless, thermotropic material can also contribute to glare protection, daylight regulation and adaptive vision whereas PCM can only store heat. PCM is also able to reduce the chance of overheating since it can store heat, however, it is not able to reduce glare.

**Wind & water**

As for natural ventilation, there is no smart component that can be applied. For this function, a register or window could be placed in the façade. The register seems wise to use in the studio’s, whereas an openable window could be applied in the offices. To humidify or dehumidify, one could apply breathable fabric or silica gel. Silica gel has the disadvantage that it needs to be heated to a high temperature in order to lose the absorbed water trapped in the gel. The breathable fabric is more or less waterproof, but still allows moisture vapor permeability. Questionable is whether the characteristics of this material differ so much from normal damming foil that breathable fabric should be chosen over the foil. Furthermore, the problem of extracting moisture from a room can also be solved by HVAC systems, which will very likely will be applied in the future faculty anyway. The problem of surplus water can of course be solved by traditional damming foil in combination with a ventilation cavity. To make the system adaptive, breathable fabric could be chosen since it will form a barrier against water. Vegetation on the outside layer is another solution to this problem but the argumentation for this solution is mostly based on architecture.

**Sound**

The need for adaptive acoustical insulation is not necessary from the perspective of seasons and day and night differences but comes from an argumentation based on the building’s location. A smart material that in theory would be able to absorb elastic energy is a piezoelectric. This material can convert elastic energy to electricity, thus reducing the amplitude of the acoustic vibrations. A comment here is that research needs to be done on the effect of piezoelectrics on acoustics. It does not become clear in literature whether its effect happens at a micro scale or macro scale.

**Conclusion**

So, as a conclusion for the smart-façade, the smart materials that could be applied in the façade are PCM, breathable fabrics, thermotropics, electrochromics and vegetation. From the argumentation above, it is best to use PCM for heat storage capacity instead of thermotropics because the expected capacity will be larger. Moreover, the daylight regulating function that thermotropic material can bring, does have disadvantages as well as opposed to electrochromics and vegetation. The decision for an electrochromic window or vegetation on the façade is mostly based on the architectural viewpoint for the façade. If, however, the choice is made for vegetation over the electrochromic window, research needs to be done on what vegetation is suitable and/or desirable and if its daylight- and heat regulating property is similar to that of an electrochromic window. The breathable fabric could be applied as a water barrier, but several reasons are mentioned stating that this function could be solved by other, non-adaptive materials or components.
A variant to the smart façade concept could be a frame-façade. This concept is similar to the previous concept, however, it has the advantage that it can ‘upgrade’ itself in time meaning it’s possible to replace or update components in the façade to keep up with increasing standards on comfort and energy. A similar approach has been developed by Auer+Weber+Architekten for the design of the BMW centre in Munich°, see Figure 38. Here, different active components have been developed to form a climate skin with prefabricated functional elements. This approach allows the envelope to be adapted to satisfy all the different requirements while providing maximal flexibility. For the façade for the future faculty, this approach could also be useful.

Figure 38: Plug in active skin for BMW centre Munich (Hausladen, Climate Design, 2005)

° A broader explanation on this specific concept can be found in (Hausladen, Climate Design, 2005, p. 77).
Design

At the beginning of this research, it was argued that an adaptive façade could contribute to a multifunctional space. A singular adaptive façade design would be able to serve multiple functions, in this case a design studio, an office, and a meeting room. The final design for an adaptive façade however, is not only based on the contents of this research. It is also influenced by the architectural design for the future faculty of Architecture.

In the architectural design for the future faculty, the design studios and the offices are separated from each other. This means that the argument of multifunctional space usage becomes less considerable. Furthermore, the separation between the studios and the offices is articulated by a difference in materialization. As a result, the façade for a studio will look different from an office façade.

Starting point for the adaptive façade design was to make two separate designs for a studio façade and an office façade. When analyzing the two functions, it becomes clear that they have different daylight requirements, see Figure 39. This is due to the fact that there is a difference in layout and storey height. As a result, the daylight strategy of a design studio differs from the strategy for an office, see Figure 40.

![Figure 39: Comparison daylight surface area](image)

![Figure 40: Daylight strategy](image)
Another important aspect is the climatic concept. The workplaces in the studios and offices are natural ventilated when possible. This means that ventilation components need to be taken up in the façade. Furthermore, the amount of users per m² façade is much greater in the studios, resulting in a different way of regulating the adaptive façade components. The amount of controllability and regulation is higher for an office façade than for a studio façade. In conclusion, the focus of both façade designs is on daylight regulation, ventilation and utilization of the façade. In the paragraphs following, both façade designs will be shown and explained.

**Studio façade design**

The design for a studio façade is shown in Figure 41 below. The idea was to create an enclosed building edge with student workplaces. The façade is like a skin enclosing the building; it is transparent yet almost completely impermeable from the outside.

![Figure 41: Studio façade](image)

The façade is a curtain wall built up from smaller components. In this way it is possible to produce façade elements in the factory, reducing building time and making them less vulnerable to exterior influences when assembling the façade. The choice for structural glazing is an architectural one, yet it also has the advantage that it is possible to replace components in the façade later on. This increases the façade's flexibility in such a way that it becomes possible to upgrade façade components.

---

6 A complete overview of the design can be found in the appendices under 'Design Drawings'.
A component is 2.7 meters wide and 4.5 meters high. It is build up horizontally in two zones. The upper zone is a daylight zone, the lower one is designed to be regulated by its users. Vertically, the component is arranged in four areas. The biggest area is the insulating panel of the façade. It’s a glassfibre reinforced polyester panel filled with Nanogel, called Scobatherm. Nanogel has several interesting properties; it’s an extremely good insulating panel ($U = 0.41 \, \text{W/m}^2\text{K}$), lightweight and translucent.

The smallest area in the façade is for ventilation purposes. In the upper zone, a ventilation register ensures the minimum amount of natural ventilation. On the exterior it’s finished by a metal fabric. In the lower zone, a small window opening enables the students to influence the amount of fresh air coming in. Again, the metal fabric is inserted, now between the two glass panes. In this way the transparency of the panel is reduced to 30%. Another ventilation possibility is taken up in the upper insulating panel, which can open parallel to the façade. This element however, cannot be regulated by the room’s occupants but is controlled automatically.

The two equal areas in the façade serve a daylight regulating purpose. The upper zone consists of a thermotropic glass panel. It has the property of responding to heat, changing specularity from transparent to translucent. In this reaction the physical properties of the glass panel alter, leading to a reduced intensity and visibility. The lower zone is made up of an Okaflex panel. The thermal protection glazing with integrated lamella jalousie provides as much sun protection as necessary and as much daylight as possible. Glare and sight protection are also adjustable.

Office façade design

As opposed to the more horizontal studio façade, the façade for the offices is much more vertically aligned. This is due to the fact that all offices are situated in a 15 storey high tower in the core of the faculty building. The materialization of the tower is similar to the public functions in the heart of the faculty. Here, natural stone is applied to give sense of a city, closed building blocks in a grid structure. These blocks form a contrast against the building’s transparent edge.

In Figure 43, the design for an office façade is shown. Again, daylight, natural ventilation and utilization are important design aspects. The daylight strategy for an office is quite similar to that of the design studios, however, the amount of daylight necessary for office work is slightly lower than for design work. This and the calculations shown in Figure 39 result in a lower surface area for daylight openings. The idea of daylight entering at the top is most effective and can reduce costs for artificial lighting. Natural ventilation is feasible due to the height of the tower. It’s underlying principle is stack ventilation, which is made possible through a ventilation chimney inside the tower. It becomes possible to naturally ventilate the workplace all year round, but some measures need to be taken to solve the heat loss in cold winter times.
The component façade for the offices can be divided into three horizontal zones. The lower zone forms a balustrade and has an insulating function. Here, prefab concrete panels are used to appear as natural stone blocks. The middle zone is the part where the office occupant is able to regulate the indoor climate by changing the amount of ventilation, regulating the amount of daylight entering and controlling the view outside. There are two adaptive components to do this. First, there is an openable window to influence the amount of fresh air entering. Secondly, perforated aluminium lamellae can be operated to control the amount of daylight. The upper zone in the façade enables a minimum amount of natural ventilation through a register at the top. Furthermore a window with thermotropic glazing ensures diffuse natural daylight reaching up to 4,5 meters into the workspace. The overhang of the concrete balustrade acts as passive sun shading, while the thermotropic glazing ensures diffuse daylight for the East and West façade even when the sun’s angle is low in spring and autumn.
Conclusion

An adaptive façade has the ability to change, responding to changing internal and/or external climatic conditions. It positively influences the building’s energy consumption, room comfort and flexibility. In order to be able to design an adaptive façade, an analysis is necessary what factors influence comfort – and therefore the façade – and what components can facilitate adaptivity.

Comfort is influenced by a difference in temperature, light, ventilation and sound. The relevant internal factors influencing room comfort are people, electrical devices and lighting. Light and ventilation need to be adaptive because all room types have different requirements. The external conditions – solar radiation, outside air temperature, humidity, precipitation and wind – are dependent on location and orientation and cannot be influenced by design; however, an adaptable façade must make best use of these conditions so a thorough knowledge of these influences is necessary.

Different façade profiles have been made to study the different functions, their amount of adaptivity and use. These profiles are based on day and night, season and the façade’s functionality. The building’s orientation and position in the moderate climate have been taken into account as well. The research shows that adaptive components in a façade are necessary to change between the different seasons and overcoming the day and night situation without a severe decline in façade functionality and room comfort.

It is hard to come up with concrete façade requirements when no computer simulation or calculations are executed for verification. To tackle this problem, another profile with different levels of adaptivity has been added to further quantify the amount of adaptivity: a minute-to-minute level, a day/night level, a season level and a year level. Every function in a façade needs different levels of adaptation. This knowledge can be taken into consideration when developing façade concepts and designing an adaptive façade.

There are a lot of different adaptive possibilities and adaptive components; the latter can fulfill multiple façade functions. The adaptive components are sorted into different categories: manually adaptive components, mechanically adaptive components and ‘smart’ materials. This selection is based on the user of the façade; he or she greatly influences a façade and its design. The components have been gathered in a diagram and are sorted by function. Three different façade concepts have been worked out with the help of user and climate profiles and the diagram with adaptive components. The possibilities to apply adaptive components in a façade are endless.

The manually adaptive components are not new and incorporating them into the first concept – a manual façade, shows that using these type of components will probably lead to a more traditional façade. The concept for a mechanically adaptive façade already becomes a bit more innovative. This can be explained by the newer mechanical components, for instance a heat pipe. Their potential in a façade is present but more research needs to be done on their effectiveness and their effects on the interior climate and users. As could be expected, the smart-façade has the most innovative character. Some of its components are quite new and need more research on their application in a façade. Other components have been developed thoroughly – e.g. the electrochromic window – and already have been applied in façades or developed into building systems.

In conclusion, adaptivity in a façade is dependent on a lot of different factors: the building’s user and the coherent practicability; the façade components’ effectiveness in time; the climate profile; the costs and of course architectural choices. By acting upon these different factors, the adaptive façade can contribute to good comfort levels inside a building taking into consideration its user and the surroundings. The future façade will potentially take in more and more functionality, with a better integration of building services and a responsible use of energy.
Recommendations

During the course of the research it became clear that this research will never be complete. The list with adaptive components cannot be completed within the timeframe, and a part of the adaptive components will be liable to further developments and need to be updated in time. Furthermore, the research assumes that adaptation in a façade is necessary for all functions. However, it is questionable how useful an adaptive wind barrier for instance is and if it will lead to a reduction in energy consumption and contribute significantly to the comfort levels of a building.

The analysis on the amount of adaptivity in the façade could be more extensive if more time was available. The hours of the day could be taken into consideration as well, like Mike Davies has done in his analysis. This would give further and extensive knowledge on the façade’s behavior due to external conditions; the amount of adaptivity in a façade could be quantified even better.

The glossary with adaptive components is endless and will never be complete. The glossary and the diagram are a result of research that was done in a specific timeframe, looking at specific literature. An extended timeframe will probably result in a more extensive list and a completer diagram. Smart materials can have interesting effects in adaptive façades, but more research still needs to be done on these type of materials since not enough research has been done up till now to guarantee its success in façade applications. However, smart materials are a research topic in itself.

For the future, it would be very interesting to work out the design concepts further and testing them on their functionality and practicability. With the current attitude towards sustainable building it is necessary to find out how sustainable and durable the concepts and separate materials or components are. This research give an initial idea of the possibilities with materials or components that have the capacity to adapt to changing conditions.
Bibliography


Appendices
An Adaptive Façade for the Faculty of Architecture
TU Delft
Syllabus

Syllabus Building Technology [AR5AB010]
Rosalie van Dijk [1140647]
Semester I, 2008-2009
Lab coordinator: Ir. F.R. Schnater
Main tutor: Dipl. Ing. T. Klein
Theme

The building technological research and design that will be done in the first semester of 2008-2009, focuses on issues in the field of sustainability that have been recognized by many academics as not yet thoroughly implemented in today’s architecture. This research will focus on the design for an adaptive façade for the faculty of Architecture in Delft. It is part of the graduation project for architecture students in the SADD1 studio. In order to execute the research and design, the process is split in two: the first part is a scientific research on the possibilities of adaptability in the façade; the second part is a translation of this knowledge into a design for a façade.

Sustainability, as an integral aspect of both the future educational program and the faculty premises, forms a theme of considerable urgency in the design for a new faculty of Architecture at Delft University of Technology. A large gain can be obtained in the design of the façade since this makes up a considerable area of the building and adaptation of the façade can contribute to a flexible use of the interior spaces. The assignment is approached from the inside by setting up requirements for the internal spaces and the adjacent façade. Instead of focusing only on a comfortable internal environment - related to installation machines - the façade should also address the user influence: an office façade will be used differently from a studio façade. Since many different people will make use of the building and its different rooms, an adaptable envelope could contribute to the answer to the problem of a well-suited yet flexible building.

To implement this research into the architectural design for the faculty of Architecture, three typical spaces related to educational buildings and their façades will be researched: a studio space, an office space and a meeting room. These three spaces have different demands from the user perspective. Ultimately, one façade design should be able to serve all spaces.

Research Question

How can adaptivity contribute to the façade design of the future faculty of Architecture at Delft University of Technology?

Key questions

Adaptiveness

What is adaptiveness?
Why should a façade be adaptable?

Interior spaces

What are the room typologies?
What are the typical room requirements per typology?
What schematic layout can be made per room typology?

Façade

What are the interior influences on the façade per room typology?
What are the exterior influences on the façade per room typology?
Can a façade facilitate different uses by adaption?

Adaptive components

What adaptive components are there in the façade?
Are there adaptation techniques from other fields that could be useful?
What adaptive components in a façade do not yet exist yet are useful?

1 Strategic Architectural Design Development
2 http://www.buildingforbouwkunde.nl/CompetitionBrief/tabid/90/Default.aspx
**Bibliography**


Brock Linda, 2005, *Designing the Exterior Wall*, Hoboken: John Wiley & Sons


Dobbelsteen Andy van den and Alberts Kees, 2005, *Bouwmaterialen, milieu & gezondheid*, Amsterdam: WEKA Uitgeverij


Hausladen Gerhard, 2006, *ClimaSkin*, Munich: Callwey


**Internet resources**

- [http://www.di.net/articles/archive/2881/](http://www.di.net/articles/archive/2881/)
- [http://gaia.lbl.gov/hpbf/casest.htm](http://gaia.lbl.gov/hpbf/casest.htm)
- [http://hpbmagazine.org/](http://hpbmagazine.org/)
- [http://www.russellbridge.co.uk/dissertation/dissertation.htm](http://www.russellbridge.co.uk/dissertation/dissertation.htm)
Schedule

Technical Scientific Research (SR)

- Research on room typologies
- Development requirements per room type
- Schematic layout per room type
- Finding the problem:
  - Research on interior influences on façade per room type
  - Research on exterior influences on façade per room type
- Research on adaptivity and possibilities in the façade (brainstorm)
- Literature study (+ case study) adaptive skins
- Diagram with types per component

Research by Design (RD)

- Pros and cons consideration of different types
- (Generate ideas for new adaptive components by checking diagram)
- Development of several strategies into idea for the façade
- Research on possible combinations of strategies
- Strategy choice
- Convert strategy into concept for façade
- Develop concept into façade design/product

<table>
<thead>
<tr>
<th>Week</th>
<th>Date</th>
<th>Aim</th>
<th>Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>02-09-08</td>
<td><strong>P1 presentation theme (PP)</strong></td>
<td>Yes</td>
</tr>
<tr>
<td>2</td>
<td>09-09-08</td>
<td>Formulate syllabus</td>
<td>Yes</td>
</tr>
<tr>
<td>3</td>
<td>16-09-08</td>
<td>Concept syllabus</td>
<td>Yes</td>
</tr>
<tr>
<td>4</td>
<td>23-09-08</td>
<td><strong>SR P2 presentation syllabus (PP)</strong></td>
<td>Yes</td>
</tr>
<tr>
<td>5</td>
<td>30-09-08</td>
<td>Altering syllabus + start-up research</td>
<td>Yes</td>
</tr>
<tr>
<td>6</td>
<td>07-10-08</td>
<td>Room typology + requirements + layout</td>
<td>Yes</td>
</tr>
<tr>
<td>7</td>
<td>14-10-08</td>
<td>Influences on the façade</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>21-10-08</td>
<td>Influences on the façade</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>28-10-08</td>
<td>Research adaptive components</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>04-11-08</td>
<td><strong>SR P3 Presentation preliminary research</strong></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>11-11-08</td>
<td>Research adaptive components</td>
<td></td>
</tr>
<tr>
<td></td>
<td>14-11-08</td>
<td>Final application date GO/NOGO</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>18-11-08</td>
<td>SR/RD Research adaptive components + new ideas</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>25-11-08</td>
<td>SR/RD Research adaptive components + new ideas</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>02-12-08</td>
<td><strong>Deadline Technical Scientific Research</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Research Feedback</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>09-12-08</td>
<td>RD</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>16-12-08</td>
<td>RD</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>23-12-08</td>
<td>RD</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>30-12-08</td>
<td>RD</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>06-01-09</td>
<td>RD</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>13-01-09</td>
<td>RD</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>20-01-09</td>
<td>RD Presentation preparation</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>27-01-09</td>
<td><strong>P4 presentation research</strong></td>
<td></td>
</tr>
</tbody>
</table>
1. Analysis room typology

Design Studio

Office space

Meeting room

2. Finding the problem // looking at examples

internal influences

external influences

adaptive components

3. Solutions // concepts
### NORTH FACADE

<table>
<thead>
<tr>
<th>Day</th>
<th>Night</th>
<th>Day</th>
<th>Night</th>
<th>Day</th>
<th>Night</th>
<th>Min.</th>
<th>Max.</th>
<th>Level of adaptation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal insulation</td>
<td>+</td>
<td>--</td>
<td>+</td>
<td>++</td>
<td>--</td>
<td>++</td>
<td></td>
<td>Day night Season</td>
</tr>
<tr>
<td>Heat storage</td>
<td>--</td>
<td>+</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>+</td>
<td>Day night Spring &amp; Summer</td>
</tr>
<tr>
<td>Dehumidification</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>++</td>
<td>Season</td>
</tr>
<tr>
<td>Natural ventilation</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Daylight</td>
<td>--</td>
<td>o</td>
<td>--</td>
<td>o</td>
<td>--</td>
<td>--</td>
<td>o</td>
<td>Hour-to-hour Day night</td>
</tr>
<tr>
<td>Overheating control</td>
<td>-</td>
<td>--</td>
<td>-</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>-</td>
<td>Day night</td>
</tr>
</tbody>
</table>

**Conclusion**

- Day night adaptiveness:
  - thermal insulation
  - heat storage
  - daylight
  - overheating control
- No natural ventilation possible through façade due to location nearby highway
- (Sun)light protection needs to be flexible on a day-to-night level and hour-to-hour level
<table>
<thead>
<tr>
<th><strong>SOUTH FACADE</strong></th>
<th>Spring/Autumn</th>
<th>Summer</th>
<th>Winter</th>
<th>Absolute</th>
<th>Level of adaptation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal insulation</td>
<td>o</td>
<td>+</td>
<td>o</td>
<td>--</td>
<td>+</td>
</tr>
<tr>
<td>Heat storage</td>
<td>+</td>
<td>-</td>
<td>++</td>
<td>o</td>
<td>--</td>
</tr>
<tr>
<td>Dehumidification</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>--</td>
</tr>
<tr>
<td>Natural ventilation</td>
<td>+</td>
<td>-</td>
<td>++</td>
<td>+</td>
<td>o</td>
</tr>
<tr>
<td>Daylight</td>
<td>+</td>
<td>--</td>
<td>++</td>
<td>--</td>
<td>o</td>
</tr>
<tr>
<td>Overheating control</td>
<td>+</td>
<td>--</td>
<td>++</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

**Conclusion**

- **Day night & season adaptiveness:**
  - thermal insulation
  - natural ventilation
  - heat storage
  - daylight
  - overheating control
- **Adaptive heat storage and overheating control in spring/autumn and summer; not in winter**
- **(Sun)light protection needs to be flexible on a day-to-night level and hour-to-hour level**
## EAST FACADE

<table>
<thead>
<tr>
<th></th>
<th>Spring/Autumn</th>
<th>Summer</th>
<th>Winter</th>
<th>Absolute</th>
<th>Level of adaptation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal insulation</td>
<td>o</td>
<td>+</td>
<td>o</td>
<td>--</td>
<td>+</td>
</tr>
<tr>
<td>Heat storage</td>
<td>+</td>
<td>-</td>
<td>++</td>
<td>o</td>
<td>--</td>
</tr>
<tr>
<td>Dehumidification</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>--</td>
</tr>
<tr>
<td>Natural ventilation</td>
<td>o</td>
<td>--</td>
<td>+</td>
<td>o</td>
<td>-</td>
</tr>
<tr>
<td>Daylight</td>
<td>o</td>
<td>--</td>
<td>+</td>
<td>--</td>
<td>o</td>
</tr>
<tr>
<td>Overheating control</td>
<td>o</td>
<td>--</td>
<td>+</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

### Conclusion
- **Day night & season adaptiveness:**
  - thermal insulation
  - natural ventilation
  - heat storage
  - daylight
  - overheating control
- Adaptive heat storage and overheating control in spring/autumn and summer; not in winter
- (Sun)light protection needs to be flexible on a day-to-night level and hour-to-hour level
## WEST FACADE

<table>
<thead>
<tr>
<th></th>
<th>Spring/Autumn</th>
<th>Summer</th>
<th>Winter</th>
<th>Absolute</th>
<th>Level of adaptation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal insulation</td>
<td>o</td>
<td>+</td>
<td>o</td>
<td>--</td>
<td>+</td>
</tr>
<tr>
<td>Heat storage</td>
<td>+</td>
<td>-</td>
<td>++</td>
<td>o</td>
<td>--</td>
</tr>
<tr>
<td>Dehumidification</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>--</td>
</tr>
<tr>
<td>Natural ventilation</td>
<td>o</td>
<td>--</td>
<td>+</td>
<td>o</td>
<td>-</td>
</tr>
<tr>
<td>Daylight</td>
<td>o</td>
<td>--</td>
<td>+</td>
<td>--</td>
<td>o</td>
</tr>
<tr>
<td>Overheating control</td>
<td>o</td>
<td>--</td>
<td>+</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

## Conclusion

- **Day night & season adaptiveness:**
  - thermal insulation
  - natural ventilation
  - heat storage
  - daylight
  - overheating control
- Adaptive heat storage and overheating control in spring/autumn and summer; not in winter
- (Sun)light protection needs to be flexible on a day-to-night level and hour-to-hour level
Climate data for the Netherlands in 2008

Temperatuurverloop De Bilt, lente 2008

Lente = 10.2°C (normaal 8.9°C)
Laagste -4.4°C (23-3), hoogste 27.4°C (10-5)

Temperatuurverloop De Bilt, zomer 2008

Zomer 17.3°C (normaal 16.6°C)
Laagste 4.0°C (17-6), hoogste 31.2°C (2-7)
Temperatuurverloop De Bilt, herfst 2008

herfst 10,2 °C (normaal 10,2 °C)
Laagste -2,3 °C (29-11), hoogste 26,4 °C (11-9)

Temperatuurverloop De Bilt, winter 2007/08

Winter = 5,1 °C (normaal 3,3 °C)
Laagste -6,9 °C (17-2), hoogste 14,1 °C (12-2)
Aantal uren zonneschijn, De Bilt, herfst 2008

Sommige maand 334 uur = 34% (normaal 298 uur = 30%)

Aantal uren zonneschijn, De Bilt, winter 2007/08

Sommige maand = 249 uur (32%)
(normaal 179 uur = 22%)
Scobatherm Nanogel™

For roof and wall

Scobatherm Nanogel was invented by Scobalit AG to meet the growing demand for translucent, highly insulating panels for roofs and walls. Scobatherm Nanogel elements are translucent sandwich panels made of glass-fibre reinforced polyester resins and filled with aerogels. These panels not only look good, they let you build efficiently and economically.

Scobatherm Nanogel panels are distinguished by:
- Translucency
- Lightfastness
- Durability
- Strong enough to walk on, withstands impact of balls
- Mechanical penetration resistance
- Outstanding thermal properties
- Permanently hydrophobic aerogels
- Weathering resistance
- Low dead weight
- Factory sizes to order

Applications:
- Glazing for industrial buildings
- Residential and public buildings
- Roofs and façades

Product specifications:

Colour: natural, translucent (standard)
Other colours (RAL system) as special order

Fire resistance rating: BKZ 4.2 is standard, BKZ 5.2, BKZ 5.3 and B1 (DIN 4102) are available as special order

Lengths: max. 8000mm (maximum table width)
Widths: max. 2400mm (maximum table width)
Thicknesses: M20 (20mm), M30 (30mm), M50 (50mm), P25 (25mm), P40 (40mm)
Weight: max. 12.5kg/m²

Technical specifications:

Thermal conductivity: 0.0219W/mK

U-value: 0.41W/m²K for a thickness of 50mm (EMPA Test Report No.175 441/1)

G-value: 0.25% (EMPA Test Report No.427377/1)

The values given apply to the standard product (BKZ 4.2)
OKAFLEX Flexible Light Control

Variable radiation, flexible use of space – OKAFLEX lets you precisely control daylight. The heat-protective glazing with integrated louvres offers as much sun protection as required and as much daylight as possible. Of course, you can also alter the antidazzle and privacy screening – by lifting, lowering and turning for wall types, and by turning the louvres for roof types.

- $g$ value up to 8 % can be realised (closed louvres), dependent on the louvre colour, louvre setting and location of the sun (refer to table for the physical properties data)
- $U_o$ value best case 1.1 W/(m²K) (closed louvres)
- manual or electrical operation
- control with flexible group size

Louvres

Width 15 mm, different colours (table with technical light properties of the surfaces), thickness 0.23 mm, can be fitted as concave or convex (dependent on the focus of the requirements concerning antidazzle, light directing function).

Ladder cord

12 x 18.5 mm, UV-resistant, consisting of 100% high-strength, meshed polyester thread, thermally fixed, double ridged. Colour: White with white louvres, grey with silver louvres.

Hoist cord

$D = 1.0$ mm, UV-resistant, consisting of 100% high-strength, bound polyester thread. Colour: White with white louvres, grey with silver louvres.

Drive

A precision motor built in to the top rail with a 4-stage planetary gear train. The motor is driven with 24 Volt DC voltage and has a rated output of 6 Watt. The control is carried out by means of a dual core cable (cable cross-section in accordance with the cable lengths and loss of output).
Physical properties data
Table with g values dependent on two types of louver, their angle of adjustment and the height of the sun.

**Louvre colour no. 2901**

<table>
<thead>
<tr>
<th>Angle of incidence</th>
<th>Horizontal louvre</th>
<th>Louvre in 45° position</th>
<th>Louvre closed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T&lt;sub&gt;v&lt;/sub&gt;</td>
<td>g</td>
<td>T&lt;sub&gt;v&lt;/sub&gt;</td>
</tr>
<tr>
<td>0°</td>
<td>0.74</td>
<td>0.58</td>
<td>0.28</td>
</tr>
<tr>
<td>30°</td>
<td>0.42</td>
<td>0.44</td>
<td>0.11</td>
</tr>
<tr>
<td>60°</td>
<td>0.16</td>
<td>0.28</td>
<td>0.03</td>
</tr>
</tbody>
</table>

**Louvre colour no. 2902**

<table>
<thead>
<tr>
<th>Angle of incidence</th>
<th>Horizontal louvre</th>
<th>Louvre in 45° position</th>
<th>Louvre closed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T&lt;sub&gt;v&lt;/sub&gt;</td>
<td>g</td>
<td>T&lt;sub&gt;v&lt;/sub&gt;</td>
</tr>
<tr>
<td>0°</td>
<td>0.74</td>
<td>0.58</td>
<td>0.24</td>
</tr>
<tr>
<td>30°</td>
<td>0.41</td>
<td>0.38</td>
<td>0.11</td>
</tr>
<tr>
<td>60°</td>
<td>0.15</td>
<td>0.22</td>
<td>0.06</td>
</tr>
</tbody>
</table>

The specified total solar energy transmittance values apply for white 15 mm louvres, with a soft thermal control coating on surface # 3. The U<sub>v</sub> value reaches 1.1 W/(m<sup>2</sup>K), depending on the louver position, cavity and filler gas.

Legend and related values:

<table>
<thead>
<tr>
<th>unit</th>
<th>standard</th>
<th>technical term</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>W/(m&lt;sup&gt;2&lt;/sup&gt;K)</td>
<td>Thermal transmittance, (ΔT=10°C)</td>
</tr>
<tr>
<td></td>
<td>DIN EN 673</td>
<td>DIN EN 674</td>
</tr>
<tr>
<td>TSET</td>
<td>%</td>
<td>Total solar energy transmittance or solar heat gain coefficient</td>
</tr>
<tr>
<td></td>
<td>DIN EN 410</td>
<td></td>
</tr>
<tr>
<td>T&lt;sub&gt;v&lt;/sub&gt;</td>
<td>%</td>
<td>Light transmission (direct/hemispheric)</td>
</tr>
<tr>
<td></td>
<td>DIN EN 410</td>
<td></td>
</tr>
<tr>
<td>R&lt;sub&gt;r&lt;/sub&gt;</td>
<td>dB</td>
<td>DIN EN 20140 Sound reduction coefficient</td>
</tr>
<tr>
<td>F&lt;sub&gt;c&lt;/sub&gt;</td>
<td>%</td>
<td>DIN 4108 Reduction factor of a solar control system, F&lt;sub&gt;c&lt;/sub&gt;=TSET/TSET&lt;sub&gt;reference&lt;/sub&gt;</td>
</tr>
<tr>
<td>SC</td>
<td>%</td>
<td>GANA Manual Shading coefficient, SC=TSET/0.86</td>
</tr>
</tbody>
</table>

The above data is approximate data. It is based on measurements of recognized test institutes and calculations derived from these measurements. At the moment, not all suppliers have adapted their key data to the currently applicable regulations. When making comparisons, please pay attention to the relevant manufacturer's notes. On the basis of the old standards, total solar energy transmittances as well as shading coefficient values are each 1-3% lower.
Lower U-values can only be achieved in combination with thermal control gases (Kr, Ar). If thermal control gases are used, a gastight perimeter seal is required. It must be protected against solar radiation by means of covering profiles or a black edge screen print and is normally not compatible with jointing silicone.

**Degree of reflection for the available louvres:**

<table>
<thead>
<tr>
<th>Louvre colour</th>
<th>$r_{dh, \text{vis}}$</th>
<th>$r_{diffus, \text{vis}}$</th>
<th>$r_{dd, \text{vis}}$</th>
<th>$r_{dh, \text{sol}}$</th>
<th>$r_{diffus,\text{sol}}$</th>
<th>$r_{dd,\text{sol}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2901: silver</td>
<td>0.59</td>
<td>0.44</td>
<td>0.15</td>
<td>0.61</td>
<td>0.44</td>
<td>0.17</td>
</tr>
<tr>
<td>2902: white</td>
<td>0.81</td>
<td>0.77</td>
<td>0.04</td>
<td>0.70</td>
<td>0.66</td>
<td>0.04</td>
</tr>
<tr>
<td>2903: matt white</td>
<td>0.74</td>
<td>0.72</td>
<td>0.02</td>
<td>0.64</td>
<td>0.62</td>
<td>0.02</td>
</tr>
<tr>
<td>2906: concave side, silver, convex side retroreflective (RAL 7030)</td>
<td>0.66</td>
<td>0.46</td>
<td>0.2</td>
<td>0.67</td>
<td>0.46</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Legend and associated dimensions:
- $r_{dh, \text{vis}}$: the direct-hemispherical degree of light reflection
- $r_{diffus, \text{vis}}$: diffused degree of light reflection
- $r_{dd, \text{vis}}$: the direct-direct degree of light reflection or the aligned-aligned degree of light reflection
- $r_{dh, \text{sol}}$: the direct-hemispherical degree of radiation reflection or the direct hemispherical degree of solar reflection
- $r_{diffus,\text{sol}}$: the diffused degree of radiation reflection
- $r_{dd,\text{sol}}$: the direct-direct degree of radiation reflection or the aligned-aligned degree of solar reflection

**Dimensions and installation**

<table>
<thead>
<tr>
<th>Type</th>
<th>SZR (mm)</th>
<th>min. width (mm)</th>
<th>max. width (mm)</th>
<th>min. Height (mm)</th>
<th>max. Height (mm)</th>
<th>Comments / restrictions</th>
</tr>
</thead>
</table>
| Facade | 27/29   | 500             | 3000            | 250              | 3000             | • Min. surface 0.13 m²  
• Max. surface 7.50 m²  
• Height > 1500 mm required 
• Width > 750 mm |
| Roof  | 27      | 500             | 2000            | 400              | 1500             | • Min. surface 0.20 m²  
• Max. surface 2.25 m²  
• Also 0° when horizontal  
• Only turning the louvres |

**Types of glass and coatings**
- TVG, if required also ESG or VSG
Thermal protection coating or sun protection coating
Coatings change the light, radiation and thermal technical behaviour of the insulated glass structure. The properties of the louvres can always also be seen.

Control
- Optional 1-channel radio remote control or 8-channel radio remote control
- Optional group control, bus connection
- Optional sun monitor control module and light sensor

Operation
- Lift and lower the louvres by pressing the button in the respective direction. Turn the louvres by lighting tapping the button in the desired direction. The button is marked with directional arrows. When reaching the upper or lower end position, the limit switch that is built in to the top rail automatically switches off the drive.
Koellast berekening studio (N)

MECHANISCHE VENTILATIE

Aangenomen

tussenvertrek studio op bovenste verdieping
noord-oriëntatie

netto hoogte
gevel breedte
vertrekdiepte
ZTA
U
Verlichting
Zittend kantoorwerk
Apparaten
Dakmateriaal = licht beton (-5,0)
Warmtestroom via wanden en daken qw

Glasoppervlak: 45 112
Glassoort: HR++
Bezetting: 35 pers, 100%
Verlichting: kunstverlichting
Apparatuur: 1 PC/persoon
Ontwerp-binnentemperatuur: 24 °C
Ontwerp-buitentemperatuur: 30 °C
Infiltratie: 0,3
absorptiecoefficient zonnestraling a
warmtestroom gevel qw
warmtestroom dak qw
q_{conv,igv zonnestraling}:

\[ \Phi_{z,gl} = z \cdot A_{gl} \cdot ZTA \cdot q_{conv} \]
\[ \Phi_{tr,gl} = U \cdot A_{gl} \cdot (\theta_e - \theta_i) \]
\[ \Phi_{z,w,borstw} = a \cdot A_{wi} \cdot qw \]
\[ \Phi_{z,w,dak} = a \cdot A_{wi} \cdot qw \]
\[ \Phi_{inf} = q_{inf} \cdot p \cdot c \cdot (\theta_e - \theta_i) \]
\[ \Phi_p = p \cdot qp \]
\[ \Phi_i = ql \cdot Avl \]
\[ \Phi_a = qa \cdot Avl \]
\[ \Phi_k = 15555 \text{ W} \]
\[ \Phi_{k,sp} = \Phi_{k/Avl} \]
\[ \Phi_{v,koel} = \Phi_k/(\rho \cdot c \cdot \Delta \theta) \]
\[ \eta = qv/V \]

Φk = 30 W/m²
Φv,koel = 0,864 ⇔
η = 1,5 h⁻¹

NATUURLIJKE VENTILATIE

\[ \Phi_{v,rv} = \Phi_k/(\rho \cdot c \cdot \Delta \theta) \]
\[ \eta = qv/V \]
\[ A_{tot} = y \cdot \Phi_k/(130 \cdot \Delta \theta^{1.5} \cdot h^{0.5}) \]

Φv,rv = 4,321 ⇔
η = 7,5 h⁻¹
A_{tot} = 73,6 m²
Koellast berekening studio (W)

MECHANISCHE VENTILATIE

Aangenomen

tussenvertrek studio op bovenste verdieping
west-oriëntatie

netto hoogte 4
gevel breedte 28
vertrekdiepte 18,6
ZTA 0,55
U 1,2 W/(m².K)
Verlichting 5 W/m²
Zittend kantoorwerk 100 W/persoon
Apparaten 12 W/m²
Dakmateriaal = licht beton (-5,0)

Warmtestroom via wanden en daken qw

Glasoppervlak: 45
Glassoort: HR++
Bezetting: 35 pers, 100%
Verlichting: kunstverlichting
Apparatuur: 1 PC/persoon

Ontwerp-binnentemperatuur: 24 °C
Ontwerp-buitentemperatuur: 30 °C
Infiltratie: 0,3
absorptiecoefficient zonnestraling a 0,7
warmtestroom gevel qw 4,9
warmtestroom dak qw -3,9
qconv,igv zonnestraling:

\[ \phi_{v,k} = \frac{\phi_k}{\rho \cdot c \cdot \Delta \theta} = 2,4 \text{ h}^{-1} \]

\[ \phi_{v,nv} = \frac{\phi_k}{\rho \cdot c \cdot \Delta \theta} = 6,931 \text{ h}^{-1} \]

NATUURLIJKE VENTILATIE
Koellast berekening hoekstudio (ZW)

MECHANISCHE VENTILATIE

Aangenomen

tussenvertrek studio op bovenste verdieping
zuidwest-oriëntatie

netto hoogte 4
gevel breedte 16
vertrekdiepte 18,6
ZTA 0,55
U 1,2 W/(m².K)
Verlichting 5 W/m²
Zittend kantoorwerk 100 W/persoon
Apparaten 12 W/m²
Dakmateriaal = licht beton (-5,0)
Warmtestroom via wanden en daken qw 4 W/m² (Zuid
4,9 W/m² (West
Glasoppervlak
Glasoort
Bezetting
Ontwerp-binnentemperatuur 24 °C
Ontwerp-buitentemperatuur 30 °C
Infiltratie 0,3
absorptiecoefficient zonnestraling a 0,7
warmtestroom westgevel qw 4,9
warmtestroom zuidgevel qw 4
warmtestroom dak qw -3,9

WESTGEVEL

\[ q_{\text{conv,igv zonnestraling}} = z \cdot \text{Agl} \cdot \text{ZTA} \cdot q_{\text{conv}} \]
\[ = 6970 \text{ W} \]
\[ \Phi_{\text{tr,gl}} = U \cdot \text{Agl} \cdot (\theta_e - \theta_i) \]
\[ = 207 \text{ W} \]
\[ \Phi_{\text{z,w,borstw}} = a \cdot \text{Awi} \cdot qw \]
\[ = 121 \text{ W} \]
\[ \Phi_{\text{z,w,dak}} = a \cdot \text{Awi} \cdot qw \]
\[ = -812 \text{ W} \]
\[ \Phi_{\text{inf}} = q_{\text{inf}} \cdot p \cdot c \cdot (\theta_e - \theta_i) \]
\[ = 714 \text{ W} \]
\[ \Phi_p = p \cdot qp \]
\[ = 2000 \text{ W} \]
\[ \Phi_i = ql \cdot Avl \]
\[ = 1488 \text{ W} \]
\[ \Phi_a = qa \cdot Avl \]
\[ = 3571 \text{ W} \]
Totaal = 14259 W

ZUIDGEVEL

\[ q_{\text{conv,igv zonnestraling}} = z \cdot \text{Agl} \cdot \text{ZTA} \cdot q_{\text{conv}} \]
\[ = 560 \text{ W/m²} \]
\[ = 440 \text{ W/m²} \]
\[ \Phi_{\text{z,gl}} = z \cdot \text{Agl} \cdot \text{ZTA} \cdot q_{\text{conv}} \cdot fd \]
\[ = 11059 \text{ W} \]
\[ \Phi_{\text{tr,gl}} = U \cdot \text{Agl} \cdot (\theta_e - \theta_i) \]
\[ = 207 \text{ W} \]
\[ \Phi_{\text{z,w,borstw}} = a \cdot \text{Awi} \cdot qw \]
\[ = 99 \text{ W} \]
Totaal = 11365 W

\[ \Phi_k = 25624 \text{ W} \]
\[ \varphi_{k,sp} = \frac{\varphi_k}{\lambda V} \hspace{1cm} 86 \text{ W/m}^2 \]
\[ \varphi_{v,koei} = \varphi_k/(\rho \cdot c \cdot \Delta \theta) \hspace{1cm} 1,424 \]
\[ \eta = \frac{q_v}{V} \hspace{1cm} 4,3 \text{ h}^{-1} \]

**NATUURLIJKE VENTILATIE**

\[ \varphi_{v,nv} = \varphi_k/(\rho \cdot c \cdot \Delta \theta) \hspace{1cm} 7,118 \]
\[ \eta = \frac{q_v}{V} \hspace{1cm} 21,5 \text{ h}^{-1} \]
\[ A_{tot} = y \cdot \varphi_k/(130 \cdot \Delta \theta^{0.5} \cdot h^{-1}) \hspace{1cm} 55,4 \text{ m}^2 \]
Warmtelast berekening studio (N)

MECHANISCHE VENTILATIE
Aangenomen
tussenvertrek studio op bovenste verdieping
noord-oriëntatie
bruto hoogte 4,5
netto hoogte 4
gevel breedte 28
vertrekdiepte 18,6
ZTA 0,55
U\text{glas} 1,2 \text{W/(m}^2\text{.K)}
U\text{borstwering} 0,41 \text{W/(m}^2\text{.K)}
U\text{vloer} 0,37 \text{W/(m}^2\text{.K)}
U\text{wand} 1,5 \text{W/(m}^2\text{.K)}
U\text{binnenwand} 2 \text{W/(m}^2\text{.K)}
U\text{plafond} 0,37 \text{W/(m}^2\text{.K)}
Glasoppervlak: 45 \text{m}^2
Glassoort: HR++
Bezetting: 35 pers, 100%
Ontwerp-binnentemperatuur: 22 °C
aangrenzende studios 22 °C
aangrenzende gang 18 °C
onder (studio) 15 °C
Ontwerp-buitentemperatuur: -10 °C
Infiltratie: 0,0009

Transmissieverlies
Raam = U \cdot A \cdot (\theta_i - \theta_e) 1935 \text{ W}
Borstwering = U \cdot A \cdot (\theta_i - \theta_e) 992 \text{ W}
Vloer = U \cdot A \cdot (\theta_i - \theta_e) 1349 \text{ W}
Plafond = U \cdot A \cdot (\theta_i - \theta_e) 6166 \text{ W}
Wand gang = U \cdot A \cdot (\theta_i - \theta_e) 1008 \text{ W}
\Phi_{tr} 11450 \text{ W}
\Phi_v = qvi \cdot Ag \cdot \rho \cdot c \cdot (\theta_i - \theta_e) 4355 \text{ W}
\Phi_{opw} = Avl \cdot 20 10416 \text{ W}
\Phi_w = 26221 \text{ W}
\Phi_{w,sp} = \frac{\Phi_w}{Avl} 50 \text{ W/m}^2
\Phi_{v,plaf} = \frac{\Phi_w}{(\rho \cdot c \cdot \Delta\theta)} 1,093 \Rightarrow
\Phi_{v,plaf} = \frac{\Phi_w}{(\rho \cdot c \cdot \Delta\theta)} 0,546 \Rightarrow

NATUURLIJKE VENTILATIE
\Phi_v = qvi \cdot Ag \cdot \rho \cdot c \cdot (\theta_i - \theta_e) 152410 \text{ W}
\Phi_w = \Phi_{tr} + \Phi_{tr} + \Phi_{opw} 174276
\Phi_{w,sp} = \frac{\Phi_w}{Avl} 335 \text{ W/m}^2
**Warmtelast berekening hoekstudio (ZW)**

**MECHANISCHE VENTILATIE**

_Aangenomen_

tussenvertrek studio op bovenste verdieping
zuidwest-oriëntatie

bruto hoogte 4,5
netto hoogte 4
gevel breedte 16
vertrekdiepte 18,6
ZTA 0,55

\[ U_{\text{glas}} = 1,2 \, \text{W/(m}^2\cdot\text{K)} \]
\[ U_{\text{borstwing}} = 0,41 \, \text{W/(m}^2\cdot\text{K)} \]
\[ U_{\text{vloer}} = 0,37 \, \text{W/(m}^2\cdot\text{K)} \]
\[ U_{\text{wand}} = 1,5 \, \text{W/(m}^2\cdot\text{K)} \]
\[ U_{\text{binnenwand}} = 2 \, \text{W/(m}^2\cdot\text{K)} \]
\[ U_{\text{plafond}} = 0,37 \, \text{W/(m}^2\cdot\text{K)} \]

<table>
<thead>
<tr>
<th>Glasoppervlak:</th>
<th>45</th>
<th>128</th>
<th>57,6 m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glassoort:</td>
<td>HR++</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Bezetting: 20 pers, 100%

Ontwerp-binnentemperatuur: 22 °C
aangrenzende studios 22 °C
aangrenzende gang 18 °C
onder (studio) 15 °C
Ontwerp-buitentemperatuur: -10 °C
Infiltratie: 0,0009

**Transmissieverlies**

<table>
<thead>
<tr>
<th>Raam</th>
<th>= U · A · (θi - θe)</th>
<th>2212 W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borstwering</td>
<td>= U · A · (θi - θe)</td>
<td>1134 W</td>
</tr>
<tr>
<td>Vloer</td>
<td>= U · A · (θi - θe)</td>
<td>771 W</td>
</tr>
<tr>
<td>Plafond</td>
<td>= U · A · (θi - θe)</td>
<td>3524 W</td>
</tr>
<tr>
<td>Wand gang</td>
<td>= U · A · (θi - θe)</td>
<td>576 W</td>
</tr>
<tr>
<td>Φtr</td>
<td>8216 W</td>
<td></td>
</tr>
</tbody>
</table>

\[ Φ_v = qvi · Ag · \rho · c · (θi - θe) = 4977 W \]
\[ Φ_{opw} = Avl · 20 = 5952 W \]
\[ Φ_w = 19144 W \]

\[ Φ_{w,sp} = Φ_w/Avl = 64 \, \text{W/m}^2 \]
\[ Φ_{v,plaf} = Φ_w/(\rho · c · Δθ) = 0,798 \, \text{W/m}^2 \]
\[ Φ_{v,plaf} = Φ_w/(\rho · c · Δθ) = 0,399 \, \text{W/m}^2 \]

**NATUURLIJKE VENTILATIE**

\[ Φ_v = qvi · Ag · \rho · c · (θi - θe) = 49766 W \]
\[ Φ_w = Φ_{tr} + Φ_{tr} + Φ_{opw} = 63934 \]
\[ Φ_{w,sp} = Φ_w/Avl = 215 \, \text{W/m}^2 \]
Koellast berekening kantoor (N)

MECHANISCHE VENTILATIE
Aangenomen

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Waarde</th>
</tr>
</thead>
<tbody>
<tr>
<td>tussenvertrek op bovenste verdieping</td>
<td></td>
</tr>
<tr>
<td>noord-oriëntatie</td>
<td></td>
</tr>
<tr>
<td>netto hoogte</td>
<td>2,7</td>
</tr>
<tr>
<td>gevel breedte</td>
<td>4</td>
</tr>
<tr>
<td>vertrekdiepte</td>
<td>5,4</td>
</tr>
<tr>
<td>ZTA</td>
<td>0,3</td>
</tr>
<tr>
<td>U</td>
<td>1,2 W/(m².K)</td>
</tr>
<tr>
<td>Verlichting</td>
<td>5 W/m²</td>
</tr>
<tr>
<td>Zittend kantoorwerk</td>
<td>100 W/persoon</td>
</tr>
<tr>
<td>Apparaten</td>
<td>12 W/m²</td>
</tr>
<tr>
<td>Dakmateriaal = licht beton (-5,0)</td>
<td></td>
</tr>
<tr>
<td>Warmtestroom via wanden en daken qw</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1,1 W/m²</td>
</tr>
<tr>
<td></td>
<td>-0,9 W/m²</td>
</tr>
<tr>
<td>Glasoppervlak</td>
<td>35</td>
</tr>
<tr>
<td>Glassoort</td>
<td></td>
</tr>
<tr>
<td>Bezetting</td>
<td></td>
</tr>
<tr>
<td>Ontwerp-binnentemperatuur</td>
<td>24 °C</td>
</tr>
<tr>
<td>Ontwerp-buitentemperatuur</td>
<td>30 °C</td>
</tr>
<tr>
<td>Infiltratie</td>
<td>0,3</td>
</tr>
<tr>
<td>absorptiecoefficient zonnestraling a</td>
<td>0,7</td>
</tr>
<tr>
<td>warmtestroom gevel qw</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-0,9</td>
</tr>
<tr>
<td>warmtestroom dak qw</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-3,9</td>
</tr>
<tr>
<td>NOORDGEVEL</td>
<td></td>
</tr>
<tr>
<td>q_conv,igv zonnestraling</td>
<td></td>
</tr>
<tr>
<td>binnen</td>
<td>140 W/m²</td>
</tr>
<tr>
<td>buiten</td>
<td>110 W/m²</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
\Phi_{z,gl} & = z \cdot A_{gl} \cdot ZTA \cdot q_{conv} & 125 W \\
\Phi_{tr,gl} & = U \cdot A_{gl} \cdot (\theta_e - \theta_i) & 27 W \\
\Phi_{z,w,borstw} & = a \cdot A_{w} \cdot qw & -4 W \\
\Phi_{z,w,dak} & = a \cdot A_{w} \cdot qw & -59 W \\
\Phi_{inf} & = q_{inf} \cdot p \cdot c \cdot (\theta_e - \theta_i) & 35 W \\
\Phi_{p} & = p \cdot qp & 400 W \\
\Phi_{l} & = q_l \cdot A_{vl} & 108 W \\
\Phi_{a} & = q_a \cdot A_{vl} & 259 W \\
\Phi_{k} & = 891 W \\
\end{align*}
\]

\[
\begin{align*}
\Phi_{k,sp} & = \Phi_{k}/A_{vl} & 41 W/m² \\
\Phi_{v,koel} & = \Phi_{k}/(\rho \cdot c \cdot \Delta \theta) & 0,093 \\
\eta & = qv/V & 5,7 h⁻¹ \\
\end{align*}
\]

NATUURLIJKE VENTILATIE

\[
\begin{align*}
\Phi_{v,nv} & = \Phi_{k}/(\rho \cdot c \cdot \Delta \theta) & 0,247 \\
\eta & = qv/V & 15,3 h⁻¹ \\
A_{tot} & = \gamma \cdot \Phi_{k}/(130 \cdot \Delta \theta^{1.5} \cdot h^{0.5}) & 1,9 m²
\end{align*}
\]
Koellast berekening kantoortuin (W)

MECHANISCHE VENTILATIE

Aangenomen
kantoortuin op bovenste verdieping

netto hoogte 2,7
gevel breedte 18,6
vertrekdiepte 15
ZTA 0,3
U 1,2 W/(m².K)
Verlichting
Zittend kantoorwerk 100 W/persoon
Apparaten 12 W/m²
Dakmateriaal = licht beton (-5,0)
Warmtestroom via wanden en daken qw 4 W/m² (Zuid)
4,9 W/m² (West)
Glasoppervlak 35 50,22 17,58 m²
Glashoek

Bezetting 20 personen
Ontwerp-binnentemperatuur 24 °C
Ontwerp-buitentemperatuur 30 °C
Infiltratie 0,3
absorptiecoefficient zonnestraling a 0,7
warmtestroom noordgevel qw -0,9
warmtestroom westgevel qw 4,9
warmtestroom zuidgevel qw 4
warmtestroom dak qw -3,9

NOORDGEVEL

q_{conv,igv zonnestraling} binnen 140 W/m²
buiten 110 W/m²

\varphi_z,gl = z \cdot A_{gl} \cdot ZTA \cdot q_{conv} = 468 W
\varphi_{tr,gl} = U \cdot A_{gl} \cdot (\theta_e - \theta_i) = 102 W
\varphi_{z,w,borstw} = a \cdot A_{wi} \cdot qw = -17 W
Totaal = 553 W

WESTGEVEL

q_{conv,igv zonnestraling} binnen 650 W/m²
buiten 440 W/m²

\varphi_z,gl = z \cdot A_{gl} \cdot ZTA \cdot q_{conv} = 2320 W
\varphi_{tr,gl} = U \cdot A_{gl} \cdot (\theta_e - \theta_i) = 127 W
\varphi_{z,w,borstw} = a \cdot A_{wi} \cdot qw = 112 W
\varphi_{z,w,dak} = a \cdot A_{wi} \cdot qw = -762 W
\varphi_{inf} = q_{inf} \cdot \rho \cdot c \cdot (\theta_e - \theta_i) = 452 W
\varphi_p = p \cdot qp = 2000 W
\varphi_l = q_l \cdot Avl = 1395 W
\varphi_a = qa \cdot Avl = 3348 W
Totaal = 8992 W
ZUIDGEVEL

$q_{\text{conv,igv}}$ zonnestraling:

- binnen: 560 W/m²
- buiten: 400 W/m²

\[ \Phi_{z,gl} = z \cdot A_{gl} \cdot ZTA \cdot q_{\text{conv}} \]

\[ \Phi_{tr,gl} = U \cdot A_{gl} \cdot (\theta_e - \theta_i) \]

\[ \Phi_{z,w,borstw} = a \cdot A_{wi} \cdot q_{w} \]

Totaal = 5225 W

\[ \Phi_{k} = 14771 \text{ W} \]

\[ \Phi_{k,sp} = \frac{\Phi_{k}}{A_{vl}} \]

\[ \Phi_{v,koel} = \frac{\Phi_{k}}{(\rho \cdot c \cdot \Delta \theta)} \]

\[ \eta = \frac{q_{v}}{V} \]

NATUURLIJKE VENTILATIE

\[ \Phi_{v,rv} = \frac{\Phi_{k}}{(\rho \cdot c \cdot \Delta \theta)} \]

\[ \eta = \frac{q_{v}}{V} \]

\[ A_{\text{tot}} = y \cdot \Phi_{k}/(130 \cdot \Delta \theta^{1.5} \cdot h^{0.5}) \]

\[ \eta = 19.6 \text{ h}^{-1} \]

\[ A_{\text{tot}} = 19.4 \text{ m}^{2} \]
Warmtelaast berekening kantoor (N)

MECHANISCHE VENTILATIE

Aangenomen

tussenvertrek op bovenste verdieping
noord-oriëntatie

bruto hoogte 3,2
netto hoogte 2,7
gevel breedte 4
vertrekdiepte 5,4
ZTA 0,3

$U_{\text{glas}}$ 1,2 W/(m².K)
$U_{\text{borstwering}}$ 0,4 W/(m².K)
$U_{\text{vloer}}$ 0,37 W/(m².K)
$U_{\text{wand}}$ 1,5 W/(m².K)
$U_{\text{binnenwand}}$ 2 W/(m².K)
$U_{\text{plafond}}$ 0,37 W/(m².K)

Glasoppervlak: 35 m²
Glassoort: Zonwer
Bezetting: 4 pers, 100%

Ontwerp-binnentemperatuur:
aangrenzende kantoren 22 °C
aangrenzende gang 18 °C
onder (kantoor) 15 °C

Ontwerp-buitentemperatuur: -10 °C
Infiltratie: 0,0009

Transmissieverlies

Raam = $U \cdot A \cdot (\theta_i - \theta_e)$ 145 W
Borstwering = $U \cdot A \cdot (\theta_i - \theta_e)$ 115 W
Vloer = $U \cdot A \cdot (\theta_i - \theta_e)$ 56 W
Plafond = $U \cdot A \cdot (\theta_i - \theta_e)$ 256 W
Wand gang = $U \cdot A \cdot (\theta_i - \theta_e)$ 102 W

$\Phi_{tr}$ 675 W

$\Phi_v = q\cdot v \cdot A_g \cdot c \cdot (\theta_i - \theta_e)$ 442 W
$\Phi_{opw} = A_{v \cdot l} \cdot 20$ 432 W

$\Phi_w = 1549$ W

$\Phi_{w,sp} = \frac{\Phi_w}{A_{v \cdot l}}$ 72 W/m²

$\Phi_{v,plaf} = \frac{\Phi_w}{(\rho \cdot c \cdot \Delta\theta)}$ 0,065 W/m²

$\Phi_{v,plaf} = \frac{\Phi_w}{(\rho \cdot c \cdot \Delta\theta)}$ 0,032 W/m²

NATUURLIJKE VENTILATIE

$\Phi_v = q\cdot v \cdot A_g \cdot c \cdot (\theta_i - \theta_e)$ 1769 W

$\Phi_w = \Phi_{tr} + \Phi_{tr} + \Phi_{opw}$ 2876 W

$\Phi_{w,sp} = \frac{\Phi_w}{A_{v \cdot l}}$ 133 W/m²
Warmtelast berekening kantoortuin (W)

MECHANISCHE VENTILATIE

Aangenomen
kantoortuin op bovenste verdieping
bruto hoogte 3,2
netto hoogte 2,7
gevel breedte 18,6
vertrekdiepte 15
ZTA 0,3
$U_{\text{glas}}$ 1,2 W/(m².K)
$U_{\text{borstwering}}$ 0,4 W/(m².K)
$U_{\text{vloer}}$ 0,37 W/(m².K)
$U_{\text{wand}}$ 1,5 W/(m².K)
$U_{\text{binnenwand}}$ 2 W/(m².K)
$U_{\text{plafond}}$ 0,37 W/(m².K)
Glasoppervlak: 35
Glassoort: Zonwer
Bezettings: 20 pers, 100%
Ontwerp-binnentemperatuur: 22 °C
aangrenzende kantoren 22 °C
aangrenzende gang 18 °C
onder (kantoor) 15 °C
Ontwerp-buitentemperatuur: -10 °C
Infiltratie: 0,0009

Transmissieverlies
Raam $= U \cdot A \cdot (\theta_i - \theta_e)$ 675 W
Borstwering $= U \cdot A \cdot (\theta_i - \theta_e)$ 537 W
Raam noord en zuid $= 2 \cdot U \cdot A \cdot (\theta_i - \theta_e)$ 1350 W
Borstwering noord en zuid $= 2 \cdot U \cdot A \cdot (\theta_i - \theta_e)$ 1074 W
Vloer $= U \cdot A \cdot (\theta_i - \theta_e)$ 723 W
Plafond $= U \cdot A \cdot (\theta_i - \theta_e)$ 3303 W
Wand gang $= U \cdot A \cdot (\theta_i - \theta_e)$ 476 W
$\Phi_{\text{tr}}$ 8138 W

$\Phi_v = qvi \cdot Ag \cdot \rho \cdot c \cdot (\theta_i - \theta_e)$ 2057 W
$\Phi_{\text{opw}} = Avl \cdot 20$ 5580 W
$\Phi_w = 15775$ W

$\Phi_{w,sp} = \Phi_{w/Avl}$ 57 W/m²
$\Phi_{v,plaf} = \Phi_w/(\rho \cdot c \cdot \Delta\theta)$ 0,657 \(\rightarrow\)
$\Phi_{v,plaf} = \Phi_w/(\rho \cdot c \cdot \Delta\theta)$ 0,329 \(\rightarrow\)

NATUURLIJKE VENTILATIE

$\Phi_v = qvi \cdot Ag \cdot \rho \cdot c \cdot (\theta_i - \theta_e)$ 41140 W
$\Phi_w = \Phi_{\text{tr}} + \Phi_{\text{tr}} + \Phi_{\text{opw}}$ 54858
$\Phi_{w,sp} = \Phi_{w/Avl}$ 197 W/m²
**STUDIO**

Glaspercentage 45 %
Glassoort HR++
ZTA 0,55

<table>
<thead>
<tr>
<th>MAXI MUM</th>
<th>Noord</th>
<th>Zuidwest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Koellast $\Phi_{k,sp}$ [W/m²]</td>
<td>30 30</td>
<td>86 86</td>
</tr>
<tr>
<td>Ventilatievoud $\eta$ [h⁻¹]</td>
<td>1,5 7,5</td>
<td>4,3 21,5</td>
</tr>
<tr>
<td>Warmtelast $\Phi_{w,sp}$ [W/m²]</td>
<td>50 335</td>
<td>64 215</td>
</tr>
</tbody>
</table>

**KANTOOR**

Glaspercentage 35 %
Glassoort 0
ZTA 0,3

<table>
<thead>
<tr>
<th>MAXI MUM</th>
<th>Noord</th>
<th>Zuidwest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Koellast $\Phi_{k,sp}$</td>
<td>41 41</td>
<td>53 53</td>
</tr>
<tr>
<td>Ventilatievoud $\eta$</td>
<td>5,7 15,3</td>
<td>7,4 19,6</td>
</tr>
<tr>
<td>Warmtelast $\Phi_{w,sp}$</td>
<td>72 133</td>
<td>57 197</td>
</tr>
</tbody>
</table>