Adaptable facade with Electrochromic material
Foreword

This document is the final report for the Building Technology part of my double master graduation project in Architecture and Building Technology (A+BT).
The mentors for this research are Ir. Frank schnater, Ir Kees van der Linden, Ir Hester Hellinga. The title of the report is “Adaptable façade with electrochromic material”.

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1.1 Introduction

Architects can draw unlimited inspiration from the fascinating contrast between the world of concepts (architect) and the world of construction (contractor, client). It is very important to know that Materialization and concept are inextricably intertwined. The SADD studio tries to integrate these two concepts into one big project which combines different demands of the building technology and architecture. In this way student can graduate from both tracks (architecture and building technology).

The double graduation program studies the sum of both tracks to come up with a single project which satisfies the requirements of both parties; however each of them has its own concerns and demands, not always sharing the same objectives. For this reason, the graduation project is focused not on the sum but on the intersection of both fields. The project aims to be within the intersection area, where the most important requirements of both parties are satisfied. Therefore for this research one subject which can satisfy the demand of design has been chosen. (Fig 1.1, fig 1.2)

In SADD studio, the design of the faculty of architecture or science centre has been selected as the architectonic design. In the first part of the SADD studio (Double graduation) the master plan of the whole university has been studied and the location of the faculty of architecture and Science center has been
Adaptable façade with electrochromic material defined (the master plan has been done for TUDelft, Netherlands). I have chosen the faculty of architecture for my architectonic design. In my master plan, due to the future requirements of the university (mainly further extension), the faculty of architecture has been located after the bridge (the highway of A470 in Delft). This place, the new location of the faculty of architecture, has a good view to the Mekel park as well as the bio chemical garden (located nearby in the master plan) (fig1.3).

Architectonic design is in fact the design of the faculty of architecture. (Fig 1.4) In this design, the adaptability of the building for future usages was the main scope. This should be in a way that the initial concept could accommodate further extension or the other usages of the building. For the sake of this purpose, two different types of spaces (long buildings and boxes) have been used. Therefore the building, which can accommodate different types of activities and get further extended if required, has been designed. (figure 1.4) The façade of the project has been made out of glass (it can be curtain wall façade) as it can provide good view to the surrounding green area. Since flexibility and adaptability of the areas are one of the main concerns, a façade which is adaptable to different lights has been chosen. There are different ways to build such a façade but for the facade of faculty of architecture, an adaptable and simple one without any additional part or sophisticated technology is important.
1.2 Adaptable façade

In general, an adaptable façade is a façade which has the ability to change, in response to changing external climatic conditions which influence the room comfort. It is 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 is that an adaptive façade can contribute to a flexible building and proper usage of the space as well. It is not the only criteria for the facade. Another important thing is to design a transparent façade. This should not limit the view to the outside or significantly affect the appearance of the building. These requirements limit the options and lead us to think only on some changes in glass. These changes can be the addition of coating or addition of blur strips. Then some other requirements narrow down my selection. Since European countries have less sunny days compared to a typical Asian country, static elements and permanent installations (like fixed louver sunshade) will not improve the quality of the daylight inside the room (in other words the room will receive less light in the whole year) [13]. It should be in a way that user can control it and it can provide good light for different activities and different situations and can be removed or changed when more daylight is necessary. One solution is using smart materials as they are capable of changing with light or other stimuli.
1.3 Intention

The intention of this research is the design of a façade with glass for a standard office place or auditorium using smart material. This place can be located in any direction. It should be designed in a way which makes a more efficient use of the daylight and performs better according to its contextual conditions (location, climate, function); In other words, it should function depending on its specific situation. My aim is to design an adaptable façade with electrochromic material (see fig.4.3 in chapter 4) which can provide a natural lit office space and a good condition for auditorium.

A good natural lit office space should provide: good outside view, support and enhance task performance, create a pleasant and healthy working atmosphere (demands). These subjective requirements are determined by measurable variables: illuminance levels, luminance level, light distribution and glare; by meeting the requirements for these variables the design could perform better.

To achieve this aim, different patterns from smart materials can be used. It is possible to have an adaptable façade by making a pattern from smart material.
1.4 Research question

Based on the intention of the design, the following research question has been formulized.

What combination of patterns can provide appropriate daylight for auditorium and staff room?

In order to find a proper answer for the above mentioned research question, the following sub question are necessary to be answered.

1. What factors are important for visual comfort of staff room and auditorium?
2. What daylight is appropriate for staff room with computer and auditorium?
3. What is the best smart material for adaptable façade of my research?
4. How computer modeling can help to provide visual comfort for staff room and auditorium?

1.5 Approach

The research approach to improve the facade adaptability to natural light is: first, to identify a problem in the design (adaptability of facade for different activities...
and its simplicity); Then a list of requirements regarding visual comfort for staff room and auditorium is shown; Finally we look for the conditioning variables (or drivers) which affect the fulfillment of the users demands in different applications of the space (i.e. Auditorium or Staff Room). These conditioning variables can drive the design and set its direction to cover the demands and requirements, and as a consequence, improve the design for adaptability. (Fig 1.5)

In order to have an adaptable façade, a proper lighting condition in offices and auditorium is crucial. The final design should respond effectively to its driver variables to enhance the natural lighting conditions and provide a comfortable staff room and auditorium for the users.

1.6 Relevance

Providing appropriate daylight conditions in an office building brings lots of benefits; natural lighting has a direct impact on the user’s well-being and improves their productivity and their satisfaction. Several studies have been done regarding the influence of good quality daylight in work performance and productivity.

According to the Heschong Mahone Group tests, office workers in a naturally lit space performed 10% to 25% better on mental function and memory recall examinations in compare with artificially lit spaces. They also worked 6 to 12% faster and were less likely to report negative health symptoms. The California
Energy Commission determined that higher levels in concentration and better short term memory recall were consistently related to exposure to daylight. Students in the classrooms with the highest daylight factors performed up to 18% better on standard tests.[1](fig 1.6)
Furthermore an appropriate daylight design should bring energy savings, not only in the amount of electricity used on artificial lighting, but can lower the HVAC (Heat, Ventilation & Air Conditioned) costs. [22]
In auditorium, this daylight should result in less usage of electricity as well as comfortable area for the users.
While the outside view will not be limited by using smart material, this can provide interesting place for the users.

1.7 Structure

The research is structured as following (fig 1.7): as a starting point, a theoretical review has been made and continued throughout the whole research, this helps to identify and define the problem.
In this research, two chapters have been developed. The first chapter (literature research) has been divided in two parts called smart material and daylight. In these two chapters, different materials and definitions have been discussed. Then the result has been summarized in one chart. (fig 1.7)
The second chapter (called modeling and experiment) has been comprised of the computer modeling and the scale model. In the computer modeling part, the light distribution has been measured for different percentages of electrochromic material on windows, in the general daylight condition and clear sky. Then the result has been shown in the one chart and based on the acceptable criteria for light distribution (which has been identified in the literature research), one percentage has been highlighted as the best option. In the scale model part the variation in glare and view with different widths and ratios of electrochromic strips (translucent or blue strip) to transparent parts have been studied. Based on the responses from the viewers about the view and glare, the best pattern has been chosen.

At the end according to the results of each part, final design and conclusions have been explained. (Fig 1.7)
Section 2
Literature research

Adaptable façade with electrochromic material
2.1 Introduction

The Literature review consists of two parts. (Fig 2.1) One part is about smart material, it covers the definition, advantages and disadvantages of different kinds of smart material with regard to the aim of the project. Then the suitable material for this project has been selected.

The second part totally focuses on daylight, different definition of daylight as well as preferable daylight for different activities. At the end a chart will be presented which can help to find the preferable values for daylight distribution in different sky conditions and for different activities.

2.2 Smart Material

"Color- and optically changing" smart materials include materials and products that are able to reversibly change their color and/or optical properties in response to one or more stimuli through the external influence of light, temperature, compression, an electrical or magnetic field and/or a chemical stimulus.[1,2]

The currently available color and optically changing smart materials can be different according to their various stimuli as follows:
<table>
<thead>
<tr>
<th><strong>PHOTOCHROMIC SMART MATERIALS</strong></th>
<th>These materials change their colour when excited by the effect of light (electromagnetic energy).</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>THERMOCHROMIC, THERMOTROPIC SMART MATERIALS</strong></td>
<td>These materials change their colour and/or optical properties when excited by the effect of temperature (thermal energy).</td>
</tr>
<tr>
<td><strong>MECHANOCROMIC (E.G. PIEZOCROMIC, TRIBOCHROMIC) SMART MATERIALS</strong></td>
<td>These materials change their colour when excited by the effect of compression, tension or friction (mechanical energy).</td>
</tr>
<tr>
<td><strong>ELECTROCHROMIC, ELECTROOPTIC (E.G. IONOCHROMIC) SMART MATERIALS</strong></td>
<td>These materials change their colour and/or optical properties when excited by the effect of electrical fields, electrons or ions (electrical energy).</td>
</tr>
<tr>
<td><strong>CHEMOCROMIC (E.G. GASCHROMIC, HALOCHROMIC, SOLVATOCHROMIC, HYGRO-/HYDROCHROMIC) SMART MATERIALS</strong></td>
<td>These materials change their colour and/or optical properties when excited by the effect of a chemical environment (chemical energy), e.g. hydrogen, oxygen, salt content (pH value), a solution or water.</td>
</tr>
</tbody>
</table>

Table (2.2) Different smart material
Table (2.3) different kinds of smart material and its usage

Among all materials in the group the material on the market are shown and described.
2.2.1 Photochromic material

Photochromic materials (PC), UV-sensitive materials are materials or components that are able to reversibly change their color in response to light. (Fig 2.2.1)[1, 2]

Applications: One of the most widely known applications of photochromic materials (PC) are self-coloring sunglasses, which have been in the market for over 20 years (fig 2.2.1). They come in various colors. A number of different products for children, such as toys, have been made of this material.

Up to now there are very few releases of this material in the fields of art or architecture. Although the use of self-coloring glass in windows or facades is an obvious application, it has not been successful because of its inadequate long-term behavior, sensitivity to heat and relatively high manufacturing costs. This material has been used in architectural design. In 1992 Becker Gewers Kühn & Kühn used this material for the Museum of Modern Art in Munich in the design however it has not been built yet.[1,2]

Advantages: without energy consumption the color of glass can change according to sunlight. This is normally in form of a coating which can be added to the glass layer. [1, 2]

Disadvantages: manufacturing process of these coating is sophisticated and requires a lot of money. These materials are also sensitive to heat and moreover they are not durable as building material. Considering these
disadvantages, usage of photochromic glasses as building material is not recommended. In addition, they can not be controlled by user which means they are not acceptable for our demands [1, 2]

2.2.2 Thermotropic / thermo chromic material

The word “thermotropic" refers to materials or components that are able to reversibly change their optical characteristics (e.g. transparency) in response to temperature.[1,2]

**Application:** thermochromic materials (TC) are more common than photochromic materials (PC) especially in the fields of art and design and also in architecture. [1, 2]

Among the first architectonic applications was a wall covered with thermochromic paint in the *Musée d’Art Moderne de la Ville* de Paris by the German artist, Sigmar Polke, in 1988. Other artists and architects have accepted the material and some of their works includes walls coated with thermotropic paints.(11,16)[1,2]

**Advantages:** without consumption of energy it changes its opacity. It has promising future in controlling natural light. (fig 2.2.2)[1,2]
Disadvantages: since this material is only affected by temperature and user can not control it according to the function, usage of this material for our purpose is not acceptable. Moreover it can limit the view to the outside.

2.2.3 Electrochromic materials

<table>
<thead>
<tr>
<th>different types</th>
<th>advantages</th>
<th>Technical limitation</th>
<th>Various color</th>
<th>electricity power</th>
<th>usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>suspended particle device(LCD)</td>
<td>can be turned too fast</td>
<td>complex installation, complex manufacturing, less safety because of electricity, the entrance of light is the same visibility will change</td>
<td>limited color</td>
<td>60-110 voltage</td>
<td>inside</td>
</tr>
<tr>
<td>liquid crystal device(SPD)</td>
<td>can be turned too fast can change from transparent to translucent</td>
<td>complex installation, complex manufacturing, less safety because of electricity</td>
<td>limited color</td>
<td>60-110 voltage</td>
<td>inside, exterior</td>
</tr>
<tr>
<td>Photochromic material on sunglasses</td>
<td>work without electricity</td>
<td>Working with UV gradually change in color, no work inside car</td>
<td>various color</td>
<td>no electricity</td>
<td>for sun glasses</td>
</tr>
<tr>
<td>wO3</td>
<td>less usage of energy</td>
<td>change color gradually high processing cost</td>
<td>battery</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EC/ECO</td>
<td>less energy usage, fast changing time</td>
<td>two position of on and off</td>
<td>various color</td>
<td>battery</td>
<td>interior, exterior</td>
</tr>
</tbody>
</table>

Table (2.2.3) different electrochromic material

Electrochromic materials or components are able to reversibly change their color in response to light or electricity. There are different types of...
electrochromic material which has promising future in construction of smart glasses and the exterior or interior windows. [1, 3, 4, 5, 6, 7, 8]

- **Application**
  This material can be used for TV, optical device, interior separation and also windows. There are different kinds of windows or separation which has been made or are under researches. Smart windows materials have a unique property and that is their ability to adjust the light transmittance upon an external stimulation. This property can be utilized to solve daylight problem. Separation walls in the offices are another common application of this material. [1, 3, 4, 5, 6, 7, 8]

- **Different groups of Electrochromic materials:**
  Since this group is made of different materials, all materials in this group have been explained and at the end the proper one for our aim has been chosen. [6, 7, 8]

**SPD or LCD device:**
Current active materials used in smart window devices mainly include suspended particles, liquid crystals, photochromic, and electrochromic layers. Suspended particle devices (SPD) (fig 2.2.3.1) and liquid crystal devices (LCD) (fig 2.2.3.2) are capable of switching quickly and performing under a reasonably high transmission range. But their drawbacks are also obvious. High voltage is needed for both of SPD and LCD to operate. The high production cost, complex manufacturing, and limited color and complicated installation for façade can count as its disadvantages hence this material are not interesting for our purpose [6, 7, and 8]
Photochromic (photochromatic) materials are used in auto dimming sunglasses, which rely on specific chemical reaction and are activated by UV light. Disadvantages of photochromic materials based sunglasses are obvious; the materials only react to UV irradiation and not to visible light. An example of this is when you sit in a car. Because the windshield blocks out most of the UV light, photochromic lenses can not work inside the car. This kind of electrochromic is not acceptable for our purpose. That is mainly because it can not be controlled by the user. In addition, response speed to the UV light is very slow. [6, 7, 8]

Inorganic Electrochromic materials (WO3): these materials, first introduced by Deb in 1969, can change their color when exposed to an applied potential due to electrochemical oxidation and reduction. In the past decades, most researches focused on inorganic electrochromic materials, such as WO3. However, this transition metal oxide electrochromic show a slow response time (tens of seconds) and high processing cost. Based on these disadvantages this material can not be used for our purpose. [6, 7, 8]

Electrochromic polymers (EC): Compared with the smart window materials mentioned earlier, electrochromic polymers (EC) have the most promising future in developing smart sunglasses and windows. (2.2.3.3) Electrochromic polymer based devices (ECD) have shown several merits: they require power only during switching, have a low operation voltage (3-8 dc voltage) and less energy consumption, show a quick response time, have a great repeatability, various
Adaptable façade with electrochromic material. These advantages encourage me to choose this material as coating for my adaptable facade [6, 7, and 8]

2.2.4 Conclusion

While there are different kinds of electrochromic windows, the last group is the best one for the purpose of this research because it can be controlled by user, can not limit the view to the outside and can limit the amount of light penetrating inside. [7,8, 23,24]

At the push of a button, the glazing can be tinted to keep out unwanted heat and glare, or cleared to allow in as much light as possible (see Figure 2.2.3.4). When tinted, the thin film stack on Surface of the insulating glass, absorbs the sun's energy and preferentially re-radiates it to the outside due to the low emissivity properties of the coating. Additionally, the low-emittance (low-e) coating keeps desired heat inside the building in the winter. [30,32,32]
By comparison, even the best conventional low-e windows are static, with a fixed visible transmission and solar heat gain coefficient. In other words, they cannot tint or clear as needed, and consequently do not achieve optimum energy savings. U.S. Department of Energy (DOE) models predict that energy
Adaptable façade with electrochromic material

use in buildings could be reduced by 20% with electrochromic glass facade, compared to today's high-performance Energy Star (low-e) windows. [30,32]

Electrochromic window also help create a comfortable environment for the people inside the buildings, because they block glare and solar heat gain while allowing the building’s occupants to maintain the desired view.

**How it works**

The electrochromic glazing product consists of a series of five ceramic layers that are vacuum-deposited onto float glass using the same thin-film sputtering technology that is used to fabricate today's static low-e glazing. [Figures 2.2.3.5, 2.2.3.6] The electrochromic coating, and how it fits within the context of an insulating glass unit (IGU), is shown in Figures 2.2.3.4 and 2.2.3.5. The coating is on the 2nd Surface of the window, where it rejects or admits incoming solar radiation depending on whether the glass is in the tinted or clear state. In this solid-state device, the electrochromic layer (EC) and a counter electrode layer (CE) are separated by an ion-conducting layer (IC). These three core layers are interleaved between two transparent conductors (TC1 and TC2). Two counter electrode layers transfer low DC current to the whole surface of electrochromic material. There is also another low e emission layer. When the coating darkens, the sun’s light and heat are absorbed and low emissive layer on glass which keeps out unwanted heat can help to provide comfortable space near the window. In design of this layer low emission layer and two electrically conductive
Adaptable façade with electrochromic material layers have been added (Fig 2.2.3.6). These five layers which can be called electrochromic material can change from being totally transparent to totally colorful by electricity current (DC voltage). This layer is thinner than 1/10 of the thickness of hair. [7,8, 23,25]

The coating stack has high transparency in the clear state. (The transparency and reflection of it is the same as standard glass material) When a low DC voltage is applied through a wire which has been embedded in frame or hinge, it passes across the transparent conductors (e.g., indium tin oxide, ITO, or aluminum-doped zinc oxide, AZO), Li+ ions move through the ion conductor and into the EC material layer, which undergoes a gradual transition from clear to blue/gray as lithium is inserted. (The transparency and reflection of glass in colorful situation is the same as colorful glass)

**How to make**

Figure 2.2.3.8 provides an overview of the manufacturing process. The glass used for sputter coating is float glass that has been meticulously cleaned and prepared. After these preliminary steps, the glass enters the clean room environment, where the electrochromic layers are deposited in the sputter coating machine. Next, these monolithic panes are tested and those that pass are fabricated into IGUs. Outside the clean room environment once again, the IGUs are tested for performance and reliability, and are then shipped to either the job site for installation or to the glazing contractor where they are framed. A
Adaptable façade with electrochromic material wire which is not bigger than 0.2 cm can be embedded in the frame and hinge (if the window is operable) and after installation this wire can be connected to switches.

**Durability**
Durability testing to assure product reliability has been conducted throughout the materials and technology development processes. Samples of the glass have been tested by several accredited third-party organizations, including the DOE. In a series of tests, which were carried out for more than 20 -30 years, the electrochromic glass was subjected to simulated solar light and heat while being continuously switched between the clear and tinted states.

The electrochromic material (EC) just uses DC current (3-8 dc voltage) which means being safer in compare with the other kinds of electrochromic materials. The wires, through which the voltage is applied, are imbedded in the frame of the window. The electric current can be connect/disconnect using a remote controller or an on/off switch.

Another important factor in this material is the cost. The Cost of this material is about 200 $/m². This price is for one square meter of dabble glazing window while one of the glass has EC layer with standard aluminum frame and on/off switch. If the switch or frame was different from factory options this price will change. This cost seems acceptable considering their potential in controlling natural light and providing an adaptable façade. [7, 8, 23, 25]
Section 2

One important disadvantages of this material is being colored (translucent) or transparent which makes inside either dark or bright. For that reason this material is common in the countries in which the sky is sunny most of the time. (Fig 2.2.4.2) The potential to be transparent or translucent leads us to the design of an adaptable façade which can control the daylight of the room. In this way different parentages of electrochromic material (different patterns) in the glass wall can provide comfortable office space in different climate condition and for different activities. Combination of patterns can make the adaptable façade for my building.

Since the technical detail and the properties of the blue electrochromic material can be counted as the base for smart material technical details (appendix fig3), in the computer modeling and scale model the same color is assumed. The performance of the electrochromic coatings with other colors (except for black) will not be significantly different except black color. [24]
2.3 Daylight

Day lighting is one of the main functions of the windows. The window design determines the distribution of daylight to a space. [10, 11, 12]

Daylight is generally perceived as more attractive and comfortable than artificial light. There are several reasons for this:

- Light emitted by the sun covers a wide spectrum of frequencies (colors). The blend of these colors makes up white daylight. Artificial light sources cannot exactly reproduce the color spectrum of the sun. The eye senses this and reacts by tiring more easily.

- Daylight is dynamic. It varies through the seasons and times of day, the position of the sun and cloud cover. Artificial light is static.

- The required amount of artificial light in interior spaces is set at a level required for minimum comfort. Daylight in interior spaces often reaches considerably greater light levels, which is perceived to be more pleasant.

- Daylight is emitted by all sides of the celestial hemisphere and by the sun. Its distribution results in the illumination of the environment. This kind of illumination is comfortable for the eye.

A further advantage of daylight is its potential for energy saving. All additional daylight not only means an increase in visual comfort, but also an energy saving
in artificial lighting. Potential savings are considerable, especially in office buildings because lighting is about 25% of energy usage of office building. [20] If the heating standard is up-to-date, the majority of energy will be spent on lighting. [12, 16]

These advantages lead us to use daylight more but if only the glass area is increased, and no other design parameters are changed, the daylight level will increase with increased glass area. However, more daylight does not necessarily mean better daylight. Although the outside view may be impressive, visual comfort may be more difficult to achieve, especially for office work. In the office rooms with computer two major factors have changed compared to paper-based work offices. Firstly, the computer screen is a self-luminous surface, i.e. a light source with a certain luminance. Therefore if too much light falls upon it, the contrast on the screen is washed out, and the image cannot be seen. This is very different from paper, which reflects any light falling upon it. The contrast between the paper and the surrounding is higher than the difference between the reflectance of those two surfaces. For example text printed on paper can be read in many lighting conditions from dark indoor environments to sunlight. Secondly, with computers, the view of sight has been raised from looking down on the working table to be almost horizontal, towards the computer screen; the surrounding field of view will thus likely include the window, especially in highly glazed facades and in so called “open landscapes”. Today, computers are a natural part of any office work. According to a Danish study, 95 % of 1800
questioned office workers use computers for more than 55% of their working time. At the same time, more than 70% of them preferred to sit close to the window. [16, 19, 20] Therefore visual comfort for new staff room with computer should be measured precisely. Since most of the calculations use different parameter, in the first part all different definitions of daylight parameter will be given. Afterward one chart can show the summary of the whole acceptable value for the office and auditorium in different sky condition.

2.3.1 Daylight definition

2.3.1.1 Illuminance and luminance

Illuminance is the amount of light coming from a light source that lands on a surface. It is measured in Foot candles, Lux in the metric system (This is shown as Lx). A typical office has an illuminance of between 30 to 70 foot candles (300 to 700 lx) on desktops. Horizontal illuminance describes the amount of light landing on a horizontal surface, such as a desk, and vertical illuminance describes the illuminance landing on a vertical surface, such as a wall or a face. (Fig 2.3.1.1)
Luminance describes the amount of light leaving a surface in a particular direction, and can be thought as the measured brightness of a surface as seen by the eye. (Fig 2.3.1.2)[10,11,23]

Luminance is expressed in Candle as per square foot, or more commonly, Candle per square meter (Cd/m²). A typical computer monitor has a Luminance of about 100 Cd/m².[12,13,16]

It should be noted that, even if the illuminance requirements are met, glare can occur when the light distribution is unfavorable. Most people feel comfortable at illuminance levels above 2000 lx. Because this is the quantity of light outdoors during the day, even in bad conditions. But as described above, the eye only requires a fraction of this light to work indoors. Studies have shown that artificial lights are switched on when the illumination drops below 75 lx. This is when color vision starts to be affected. [12, 16]

2.3.1.2 Glare

Glare, caused by a bright object in the field of vision, interferes with the visual task. For the ear a comparable situation would be a loud and interfering noise (traffic) that detracts from the sound of the acoustic task (speech). Glare is a form of visual noise; or in other words, noise is acoustic glare.
Physiological glare verifiably interferes with the visual task. When looking at a bright window it will be difficult to read information (blackboard/picture) on the wall adjacent to the window.

With a person standing in front of a window, one sees a dark silhouette, but not the face. Ceiling luminaries (artificial light) reflected on a computer monitor make it difficult, or even impossible, to read what is on the screen. There are two kinds of glare.

Disability glare results when a light source reflects and covers the visual task, like a veil, obscuring the visual target, reducing its contrast and making the viewer less able to see and discriminate what is being viewed. (fig 2.3.1.4)

Discomfort glare arises when light from the side of the task is much brighter than the light coming from the task. The eyes attempt to focus on the light from the task, but so much extra light is entering the eye from the side that the visual processes are confused and it is difficult to concentrate for long periods. [23] (fig 2.3.1.4)

Therefore proper contrast of visual task and surrounding are necessary. For good perception the contrast – the relation of the luminance of background and nearby objects - should be between three and fifteen. In the actual work area it should be below three. [12, 16]

Contrast can be defined as the difference between the luminance of the target and the background relative to the average luminance of the scene. [18, 24]
Contrast = \frac{\text{Target luminance} - \text{Background luminance}}{\text{Target luminance} + \text{Background luminance}}

While the contrast can be measured by luminance of target to luminance of background and different color has different luminance, the result of glare for target with different color can change the result of contrast and glare. In other words different colors of glass can change the result of contrast and glare. [18, 24]

There is another important factor in the formula. Since contrast can be measured by luminance of target and luminance of background, changing the orientation of audience can result in different target and different contrast. In other words when the computer is in front of window viewers can feel more glare however when the computer is perpendicular to the window the viewers may feel less glare. [18, 24]

2.3.1.3 Daylight factor

The amount of light received inside a building is usually only a small fraction of that required - because of modifications imposed by the size and position of openings - and will also constantly vary owing to the influences imposed on the ‘whole sky’, illumination level by clouds, buildings and/or other reflecting planes. Therefore, it is impracticable to express interior day lighting in terms of the
Adaptable façade with electrochromic material

illuminatoin actually obtainable inside a building at any one time, for within a few minutes that figure is liable to change with corresponding changes in the luminance of the sky.

For practical purposes, use is made of the daylight factor (DF). This is a percentage ratio of the instantaneous illumination level at a reference point inside a room to that occurring simultaneously outside in an unobstructed position. It can be expressed in percentage.

The daylight factor DF is determined solely by the geometry of the space (dimension of room, size and position of windows, shading elements) and the light transmittance properties of the glazing, but not the external illuminance at that particular moment. It varies on a 2-D plane in the room itself. [21, 26]

Daylight factor depends on Sky component (SC), direct illuminance from the sky (if it is visible), externally Reflected Component (ERC), illuminance from outdoors reflections and Reflected Component (RC), Illuminance from interior reflections. [16, 18, 19, 21]
2.3.2 Sun position in different times of the year

Sun position
The apparent sun position in the sky dome changes during the day and seasonally throughout the year. Since it is the same for a particular time and date in different years, it’s predictable and can be calculated for a specific date and time. The sun path (fig 2.4.2.1), which is the apparent followed trajectory by the sun every year in a determined location in the earth, changes depending on the latitude and longitude. (2, 7)

The Earth’s elliptical orbit and its inclination (23.45°) respect to its own axis are the main reasons for seasonal climate changes, which are obvious in locations far away from the Equator; specific dates are defined when these seasonal changes occur.[25,26]

Summer position: June 22nd is the Summer Solstice in the northern hemisphere (fig 2.3.2.2), the Earth is located in its orbit furthest from the sun; the northern hemisphere is more exposed to radiation from the sun than the southern hemisphere and the light reaches to it perpendicularly; the sun appears higher in the sky vault and is visible more hours during the day. [16, 17]

Winter position: December 22nd is the Winter Solstice in the northern hemisphere (fig 2.3.2.2), the Earth is still located in its furthest point from the sun but the sunlight is more tilted, reflected on the southern hemisphere; the sun appears lower in the sky vault and the days are shorter with less hours of sunlight. [16, 17]
sun, but in the opposite direction comparing to summer; so in this case the southern hemisphere is more exposed to solar radiation; the sun appears much lower in the sky dome and less hours a day. [16, 17]

**Spring or fall position:** in March 22nd and September 22nd the midpoint between the two Earth’s position boundaries (fig 2.3.2.2), occurs [16,17]

### 2.3.3 Mathematical Sky Models

The main light source is the sun, nevertheless due to atmospheric scattering and reflection, the sky dome also emits light; the light distribution depends on environmental conditions as climate conditions are always changing, average conditions has to be used. The Commission *International de l’Eclairage* (CIE) developed a series of mathematical models which represent ideal scenarios for different climate conditions: clear sky (sunny) and overcast (cloudy), intermediate sky and uniform sky. The models describe luminance levels in the entire sky dome depending on angle from the horizon to the zenith and the sun position. Mathematical calculations are as follows: [27]

**CIE Uniform Sky (for daylight calculation in Dialux)**

This mathematical model assumes a constant luminance level in the entire sky dome. (Fig 2.3.3.1) [27]
CIE Overcast Sky (overcast sky in Dialux)

A completely clouded sky where the sun is not visible is the fundament of this distribution; the radiation passing through the clouds provides a white light. The distribution is symmetrical along the zenith and diminishes as approach to the horizon. The luminance levels are three times higher in the zenith than the horizon. The sky vault itself is the brightest element; shadows are indistinct and uncommon (Fig 2.3.3.2) [16, 20, 27]

CIE Clear Sky (Clear sky with direct sun in Dialux)

The clear sky distribution assumes that the sun is visible therefore is the brightest element in the sky dome, the luminance varies over altitude and azimuth. The sky vault provides diffuse light; there are sharp shadows and contrasts. ) [16, 27] (fig 2.3.3.3)

CIE Intermediate Sky (mix sky in Dialux)

This distribution is a variant of the CIE Clear Sky; the sun is not bright and the luminance changes are not strong. (Fig 2.3.3.4, 2.3.3.5) [16, 15, 27]
2.3.4 Conclusion

The aim of this project is to provide optimal façades for two different activities (auditorium, office). The final design should be capable of providing comfortable staff room and auditorium in all orientation.

A comfortable office space should provide a good seeing condition, create healthy space for working atmosphere and improve task performance. Therefore it is important that the light distribution be within the average interval of minimum acceptable light distribution and lower than maximum acceptable light in all of the orientations. To find visual comfort and comfortable working area, four important factors should be considered which are illuminance, luminance, glare and view.

To know if the light of the building in the overcast sky is good enough, one factor can be used. That is Daylight factor which can show the relation of inside illuminance to the outside illuminance. Daylight factors can give general idea about the light of the room in overcast sky. On the table 2.3.4 there are preferable values related to daylight factors which can be helpful in comparison after computer modeling (see table 2.3.4).

There are several factors that influence visual comfort in an interior. One of them is Illuminance. Illumination levels are generally dictated by the needs of
the visual task. Typically, the more light available, the easier it is to perform a specific task. Illuminance levels are influenced by:

- a) Details of the task
- a) Reflectance and contrast (task and background)
- b) the eye - (age and condition)
- c) Importance of speed and accuracy

Since 1958 the Illuminating Engineering Society has published illuminance recommendations in a table form. These tables cover both generic tasks (reading, writing etc), and hundreds of very specific tasks and activities (such as drafting, parking, milking cows, blowing glass and baking bread). After the acceptable light for different activities has been studied, one of them has been chosen to represent the preferable values of my research.

Another important factor for visual comfort is the luminance distribution of the surfaces. The luminance distribution should be treated in a way that high luminance contrasts on interior surfaces is prevented. To have better light distribution inside the room, some standards have been defined. These standards have been used in my calculations (see table 2.3.4).
<table>
<thead>
<tr>
<th>Performance Indicator</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-5% DF</td>
<td>Preferable, large potential for daylight utilization</td>
</tr>
</tbody>
</table>

**Acceptable value for office in clear sky**

<table>
<thead>
<tr>
<th>Performance Indicator</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work plane illuminance</td>
<td></td>
</tr>
<tr>
<td>300-700 lx</td>
<td>Acceptable for paper work/ ideal for computer work</td>
</tr>
</tbody>
</table>

*Luminance of surfaces in the room*

<table>
<thead>
<tr>
<th>Luminance</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-500 cd/m²</td>
<td>Preferable</td>
</tr>
</tbody>
</table>

**Acceptable daylight factor for auditorium**

<table>
<thead>
<tr>
<th>Performance Indicator</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2%DF</td>
<td>Acceptable, small potential for daylight utilization</td>
</tr>
<tr>
<td>&lt;1%DF</td>
<td>Unacceptably dark, negligible potential of daylight utilization</td>
</tr>
</tbody>
</table>

**Acceptable value for auditorium in clear sky**

<table>
<thead>
<tr>
<th>Performance Indicator</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>100-300 lx</td>
<td>Too dark for paper and acceptable for computer work</td>
</tr>
<tr>
<td>&lt;100 lx</td>
<td>Too dark for paper and computer work</td>
</tr>
</tbody>
</table>

Table 2.3.4 all standard and acceptable value for different mood [13, 14, 15]
The other conclusion from literature study can be listed as following

1) In overcast condition the preferable daylight factor near window is 2-5% for office room.

2) In clear sky condition the preferable illuminance near window should be 300-700lx for an office room. In clear sky condition different orientation should be simulated separately and the maximum light received should not be more than suggested average.

3) Position of the opening affects the light distribution. If some big parts of electrochromic material are going to be used, it is better not to locate it on the upper part of the window. That is because the upper part of the window provides better daylight distribution.

5) In an office, different orientations of the computer can change the results of the glare. If the computer stands in an angle of 90 with windows you feel less discomfort glare comparing to the time when your computer is in front of the window.

6) To have fewer glares, the contrast – the relation of the luminance of the nearby objects to background - should be between three and fifteen. One
way to check the glare is contrast. The contrast near the eyes and on the task paper should be 1/5 while the contrast between the eyes and the surrounding can be 1/15.

7) In the Netherlands June 22nd is the Summer Solstice. In other words 22nd of June can represent the highest position of the sun in the summer.

8) In the Netherlands December 22nd is the winter Solstice. In other word 22nd of December can represent the lowest position of the sun in the winter.

9) In the Netherlands, March 22nd or September 22\textsuperscript{nd} is the midpoint between the two Earth’s position boundaries and can be used as the position of sun in spring or fall.
Section 3
Modeling and Experience
3.1 Introduction

Lighting quality is a perceptive parameter which is determined not only by physical variables, but also by psychological factors. However there are series of physical factors that have influences on the light quality perception: brightness, contrast and color rendering; these physical factors depend on measurable variables: illuminance levels, light uniformity, luminance ratios, glare, and daylight factors; Then by reaching adequate values for these variables, the design could fulfill the users demands.

Therefore in my approach two steps are taken (fig 3.1.1): the first is computer simulation using Dialux software. At this step, it is intended to identify the appropriate values for the physical factors affecting the visual comfort. The second step is a survey based on the ideas of different viewers. This step aims to determine the compatibility of different designs with psychological factors.

The methodology part has been made of two sections called computer modeling and scale model. In computer modeling part, it has been tried to define the best percentage of using electrochromic material on glass in different sky condition (clear sky and overcast sky).

In the computer modeling firstly the light distribution for different coverage ratios of electrochromic material for overcast sky condition in an office has been calculated. The results have been benchmarked and the acceptable one has
been highlighted. Then in the second one the light distribution for different coverage ratios of electrochromic material for clear sky has been calculated and all of the required values for clear sky condition have been checked. At the end the light distribution for a window completely covered with electrochromic material has been calculated.

In the second part (scale model), the effect of size and distribution of electrochromic strips on view and glare has been studied. Windows with different widths of transparent and blue (translucent/electrochromic) strip has been made and based on people’s idea the best one has been selected.

3.2 Methodology

The daylight studies are made to have a better understanding of the daylight and the influence of geometry and opening settings in interior illuminance levels. The results helped to create design strategies which were applied to the final design.

In the design of an adaptable façade, achieving a comfortable area for different activities (staff room and auditorium) is the aim. My design is made of some boxes and some long building (fig 3.2.1). Boxes are places for staff rooms and different activities while long buildings are the designated for studios. Different activities (like staff room or auditorium) can take place in boxes (fig 3.2.1). Since the façade of the boxes is made of glass, they can be oriented in any direction.
Adaptable façade with electrochromic material (north, south, west, and east). The plan for the staff room is an open plan and is made of different partitions.

In receiving daylight three areas on boxes are really important (fig 3.2.2). The first one is an area in which glare should be studied. The second one is an area in which daylight can penetrate and the last one is an area in which artificial light should be used. Since most of the people prefer to sit near the window, the area in the middle can be used mostly as corridor. Therefore the area near the windows is really important and should be studied. In computer modeling and day light distribution the area within 5 meters from the windows has been considered to be the region at which standard light distribution criteria should be met. The reason is that most of the people sit in this region and glare may happen.

### 3.3 computer modeling

All of the modeling has been done with a specialized computer modeling software called Dialux.

The adaptable facade made with electrochromic layers could have four states. The first state can be considered as a situation when all electrochromic layers are off. It happens when the sky is grey. (Fig 3.3.1) and Another state can provide proper light for staff room in the minimum daylight condition (Fig 3.3.2) the third state can provide proper light for staff room with computer in maximum
Adaptable facade with electrochromic material

bright condition (Fig 3.3.3) and the last one can be the time when the whole glass is covered with electrochromic material to provide a suitable place for an auditorium. (Fig 3.3.4) as a matter of fact, this is the overall width of the blue (translucent/electrochromic) which changes in each of these states. As the first stage is a totally transparent, the descriptions start from the second state.

The Second state: This state of window (fig 3.3.2) is suitable for the time when there is no direct light on the sky but sky is bright enough. In this type of sky, the transparent facade makes inside area too bright and translucent facade make it too dark. Therefore an intermediate state should be chosen and some percentage of electrochromic material should be used. It has been tried to provide comfortable space when the sky is in overcast condition or there is not any direct light on the sky.

According to statistics, during 30% of the year, the Netherlands has sunny days and it mostly happens in summer. The sky with indirect light happens during spring, falls and sometimes in winter. [28]

In computer modeling daylight factor (DF) of facade with different percentage of electrochromic material will be calculated. As it has been mentioned, DF values between 2-6% are preferable for a naturally lit office. The objective is to achieve this value for staff room. A research in Denmark shows 70% of people, even the ones working with computer, want to sit near the windows. This factor should be
achieved nearby the windows when the sky is overcast otherwise glare can happen (see table in appendix which shows preferable average values of DF for different activities) [15].

The third state: this state is for the time (fig 3.3.3) when the maximum illuminance can be received. The maximum light or direct light can be received in the clear sky condition. To define the maximum value, the sky condition is important. In clear sky a room can receive more illuminance. In the Netherlands the weather condition for the Working hour (which is from 9:00 to 17:00 hrs) for the whole year has been measured. The Netherlands has clear sky condition 30% in the whole year and it is mostly in August (50%) and in December (20%). [28] Since conditions are always changing, specific locations have repetitive conditions; with statistical measurements climate conditions could be predicted. Global illuminance (daylight & sunlight) could be measured and analyzed to predict the clear sky frequency.

In the computer modeling the maximum illuminance which the room can receive from the façade (glass wall) with different percentages of electrochromic material has been calculated. The maximum is preferred to be between 300-700lx. In this part contrast and luminance can help to choose the best percentage of using electrochromic material. (Table 2.4.4 for preferable values)
To know the time that the highest illumination is receives, Computer modeling for each orientation (east, west, north, south) in different times and in 22\textsuperscript{nd} of June (this time represent summer solstice) has been done. Based on computer modeling, the maximum illumination on east, west and south and north is at 10:00, at 16:00, at 12:40 and at 12:40 on the 22nd of June respectively (fig1, fig2 in appendix). Therefore for each percentage of using electrochromic material on glass wall, computers modeling in each orientation and based on the mentioned time is necessary. In this way the maximum illuminance that the room can receive in each orientation can be identified.

**The fourth state:** it happens at the time when the window is totally covered with electrochromic material and therefore the space is used as an auditorium. In this way the daylight factor is preferred to be between 1-2\% and in clear sky condition it is preferred to be between 100-300 lx (table2.4.4). When the façade is in this state, the room can be used as an auditorium. (Fig 3.3.4)

### 3.3.1 Computer modeling method

All computer modeling has been done in Dialux. Dialux is the international market leader for light planning software. This program can enable user to plan the lighting in a room, scene or building. The program allows the user to calculate and visualize the daylight, as well as planning the lighting scenes, the
Adaptable façade with electrochromic material

color and intensity of the lights used, position the emergency lighting on the project, with the right legal number of luminaries and many more.

**Different sky condition**: times and date and sky condition for this computer modeling should be defined. In this research, based on previous explanation, maximum daylight received should be calculated. Therefore in each orientation one date and time has been considered. In that specific date and time the maximum daylight will be received by the room. In other words for each percentage of electrochromic material 4 computer models are run and they can show maximum illuminance which a room can receive in four different orientations.

**Daylight factor**:

As it has been mentioned Daylight Factor (DF) will give one result for the whole year with the assumption that the light is uniformly distributed in all orientations. DF will be in percentage. Therefore for each pattern one computer modeling can lead us to the light distribution inside the room in all orientations. According to references, Spaces with DF of 5% are good for staff room and with DF of 1-2% will have high potential for auditorium (see table in appendix).

**Input**

3d geometry
To draw the 3D model of the room, two ways are possible. The first way is using Dialux wizard. Another way is using drawing geometry in AutoCAD and importing the result in Dialux or using Dialux toolbar. Simple geometry like L or rectangular or polygonal shape can be designed by wizard. Other geometry can be drawn by Dialux or by importing into Dialux. Since my geometry was rectangular, wizard option was good enough for my drawing. Therefore the height, width and length of the room have been defined. The simulated part is a room with a height of 4 meter and width of 8,1 and length of 12 meter. These dimensions are standard dimension for my auditorium. If that place should be used as staff room all interior walls will be removed and an open space for the offices can be designed which means 5 meter of this distance should be provided with good daylight for staff’s table.

After drawing of the plan its location should be defined. The location can be defined in project information. The calculations were simulated in Amsterdam: Latitude: 52°2’. (Amsterdam was the only Dutch city enlisted in this program) the location will have influence on the sun position and in the sunny day’s frequency.

**Material**

One important thing in luminance is the material and its reflection. In Dialux there is one tab in which all material can be found. On that tab the material related to wall has been selected. The wood has been chosen as the material for the table and at the end the material for seats has been assigned. And all standard material for finishing the wall has been defined.
After that it is possible to define their refraction individually. (Fig 3.3.5)

**Light**

In this research, (fig 3.3.6) the light distribution has been simulated for clear sky at which the maximum amount of light enters the room. Another series of computer modeling are done to calculate the daylight factor which shows the relation of outside illuminance to inside illuminance for the whole year (70% of the year) [25]

**Calculation surface**

For daylight calculation two things should be adjusted. One of them is selection of daylight tab another one is the addition of one surface called daylight factor calculation surface. Therefore on one surface all daylight factors will be calculated and result can be shown as minimum, maximum and average as well as some grey scale rendering on plan to show differences in daylight distribution on the plan of the room. (Fig 3.3.7)

**Calculation points**

To know the exact amount of light entering the room, 12 point in the middle of the room in height of 75 centimeter from the floor has been defined. These point are along a line which is perpendicular to the window. It is possible to get the results in a pdf file for each point.(Fig 3.3.8)

**Output**
There are different ways to show the output of the program some of them have been shown below.

**Rendering**
It is possible to have rendering of room regarding daylight factor. This rendering can be exported as jpg or bmp .it is also possible to see ray trace of sun in different times of the day. (Fig 3.3.9, 3.3.10)[21]

**Isoline**
Isolines connect the points with equal values of illuminance measured in the room. It is possible to have different colors for different values. It can be displayed after calculation of this item on Dialux. It can also be exported as jpg or bmp. (Fig 3.3.11)[21]

**False rendering**
With Dialux the user has the option to display the 3D rendering in a false color rendering presentation. The presentation of illuminance and luminance with freely scalable value ranges and definable color gradients is available. It is possible to export the result in PDF or jpg or bmp. (Fig 3.3.12)[21]
3.3.2 The Result for computer model for the second state of window

In the first part of computer modeling, 8 different percentages of using electrochromic material in windows for the overcast sky condition have been modeled. The daylight factor of them has been shown on the table 3.3.2.1. As it can be seen in diagram 70% of blue (translucent/electrochromic material) in windows can meet requirement of 2-5% of daylight factor. In order to find the exact percentage another computer modeling for 65% has been done and the result shows 65% also can meet these requirements. Therefore 65% as acceptable percentage of using electrochromic material on glass wall for the second state has been accepted.

<table>
<thead>
<tr>
<th>Points</th>
<th>10%</th>
<th>20%</th>
<th>30%</th>
<th>50%</th>
<th>60%</th>
<th>70%</th>
<th>80%</th>
<th>65%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11</td>
<td>9.95</td>
<td>8.53</td>
<td>7.11</td>
<td>6.68</td>
<td>4.26</td>
<td>2.84</td>
<td>4.9</td>
</tr>
<tr>
<td>2</td>
<td>17.2</td>
<td>16.3</td>
<td>15.2</td>
<td>13.1</td>
<td>12.1</td>
<td>8.7</td>
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<td>11.2</td>
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<td>5.7</td>
<td>3.4</td>
<td>2.1</td>
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<td>9.0</td>
<td>8.0</td>
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<td>4.5</td>
<td>2.8</td>
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<td>6.3</td>
<td>5.3</td>
<td>4.3</td>
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<td>3.7</td>
<td>2.7</td>
<td>1.7</td>
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<td>1.3</td>
<td>0.8</td>
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<td>7</td>
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<td>0.2</td>
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<td>0.1</td>
</tr>
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<td>9</td>
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<td>0.1</td>
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</tr>
</tbody>
</table>

**Table 3.3.2.1 daylight factor for different percentage of electrochromic**
Adaptable façade with electrochromic material

Fig 3.3.2.2) Daylight factor of 20% percentage of electrochromic

Fig 3.3.2.3) Daylight factor of 30% percentage of electrochromic

Fig 3.3.2.4) Daylight factor of 40% percentage of electrochromic

Fig 3.3.2.5) Daylight factor of 50% percentage of electrochromic

Fig 3.3.2.6) Daylight factor of 60% percentage of electrochromic
Fig 3.3.2.7) Daylight factor of 70% percentage of electrochromic

Fig 3.3.2.8) Daylight factor of 65% percentage of electrochromic

Adaptable façade with electrochromic material
3.3.3 The result for computer modeling for the second state of window

In this part office in clear sky condition has been modeled and the maximum illuminance in different orientation for façades with different percentages of electrochromic has been calculated. The result has been shown on the table (table 3.3.3.1).

Since the objective is to provide suitable daylight conditions for staff room in clear sky, it is preferable to be between 300-700lx. The result shows 75% of electrochromic material on glass wall can meet this requirement.

<table>
<thead>
<tr>
<th>Percentage</th>
<th>North (at 12:40 in June)</th>
<th>South (at 12:40 in June)</th>
<th>West (at 16:00 in June)</th>
<th>East (at 10:00 in June)</th>
</tr>
</thead>
<tbody>
<tr>
<td>65%</td>
<td>40 141 505</td>
<td>75 322 960</td>
<td>80 349 1005</td>
<td>100 440 1024</td>
</tr>
<tr>
<td>70%</td>
<td>35 114 405</td>
<td>60 260 798</td>
<td>65 280 800</td>
<td>85 354 803</td>
</tr>
<tr>
<td>75%</td>
<td>30 94 350</td>
<td>50 214 640</td>
<td>60 230 680</td>
<td>70 291 680</td>
</tr>
<tr>
<td>80%</td>
<td>23 67 240</td>
<td>33 154 480</td>
<td>35 164 490</td>
<td>45 170 492</td>
</tr>
</tbody>
</table>

Fig 3.3.3.1) computer modeling for the second mood of window
Adaptable façade with electrochromic material
Adaptable façade with electrochromic material

Fig 3.3.3.6) Computer modeling of 70% of electrochromic in north orientation at 12:40 on June

Fig 3.3.3.7) Computer modeling of 70% of electrochromic in south orientation at 12:40 on June

Fig 3.3.3.8) Computer modeling of 70% of electrochromic in east orientation at 10:00 on June

Fig 3.3.3.9) Computer modeling of 70% of electrochromic in west orientation at 16:00 on June
Adaptable façade with electrochromic material

Fig 3.3.3.10) Computer modeling of 75% of electrochromic in north orientation at 12:40 on June

Fig 3.3.3.11) Computer modeling of 75% of electrochromic in south orientation at 12:40 on June

Fig 3.3.3.12) Computer modeling of 75% of electrochromic in east orientation at 10:00 on June

Fig 3.3.3.13) Computer modeling of 75% of electrochromic in west orientation at 16:00 on June
Adaptable façade with electrochromic material

Fig 3.3.3.14) Computer modeling of 80% of electrochromic in north orientation at 12:40 on June

Fig 3.3.3.15) Computer modeling of 80% of electrochromic in south orientation at 12:40 on June

Fig 3.3.3.16) Computer modeling of 80% of electrochromic in east orientation at 10:00 on June

Fig 3.3.3.17) Computer modeling of 80% of electrochromic in west orientation at 16:00 on June
<table>
<thead>
<tr>
<th>maximum acceptable value for comfortable office</th>
</tr>
</thead>
<tbody>
<tr>
<td>preferable</td>
</tr>
<tr>
<td>value</td>
</tr>
<tr>
<td>work plane illuminance</td>
</tr>
<tr>
<td>300-700lx</td>
</tr>
<tr>
<td>Luminance of surfaces in the room</td>
</tr>
<tr>
<td>30-500 cd/m2</td>
</tr>
</tbody>
</table>

Table 3.3.3.18) result of maximum value for percentage of 75%

Adaptable façade with electrochromic material
3.3.4 The result of computer modeling for the third state

In this part light distribution has been simulated with the whole window being covered with electrochromic material. Since in this way the activity of area is assumed to be auditorium, the acceptable value for the overcast sky (1-2% DF) and for clear sky condition (100-300 lx) should be met. The pictures show that this value has been met for daylight factor and illuminance.

Fig 3.3.4.1) North orientation at 12:40 on June
Fig 3.3.4.2) South orientation at 12:40 on June
Fig 3.3.4.3) West orientation at 16:00 on June
Fig 3.3.4.4) East orientation at 10:00 on June
Fig 3.3.4.5) Daylight factor when the whole windows cover with electrochromic material.
### 3.3.5 Conclusion

In the first chapter, different acceptable values for daylight distribution have been explained. In this part, the best percentage of using electrochromic material in the facade has been selected.

<table>
<thead>
<tr>
<th>acceptable daylight factor for office</th>
</tr>
</thead>
<tbody>
<tr>
<td>preferable value</td>
</tr>
<tr>
<td>2-6% DF</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>acceptable value for daylight of office in clear sky condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>preferable value</td>
</tr>
<tr>
<td>work plane illuminance</td>
</tr>
<tr>
<td>300-700 lx</td>
</tr>
</tbody>
</table>

**Luminance of surfaces in the room**

- 30-500 cd/m²: In 5 meter of window was in this limitation

<table>
<thead>
<tr>
<th>acceptable daylight factor auditorium</th>
</tr>
</thead>
<tbody>
<tr>
<td>preferable value</td>
</tr>
<tr>
<td>1-2% DF</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>maximum acceptable value for auditorium</th>
</tr>
</thead>
<tbody>
<tr>
<td>preferable value</td>
</tr>
<tr>
<td>100-300 lx</td>
</tr>
</tbody>
</table>

Table 3.3.5.1 summary of acceptable result of computer modeling
3.4 Scale model

In this part, the scope is to find the best pattern and ratio of the width of transparent to blue (translucent/electrochromic) strips regarding glare and the view to the outside. Firstly three different ratios of width of transparent to blue (translucent/electrochromic) have been defined. Then as shown in figure 3.4.1.1, the window which is initially fully transparent has been covered with discrete blue foils which can represent electrochromic material. The ratio of electrochromic material and transparent material can be categorized in different groups. Each ratio can be made of different widths of transparent to blue (translucent/electrochromic) materials which are called patterns. These ratios are 1:2 (33\% of electrochromic material), 1:1 (50\% of electrochromic material) and 2:1 (67\% of electrochromic material). To clarify the ratios and patterns these patterns have been shown in one matrix (table 3.4.1.5).

In this part, people’s idea about the view and the glare has been asked during two tests. In the first test, 4 patterns of ratios of 1:1 and one pattern of ratio of 1:2 and one pattern of ratio of 2:1 has been made (table 3.4.4). These six patterns have been randomly shown to people. In this way their idea about patterns will not be related to being tired of questions or any distractions.
In the second test, based on the results from test 1, 5 other patterns have been evaluated again using a questioner. Some of these patterns are selected based on the results of test 1. Two with ratios of 1:2, one with 2:1, one with ratio of 1:1 and the last one was the proposal design.

While this test has been done in order to understand the people’s idea about view and glare, some limitations exist in test. These limitations are mostly due to cost and time limitations. This test has been done in the scale model (which was 1 to 5 of real scale) and it has been viewed by a limited number of viewers (11 in the first test and 14 in the second test). The test has been done in one view and one sky condition (overcast sky). Also the scale model represents an office room with the height of 3 meter while the height of my design was 4 meter. Therefore this test was done in a smaller scale compared to the real visual comfort and It has been tried to find acceptable patterns regarding the view and glare in this test.
3.4.1 The first test of scale model

In this test 6 different patterns have been made. Then these patterns, as the façade of the scale model of the standard office, have been shown to people. The scale model was 1/5 of real size. People could look through and answer the questions. There were 7 questions for each pattern. One yes, no question and 6 multiple choice questions (with 5 choices). The viewers have been asked to write their reasoning as well. In this test 11 people saw the model and answered the questions. Once each person fully observed the model, some pictures were taken for reference purposes. (Fig 3.4.1.1, 3.4.1.2)

In the first test 4 patterns of ratios of 1:1 have been made. These patterns were 25:25mm, 50:50mm, 100:100mm, 200:200 mm (these are the real size of patterns. Scale model was 1/5 of reality), and two other patterns of ratio of 1:2 (blue :transparent) and 2:1 (blue :transparent) have been made. These patterns were respectively 50mm: 100mm and 100mm: 50mm. (table 3.4.1.5)

The result of their answers can be seen in the diagram. Diagrams firstly showed the result on one ratio and then in different ratios. The best result has been highlighted.

As it can be seen on diagrams 3.4.1.6,3.4.1.7,3.4.1.8, 3.4.1.9,3.4.1.10,3.4.1.11 the best size of ratio of 1:1 according to the view and glare was 100, 100 mm and in different ratios (1:2, 1:1, 2:1) the best size of pattern regarding the view to the outside and glare was 50mm: 100mm (10mm width of blue strip and 20mm...
Adaptable façade with electrochromic material.

width of transparent part in the scale model). Their answers to the questions can
be summarized in these explanations.

- Most of the people found 25:25mm really confusing and difficult to see the
  outside. The reason was the impossibility to concentrate on any parts (blue
  and transparent part) due to the difference in light transmission.
- The pattern of 50,50mm was better comparing to 25,25 mm while most of
  the people preferred wider one.
- The pattern of 100,100mm was the best regarding the view to the outside
  and glare.
- The pattern of 200*200 was not acceptable (90% of audience) because
  these strips seems not to be uniform and glare was really uncomfortable
  which was the result of huge opening parts.

by comparison of three different ratios (1:2,1:1,2:1), one pattern in ratio of 1:2
(blue: transparent) has been made which was 50,100mm. This pattern was
acceptable due to the fact that transparent part let people see the outside and
small blue parts made an integrated facade.

- In ratio of 2:1 one pattern was made (100mm, 50mm) most of people were
  not satisfied with the opening part and they found that glare was
  uncomfortable. People thought bigger patterns in this ratio can solve this
  problem.

At the end, one question has been asked. It was about the usage of two
patterns in one façade.100% of the people answered “it is not acceptable" with
regard to the outside view. They explained this would be a difficult situation for the eyes to concentrate on and it would be too much information for eyes to focus on.

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Ratio of 1:2 (33%)</th>
<th>Ratio of 1:1 (50%)</th>
<th>Ratio of 2:1 (67%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pattern1</td>
<td>25mm/25mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pattern2</td>
<td>50mm/100mm</td>
<td>50mm/50mm</td>
<td>100mm/50mm</td>
</tr>
<tr>
<td>Pattern3</td>
<td></td>
<td>100mm/100mm</td>
<td></td>
</tr>
<tr>
<td>Pattern4</td>
<td></td>
<td></td>
<td>200mm/200mm</td>
</tr>
</tbody>
</table>

Table 3.4.1.5) Table for first test (scale model 1/5)
Table 3.4.1.6) Table of patterns for the first test of scale model (scale of model was 1/5)

<table>
<thead>
<tr>
<th>Glare for the whole room in the same ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pattern</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>200,200mm</td>
</tr>
<tr>
<td>100,100mm</td>
</tr>
<tr>
<td>50,50mm</td>
</tr>
<tr>
<td>25,25mm</td>
</tr>
</tbody>
</table>

Fig 3.4.1.7) People’s idea about the Glare of the whole room in the patterns of same ratio

Adaptable façade with electrochromic material
Adaptable façade with electrochromic material

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**Fig 3.4.1.8** People’s idea about the Glare of the whole room in the patterns of different ratio

**Fig 3.4.1.9** People’s idea about Glare of window in the patterns of different ratio
Adaptable façade with electrochromic material

Fig 3.4.1.10) People’s idea about the view of the patterns of the same ratio

Fig 3.4.1.11) People’s idea about the view of the patterns of the different ratio
3.4.2 Preparation for the second test

Although the computer modeling showed that 65% of blue material (translucent/electrochromic material) for overcast sky is acceptable, the scale model test showed that patterns of 100:500 mm (about 67% of electrochromic material) were not acceptable due to poor view and high glare. Therefore two ways can help to find the best design between computer modeling and people's idea.

1) The big strip of blue material (translucent/electrochromic material) can be added to reach the desired ratio of 65% electrochromic material (which has been accepted by computer modeling in previous part). In this way 4 types of design have been suggested. The effect of the big strips on the light receiving has been checked in Dialux. The big strip in design has been modeled and the width of big electrochromic strip has been found. If patterns of 50:100 mm are going to be used then the width of the blue (translucent/electrochromic) part at the top and the bottom of the window should be 60cm (totally 120cm, but if only one big strip is used, it should be wider than 120 cm (about 150) and the rest of the window should be covered with intermittent layers of transparent/translucent materials with widths of 50:100 mm. In the pattern of 100:100 mm two big strips of 40 cm should be used (If we want to use only one strip then it should be 100

Fig 3.4.2.1) The first proposal design

Fig 3.4.2.2) The second proposal design
Adaptable façade with electrochromic material

and the rest of the window should be covered with intermittent layers of transparent/translucent materials with widths of 100:100 mm.

- Based on the answers from the audiences in the first test, the first design (3.4.2.1) is not preferable because the usage of two patterns in one façade.
- The second design (3.4.2.2) has a really big part at the bottom (about 150, 100 has been shown in computer modeling) which limits the view to the outside and therefore is less preferable.
- The third design (3.4.2.3) is not preferable, due to the usage of electrochromic material on the upper part which limits light distribution in the inside of the room.
- The last design (3.4.2.4) seems really good due to light distribution. The height of the room is 4m and only the bottom 3 meters of the window are required to see outside. Therefore if the big strip is used in the top one meter of the window, it will not affect the view to the outside and at the same time can provide a good daylight distribution.

2) Wider patterns with the ratio of 2:1 are more preferable. This pattern can be 200:100 mm in this way it might be possible to meet people’s requirement.
In order to figure out which pattern can help to provide a better daylight condition, the second test should be done.

### 3.4.3 Second test of scale model

Based on the conclusion of the first test, the second test of scale model and its questionnaire have been designed. This test has two objectives. Firstly the best pattern regarding the view and glare should be chosen. There are two selected patterns from the first test. Based on chart 3.4.1.5 and selected patterns, it seems as if the wider pattern of ratio of 2:1 makes it a more preferable option and it also seems as if the wider patterns with the ratio of 1:2 are more acceptable. Therefore two patterns have been chosen from them. Secondly the design should be studied. It was important to understand whether two wide strips can make people satisfied or they will get the same score as the worst patterns?

Therefore in the second test the following patterns have been selected. (Table 3.4.34)

- The selected patterns of the first test in different ratio(50mm:100 mm)
- The selected pattern of the first test in the same ratio (100mm:100mm)
- 200:100mm (wider pattern of ratio of 2:1)
- 100:200mm (wider pattern of 1:2)
one of the proposed designs regarding the ratio of 1:2, since the scale model represents height of 3 meter the big strips have been allocated on the top near ceiling. The office room in my design has 4 meter height.

The result of scale model can be seen on diagrams 3.4.3.5 to 3.4.3.7. As it can be seen the proposed design and pattern of 100:200mm is really acceptable regarding the view and glare. The answer of people and their explanation can be summarized as following.

- **Design:** most people have found it really good regarding the view to the outside. The distance of the strips and size of the strips do not limit the view to the outside regarding people's idea. The usage of big blue (translucent/electrochromic part) on the bottom and top parts of the window makes them feel safe as if there is a fence. Even in some of their answers these parts make them feel as if there is less glare comparing to the same sample.

- **100:200mm (blue/transparent):** this pattern is one of the best patterns regarding the view and glare. Most of people have found it really satisfying.

- **100mm, 100mm:** more usage of strips and the same size of transparent and blue (translucent/electrochromic) part is the main reason of dissatisfaction from this pattern. Most of the people found it really confusing.

- **200mm, 100mm (blue/transparent):** in the previous test, there was a doubt about accepting this pattern, in this test most of the people have not been satisfied with the view and even the result of glare has not been acceptable.
- 50mm, 100mm (blue/transparent): while in previous test this pattern was really acceptable according to the view and glare, it has been rejected in the second test in compare with the other selected and proposed patterns, this has not been good. The reason can be the poor view (from inside to the outside) comparing to the other patterns.

### Second test of mock up

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Ratio of 1:2 (33%)</th>
<th>Ratio of 1:1 (50%)</th>
<th>Ratio of 2:1 (67%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pattern1</td>
<td>25mm/25mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pattern2</td>
<td>50mm/100mm</td>
<td>50mm/50mm</td>
<td>100mm/50mm</td>
</tr>
<tr>
<td>Pattern3</td>
<td>100/200mm</td>
<td>100mm/100mm</td>
<td>200/100mm</td>
</tr>
<tr>
<td>Pattern4</td>
<td>200mm/200mm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ratio</th>
<th>0%</th>
<th>20%</th>
<th>40%</th>
<th>60%</th>
<th>80%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>50,100mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200,100mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100,100mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100,200mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.4.3.4) Table for the second test (scale of model was 1/5)

Table 3.4.3.5) People's idea about glare of the whole room
### Section 3

#### Glare for the window

Table 3.4.3.6) People’s idea about glare window

<table>
<thead>
<tr>
<th>Design</th>
<th>Barely Preceptible</th>
<th>Preceptible</th>
<th>Uncomfortable</th>
</tr>
</thead>
<tbody>
<tr>
<td>50,100mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200,100mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100,100mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100,200mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50,100mm</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### View to the outside

Table 3.4.3.7) People’s idea about view to the outside

<table>
<thead>
<tr>
<th>Design</th>
<th>Satisfied</th>
<th>Fairly Satisfied</th>
<th>Dissatisfied</th>
</tr>
</thead>
<tbody>
<tr>
<td>50,100mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200,100mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100,100mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100,200mm</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Adaptable façade with electrochromic material
3.4.4 Conclusion

The results of the first and second test have clarified the best pattern regarding the glare and outside view. While this result of scale model does not match the results concluded from the computer modeling, a new design is created which can satisfy both requirements.

The result of second test shows one of the proposed designs has been acceptable and also one pattern is acceptable as well. Therefore the design with narrow strips (fig 3.4.4.1) and the new design (fig 3.4.4.2) with wider strips can be used for façade.

As it is clear there are a lot of limitations in the test. Without these limitations the result can be more scientific and reliable. Therefore some recommendation for further research can be titled as following.

1. It would be more scientific if a larger number of viewers could see the patterns and fill the questions (the preferable number of viewer is 100)
2. To be sure that the result is independent of the outside view, the tests should be done with different views.
3. To have scientific answer about the view and glare, three different climates (overcast sky, mix sky, clear sky) should be questioned.
4. The real scale (1 to 1) can be more helpful for the viewer to answer the questions more effectively.
Section 4
Final Design

Adaptable façade with electrochromic material
4.1 Introduction

This chapter aims to summarize the conclusions from all previous chapters in a way that it can be used for the design of different façades with this material. Afterwards, other options and further research has been suggested. (Fig 4.1)

4.2 Summary

In this research, finding an adaptable façade for different activities (auditorium, staff room) is the aim. Based on a literature survey on different available smart material, electrochromic material has been selected. This material can change its color and in this way can control the amount of daylight penetrating inside. Since this material does not limit the view to the outside, works with 8dc voltage and can be controlled by user, it can meet the requirements of the design. The price of this material is 200 euro per square meter. The thickness of the glass with electrochromic layer in between can be 5mm or higher. This smart material comes in any color.

To construct an adaptable façade out of this material three steps have been taken. Firstly all of the standard parameters of the light distribution for two different sky conditions (clear sky and overcast sky) have been shown. Then four different states for the transparency of the glass wall have been assumed.
The computer modeling has been done for two different sky conditions. The ratio of the width of the transparent layers to the overall thickness which results in the best lighting condition for the office has been found. At the end, in the scale model, the best ratio and pattern regarding the view to the outside and glare had been found. The whole result of this research can be summarized as below.

**Conclusion from computer modeling**

In computer modeling firstly it has been tried to find the time when the maximum daylight penetrates in each orientation and then based on that time other computer simulations have been done.

1) Maximum daylight in East orientation in the Netherlands happens at 10:00 in 22\textsuperscript{nd} June.

2) Maximum daylight in West orientation in the Netherlands happens at 16:00 in 22\textsuperscript{nd} June.

3) Maximum daylight in north and south orientation in the Netherlands happens at 12:40 in 22\textsuperscript{nd} June.
4) All results should be checked for working plan which is in 75 cm from the floor. That is because the light distribution in the working plane is different from the floor.

5) For every ratio, the light distribution is the same in all patterns.

6) Usage of 65% of blue material (translucent/overall material) in glass can provide an acceptable light distribution in minimum condition.

7) Usage of 75% of blue (electrochromic material/overall) can provide an acceptable day light distribution in clear sky (when the room can receive the maximum illuminance).

Conclusion from scale model

1) In order to have an acceptable outside view, the width of the blue strip is preferred to be 100mm.

2) Any blue strip wider than 100 mm makes it more inconvenient for the people to see the outside.
3) More blue strips make the inside viewers more confused and will not let them see the outside.

4) The smaller distance between blue strips makes people feel as if there is more glare.

5) In order to have an acceptable outside view, the width of transparent part is preferred to be 200mm.

6) Further increase in the distance between blue strips (translucent strip/electrochromic material), increases the glare and decrease the uniformity of the façade.

7) Addition of wide blue strips (translucent/ electrochromic) to the upper and lower part of the glass window, reduces the inside glare.

As it has been mentioned before there are four different states for glass façade. These four states can provide comfortable space for staff room and auditorium. The first state can happen in the time when the sky is grey. Therefore the whole façade (glass wall) can be completely transparent. And office room can receive all the natural light from the sky. The next state can happen in the overcast sky when there is no direct light on the sky. In this case, the transparent façade will
Adaptable façade with electrochromic material provide a space which is too bright. However the designed facade, with selected pattern and 65% of the electrochromic material, can provide comfortable space inside the building. The third state happens when there is direct light on the sky (mostly in summer) and 75% of electrochromic material can help in providing a comfortable space. The last state will happen when the space is going to be used as an auditorium. In this situation the glass wall which is completely covered with electrochromic material can control the amount of light penetrating inside the room and provide comfortable space for presentation room (auditorium)
4.3 Different design options

The result of this research can help to design different patterns or understand the problems of different façades regarding the view and glare. At first two designs, which are similar to the last design (in terms of pattern and ratio), have been shown. Then final design has been explained at the end another example has been discussed to show how this result can be used. All design has been done in one building. This building has three floors and each floor is 4 meter high. It has been assumed that each floor has been made of three façades of office room.

Suggested design based on the results of the research

The first option: this design (Figure 4.3.1) is based on concluded percentage of transparent to blue (translucent/electrochromic) of computer modeling as well as the result of the scale model. Therefore it can be more acceptable regarding the view to the outside and glare. Of course in this design the frequency of the waves in one line can affect the view to the outside and fewer waves might be more acceptable as people feel less distraction in their view to the outside.
The second option: this design (Fig 4.3.2) gives another pattern based on the results of the scale model and computer modeling. In this pattern the length of the horizontal strips are different and the length of the line can change the design of the facade. While the ends and lengths of the strips will affect the outside view, simpler patterns are more acceptable. These patterns should be controlled in a way that the strips are spread in all places and not only in the middle of the facade.

Final design
To apply these conclusions in architectural design, many squares with length of 10 cm by 10 cm have been used. This square will make approximately the same pattern as strips but there will not be a sharp border between electrochromic and blue strips. Using this method, we can create QR codes in particular parts of the façade like those some areas in which outside view is not as important as the other areas.

A QR Code is a specific matrix barcode (or two-dimensional code), readable by dedicated QR Barcode reader and camera phones. The code consists of black modules arranged in a square pattern on a white background. The information encoded can be text, URL or other data. The square can be any color and the QR code can store different information so it acts as billboard. In our architectural design the name of the famous architects, famous buildings in architectural history, important motto of famous architects and URL of faulty of

Adaptable façade with electrochromic material
architecture; have been stored in QR code in different façades and different buildings.

The other design

The first facade: In this facade (Fig 4.3.3) 65% of each window is covered by electrochromic material and it has been made of circles with different diameters. The diameter of the biggest circle is twice bigger than the suggested width of the transparent strips in the scale model (about 400cm in this design). According to the results of the scale model, the view to the outside in this design might not be good for the inside viewer. In the questionnaire of scale model most of the people did not like complicated patterns or more than one pattern. It seemed to expose too much information to their eyes and really distractive. Therefore it might not be acceptable because of the poor outside view. Based on the result from the questionnaire, glare emerges when the width of the transparent part goes far above or below 200 mm. In this design the variation in the size of the circles are too much and this might cause glare. That is because the dimensions of the circles are much higher or lower than the suggested distances between the blue (translucent/electrochromic) strips. To provide better pattern, the usage of limited dimension of circle is recommended. In this way the size of the circles should be such that the outside view is optimized and the glare is minimized.
**The second facade:** this façade (Fig 4.3.4) has been made of a lot of small windows. They can randomly be blue (translucent/electrochromic) or transparent. 65% of the wall glass has been covered by electrochromic material. This design can provide a good view but it can not prevent discomfort glare. Since each window can be transparent or blue (translucent/electrochromic), the glare might happen for the whole room and people sitting in front of windows. There might be one solution to decrease the glare. In this solution each user can control some of the windows which are located in its view or near its table. Therefore user can turn on or off the window near his table to prevent discomfort glare but glare for the whole room seems to be inevitable.

**The third facade:** in this façade (Fig 4.3.5), based on the result of computer modeling, 65% of windows have been covered by electrochromic material. Based on the results of the questionnaire about the view, complicated patterns might block the outside view because it can be confusing for inside viewer when they want to see the outside. Since the transparent part is really wide, it might cause glare. This pattern might satisfy people’s requirement for glare and view if the lines are less randomly oriented and the distance between the transparent parts becomes smaller.
4.4 Usage in the design

4.4.1 Requirement for design

To make adaptable façade with electrochromic material the following are requirements:

1. Electrochromic material: This material will be installed as an intermediate layer between two layers of glass and works with dc voltage. It will change its color and in this way the amount of natural light penetrating inside will change.

2. Curtain wall: A curtain wall is a building façade that does not carry any dead load from the building other than its own weight or one that transfers the horizontal loads (wind loads) which might incidentally be applied on it. These loads are transferred to the main building structure through connections at floors or columns of the building. A curtain wall is designed to resist air and water infiltration, wind forces acting on the building, seismic forces (usually only those imposed by the inertia of the curtain wall), and its own dead load forces. Curtain walls are typically designed with extruded aluminum layers, although the first curtain walls were made of steel. The aluminum frame is typically infilled with glass, which provides an architecturally pleasing building, as well as benefits such as day lighting.[30,31,33]
3. DC power supply: this electrochromic material will use Direct Electric current (DC). The switches for electrochromic material can be installed on the curtain wall or the interior wall or on the tables. The switching can be for the whole building or individually for each office space.

To make such a façade the following steps should be taken.
1. Installation of the main structure of the curtain wall and connections of curtain wall to the columns or floors at the same time.
2. Embedding the required wiring in the structure to conduct the DC current to the EC material.
3. Installation of horizontal frame in between.
4. Installation of the double glazing glass windows (which has the layer of electrochromic material) to the frames.
5. The last step is to connect all different elements of this circuit, i.e. electrochromic material, the embedded wirings in the curtain facade, the DC power supply and the switch.

In the following parts some considerations about curtain façade, electrochromic material and heating and cooling systems of this building has been explained.

4.4.1.1 Electrochromic material in facade

As it has been mentioned (in material part), the Ec electrochromic material can be added as a layer to the glass and one embedded wire in the hinges or in
Adaptable façade with electrochromic material frame can help controlling the state of the window. Therefore the technical details of dabble glazing window is not that much different from dabble glazing with electrochromic material. Electrochromic material, which is on the 2nd layer of double glazing window, can be connected to low dc voltage by one wire. This wire can be embedded in the frame or the hinge of the window. Since there are two layers of conductive material in the electrochromic layer, the electrical current will be spread on this layer and change the color of the glass. (Fig 4.4.1) The durability of electrochromic material is about 15-20 years.

4.4.1.2 Curtain wall

In architectonic design curtain wall for façade has been chosen. Usage of this structure can help us make adaptable façade with glass. The curtain wall can have operable or fixed windows.

Maintenance and repair of curtain wall

Curtain walls and perimeter sealants require maintenance to maximize service life. Perimeter sealants, properly designed and installed, have a typical service life of 10 to 15 years. Removal and replacement of perimeter sealants require meticulous surface preparation and proper detailing. [30,31,32] Aluminum frames are generally painted or anodized. Factory applied fluoropolymer thermoset coatings have good resistance to environmental degradation and require only periodic cleaning. Recoating with an air-dry
Adaptable façade with electrochromic material is possible but requires special surface preparation and is not as durable as the baked-on original coating. [30,31,32]

Exposed glazing seals and gaskets require inspection and maintenance to minimize water penetration, and to limit exposure of frame seals and insulating glass seals to wetting. [30,31,32]

**Windows and vents of curtain wall**

Most curtain wall glazing is fixed (fig 4.4.2), meaning there is no access to the exterior of the building except through doors. However, windows or vents can be glazed into the curtain wall system as well, to provide required ventilation or operable windows. Nearly any window type can be made to fit into a curtain wall system (fig 4.4.3, 4.4.4). [30,31,32]

**Fire safety of curtain wall**

Fire stopping at the "perimeter slab edge", which is a gap between the floor and the back pan of the curtain wall, is essential to slow the passage of fire and combustion gases between floors. Spandrel areas must have non-combustible insulation at the interior face of the curtain wall. Some building codes require the mullion to be wrapped in heat-retarding insulation near the ceiling to prevent the Mullions from melting and spreading the fire to the floor above. It is important to note that the fire stop at the perimeter slab edge is considered a continuation of the fire-resistance rating of the floor slab. The curtain wall itself, however, is not ordinarily required to have a rating. This causes a quandary.
as Compartmentalization is typically based upon closed compartments to avoid fire and smoke migrations beyond each engaged compartment. A curtain wall by its nature prevents the completion of the compartment (or envelope). The use of fire sprinklers has been shown to mitigate this matter. Therefore for the fire safety both the active fire protection (sprinklers) and the passive fire protection (fireproofing) are helpful [30, 31, 32]

4.4.1.3 Heating and cooling system
Since curtain wall for façade as been chosen heating and cooling system of façade should be allocated in floors or ducts. There are different kinds of heating and cooling system which can be allocated in floor or in ceiling. These heating and cooling systems can be heating and cooling pipes (fig 4.4.5) or air balanced ventilation system. Air Balanced ventilation systems can provide a significant level of indoor comfort. This ventilation can combine fresh air treatment and air conditioning. It is possible to have all combination systems on the roof of the last floor. Therefore all fresh air can be received from the top floor of the building. (fig 4.4.6) All ventilation can be located on the floors and the connections of ventilations can be done through ducts which are inside the building and not on the façade. [30,31,32]
4.4.2 The design detail

In this part the technical drawing of my design has been shown. As it has been mentioned before electrochromic material will not change the technical details of façade and just one wire which has been embedded in the frame can provide electric current. On and off switches can be installed near the façade and on the structure of curtain façade or on separation walls. In my design the switches have been installed on the columns next to the curtain wall and each can control 8 meter intervals. In this part two kinds of details have been shown, one with a fixed frame and one with operable windows. Since I wanted to have the glass on the outside and frame inside the building, gluing method for Curtain façade has been used.
Adaptable façade with electrochromic material
Adaptable façade with electrochromic material

4.4.10 Details of curtain façade with fixed window

4.4.11 Curtain wall with gluing system
Adaptable façade with electrochromic material
4.5 Further research

Based on the results of this research, it might be possible to figure out the problems of some patterns which have been designed by this material. It is recommended to study each patterns individually, especially if any of them are going to be used. In this part, the recommended researches for the previously discussed façades have been outlined.

**First option**

In designs like fig 4.5.1
1) The effect of the radius of the waves on the view and glare should be studied.
2) The effect of the number of the waves on the view and glare should be studied. However, from the results of this research, it can be concluded that less curve and simple shapes are better.

**Second options**

In designs like fig 4.5.2, the effect of the following should be studied on glare and view:
1) The number of strips which are not continuously drawn from left to right
2) The best place for the discontinuous strips. For example, upper, middle or bottom of the windows.
First design
In designs like fig 4.5.3 the effect of the following should be studied on the glare and view:
1) The number of the circles
2) The minimum and maximum diameter of the circles
3) The distribution of the diameters between the minimum and maximum size
4) The location of the circles with different sizes

Second design
In designs like fig 4.5.4:
1) The optimum size of window blocks regarding façade, view, glare, technical design and cost should be found
2) Different ways to make random design should be studied.
3) Since changing the state of one or two of the windows near user table can decrease the effect of glare for people sitting near the window, the whole facade should adapt itself in such a way that the overall ratio of translucent material does not change. This requires further study.

Third design
In designs like fig 4.5.5:
1) The effect of random lines on view and glare should be studied
2) Different direction of random patterns should be studied
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Adaptable façade with electrochromic material

Fig 1: Maximum natural light in east orientation of standard glass wall

East at 08:00 on June
East at 09:00 on June
East at 10:00 on June
East at 11:00 on June
East at 12:00 on June

Fig 2: Maximum natural light in west orientation of standard glass wall

West at 15:00 on June
West at 16:00 on June
West at 17:00 on June
West at 18:00 on June
West at 19:00 on June
**Technical Information**

Any shape (made to fit)
Colors — 7 shades of blue

**Dimensions:**
- Height from 0.3 to 2.5 m
- Width from 0.9 to 4.0 m

**Timing:**
- Dimming from 2 to 10 min
- Cycling from 6 to 15 min

**Depends on dimensions:**
- Weight 20 kg/m²
- Thickness 8.5–9.0 mm
- Working voltage 1.5 – 2.5 V
- Energy consumption — 0.3 — 2.0 W/m²
- Working temperature range — 40 – 60°C
- U-values (IGU) — 1.6
- Sound Transmission — 34 dB

**Optical Features**

<table>
<thead>
<tr>
<th>Color — STEEL BLUE</th>
<th>Off</th>
<th>On</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Transmittance</td>
<td>0.81</td>
<td>0.19</td>
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<tr>
<td>Light Reflectance</td>
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<td>0.05</td>
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<tr>
<td>Light Absorbance</td>
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<td>0.25</td>
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<tr>
<td>Solar Radiant Heat — Direct Transmittance</td>
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<td>Solar Radiant Heat — Reflection</td>
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<tr>
<td>Shading Coefficient</td>
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<td>0.53</td>
</tr>
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Adaptable façade with electrochromic material

Fig 3: Technical Details of electrochromic[22]
Appendix

Adaptable façade with electrochromic material

Fig 4: Daylight distribution of pattern of 25/25mm
Fig 5: Daylight distribution of pattern of 50/50mm
Fig 6: Daylight distribution of pattern of 100/100mm

Fig 7: Daylight distribution of pattern of 200/200mm
Fig 8: Daylight distribution of pattern of 50/100mm
Fig 9: Daylight distribution of pattern of 100/50mm
Adaptable façade with electrochromic material
Adaptable façade with electrochromic material

Fig 14: View to the outside of pattern of 25/25mm
Fig 15: View to the outside of pattern of 50/50mm
Fig 16: View to the outside of pattern of 100/100mm
Fig 17: View to the outside of pattern of 200/200mm
Fig 18: View to the outside of pattern of 100/200mm
Fig 19: View to the outside of pattern of 100/50mm
Adaptable façade with electrochromic material

Fig 20: View to the outside of pattern of 100/200mm
Fig 21: View to the outside of pattern of 100/100mm
Fig 22: View to the outside of pattern of 200/100mm
Fig 23: View to the outside of pattern of 100/200mm
Fig 24: View to the outside of Design
Question for scale model

Dear student,

This experiment aims to understand how width of strip and ratio of them has effect on discomfort glare and outside view. The scale model represents an office room. Assume that you are working on with computer on one of the chairs inside the model. Five tests will be done with five different facades.

This questionnaire will ask you about effect of different width of colorful strip on your view to the outside and discomfort glare. It is structured in 7 parts. The first part will ask about personal information and has to be filled out only once. Parts 2, 3, 4, 5, 6 and 7 are respectively related to different patterns, general impression of the outside view and glare regarding to width of strip. They should be filled out for each facade. Please tick the appropriate boxes; do not circle the words. You just have to answer freely based on your first impression; there is no right or wrong answers.

Thank you very much for your cooperation,
Appendix

Personal information

1) Name:

2) Age:

3) Gender:

4) Nationality:

5) Do you wear glasses?
   Yes ☐ No ☐

6) Do you have contact lenses?
   Yes ☐ No ☐

7) Are your eyes sensitive to intense light?
   Yes ☐ No ☐

8) Do you use sunglasses in sunny days?
   Yes ☐ No ☐

9) Do you have any eyes problem?
   Yes ☐ No ☐

10) If yes what kinds of problem do you have?
Appendix

First sample (different patterns)

11a) Would you like to work in this space?
   Yes ☐  No ☐

12a) How would you evaluate the degree of discomfort glare\(^1\) in the entire space?
   Not perceptible ☐ Barely perceptible ☐ Perceptible ☐ Uncomfortable ☐ Intolerable ☐

13a) How would you evaluate the glare, if you sit on the chair in front of window?
   Not perceptible ☐ Barely perceptible ☐ Perceptible ☐ Uncomfortable ☐ Intolerable ☐

14a) How would you evaluate the brightness level of window?
   Not perceptible ☐ Barely perceptible ☐ Perceptible ☐ Uncomfortable ☐ Intolerable ☐

15a) How would you assess the view of outside according to strips?
   Very satisfied ☐ Satisfied ☐ Fairy satisfied ☐ Dissatisfied ☐ Very ☐ Dissatisfied

16a) Is the view comfortable?
   Yes ☐  No ☐

17a) How wide would you like the size of strip to be regarding to the outside view?
   Much wider ☐ wider ☐ acceptable ☐ narrow ☐ much narrower ☐

18a) Do like this pattern regarding view and glare? why?

---

\(^1\) Glare is difficulty seeing in the presence of bright light