Innovative display technique for the building envelope

A research on electrowetting as a new glazing method
fig.1. Top left: inventarisation of electrowetting potentials
fig.2. Top right: surface tensions of a droplet on a surface
fig.3. Bottom left: expected curve of the transparency of a façade cell by the applied voltage
fig.4. Bottom right: personal preferences made possible by an electronic façade
This thesis is about electrowetting. Electrowetting is an advanced display technique that is going to take a part in the display competition against LCD screens and LED displays. Display techniques are becoming very important for the building envelope. The desire to have a responsive or adaptive building skin has never been as serious as the coming decade. In 2020 the new policy with only energy neutral buildings will take effect. The consequence is a growing interest in building skins that are capable of fulfilling multiple comfort levels. The degree of complexity is desired to not be too much increased that it is almost too difficult to build. Next to that, its energy performance and durability are of key essence and co-review the qualities of the building skin. Electrowetting could be such new technique as an answer for the responsive building envelope, but its feasibility has to be evaluated first. The paper will start with the research question and a brief history of the development of the smart building skins, where after the electrowetting techniques and its properties are amplified. Chapter three evaluates the responsive building skin and the role of display techniques in this. Chapter four shows the potential applications of electrowetting with a preference for usage in the building skin, as was reviewed in the previous chapters. A performance simulation gives inside in the energy usage of one of the potential solutions for electrowetting. This is set out in chapter five. At last some design questions are still unanswered, i.e. the architectural benefits versus the increased comfort levels; this can be viewed in the last chapter before the conclusions. The conclusions finally discuss if electrowetting is feasible for the building envelope. The thesis is also providing some fundamental theories and basic formulas from different research fields, to not let this distract from the main story, those texts are cursive and always on the left page.
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1. Display for the Façade

Assuming that you do not have any knowledge about the electrowetting technique at the start of this paper, you can imagine having a building skin made up of displays. Electrowetting is an advancing display technique and, in some ways, comparable with LCD screens or LED screens. When implemented in a façade, this is often called a media façade, for entertainment, advertising, culture or any other type of expressive image in the urban context. The communicating function of the building skin seems to become even more important than its other functions; being the interface between outside and inside. To clarify this, the big disadvantage of media façades is its closed structure. Also, a media façade is questionable on the term ‘adaptive’ or ‘responsive’ façade, because of the lack of some other building skin functions too. A façade based on the electrowetting technique has the potential to be an adaptive media façade. Its potential reaches even further, but before we go deeper into its techniques, an introduction to the subject and a short explanation of electrowetting is appropriate.

1.1 A history lesson

The potentials of electrowetting are just recently noticed, only a few decades ago, but the development of the building envelope has a much longer history of setbacks, new innovations and new developments. So what can a rookie as electrowetting do for the building envelope? That is a question that can only be answered when you realize how quickly the façade industry is evolving. Furthermore, there is also the fact that the original purpose of how a façade should function is about to change, as you will read below.

1.1.1 Windows

It is becoming more common that every room that is used for some sort of activity should have windows to let daylight in, because humans need daylight to stay healthy. Without it, we cannot produce vitamin D, which eventually will lead to sickness and inter growths. “Lack of light might negatively influence alertness, performance, sleep quality and the degree of discomfort and well-being” (Begemann, van den Beld, & Tenner, 1996), but also do “Windows have a positive impact on performance, productivity and health, as long as they do not cause glare or thermal discomfort or a loss of privacy” (Hellinga, 2013). Windows can have both a positive and negative impact on our daily performance.

The rooms we work or live in are just not always suitable for the tasks we want to do. This is because of excessive light, like glare and reflections or a lack of light. Therefore it will always be a challenge for architects to design with light. But
then, what is happening at the moment is that the decision of an architect on window size is primarily based on his design choices, which often means bigger is better. This is driven by a healthy economy and everyone’s desire to have it larger and brighter, by following the example of the American façade architecture (Renckens, 1996). Technology has developed from standard window openings to total glass façades. As we can see from streetscapes, glass façades in the 21st century are still very popular, despite climatological problems as ventilation and the light-related problems. “Nowadays, decisions on window size and materialization are increasingly driven by demands regarding the access of daylight on the one hand and energy demands and available budget on the other hand. By taking all this into account, it is easy to forget the preferences of the occupants of the building” (Hellinga, 2013), while in fact the users have to deal daily with the light entering through the windows designed.

1.1.2 Preferences of humans

The Dutch NEN 2057 (2011) describes that a minimum amount of at least 2 hours daylight penetration per day during the summer period, from the 1st of March until the 1st of September should be sufficient, which is about the standard in Europe too. Hellinga (2013) compared the legislation on sunlight in Europe, it prescribes a minimum number of uninterrupted sun hours, which varies between the different countries from 1 to 2 hours during the summer and/or winter months. According to some recent research on the subject, this amount is way too low. Cited from Hellinga (2013) ‘Aries (2005) and Hubalek (2010) found that exposure to higher vertical illuminances during the day than the usual levels of today, namely 1000 to 2000 lux instead of 200 to 500 lux, has a positive influence on sleep quality during the night’. The new knowledge that the human eye is very capable of adapting to a large range of light situations means that the current approach to aim for a constant light level to determine the needed illuminances in a room has to be changed. This was already described by Begemann et al. (1996), who shows that despite individual preferences, the preferred artificial lighting levels are much higher than values given in present standards. A better approach would be by three types of measurement, from more important to less: the vertical illuminance at the eye, the spectral distribution of the lighting and the color of light (Hellinga, 2013). It is reasonable to think that there is no maximum amount for light penetration for most indoor activities; on the other hand computer work is one that does. Your screen is not visible if light intensities on it are higher than the light it emits.

1.1.3 Glass façades

Simultaneous to the growing awareness of the influence of daylight on health and productivity, the glass façade was being redeveloped (again). In this case it is about smart materials for the building envelope. The building envelope encountered a fast follow up of incorporation of new materials and systems that each solve and create their own problems. “No other group in the architecture field has embraced smart materials as wholeheartedly as have the designers and engineers responsible for façades and enclosure systems” (Addington & Schodek, 2005). The fast development of the building envelope, has led to some remarkable façade types. To highlight this, we use the example of the climate façade of the late 70s; it is a fully enclosed system with the highest possible insulation, but still beholding the view and daylight penetration. In this time the importance of thermal stability got noticed, caused by the high thermal fluctuations of glass façades. The development lead to "offices that are fully closed reflective strongholds" (Renckens, 1996), but “it was only further exacerbating the thermal and optical swings of the façade. A host of new technologies were incorporated into the façade or enclosed systems, to dampen the thermal swings” (Addington & Schodek, 2005). The search for new techniques went on and typically called smart materials is now being broadly explored.

1.1.4 Smart materials

"Initially, when architects began to think about smart windows in the late 1980s, their desire was to create a glazing material that responded directly to environmental changes” (Addington & Schodek, 2005). Materials like thermo-chromics and photo-chromics were developed into glass coatings, which meant great improvements on hot days, but a typical problem occurred in temperate climates during the winter. The systems were activated (by sunlight) to reduce glare, but the blockage of light also caused a higher heating demand. Later on, the idea found a more stable ground when people realized electrically activated systems were a better solution. Electrical activated systems can be turned on by hand and by environmental changes. The research in electrically activated systems is well developed in different fields, but little is known when it comes to building envelopes. Experts in those other fields tend to go smaller and smaller, far beyond the visibility levels for the eye or microscope and do not oversee the possibilities of their techniques in building technology.

1.1.5 Risks and challenges

As history has taught us, the incorporation of smart materials in the building envelope has great potentials and the dream of the polyvalent wall of Davies and Rogers (1981) is becoming more and more a reality. Only the risk is that we “tend toward treating the smart material as a replacement technology that fits within normative design practice” (Addington & Schodek, 2005) and skip the design part that is necessary for each new material. For example, using adhesion glue instead of bolts or screws to connect two structural glass panes is a different or even better way. “It may be argued that concentrating exclusively on improving the glazing is a dead-end approach: if one tries to incorporate all functions in the glass, problems still remain in the design of a particular building component or the choice of the best building material” (Renckens, 1996).
1.1.6 Toxicity and (bio-)degradability
Many of the proposed layers from the polyvalent wall were initially toxic or non-degradable. In the time only a few realised and cared about the effects it has on our environment. The sustainability of façades is still a difficult topic. On the one hand there is "a danger that surfaces invested with functionally improved properties may no longer age naturally" (Leydecker, 2008), but on the other hand, the coatings used on those surfaces can create more freedom in design for an architect. If the degradability of a smart material or layer of the polyvalent wall is not an option anymore, let us at least develop a system with a recyclable process.

1.2 Problem statements

From the history of glass façades and smart materials it is possible to conclude with five problem statements. The following list presents these problems:

- Today’s buildings do not meet the needs of the user;
- Today’s buildings will no longer meet the norms;
- Smart glasses are not yet user friendly;
- Smart materials can be toxic and should be more sustainable;
- Smart materials are only reacting on certain environmental impulses.

The first two statements relate to windows and façades in general, the last three are about the setbacks of integrating smart materials in the building envelope along the way. Among the points about user friendliness, there can be emphasized that at this point there is still no (smart) façade in use that can be turned on and off gradually by both the user and the environment. This year however, everything points in the direction of electrochromic glass, because the technique itself is already capable of doing so. Of course there are some flaws to it too; nevertheless it can be pointed out as a milestone in the development of smart materials. One of those flaws is its lack of adapting to the wishes of multiple people simultaneously. It still is a one-size-fits-all solution, whereas with further research this problem might be tackled. Another flaw that many smart materials or adaptive systems (for façades this is the same thing) still have is less view when shading is needed, even electrochromic glass. Those problem statements as mentioned in the previous paragraph has led to a search for another smart material, derived from the display industry: Electrowetting.

1.3 Research description

1.3.1 Electrowetting
On a micro-scale level, electrowetting is the ability of changing the contact angle of a droplet on a surface by applying a voltage. The hydrophobicity of the droplet on the surface can change the shape of the droplet and even let it move. When light hits a droplet of water, the light would partially reflect on its surface, but the droplet will also transmit light. If the shape of the droplet’ surface changes, the direction of the light rays will do too. In theory it is possible to change the direction and intensity of incoming light into a building and create optimal light surroundings for every task you are doing.
1.3.2 Research question:
The research question on this subject is as follows:

What are possible applications of electrowetting for the building envelope and could those applications be feasible with regard to user comfort, energy performances and architectural interventions?

The following sub-questions, derived from the main question will be used to answer it.

- What is electrowetting?
- What are the properties and limitations of electrowetting intended as a façade system?
- What are the possible applications of electrowetting for the building envelope?
- What are the criteria to evaluate electrowetting for the building envelope?
- Is electrowetting feasible for the façade?
- How can electrowetting be integrated in the façade, with respect to the building aesthetics and comfort?

1.3.3 Goal
The purpose of the research project is to find out whether electrowetting is feasible as a façade system or not. At the moment, nobody has researched this before. The focus will primarily be on increasing the light quality and visual comfort within buildings, with reducing the chances on overheating and glare, and therefore potentially reduce the energy usage also. The research on the application of electrowetting for the façade is not finding another one-size-fits-all solution. Embracing the qualities of light and view should be personal adjustable. With the use of an electrically activated system it should be possible to regulate and operate it automatically by environmental impulses and by hand for many different users at the same time.

1.3.4 Relevance
Imagine being in a building of a fully glazed façade in which it is possible to turn a shading device on automatically, with changeable preferences on your tablet on demand, with only a hand gesture; it would block the sun when it is bothering you, although the view to outside is not decreased; a façade that is able to lighten up darker spaces in the building or provides extra light when you are doing very meticulous work; a façade that makes objects visible with less artificial light or improves your visionary when the light intensity contrasts are very high; a façade that could be used as an electronic drawing board with the surroundings as a background layer or as a billboard that can show your company name to the world. A façade that increases productivity by providing a better work space, but also reducing the energy demand by a lower heating and cooling load and therefore will have less impact on the environment.

The necessity of such type of façades (commonly called smart glazings) is increasing, although the expenses are still high. The future is bringing new demands to our traditional shadings which will eventually be integrated with other applications that makes our lives easier, faster and healthier. It is just a matter of time before the electrowetting technique to be part of this roller coaster that is called the innovative building envelope.

1.4 Method description
The following method as shown in figure 7 for this feasibility study is applied. The research can be split into three categories, the necessary input, the used method and the output results. The display techniques, the light regulating techniques and the electrowetting techniques. All together they form the basic knowledge that provides the information needed to develop a new façade system. For decades scientists and engineers from other fields have developed smart materials and their advanced technologies to produce mobile displays, but now is the time to pace this into architecture and design. “To herald a switch from catalogue materials to made-to-measure materials with a definable combination of properties is the aim to create a perfect modular system.” (Leydecker, 2008) This will require knowledge from experts of each discipline to provide the information needed to develop the appropriate design for each material/technique.

1.4.1 Input
The input consists the different types of display techniques that are available now, and the techniques which show potential in the future, but are still developed at the moment. Electrowetting is one from this last category. The light regulating techniques are an exploration of the demands and requirements for light in a façade according to its users. This is needed for the comparison in the simulation phase. The last two inputs that are needed for this research are the production process of electrowetting and a safety certificate at the chemistry lab of the TU Delft.

Side note: During the making of this thesis it turned out there was no need for a physical prototype to do the simulation studies and the safety certificate was not necessary anymore.

1.4.2 Method
1. Literature study; The literature study focuses on the basics of electrowetting and the potentials and applications of it in every field possible.
2. Define benchmarks; Criteria on which the electrowetting façade can be
3. Possible applications: All possible applications of an electrowetting façade are researched, varying for every part of a building, every type of building and every function.

4. Performance simulation: one of the possible applications. A feasibility study according to the energy potentials of this application is given.

5. Design: Further development of both types can lead to a design to use in that typical building, but in the end also as a universal solution.

6. Reflection: The results from the simulations and design are discussed and conclusions can be drawn about the feasibility of an electrowetting façade. Recommendations for further research will be explained.

1.4.3 Output

The first three steps of the method will lead to an understanding in the electrowetting techniques, a description of the competitive techniques for façade systems and a target definition. Step 4, the simulation will give an output of energy and light performances. The design step gives concept and façade drawings and with a reflection the reliability of the research is discussed.
2. Electrowetting

As mentioned earlier, electrowetting is capable of changing the shape of a droplet by an applied voltage. The form of the droplet changes by a change in surface tensions that influences the droplet. This is further explained in this chapter. How to activate it and other properties and limitations are also explained in this chapter. The way electrowetting can be seen in our daily lives is the next paragraph. This includes its biggest potential in relation to the building envelope: the electrowetting display. This chapter concludes with the most important issues of electrowetting for the building envelope, because it is a technique that is still in its infancy.

2.1 Basics of electrowetting

A droplet is in a spherical shape when it is not in contact with a solid. When this happens, the droplets surface tensions cause the droplet to change its shape to a more stable state. It always minimizes the free energy in the system. Figure 8a shows a droplet in this state. The solid surface the droplet is lying on can be made less hydrophobic by a voltage, as shown in figure 8b. In other words, the wettability of the solid substrate is changeable. The images are recreated from an experiment in the late 1800s by Lippmann. A translation of this experiment is given in the appendix of Mugele and Baret (2005). From the 19th century this technique was used as an electrometer with the usage of a liquid metal. Only recently the meeting of those two disciplines, electrostatics and interfacial chemistry has led to more remarkable applications. Without the changing of materials, but still having the possibility of reversible switching between a hydrophilic and hydrophobic state is a very interesting phenomenon.
Surface tensions

Every particle of a rain droplet exerts forces on one another, that way the droplet stays together and minimize changes in shape. Surface tension or surface energy is a tensile or contractile force. Water molecules in the droplet encounter cohesive forces with its neighbouring molecules. The fact that they attract each other is a result of the reduction in the energy state of the molecules. There are less attractive forces possible at the edges, since there are less water molecules and thereby the tension in this area is higher. Therefore, a liquid will always take the form with the smallest possible surface area. In space, their shape is therefore spherical. However, the rain droplet is surrounded by air, so the surface tension as just discussed is actually the surface tension between water and air. Once the droplet hits the ground, it is experiencing other surface tensions too, namely the surface tensions between the liquid and the ground and the solid and vapour. The surface tensions are in balance and can be expressed by the Young’s relation, given in N/m or \( \text{E/m}^2 \):

\[
\gamma_{LV} \cos \theta = \gamma_{SV} - \gamma_{SL}
\]

When applying a voltage the effect can be described with the Lippmann equation:

\[
\gamma_{LV} \cos \theta = \gamma_{SV} - \gamma_{SL} + \frac{1}{2} CU^2
\]

With,

- \( \gamma \) surface tensions
- \( LV, SV, SL \) the interfaces
- \( \theta \) contact angle
- \( C \) capacitance
- \( U \) applied voltage

Without an applied voltage, the \( \frac{1}{2} CU^2 \) part of the formula will be 0. The surface tensions are in the formula in equilibrium and have a corresponding droplet shape as shown in figure 8a. Adding an electro-static term to the equation will result in a change of the surface tensions according to the amount of voltage. One part of the formula is still not clarified, the \( C \) is the capacitance of the interface.

The intent of electrowetting is simple, the images show the experiment on a single droplet. It is an aqueous salt solution droplet on a hydrophobic surface. Below this insulating surface there is an electrode layer. By applying a voltage, the interface between the droplet and hydrophobic layer becomes charged. The shape of the droplet is not sufficient anymore, because the voltage influences the surface tensions, i.e. the droplet spreads. By reducing and eventually removing the voltage the droplet returns to its original state.
Scientist have been trying to switch between both states, the Cassie-Baxter state and the Wenzel state and a hydrophilic surface even more hydrophilic (MITK12Videos, 2012). Some sort of roughness, because no surface is completely smooth at a molecular level, you can assume the solid surface underneath is called the Cassie-Baxter state, also after its founder. Since every surface has some sort of roughness, air bubbles have a chance to decrease the stickiness of the droplet on the surface. In this state there are no air bubbles trapped underneath the droplet. If a liquid on the surface, the most hydrophilic surface possible is an ideal flat surface; this is also called the Wenzel state after its founder. In this state there are no air bubbles trapped underneath the droplet. If a liquid on the surface and roll off. There are two different reasons why a surface could be hydrophobic or hydrophilic. The first reason is all about surface chemistry and the second reason is the microscopic structure of the surface. Surface chemistry determines if a surface has a high or low surface energy state. A hydrophobic surface has a low energy state and hydrophilic surfaces have a high energy state. The interesting thing is that you can change the hydrophobicity of a surface with a voltage, in the next paragraph this is explained further. The surface roughness is the second reason what could determine the behaviour of a liquid on the surface. The most hydrophilic surface possible is an ideal flat surface; this is also called the Wenzel state after its founder. In this state there are no air bubbles trapped underneath the droplet. If a surface is more rough, air bubbles have a chance to decrease the stickiness of the droplet on the surface and therefore makes a surface more hydrophobic. A state in which the droplet is not fully touching the solid surface underneath is called the Cassie-Baxter state, also after its founder. Since every surface has some sort of roughness, because no surface is completely smooth at a molecular level, you can assume that the real surface area divided by the projected surface area is greater than 1. The image on the right shows this formula, it also shows that roughness makes a hydrophobic surface even more hydrophobic and a hydrophilic surface even more hydrophilic (MITK12Videos, 2012). Scientists have been trying to switch between both states, the Cassie-Baxter state and the Wenzel state. "In contrast to the morphological transition discussed in the previous section, the transition between the Cassie-Baxter state and the Wenzel state in was not reversible." (Mugele & Baret, 2005). Once there is air trapped underneath the droplet it was not possible to remove this. For electrowetting displays, there is no air part of the system, also the oil and water are staying cohesive to itself and are never mixing.

**Hydrophobicity of the surface**

If the equilibrium contact angle is greater than 90 degrees, the surface is hydrophobic and greater than 150 degrees it is being defined as super-hydrophobic. On the other hand, if the contact angle is less than 90 degrees, the surface is hydrophilic. On a super-hydrophilic surface (contact angle is less than 5 degrees) like anti-fog coatings the droplet will immediately spread out and form a thin surface. Teflon sprays for water protecting clothes create a hydrophobic top layer and therefore water will form droplets on its surface and roll off. There are two different reasons why a surface could be hydrophobic or hydrophilic. The first reason is all about surface chemistry and the second reason is the microscopic structure of the surface. Surface chemistry determines if a surface has a high or low surface energy state. A hydrophobic surface has a low energy state and hydrophilic surfaces have a high energy state. The interesting thing is that you can change the hydrophobicity of a surface with a voltage, in the next paragraph this is explained further. The surface roughness is the second reason what could determine the behaviour of a liquid on the surface. The most hydrophilic surface possible is an ideal flat surface; this is also called the Wenzel state after its founder. In this state there are no air bubbles trapped underneath the droplet. If a surface is more rough, air bubbles have a chance to decrease the stickiness of the droplet on the surface and therefore makes a surface more hydrophobic. A state in which the droplet is not fully touching the solid surface underneath is called the Cassie-Baxter state, also after its founder. Since every surface has some sort of roughness, because no surface is completely smooth at a molecular level, you can assume that the real surface area divided by the projected surface area is greater than 1. The image on the right shows this formula, it also shows that roughness makes a hydrophobic surface even more hydrophobic and a hydrophilic surface even more hydrophilic (MITK12Videos, 2012).

Where $\varepsilon$, and $d$ are the dielectric constant and the thickness of the hydrophobic insulator, respectively. Plotting this graph gives a parabolic line. Only in practice the test results will not follow the parabolic fit as is visible in the experiment results of Mugele & Baret (2005) in the graph in figure 12. The reason for this is contact angle saturation, but why this happens is not certain, reasons could be charge trapping or air ionization or something else. The fact is, at a certain voltage level the droplet would not change its shape any further, which has long been a tedious problem within the electrowetting research field. The introduction of using an insulating layer between the droplet and the electronics has resulted in much better results. Improvements by making that same layer paper thin had consequently an influence on the applied voltage, which could be much lower now. Instead of voltages building up into the 100ths, only a voltage of 20 or less is now capable of doing the same thing.

![Figure 11. The different states a droplet can be in when lying on a surface: the Cassie-Baxter state and the Wenzel state](image1)

![Figure 12. Contact angle versus applied (RMS) voltage for a glycerol–salt (NaCl) water droplet (conductivity: 3 mS cm$^{-1}$; AC frequency: 10 kHz) with silicone oil as the ambient medium. Insulator: Teflon AF 1601 ($d = 5 \mu m$). Note that $\theta Y$ is almost 180$^\circ$ for this system. Filled (open) symbols increasing (decreasing) voltage. Solid line: parabolic fit according to the Lippmann equation](image2)
The bond number

In electrowetting, one is generically dealing with droplets of partially wetting liquids on planar solid substrates (see figure 1). In most applications of interest, the droplets are aqueous salt solutions with a typical size of the order of 1 mm or less. The ambient medium can be either air or another immiscible liquid, frequently an oil. Under these conditions, the Bond number,

$$B_0 = \sqrt{\frac{g \Delta \rho R^2}{\gamma_{lv}}}$$

which measures the strength of gravity with respect to surface tension, is smaller than unity. Therefore gravity is neglected throughout this thesis. In the absence of external electric fields, the behaviour of the droplets is then determined by surface tension alone. The free energy $F$ of a droplet is a functional of the droplet’s shape. Its value is given by the sum of the areas $A_i$ of the interfaces between three phases, the solid substrate $(s)$, the liquid droplet $(l)$, and the ambient phase: vapour $(v)$, weighted by the respective interfacial energies, the surface tensions. (Mugele & Baret, 2005)

2.2 Properties of the droplet

2.2.1 Velocity and droplet transport

The shape of the electro-optic curvature is dependent on several parameters, including the size and shape, and also the dimensions of the substrates. The parameters can be perfectly tuned to the desired response for any applied voltage. “All intermediate states on the curve are stable, due to the balance between electrostatic and interfacial forces” (Bhowmik, Li, & Bos, 2008, p. 526). Not only can droplets be changed in shape, a typical application is lab-on-a-chip, in which the technique is used to split and move liquids in certain directions. The velocity of those droplets is at least one order of magnitude faster than all other liquid transport technologies, as shown in the table in figure 14 (Bhowmik et al., 2008). The speed of the liquid transport of electrowetting is fast enough to show video-content.

2.2.2 Gravity

The droplets that were used for the experiments to test its sensibility to a voltage were a few millimetres in diameter. Typical applications of electrowetting use droplets with sizes in the order of 1 mm or less. The droplets are of an aqueous salt solution in a medium. The medium has to be of a substance that will not solute with the droplet; air or oil are frequently used substrates. Salt is the conductive factor; without salt, the droplet will serve as another insulating layer and no surface tension is interfered.
Of course the sizes of the droplet are of influence too, but are irrelevant for most applications. For example, electrowetting displays, which have a droplet in each pixel, have pixel sizes smaller than or around 200µm, and gravity is of very small influence. “... The surface tension forces are more than a 1000 times stronger than gravitational forces. As a result, the oil film is stable in all orientations” (Feenstra & Hayes, 2009). The bond number, which measures the strength of gravity with respect to surface tensions, is smaller than unity. More information about the bond number is explained on the previous spread.

2.2.3 Dye improvements

It is possible to add a colour to the droplet, electrowetting displays are based on this principle. The traditional pigment colours yellow, magenta and cyan are used in this technique (note that displays act on red, green and blue coloured pixels). Thanks to chemical improvements of the dyes it has become much more stable. The chances on fading colours and segregation have become almost nil. From the purpose of electrowetting displays to also being used outdoors (billboards and e-readers), the conclusion can be drawn that the dyes are UV-resistant too.

2.3 Applications of electrowetting

The very first application of electrowetting was the electrometer to measure voltage magnitudes. The electrometer contains two non-interfering liquids within a capillary. The liquids, a metal and an electrolyte are placed within the rod and by applying a voltage the curvature of the liquid will be more or less convex. The amount of voltage can now be verified.

2.3.1 Bio-chemical and medical

As mentioned before, lab-on-a-chip is one of the applications of electrowetting, another form is micro pumps. The purpose is for example to separate a small amount of blood into even smaller amounts. The smaller the droplet, the many tests there can be done. The processes the droplet can endure vary from moving, splitting, mixing and other. To have a kind of analysis system on such a miniature scale it can be put on a chip is very convenient.

2.3.2 Electrowetting displays

The reason this is a hot topic is because of the simplicity of the switch, with only contracting a coloured oil film electrically. This switch also has many attractive properties that make it suitable to be used as a display, as it can combine high color brightness, videospeed and low power consumption. A mix which is sought after but seldom found in a single technology. Clearly, as the droplet represents a curved surface of which the curvature can be tuned by applying a voltage, one can use electrowetting to make adaptive, non-mechanical lenses. Varioptic is a company that is producing liquid lenses (Gabay, Berge, Dovillaire, & Bucourt, 2002).

2.4 Properties and limitations of electrowetting displays

Common applications for displays are computer monitors, televisions, e-readers and billboards. A broad market of devices with variations from displays that can only show digits to full area 2- or even 3-dimensional displays. The underlying technologies are optimized for their specific function.

2.4.1 Stakeholders

A select amount of stakeholders has the ambition to develop electrowetting displays. This is a combination of research institutes and companies from Europe and the United States of America. At the beginning of the 21st century the first electrowetting display was presented by Rob Hayes and Johan Feenstra, at that time still under the name Philips (Hayes & Feenstra, 2003). Shortly afterwards it developed into the company Liquavista. Suspected release date of the first commercial electrowetting display would be this year (2015). Besides Liquavis-
Electrowetting, how it works

The images on this page show the basic layout of an electrowetting display. Between the two substrates, these layers are present of which two liquids: an oil and water. In the off state the hydrophobic insulator is touching the water for a minimum amount as possible. When a voltage is applied, the hydrophobic layer will become less hydrophobic, attracts the water and therefore the oil is pushed aside. The tensions in the system are reduced again to a minimal possible amount. With respect to the oil the electrowetting layer will become less hydrophobic, attracts the water and therefore the oil is pushed aside. The tensions of these layers are present of which two liquids: an oil and water. In the off state the hydrophobic insulator is touching the water for a minimum amount as possible. When a voltage is applied, the hydrophobic layer will become less hydrophobic, attracts the water and therefore the oil is pushed aside. The tensions in the system are reduced again to a minimal possible amount. With respect to the oil the electrowetting display is like a reverse version of the basic electrowetting technique. The coloured oil makes the cell transparent if a voltage is applied. The images on the right show a display in the related states, the oil is of a blue colour. In the lower right image the oil is only visible as a small line around the black hole. The black hole is part of the electrode and controls the oil motion. By making the electrode as big as in the image, the pixel-to-pixel homogeneity was improved and hence a display uniformity for this experiment. The group of pixels together forms a 160x160 µm² area, which resulted in an 80% white area for a 70% in-pixel colour reflectivity. The results were presented in Mobile displays, technology and applications by Bhownik, Li, & Bos (2008).

There is one other university that looks at the importance of electrowetting façades for buildings. The way electrowetting can work as a non-mechanical lens is used as a designing method at the University of Cincinnati as published by Robinette (2013). The renders in figure 18 show an on and off state with light rays penetrating deep into the room. At another faculty at the same university investigates the electrowetting displays. As a spin-off the Electrofluidic display has been arisen. The TU Eindhoven is currently doing no additional research on electrowetting displays, although they did have a number of projects in the past.
Manufacturing process
The manufacturing process is comparable with other display production processes and do have many of the same considerations. The process contains several steps which are given in an overview image on the left. The steps are selecting a bottom and top substrate with a choice in many different coatings and insulating layers, a liquid and dye selection, electrode selection and design of the hydrophilic grid. When this is done, the system has to be optimized, this is done by changing the dose of the liquids, the volume of each pixel between the grid, the applied voltage levels among others. Almost every step can be done in a production factory of another type of display, so to speak (Zhou et al., 2009). Productions flaws cause a slower closing and opening of the cells, an example is sketched in the image below.

2.4.2 Lay-up
Electrowetting displays is in its basis a lay-up of four layers in between a bottom and top substrate. The substrates can either be glass or something else, i.e. a plastic. The image shows the water layer which is capable of pushing the coloured oil aside. Colourization is done with a dye. The electrodes are printed on a layer which can be made transparent. A hydrophobic insulator optimizes the effects, so there is a smaller amount of voltage needed. The pixel walls are hydrophilic. The insulator is an applied coating on the bottom substrate which already includes the electrodes. Also the insulator coating can be made transparent. Electrowetting displays are not emitting any light, their visibility is dependent on surrounding lights. That is why the bottom substrate in the example is white (a metallic layer is also possible), the reflectancy is at a maximum now, which provides the best visibility. The total lay-up of an electrowetting display is very thin. It was even possible to “… produce flexible electrowetting display modules, and modules on glass substrates that were driven by an underlying array of industry-provided thin-film transistors” (Zhou, Heikenfeld, Dean, Howard, & Johnson, 2009). The modules on glass showed that it was possible to look through it as they had showed in a corresponding video. It can be assumed that in theory the transmittance of a transparent electrowetting display in the on-state can definitely be up to 70% and in the future possibly more. “Progress is under way, as recent single pixel tests now show >90% reflective area (Heikenfeld et al., 2009)” Which means there will be only 10% of light blocked after it had been reflected by the pixel walls among others.

2.4.3 Energy usage
The modules mentioned in the previous paragraph have a typical size of 160-ppi resolution. To get to the white reflectance of 70%, a corresponding voltage of 20 is necessary. The image shows the energy consumption of this 160-ppi screen in comparison with other display techniques. Future OLED displays will probably be much more energy efficient than they are now, which is why the power consumption is modified with a factor of 90%. Back-lit LCD have a power consumption of 80 mW/sq inch, but 90% of this amount is caused by the light emitting back-
**2.5 Conclusions**

For electrowetting façades it is not necessary to have such high droplet velocities, also the pixel sizes do not have to be as small as used in displays, but there are certain limitations to the electrowetting technique. In this conclusion the most important aspects of electrowetting are set out with respect to the potential usage in façades.

Electrowetting is activated by a voltage; this has to be low enough that when being in contact with it, there is no chance of getting electrocuted. Although the active parts would probably not be within reach, when the protection layer, probably glass, breaks, there should be no risk. As an answer to this, electrowetting displays would have the same problem, which is not mentioned in any paper. A voltage of maximum 20 volts is not tangible for humans.

Gravity is of no influence, because the bond number is smaller than unity for most electrowetting applications. Droplet sizes can go up to 10 millimetres, as proven by Blankenbach and Rawert (2011) in Bistable electrowetting displays. "Pixel size ranges from 0,5 to 10 mm and a wide temperature range is covered". Which is bringing us to the following potential setback; does it also work when it freezes outside? Chances are it does not when the temperature is really low, but there are ways to circumvent this problem. It could be possible to add antifreeze or by heating the façade, at the moment the answer to this question remains unknown.

The fast droplet movement is usable in façades for motion videos, but is of less importance for sun tracking of a façade. The possibility to have an immediate reaction has further no disadvantages for a façade. To conclude, the speed of the droplet is not dependent on the height of the applied voltage, however the shape of the droplet is gradually changeable and stable in every intermediate state.

Applying the amount of voltage could be done very accurate. The information and conclusions from this indention are derived from Bhownik et al. (2008, pp. 518-538).

The layout of electrowetting displays can be made transparent to a certain extent. At the moment, displays are developed with a white reflectance of 70%, assumptive this can be translated to a maximum of 70% light transmittance. The minimum amount of light transmittance is estimated to be 10%, on the basis of an opaque dye and a pixel-size to pixel-wall ratio of displays around 1:10. The bottom graph shows the expected transparency versus applied voltage if the pixel walls are made of a fully transparent material instead of opaque, therefore the graph reaches zero. As stated before, the dyes are not susceptible for UV light, also the substrates, electronic layer and the insulation layer can be made UV-resistant, which makes it usable in a façade. The dye itself does not have to be in one of the three gamut colours, it could be a black, white or maybe a near-infrared absorbing dye too (Fabian, Nakazumi, & Matsuoka, 1992). There is no such thing as a near-infrared reflecting dye.

An electrowetting display only usage its energy on providing enough voltage to keep the droplets in a stable position. The electrowetting display is compared to other display techniques. A result of this comparison is that its energy usage is low enough to take part in the display competition. The amount is probably also low enough to be feasible in a façade. This conclusion is drawn from the comparison with the back-lit LCD without the back-light, which is comparable with the cholesteric LCD that is also researched as a potential façade. Further research on both techniques will be needed to confirm this. Later in this paper is a closer look at the energy efficiency of electrowetting for the façade.
3. Responsive building skin

In the previous chapter the properties of electrowetting displays were carried out. At the end of the chapter, the conclusions suggested that electrowetting has great potential as an electronic transparent part of the façade. What does this mean for the building skin as a whole? Well, electrowetting is definitely a smart technique, but can it also be a part of a responsive building skin? Critics on the responsive building skin suspect that the future of façades and buildings as a whole is heading towards this responsive system. This chapter will review the term responsive building skin. Therefore it is necessary to know what determines if it is a responsive building skin. This information provides some answers to the question whether or not electrowetting as a display could become a responsive building skin. The reason why electrowetting instead of other display techniques has been chosen can be explained afterwards.

3.1 Smart, adaptive and responsive building skins

Another word for adaptive, and nowadays a more representable word to describe the same issue is responsive. In the image (fig. 25), the evolutional translation from a passive, to a smart and into an adaptive façade furthermore from a responsive building concept is outlined. You can tell if it is a responsive building skin if it has a dynamic behaviour, is adaptable to the environment, is fulfilling multiple functions and has an intelligent control system that operates it. To summarize: “A responsive building skin is one that facilitates co-evolutionary interaction between the building, the inhabitant and the environment in a meaningful way” (Velikov & Thün, 2013). An electrowetting façade, if only used as an urban screen as mentioned at the start of this paper is not yet a responsive building skin, because it does not effectively improve performance nor is it adaptable to the environment.

3.1.1 Responsive building skins in the paradigm shift

“Responsive building skins are the solution for our current under-performing, unsatisfactory building skins, and now is the time to put that way to work for new and refurbished buildings alike” (Solla, 2014). Responsive façade systems are the answer to this paradigm shift at the start of the 21st century. The goal is an energy reduction in buildings and achieving higher levels of indoor environmental quality. Crucial in this is the zero energy building target starting in 2020. The reason why responsive buildings would be a solution is because of the following: “An expanded understanding of building performance acknowledges that all forces acting on buildings (climate, energies, information, human agents) are not static and fixed, but rather mutable and transient. This has serious consequences for the building envelope whose design must transcend its role as mere protective..."
The technology that is required is already here. Then what does a new material mean in architecture? It is about improving our building stock by performance and sustainability. To take building skins as an example, performance is more of a practical matter, it is an improvement or addition, whilst keeping the basic requirements like no leakage, wind protection, etc. The necessary technology to implement a new material in the building skin is already here and available for everybody interested. This also counts for an advanced display like the LCD or electrowetting, the production manual is free to download for everybody.

3.1.2 Al Bahar towers
An iconic example of an adaptive façade system is designed for the Al Bahar towers in Abu Dhabi. The flower shaped external shading system blooms according to the position of the sun. It provides shade for the offices inside by adapting to the changing environment. Although for a moving system like this, it is exceptional that it functions this well. Adding to that fact, one of the architects of the façade called it a solution for a self-created problem at the Façade conference in Detmold, Switzerland (Karanouh, 2014). It is kindly noticed that the buildings rising in an Arabic oil-financed city as Abu Dhabi is mimicking the architecture from western places around the world. Looking at it, it becomes clear that this type of architecture (fully glass façade high rise) is not following climatological ideal design decisions, but rather bases its designs on aesthetics and view. Office buildings like the Al Bahar Tower tend to go into extreme climate conditions because of the high glass percentage in the façade. Unfortunately this is at a cost of the environment, because of the high energy demand for the air-conditioning system. Therefore the...
Optical cavity in lasers

When a spiral wave enters from the higher-refractive-index layer, the angle of incidence increases as it propagates to a layer with lower refractive index, until it reaches the critical angle at a certain point and total internal reflection occurs. In reality, the index changes in a continuous fashion, but the underlying physics is the same. From figure 28 we can see that a gentle index slope along the axis of a dielectric cylinder can serve as a total reflection mirror for the spiral waves, which can be used to make an optical cavity.

fig.29. An index slope is a virtual total reflection mirror that can be used to control the transmission of spiral light. \(n\): Refractive index. \(\Delta n\): Change in refractive index.

3.2 Micro-scale façade system

The Al Bahar Towers in Abu Dhabi is an example of a macro-scale type of dynamic shading. A macro-scale shading is typified as a mechanism of adaptation that is capable of changing its geometry by moving its components. Micro-scale systems are able to change the characteristics and properties of the material. The trigger for a micro-scale shade is almost always by the reaction of a smart material on the environment or an electric pulse. Sage Glass, a subsidiary from Saint-Gobain has developed electro-chromic glass, the early versions of the glass are easily recognized by its blue tint in the active mode (Saint-Gobain, 2015). The active mode is when the transmittance has to be low, because of excessive sunlight. Electro-chromatic stands for electronically activated colour changing glass. In other words, it is able to change the transmittance of light waves with a voltage. The type of façade that is the topic of this thesis could also be called an electro-chromic glass. Although electrowetting is not applied in a façade yet, its potential to become one is already recognized (Robinette, 2013). This happened when researchers were developing a transparent display. This might sounds a bit far from the plate of expertise of an architect, but there is and in the future will be more and more overlap between the display and façade industry. The display market, with a quite larger circulation than façades, is heavily searching for an alternative for, or improvement to the LCD screen. Not only electrowetting will potentially be implemented in a façade, cholesteric liquid crystals (Bouwhuis, 2013; Lammerink, 2013) and maybe other display techniques, like Mirasol (Heikenfeld, 2010) or OLED and system on glass (Bhowmik et al., 2008) could mean a radical difference for both industries.

Both industries look at the way light can be reflected, transmitted or absorbed by a material. The reason why we are able to see different colours is because not all light rays have the same wavelength. Scientists are able to (mechanically) change the space between two materials on a small scale. If the distance of the space, the optical cavity, between two materials is smaller than the length of a certain light wave, but not for another then the light will only be partially reflected and transmitted. The fact that the display industry is researching techniques that can change its optical cavity is very interesting for the façade industry. If we could integrate our façades with those new types of displays, a typical transparent mobile display, the possibilities will be significant. Broadly, you can think about electronic façades, transparent electronic drawing boards all around you or mood changing façades on the rainy days and this all in combination with a perfect view to the...
3.3 Display industry as an example for the building envelope

Both façade technologies as the display technologies aspire the idea of full invisibility, it is an old dream that is getting more realistic every day. “The ultimate display experience is a screen that is easy on the eyes in all sorts of lighting conditions, displays full-motion and full-color images, is rollable and durable, and uses precious little power” (Heikenfeld, 2010). Next to this, there is a wish for transparent displays, although there are also people sceptical about the actual benefit of this feature. Samsung has published a type of OLED display that is providing a see-through view from one side (#source). Current display types are transformed into these magical transparent displays. Next to this there are new display techniques fighting its way on the market, those displays are compared in the diagram on page 46-47. Most of them are still in the prototyping phase and not available for commercial usage yet.

The biggest on the market is the Liquid Crystal Display and rightfully so, there are only a few properties in which the LCD doesn’t score highest. But this display, just like any other is not yet capable of fulfilling the ultimate display experience. In the first place, the LCD is not efficient; the cause is the high light intensity it is emitting. It is a necessity, only half of the light passes through the polarization filter, and after that a part is further blocked to create colours. In the end only 10% of the light is transmitted. On the other hand, LCD screen convert electricity with an efficiency of 97% into light. Other disadvantages of the traditional LCD screen are eyestrain, limited viewing angle and non-visibility in bright light (Heikenfeld, 2010). The limited viewing angle is caused by the polarizing filters. When looking at the screen from the side the colors shift. This happens because light is not transmitted in that direction. The small viewing angle can be very functional in a public space and you’d desire the privacy of your work. There exists variants in which this feature is honored; somebody has to have its head right on your shoulder to view the same information. It is not a logical choice to use in a façade. A very promising renewal of the LCD screen is the Cholesteric LCD.

3.3.1 Cholesteric LCD

There is no usage of a double polarization filter anymore, it has for every light wave, red, green and blue, a different liquid crystal that polarizes the light. The molecular structure of the liquid crystal matches with a certain wavelength. Therefore it only transmits half of the lightwaves (the other lightwaves have an opposite rotation). Therefore it is also with this technique impossible to get to the critical value of 80% reflectivity in the display industry by (Heikenfeld, 2010). This is the reflectivity index of white paper, which every display company aspires. The polarization filters that are used could have a dubious influence on people. Polarized light has an influence on organisms, light therapies are based on the effects of this form of light and in this source plants were growing stronger on this type of light. http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2140871/ If windows would only transmit polarized light, it could have a dubious influence on people. There is definitely more research needed on this topic.

Within the display industry a number of alternatives are being developed. An example of what is already on the market is the e-reader. Current e-readers are now being produced with different techniques; the older version is the electrophoretic pixel. Scientists at the University of Cincinnati are also working on an e-book reader that works on electrowetting (Heikenfeld, 2013).

3.3.2 Electrophoretic pixels

The technique of electrophoretic pixels was developed with the aim to simulate a printed paper. The technology has for each pixel a capsule with black and white pigment parts, by varying the voltage the pigment parts may or may not be drawn so that they appear black, white or in a grey-scale. The black and white grains are of reverse polarity. The capsules are laminated to a panel that carries the electrical circuit. The circuitry can be printed as thin as paper, it is bendable and it is...
<table>
<thead>
<tr>
<th>Category</th>
<th>Type</th>
<th>Company</th>
<th>Status; as display</th>
<th>Status; as façade</th>
<th>How it works</th>
<th>Pro's</th>
<th>Con's</th>
<th>Activation cost</th>
<th>Production costs</th>
<th>Energy demand</th>
<th>Transparent</th>
<th>White reflectance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrophoretic Pixel</td>
<td>E Ink</td>
<td>available now</td>
<td>-</td>
<td>-</td>
<td>Black and white pigment particles with opposite charges migrate inside capsules, depending on the applied voltage</td>
<td>Simple to produce</td>
<td>Slow switching limits video</td>
<td>voltage</td>
<td>very low</td>
<td>very low</td>
<td>No</td>
<td>40%</td>
</tr>
<tr>
<td>backlit LCD</td>
<td>many</td>
<td>widely available</td>
<td>-</td>
<td>-</td>
<td>White emitted background light is polarized and colorized by a polarization filter and liquid crystals</td>
<td>Reflectivity and transparency is adjustable and it can be stacked</td>
<td>Not efficient</td>
<td>voltage</td>
<td>low</td>
<td>very high</td>
<td>No</td>
<td>10%</td>
</tr>
<tr>
<td>3QI multimode</td>
<td>Pixel Qi</td>
<td>available since 2011</td>
<td>-</td>
<td>-</td>
<td>A combination of electrophoretic technologies and the LCD, now it both reflects and transmits light</td>
<td>Consumes less power and is visible outdoors and at night</td>
<td>Brightness and color saturation are both compromised</td>
<td>voltage</td>
<td>low</td>
<td>depends</td>
<td>No</td>
<td>differs</td>
</tr>
<tr>
<td>Cholesteric LCD</td>
<td>Kent Displays; TU Eindhoven</td>
<td>available in Japan (2010)</td>
<td>In laboratory (2013)</td>
<td>-</td>
<td>Liquid in each of three layers has a molecular structure that matches a different color of light</td>
<td>Layers go transparent and can be stacked</td>
<td>Inefficiencies limit</td>
<td>voltage</td>
<td>medium</td>
<td>high</td>
<td>Yes</td>
<td>30%</td>
</tr>
<tr>
<td>Mirasol</td>
<td>Qualcomm</td>
<td>Available in small screen sizes (2010)</td>
<td>-</td>
<td>-</td>
<td>A MEMS device moves a membrane to and from a stack of optical films, changing the wavelength of the light reflected</td>
<td>Has crisp, fast video, low power consumption, and visibility in sunlight reflected</td>
<td>Expensive to produce; white is a challenge</td>
<td>electric</td>
<td>very high</td>
<td>?</td>
<td>No</td>
<td>25%</td>
</tr>
<tr>
<td>Electrowetting</td>
<td>Liquavista; Etalipa</td>
<td>Available in 2015</td>
<td>Idea dropped</td>
<td>-</td>
<td>Modifying the wetting properties of a surface with an applied electric field</td>
<td>Visibility from different angles</td>
<td>Switching is quite slow and limited pigments</td>
<td>voltage</td>
<td>high</td>
<td>low</td>
<td>Yes</td>
<td>40-55%</td>
</tr>
<tr>
<td>Electrofluidic</td>
<td>Gamma-Dynam-ics; University of Cincinnati</td>
<td>available in 2015</td>
<td>Idea dropped</td>
<td>-</td>
<td>Voltage pulls an inklike fluid out of a small reservoir and into view</td>
<td>Materials and mechanism are similar to ink on paper; switches fast enough for video</td>
<td>coming late to the race</td>
<td>voltage</td>
<td>high</td>
<td>low</td>
<td>Yes</td>
<td>70%</td>
</tr>
<tr>
<td>Photonic ink</td>
<td>Opalux</td>
<td>In laboratory (2010)</td>
<td>-</td>
<td>-</td>
<td>Electrically active polymers between nanobeads swell or shrink to change the size of the optical cavity and thereof the color</td>
<td>A single pixel can generate any color</td>
<td>To-date, brightness is a problem and devices have limited lifetimes</td>
<td>voltage</td>
<td>?</td>
<td>?</td>
<td>Not well</td>
<td>educ. guess: 70%</td>
</tr>
<tr>
<td>OLED</td>
<td>Samsung &amp; LG</td>
<td>available since 2014</td>
<td>-</td>
<td>-</td>
<td>Ionsing sandwiched blue-yellow organic light emitting diodes and an RGB colour filter above it</td>
<td>Easier to manufacture; cheaper in usage; better longevity</td>
<td>A low customer interest level</td>
<td>voltage</td>
<td>lower than LCD &amp; plasma</td>
<td>?</td>
<td>possible</td>
<td>educ. guess: max. 50%</td>
</tr>
</tbody>
</table>

fig. 31. Overview of emerging display techniques; properties are compared to its potential usage in façades.
3.3.3 3QI mode

By comparing the LCD screen and the electrophoretic pixels you get something like the 3QI mode. Primarily intended as a computer screen, this 3QI display is triple layered which individually can be switched on one at a time. The three types are LCD light emitting, the black and white electrophoretic version and a limited color mode (also based on electrophoretic). The 3 layers is at the expense of sharpness and contrast. Advantages and disadvantages found in the façade remain the same as in the electrophoretic pixel display and the LCD. For this reason, a 3QI display is no option for the building envelope, although the idea of combining three different techniques certainly has potential.

3.3.4 Interferometric modulator display (IMOD, trademarked Mirasol)

Interferometric modulator displays only consists of two layers, the top layer contains optical films, the bottom layer is a membrane. Mechanically the membrane can be moved closer to and further away from the optical films, which leads to a reflection of different colours of light. The microcavities or optical cavities between both layers is variable. Therefore this technique is comparable with the cholesteric liquid crystal technique. The reflection of light is possible by the mirror behind the Mirasol membrane. The effects of Mirasol without the reflective layer is not known yet. In theory, Mirasol without the reflective layer should be able to change the colour selective transmissibility of light and therefore be a potential adaptive façade system. https://www.qualcomm.com/products/Mirasol

3.3.5 Photonic ink

Photonic ink is another way of changing the optical cavity. This is done by a swelling and shrinking of an electroactive polymer. This way a single pixel can generate any color. Although this technique is only recently discovered and there is still much unknown, a photonic ink is potentially a good option for an adaptive façade. http://opalux.com/technology/photonic-ink-technology/

3.3.6 Electrowetting & electrofluidic displays

The Electrofluidic display is the trademark name of electrowetting at the university of Cincinnati. The droplet is in a reservoir and will come out if a voltage is added to system. The materials are similar to that of ink on paper. The result is a display that looks like paper behind a glass. The velocity of electrowetting is fast enough for fluid motion and video. The energy demand is low enough to be in competition for other display techniques. Other aspects of an electrowetting display are that it can be made paper thin, and therefore is visible from a broad angle. A disadvantage is that it has only a limited amount of colours it can produce,
3.5 Conclusions

A paradigm shift for the building envelope is noticeable by several literature reviewers. The paradigm shift leads to a growth in interest for responsive building skins. A responsive building is based on four parameters: a) dynamic behaviour; b) adaptability; c) multi-functionality; and d) intelligent controls. Responsive building skins will be a solution for the zero energy building demand of 2020. This has all led to a search for new building materials and techniques. The search discussed in this chapter focussed on micro-scale smart materials; and in particular the display technique as an example for the building skin. Several advancing display techniques are suitable for the building skin. Before the start of the paper, there has already been a reduction of potential display techniques. The techniques with seemingly the largest potentials were selected. For example, LED screens and 3D- or hologram displays were ignored. The fact that some already mentioned electrowetting as a potential for the façade has lead to writing this paper. Other techniques are very promising too, but the available information was limited. LCD screens are not suitable for a façade, it cannot be called a responsive façade. Cholesteric LCD on the other hand has great potential. Only a major disadvantage is the limited viewing angle. Electrowetting was the only display technique that has already stated it could be made paper thin and that is why electrowetting was elected.

but his real disadvantage is that it is coming late to the race. This is no problem for the façade industry. The façade industry is just about to have a paradigm shift in which different display techniques will be tested on feasibility as a responsive building skin.

3.4 State of the art transparent displays

At the moment this is written there are only a few techniques that have made it to a transparent version. Since 2012 both LG and Samsung have published the possibilities with the liquid crystal technique and at that moment a rather new one: the OLED display. Although OLED displays are still state of the art, the interest in the display seems to be lagging behind. An OLED display has a different form of lighting unit compared to the LCD. It uses blue and yellow LEDs that together emits white light. In 2014, Apple was awarded a patent for a transparent display that used lasers to show images. When it was off, the screen would just look like a pane of glass — rather like the televisions in Back to the Future II — but theoretically would look like a regular television when it was turned on. According to the Wall Street Journal, Apple shelved this radical design as it couldn’t get a high quality picture and it used “an enormous amount of power.” On any display, picture quality requires clarity — black blacks, white whites and vibrant colors. If the background bleeds through from the other side, picture quality will suffer, even if companies figured out how to make a see-through screen as high resolution as a conventional display.

Other techniques that are comparable with transparent displays are collected in the appendix. For example, the Hololens of Microsoft, the Winscape display window that simulates 3D views and European group that developed fluidglass.
II Design and performance studies

4. Application

The potential of electrowetting for the building envelope is very broad. Variations to the traditional electrowetting technique allow for multiple purposes. Sorts of applications can be found in different aspects of the façade, or in different building skin functions. To find and compare different applications for electrowetting, the focus remained on façades. Sometimes a solution could be implemented into another part of the building too. The overview of the potentials can be found in the first part of this chapter. It is the summary of a brainstorm session in which all of the building skin functions were evaluated on a potential electrowetting application.

In this chapter the strategy and classification factors are introduced to compare the different electrowetting techniques. The importance of doing so, lead to a full overview of what is possible and after that feasible.

In the next part of this chapter the potentials are clear and can be categorized according to its application properties. Examples of application properties is the location of electrowetting in the building, its adjustment speed and the state of development of its techniques.

fig. 36. Inventarisation of possible electrowetting potentials in an office building
4.1 Explanatory

The following pages give an overview of the possible purposes of electrowetting integrated in the façade. The solutions vary a lot, for example glare protection, optimization of PV cells, but also a large media façade is discussed. Therefore it was important to first introduce you to the façade related problem that possibly can be solved with this technique, before it is explained how this would be done in particular. The different solutions are ordered according to its theme. The theme is determined by the building physic it has an influence on. Although sometimes it has an effect on more than one building physic or aspect (light, temperature, ventilation, view, or it is irrelevant for its purpose.) In the left column the labels give you an indication what type of climate is preferable for the solution, if it is manually or automatically controlled or both, the level of innovativity, based on the fact if it exists already, to which system it could be competing with and a subjective predicted year it will be on the market based on the graphs from the previous paragraph.

The top image on those pages give an impression of how it would look like.
Do you know the act of turning your screen over the course of the day to avoid being unable to do your tasks on the computer? The greatest benefit of personal shading is the use of less artificial lighting. “77% of office workers believe there is a connection between the amount of natural light in personal office space and work performance” (Saint-Gobain, 2015). “Multiple studies show that it is important to work under natural light for every person” (Edwards & Torcellini, 2002). Traditional shading systems as blinds and shades are limiting this requirement.

Solution
To have unlimited access to natural light without letting it cause glare or overheating is one of the biggest challenges in the history of façades. The upside is that the necessary techniques and materials are already developed, now is the time to implement it rightfully. Personal shading is not yet an understanding in the architectural world, but will be soon, once people notice it is not science-fiction anymore. Although many smart glass companies (from electro- to photo-chromic) are still optimizing their system to only replace traditional shadings, but to develop a personal shading system with smart glass is not far-fetched. The preferences of each individual can be considered, to ultimately create personally bound shades over the course of the day.

Limitations
The techniques to recognize the position of a person in the room is high-tech, a motion sensor has to be really sensitive to notice movement. A preprogrammed system that knows your position behind the desk or a system that can be taught what the right shading is on each moment of the day is really advanced. There could be slight flaws in the system when two people are close together and desire a different shading type. Compromises have to be made. The advancement and sensitivity of it has the consequence of being quite expensive at first, although within a year, preferences should be known and there are only costs left for its power consumption. Assumptive, this is extremely lower than of a traditional shading system.

Glare is a form of excessive light that causes difficulty seeing. There are multiple causes for it, because it can be a result of both artificial and sunlight, also it can be from direct and reflected light. For this reason it is difficult to estimate when someone suffers from glare, because when the person would rotate about its axis a bit, he would no longer suffer from glare anymore.

Solution
To reduce the risks on excessive lights, the façade will have a vertical sunscreen in front of the glass, but only on the spot where you need it. No light is able to penetrate from this point in the façade, but the surrounding façade is still letting light pass. The ability to look outside is still intact, because the sunscreen is only a small part of the whole façade. To eliminate the chances on screen invisibility by glare, assumable the shading is only a few percent of the total glass percentage for a 15-21 inch screen. Diffuse light can cause invisibility of your screen too, to eliminate this, you would need a full window shading to decrease the illuminance levels. Glare is the most difficult form of light to get a hand on.

Appearance
At this point, it is not fully known how the façade with an anti-glare window would look like, probably like any traditional window opening, only with a dead pixel. Chances are it looks like a persistent stain that no cleaner can get rid of. What kind of consequences will this have on the architectural appearance?

Method
A fully automatic operating system is the driving force of this principle. It is able to track your position, in particular your eye movement, it knows the location of reflective objects and the position of the light sources, but most of all it is able to determine whether or not it should provide shading. Assuming there are no personal preferences for the light transmittance of the shaded part, it could be completely closed.
Although it is not possible to intensify daylight, there is however a way to illuminate darker area’s which normally would be out of reach. Electrowetting, when used as a non-mechanical lens or prism (in chapter 5 this mechanism is explained) can be used to direct light rays. It is comparable with the way heliostats, optical fibers and more of that type are directing light. In architecture, the way those techniques are being deployed are for increase of light intensities in darker hallways and rooms without windows, because light penetration on the ground - and lower floors decreases when buildings are higher. Another application is for activities that require extra daylight, examples vary from craftsmanship to medical jobs, but are often very precise tasks. Another application: older people need more light for doing the same tasks as younger do, inter alia by pupils getting smaller and their lenses cloudier.

Appliance
A lens is used to focus light. It is possible to create liquid lenses with variable curvature by changing the voltage. It is possible that you would like to have a certain amount of daylight on your workplace, but when you leave, the light can better be used in another part of the building where you are headed.

Limitations
Although the traditional lighting systems have the same problem, there are only a few hours in a day that provide the right lighting conditions to do such thing. Clouding reduce this number even further. The liquid cells would be under constant voltage to get the right shape according to the dynamics of the sun. Another aspect which requires consideration is the emergence of a focal point. There is nothing to worry about as long as this point is somewhere in space and not on any surface (air is capable of absorbing and distributing this heat easily).
A similar lighting problem as the previous paragraphs ‘light intensifying’ and ‘anti-glare solution’ is the following: luminance ratios. Rooms, corners and hallways that are not illuminated enough can be valued as underexposed locations, although the measured illuminance levels in those darker areas indicate that it should be sufficient enough. The reason is highly contrasting luminance ratios in the room, in other words your visual perception is off balance.

Solution
There are two solutions for fixing the extreme luminance ratios, one is by providing shade in the overexposed areas and the other is by directing light to the underexposed areas. Another solution is by doing both, so they can meet halfway. The images on the right show the problem and the edited photo with fixed contrasts.

Method
Luminance ratios are easily measured (there are smartphone applications that can do the job) and the rule of thumb (1:3:10) indicating the boundary levels for luminance ratios suggest fixing the problem is an easy job done. Unfortunately, it is not that easy. For the same reason as the previous paragraph, it is also dependent on the direction you are looking. Therefore, not everyone experiences the same luminance ratios. To get the right amount of luminance levels by using both the shading system and the light directing system, one should implement multiple layers of electrowetting in the façade. A loss of light direction is the result if both a shading layer and a directing light layer are over each other. Therefore, it is suggested to let them work side by side. The upper part of the window is directing light, the lower part is able to provide shade.
A view to the outside could work relaxing, but it could also have the opposite effect. A busy street could distract you from working. Light reflections from rooftops, wrist watches and other (moving) reflective objects could annoy you and decrease your work performances.

Solution
To improve your concentration levels, but still having a view to a part of the surrounding is possible with the electrowetting technique. As the technique is capable of tracking the sun and providing shade, the technique should also work for other light reflections. A personal shading with your preferences could help you concentrate better on your tasks. The purpose of this application is creating higher comfort levels, which is closely related to the first two examples: personal shading and the anti-glare solution. The method is by using the same kind of techniques.

Limitations
The electrowetting façade is not capable of muting annoying sounds, something that needs some consideration for even higher work performances. This also counts for smell or annoying colleagues.
Not only birds fly south, when the days get shorter and the weather colder some people migrate too. The intensity of light could have an impact on the intensity of our emotions, a study suggests. Research published in the Journal of Consumer Psychology shows that the more intense the lighting, the greater a person’s emotions - both positive and negative. More controversial conclusions were found after evidence had showed "... that on sunny days people are more optimistic about the stock market, report higher well-being and are more helpful; while extended exposure to dark, gloomy days can result in seasonal affective disorder."

To conclude, the intensity and colour of light affects people’s emotions, health and biorhythm.

**Solution**
The elder, sick and anybody else can benefit from windows that can adjust the intensity and colour of incoming light. Next to that there is the fact that people will desire to be less dependent on artificial lighting in the near future. Electrowetting can absorb or transmit the desired colours of light, which will have a positive influence if installed correctly. It is closely related to practicing light therapies, from the most alternative form to the more common. Light therapies is commonly associated with the treatment of skin disorders, but it is also used to treat circadian rhythm disorders such as delayed sleep phase disorder and can also be used to treat seasonal affective disorder and non-seasonal psychiatric disorders. The light is administered for a prescribed amount of time and, in some cases, at a specific time of day.

**Method**
Light therapy consists of exposure to daylight or to specific wavelengths of light using polychromatic polarised light, lasers, light-emitting diodes, fluorescent lamps, dichroic lamps or very bright, full-spectrum light. This electrowetting technique is closely related to a certain type of smart glazings: the spectrally selective type. Spectrally selective glazing is a glass that permits some portions of the solar spectrum to enter while blocking others.
The more common way than the previous paragraph in which spectrally selective glazing is used, is for reducing peak demands and total energy consumption. The glass is selective for different types of wavelength: heat radiation, visible transmittance and short-wave radiation.

**Appliance**

One of the applications is by letting UV-radiation through for only a small amount during the day. This is to increase the health of occupants, because it promotes the production of vitamin D. Your body will not turn red on the first summer day of the year, because although you were inside your skin was receiving just the right amount of radiation to prepare you for this. Another application is the prevention of as much solar heat as possible on hot days, while admitting as much daylight as possible. By controlling solar heat gains in summer, preventing loss of interior heat in winter, and allowing occupants to reduce electric lighting use by making maximum use of daylight, spectrally selective glazing significantly reduces building energy consumption and peak demand.

**Method and limitations**

The electrowetting façade is equipped with a certain type of dye that is capable of absorbing, but rather reflecting infrared radiation. The cost-effectiveness varies by geographical area, type of use, and utility rates. The limitation for spectrally selective glazing is not determined by its performance or the advanced technique, but the optimization to the right climate and right comfort levels.
The mechanic cooling system of the building does not take the amount of people in a room into account. With large groups a room can feel tight and oppressive. The chances of overheating are larger if you're not able to open windows.

Method
An adaptive façade system could help in the cooling load of the building. If the mechanic system can take the amount of people into account, than the shading will come down when more people are in the room. The load on the ventilation system will increase less and the amount of energy for cooling the building will decrease, because the system will always be optimized to the amount of persons in the building.
Sage glass from Saint Gobain has polled the believes of office workers according to light and shading systems in their workplace (2015). One of the results from there survey was that 88% of the employed U.S. adults believe there is a connection between worker productivity and their ability to regulate the temperature within the personal office space. There is only one flaw with this, and that is that not everybody has the same temperature desires. When designing the climate system for a building, the results accounting for comfort of the occupants will never be a 100%. The current standard is around 90% satisfaction rate, because there will always be a person having a cold or is dressed differently. Feelings of warmth increase if a body is exposed to light, even when the room temperature is kept the same.

Solution
What if it would be possible if everybody could regulate their own perceived view to the outside or heating from light? The building would allow for everybody to have their own perceived temperature that is close to the real room temperature, but everybody would be just a fraction more satisfied. Also, there would be no discussions about turning the radiator on or off anymore, because you can regulate this for yourself.
The electrowetting technique has made an interesting turn towards energy reduction by collecting thermal heat. The idea is that micro channels in the window pane are transporting the collected heat by radiation to a heat exchanger and store it for later usage.

"The water comes in at a low temperature, runs next to a hot window, and carries that thermal energy away," said Benjamin Hatton, Ph.D., lead author of the study (Ferber, 2013). The circulatory system functions like those of living animals, including humans, which contain an extensive network of tiny blood vessels near the surface of the skin that dilate when we are hot. This allows more blood to circulate, which promotes heat transfer through our skin to the surrounding air.

The artificial circulatory system can cool a glass window pane significantly. Enough it is said, if used throughout a building, to save significant amounts of energy and chop cooling costs.

**Method**

"Similarly, the new window-cooling system contains an extensive network of ultrathin channels near the "skin" of the window pane through which water can be pumped. The channels consist of long, narrow troughs that are molded into a thin sheet of clear silicone rubber that, when stretched over a flat pane of glass, create sealed channels."

To harvest solar energy, the most common way is to use solar panels with photovoltaics (PV) or concentrating photovoltaics (CPV) cells. Most conventional solar concentrators use mechanical moving parts (e.g. a motor) to track the sun. Typical solar collecting fields found in the desert are commonly using these moving motors. They are not suitable for residential rooftop applications due to their high power consumption and their bulky body, which raises reliability concerns.

**Solution**

Another method is a domelike solar concentrator based on the electrowetting technique with a moving mechanism that is silent. It will allow for extensive residential deployment of concentrated solar power. "In comparison with traditional silicon-based PV solar cells, the electrowetting-based self-tracking technology will generate ~70% higher green energy with a 50% cost reduction," according to Cheng (2011).

**Method**

Key features of thus-formed solar house include adaptive sun tracking, no mechanical moving parts, low-power consumption, and quiet operation. The supplies for this type includes a glass with presumably a triple layer of electrowetting droplets, a motion detector and a program that measures or knows the position of the sun with respect to the façade on every moment. The curvature of every droplet can be changed individually on a very accurate applied voltage. Only this way light that penetrates can be directed to the desired location.

**Limitations**

Solar panels do already have a high efficiency. The chances of overheating of a PV cell are probably larger than the extra efficiency it would gain with the electrofluidic techniques.

The problem with media façades is its enclosed structure, although there do exist media façades that are capable of providing view. This is done by LED lights on a grid or web, but this is not the same as a display on the façade. If it is important to have a high resolution, video speed operating and transparency, electrowetting might be your mechanism.

Solution
The combination of a display that has fast enough velocities to be compared with LCD screens and is transparent is unique. Although for buildings it is not necessary to have a high resolution, the distance to the screen in the urban environment is far enough that you would not notice the large pixels. With electrowetting, there is no other way available than building a media façade out of micropixels. Etulipa, the billboard company from the Netherlands is joining multiple pixels to simplify the control.

Method
According to the modular electrowetting display developed at the university of Cincinnati, there is a triple layer of electrowetting pixels needed with a transparent substrate. Three layers are needed to create the primary colours, cyan, magenta and yellow, but that also means that white is a difficult colour to produce.
The image shows a person drawing on the glass sliding doors, something that is already ordinary in movies, but could really be improving our lifestyles. The competition has become real in 2015. There are multiple display companies that are bringing transparent displays on the market, from the transparent LCD screen from Samsung (2012) or the ‘Glass Shop Wall’ in Babylon, The Hague (2015) to the laser display from Apple (patented in 2015). Compare it with the transparent LCD screen from Samsung (2012).

**Appliance**
The electronic indoor wall are connected to your computer, sharing your files has never been this easy. Your whole surrounding becomes interactive and is able to be drawn on. As a child you were never allowed to do this, now it becomes your lifestyle. The displays are able to give advice, for example your refrigerator door is suggesting recipes with the ingredients it has inside.

**Limitations**
Everything you write will be mirrored and non-readable from the other side. The problem does of course not occur with drawings. Not only transparent displays face this problem, if holograms and the 3D-display technologies are really becoming a major part of our life, the whole western language system will be reconsidered.

A recent Dutch project: the glass shop wall; http://www.glassshopwall.com/dh/
One of the building skin functions is communication. Media façades are not turning this to good account, buildings with a media façade are closed and a barrier between the insides of a building and the environment. Traditional shading systems do have the same effect, but sometimes it would be nice to block the sun at the same time, as show the world what is happening inside. Therefore entrances are preferably of glass, to show pedestrians they are welcome to come inside.

Solution
With electronic switching glass, like electrowetting, this could all be dynamic. The times that a building has to be an enclosed threshold or a welcoming shopping window in the urban environment are switchable with only a-push-on-the-button away. The image shows a kitchen that is facing the same privacy versus public discussion that many others are having too. Shopping windows can show information and the price tag on the glass. There could also be made a difference in what is visible for certain persons, children see the world from a lower angle, therefore the screen could potentially be showing only child’s related stuff, while adults are able to see more as their view is perpendicular to the window. In theory, even the location of entrances is interpretable, think about different entrances for visitors and employees.

Method
Transparent displays that are also capable of serving for some building functions. According to the modular electrowetting display developed at the university of Cincinnati, there is a triple layer of electrowetting pixels needed with a transparent substrate. Three layers are needed to create the primary colours, cyan, magenta and yellow, but that also means that white is a difficult colour to produce.
Finding your way around an unknown building can be a pesky task. For several reasons the building is obstructing your search, the build is quite large, not to mention the amount of floors, construction workers are blocking the way and the room numbering seems like a total mess. All in all, it feels like you are trying to find your way in a maze. The same problem can also be faced by employees if they have flex spots. Next to that people find it annoying if they look like they are lost and searching around. A confident person, that is somewhere for the first time has appearance.

Solution
Personal routing would be an ideal solution. You would set your final destination at the entrance of the building and a personal virtual guide would show you the way. Appearances of the virtual guide are shown on the electronic indoor walls and are free for personal interpretation. You could think of just an indicator, like a hand or arrow pointing the way, walls that can switch from transparent to opaque to show you have no business behind those opaque walls or a virtual person that walks (and talks) with you along the way.

Limitations
The goal is of course to let multiple people use the system at the same time. This could cause some problems if two people are close by and have both a different goal. Everything one person sees, the other will do too. It is not something the electrowetting walls have to solve, if it occurs, it will be a programming flaw. To let it function it needs research in virtualizing the rooms: space subdivision, localization and navigation and programming of personal locations. The electrowetting walls would only provide the necessary information that functions as a privacy barrier or a display. The building has become a glass maze in which everybody is always finding the way.
5. Electrowetting potential

The purpose of this chapter is to figure out how to use electrowetting in the most useful way. The design of this chapter is dedicated to discover the true potential of electrowetting for the building envelope. A singular answer is not possible, therefore there is a selection process developed. Different design considerations are taken into account which lead to the best design choice. The selection program, a derivative of the game ‘guess who?’ works best by analysing a current building or your design idea. The output considers one or a few applications of the technique. This chapter is substantiating the parameters and explains the reason why one choice will lead to a certain solution.

5.1 Running the program

The first time running the program will only bring you to implement electrowetting in your next design. When running it a second time, you will become aware of the advanced settings that are involved in the design process. One of the goals now is to understand that electrowetting for the building envelope is still in a prototyping stadium, which means it is definitely possible that there will be more applications and different types of mechanisms than mentioned. Image 38 shows a preview of the program. The first step is selecting your preferences (in the image: each orange line is a preference input), the best way to do this is by evaluating which aspects are most important for your design and starting with those. The aspects are categorized in types of design considerations, the categorization:

- Climate specifications

\[ fig. 39. Preview of the program: Derivative of the game ‘Guess Who?’ \]
5.2 Climate specifications

The importance of climate specifications is a derivative of the search for the properties of an ideal adaptive glazing (in terms of range, speed and adaptiveness). The climatological parameters that are of interest are the direct normal radiation and the global radiation, which is the sum of the direct radiation and the diffuse radiation. The tools from the program EnergyPlus allow to identify a set of thermo-optical properties and compare those values for different climates. Exactly this is done for an imaginary cellular office building located in Helsinki, London and Rome (Favoino, 2014). The results of the south façade are presented in the graphs on the next page. Heating, cooling and lighting are the primary energy consumptions in such offices and are the function for the costs. The performance and properties of the reference static façade R are compared with a yearly optimised one (Y), a monthly adaptive (M) and daily adaptive (D). Even an hourly adaptive switch has been evaluated, only for a timespan of 4 days (not included in the graph). It is noticeable that the energy saving potential of adopting an adaptive façade substantially increases with the increased speed of the adaptive mechanisms. Moreover the more temperate the climate the higher the achievable energy saving in both relative and absolute terms, this is due to the fact that the highest benefit in having such an adaptive façade is the reduction of unwanted solar heat gain, thereby leading to reduced cooling loads and the energy consumption for cooling purposes, which is reduced from 80 to nearly 100% (moving from Rome to Helsinki). Nevertheless, the benefits of adaptive façades can still be significant in colder climates such as Helsinki.

5.2.1 Hours of radiation

As the purpose of smart glazings is primarily reducing the energy costs to a minimum whilst keeping high comfort statuses, there is another approach in deter-
mining the benificence. The amount of sun hours is taken into consideration. The application of increasing the efficiency of PV-cells is one of the examples for it. A distinction is made between the percentage of direct solar radiation and the total amount of radiation, including diffuse radiation. The graphs in figure 41 show the sun hours three different climates. Obviously, Rome has more sunlit hours than the more northern climates.

5.3 Building type & location influences

5.3.1 Building height

Electrowetting is a more interesting technique for lower floor plans than higher, because of two reasons. The first reason not to choose electrowetting for higher floor plans is the risk of cold, caused by the drop of air temperature. When temperatures are below 0 °C, chances are the liquids in the electrowetting façade will be freezing and the whole thing will not work. As discussed before, anti-freeze or alcohol based liquids could potentially be a solution. The other reason concerning building height is the light penetration on ground floors versus upper floors. If the electrowetting façade requires a sunny sky, the effectiveness of the electrowetting façade will be higher in the lower floors than in the top floors. A light directing system (based on the electrowetting technique) could be addressed. If those reasons are irrelevant for your desired purpose, you can neglect the choice of building height. Note that electrowetting is still a suitable solution for higher floor levels too, even on higher floors there are underlit places and in winter, even on lower floors it can be too cold for electrowetting to work.
5.3.2 Application area

The potential of electrowetting as a new glazing method is significant and probably the main application for the building skin in the future, nevertheless the application of electrowetting can also be in other parts of the building. The location in the building where the system is used will affect its appearance in the built environment. It is important to consider this when applying it, because it would probably not be renewed in the following 10 to 20 years. On the other hand, the dynamics of the system continually provide a different look. A division was made in application area, because every application area would require a different installation and technique.

- In the opaque section of the façade
- In a window and other transparent/translucent sections of the façade
- Within the building
- Away from the building façade

5.4 System & control methods

5.4.1 Control type

In an ideal situation the electrowetting skin is a responsive façade design that reacts on multiple environmental impulses, from both outdoors and indoors and takes peoples preferences into consideration. It also means the electrowetting skin is able to morph into several different building skin functions as presented in Chapter 4. Two main types of control systems do exist, an open loop and closed loop. The most relevant control system for an electrowetting skin, a closed loop, is sketched in image 44. The indoor climate influences are a compilation of energy and air movements caused by the equipment and the metabolism of the occupants. Next to that, it should be possible for occupants to overrule the automated system when desired, this is the active input by people. The outdoor climate influences are based on the weather elements as mentioned in the previous paragraph. Such actions are not necessarily of immediate impact, the time scale the building is subjected to environmental impulses can vary from (sub)seconds to a decades. The sensor translates the inputs into readable data for the processor, which on its turn gives a signal to the actuator. The result is an action. An extra controller is needed to compare the data of the sensor with the data received at the actuator. This type of system is called a closed loop.

5.4.2 Time scale dependency

The electrowetting façade allows for very fast to longer scale changes over time. In comparison with other adaptive façade systems, that vary from impacts within seconds to decades, the main purposes of electrowetting will probably be milliseconds for video-display, hourly for suntracking shading and seasonal and hourly for temperature changes. The table compares this with the different building functions.
5.5 Mechanism

The previous chapters have already shown several different electrowetting methods, as you might have noticed. There was already made some distinction between the active displays or a bistable mechanism. In this paragraph there are two more mechanisms explained. Those mechanisms are necessary to understand if combinations are possible between different applications and if they are necessary to evaluate the probability of the application type according to its mechanism. For the convenience they are named after the way they work. For example, the bistable technique is using the position the droplet it is in, which has only two states, an active state and a non-active state or a reservoir. These are the different techniques or mechanisms:

- using the position of the liquid, the bistable method;
- using the interface between droplet - substrate, single layer;
- using the colour of the droplet, triple layered;
- using the shape of the droplet, liquid prism / lens;

Every type is further explained with typical applications, non-façade related, façade related and a unique application.

5.5.1 Using the position of the droplet: Bistable technique

The droplet switches between an in-view state and an out-of-view state, which means there is a reservoir for the droplet that stays out of view. The most energy efficient way to use electrowetting is by this technique. To enlighten this, there is only a small impulse needed to move the droplet and then it will stay there. Another impulse is needed to move it back, or to the next spot. Variations to this technique are possible, one can imagine that the droplet is more like a flat surface that is able to rotate around an axis to be able to absorb light from a certain directions. In this case it does not have a storage place in the opaque section of the façade, but is always in view. The difference with the single layer technique is the energy demand. The bistable electrowetting mechanism is the most sustainable. With both the bistable technique and the single layer technique it is possible to create gradients, although the resolution is higher with the single layer technique.

Typical application: indicators / sunshading / (thermal energy) transport

5.5.2 Using the interface between the droplet and the substrates: Single layer technique

The single layer technique uses the voltage to spread and shrink the droplet. Every pixel has its own droplet and is not connected. The single layer technique is frequently tested with the purpose of displays, but not yet as a façade. Therefore, the following variation is introduced. The droplets that were used for the display testing contain a dye, to have it more visible, but what if the substrates are of a transparent material, for example glass or perspex and the liquid is also transparent and of the same refractive index as the substrate, then some interesting light effects occur. What happens with the light is further explained in the heading on the left page. If there is no trapped air between the liquid and the substrates, the liquid would seem invisible. The images of figure 47 show this effect with glass
The way an opening and space are designed can direct or distribute the light, but it cannot be made stronger. When light penetrates a medium, it behaves differently than when it enters another medium. The effect can be explained by the example of light hitting water; the light is refracted at the interface of water and air. The refraction index \( n \) of an optical medium describes how light and other radiations behaves in that medium. It can be calculated with \( n = \frac{c}{v} \). With \( c \) for the speed of light and \( v \) the speed of light in the substance. The refractive index of water is 1.33, which means that light travels 1.33 times faster through vacuum than through water. The refractive indices of some key materials at room temperature are given in the appendix. A refractometer is a device that measures the refractive index of materials, but it can also be simulated with a sugar solution. By adding more sugar, the refractive index of the substance will increase. This experiment is given in the same appendix. Because the refraction is not the same for every wavelength of light, dispersion occurs (rainbow effect). The graph shows the refraction index compared to the wavelengths of a type of float glass.

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \]

**Snell’s law**

![Graph showing refractive index for different wavelengths.](image)

**Typical application:** e-reader / shading / reflective shading

### 5.5.3 Using the colour of the droplet: Triple layer technique

The triple layer allows for creating multiple colours, although black is a challenge - to the contrary of light emitting displays. The triple layer technique uses three stapled layers, Yellow, Magenta and Cyan to create images. The principle of this method is exuberantly explained in the second chapter of this thesis. The figure above shows a display from the University of Cincinnati that has developed such display, although it is not clear why and how the display is emitting light, something that should not be necessary. The expectation is a LED strip on the side of the screen that enlightens the pixel cells in the display. For absorbing light or as a sunshade, this technique is less attractive as it uses trice as much energy as a single layer. Although, an interesting theory is the potential of spectrally selective glazing that is sensible for different types of light waves. Spectrally selective smart glazing is one of the most interesting smart glazings now available, because speaking in energetic terms, visible light waves are still passing through, but the glazing does not allow this for long wave radiation. Which indicates in a room with stable temperatures (less fluctuations). A poly-spectrally selective glazing is

![Image showing an example of using the colour of the droplet.](image)
only increasing the amount of possible features of the electrowetting skin. Some out-of-the-box-thinking examples of those new possibilities: A glass that allows for UV-light penetration only a few minutes every day - to increase the vitamin D production in your body, to stay healthy even on busy working days. Another idea is the colouring of glass to alert birds, so they will not fly against the window (birds are sensitive for other wavelengths than humans).

Typical applications: full colour displays / transparent media façade / spectrally selective potential

5.5.4 Using the shape of the droplet: liquid prisms and lenses technique

The mechanism behind directing light with liquid prisms and lenses is very advanced. The supplies for this type includes a glass with presumably a triple layer of electrowetting droplets. The shape of the droplets determine the convexity of the lenses. The curvature of every droplet can be changed individually on a very accurate applied voltage. Only this way light that penetrates can be directed to the desired location. The droplet can have a prismatic shape too, as is used in the photography sector (Varioptic, 2015); for a faster auto-focus and better optical images. The image on the bottom of this page shows a combination of two regular prisms and a lens that are directing light with a rotation factor of ~90°. As we also can see is a reduction in sharpness and intensity of the new lightray. All in all, this method is very promising not only for the photography sector, but notably for the building sector.

Typical applications: photography & zoom / light directing façade systems / colourful rooms

fig.56. Snapshot of a video in which is explained how light can be directed with prisms & lens

Using liquid lenses and prisms in photography

The technology uses the Electrowetting principle and a combination of transparent and optically defect-free liquids to create a lens and change its characteristics in real time. Liquids have been used since 40 years in optical systems for high-end products such as goggles or camcorders, but Varioptic’s innovation is to have created a real-time programmable platform that offers to change the shape of the liquids in a very fast, repeatable, precise and controlled way. The bottom image shows the liquid prism principle used in cameras. The liquid lens can simultaneously change tilt along 2 axes, plus it can vary focus.
There still remains the question if it all would even be possible, independently of the desire for it. Therefore the techniques have to be evaluated and compared. There are existing prototypes of using the colour of the droplet and the position of the droplet. There are no build examples of using the interface nor the shape of the droplet. As far as our expertise in the field goes, one would say that using the shape of the droplet is still science fiction. Even if the operating system is secure enough, it is the behaviour of light through the liquid prisms and lenses that causes the doubts. If a light wave is hitting another medium, i.e. air to water, than not every wavelength shows the same refraction. This effect is called dispersion. This does not necessarily have to be a problem, because by changing the distance between the prism, lens and prism, the effect can be ‘undone’. In a façade, how would somebody do this? A problem that has not yet been solved.

Using the interface is a different case. If two materials would have the same refraction index (and they are both transparent) than it is understandable that it would look like as if it was only one material. The flaw in the system is caused by the choosing the right material. Maybe it is not possible to have a liquid material that has the same refractive index as a certain glass and is sensitive for the electrowetting reactions.

Another aspect that needs some real consideration is the effect of light bending. The effect with which they make seemingly invisible objects is appearing in the electrowetting techniques too. The convex shape of the droplets is causing light rays to converge.

There is no such thing as a perfect glass. There will always be some aspect that makes it less transparent, less bright or less fill-in-the-term.

5.5.5 Reviewing the techniques

Dispersion

Which is the appearance of rainbows for example. In optics, dispersion is the phenomenon in which the phase velocity of a wave depends on its frequency.

Refraction

Refraction is the phenomenon of light bending. A very interesting effect that is finding some ground in art and architecture.

5.5.6 Architectural appearance

fig.57. Animated prism shaped crystal causing dispersion, non accurate

fig.58. Invisibility shield proposal for a real life game

fig.59. The effect of dispersion from an electrowetting skin
5.6 Display preferences

5.6.1 Resolution & distance to screen
The pixel size determines the resolution of a screen. High resolutions are required if the distance from the screen to your eyes is small, but in an urban context when the distance from you to the screen can be up to 50 meters (or even more), the resolution gets less important. The graph shows the desired resolution dependent on the distance to the display and the size of the screen itself. Electrowetting is capable of reaching sufficient resolutions for usage as laptops or e-readers. The maximum electrowetting pixel size that is possible to make is in the order of millimeters. Beyond that gravity will be of influence, and the electrowetting phenomenon will not occur. The consideration of electrowetting for the built environment should focus on indoor applications with a relative small viewing distance. This is in contrast with current types of media façades, in which most of them are adapted to the outdoor architecture.

5.6.2 Colour gamut & day / night visibility
The greatest difference between electrowetting and LCD or OLED techniques is the colour gamut (both types are being praised and rejected). The colour gamut of LCD screens is Red, Green and Blue, as for electrowetting it is Cyan, Magenta and Yellow. Electrowetting displays do not emit light by itself and are only absorbing and transmitting surrounding light. The result of this difference is a high visibility / clarity of electrowetting displays during daytime versus low at night and RGB screens, which have high visibility at night and low during the day. As a problem solving solution RGB screens are emitting more light during daytime. The more obvious solution is to use electrowetting during the day. Speaking in terms of sustainability with a focus on less light pollution, CMY screens should be considered more often.

If visibility during the day is preferred, but visibility at night should not be excluded, then you should think about adding an external lightsource, emitting light on the façade. If visibility during the night is preferred, but visibility during daytime should not be excluded, go for a highly light emitting façade, for example LED lights.

5.7 Research status

5.7.1 Limited information
Unfortunately the available information of electrowetting for façades is limited. This is due to two reasons. Firstly, the electrowetting techniques are only recently explored. At the moment, only a few companies work on electrowetting displays, the research that is most alike the adaptive façade industry, and they are still in the developing phase. Despite the promising look of electrowetting displays, there is not yet one released which is as good as the newest screen technologies. Next to that, large scale electrowetting displays are also not yet developed (only with subdivisions), something that needs some real consideration when the time comes.

The second reason is because the adaptive façade industry is still an immature field of research with lots of companies and systems in their design and prototyping phase. The result of this is a limited amount of writers about the subject.

5.6.2 Development
Nevertheless, the research that is already done in the adaptive façade systems is very promising. Loonen is keeping up a full overview of every different adaptive building shell since his graduation (2010). As we can see now from this overview is that there are only a select group of ideas that have made it into a real building, most of the adaptive building shells are still in the prototyping phase. The same goes for potentials of electrowetting or electrofluidic glasses. Sources date from the second decade until now and are not yet realised.

The process of every new technology for an adaptive façade is closely related to the process of product development, rather than a building process. Where a building process is characterized by a succession of the initiative, design, implementation and use phase. So is there a prototyping phase in advance of product development and the operation phase is also characterized by the usage of subsystems and components rather than a building. A result of this is a very late design phase as is known in architecture. The adaptive façade development, as a part of the building technology studies is in between and is shown in the picture. The potentials of an electrowetting façade are varying from the initiative phase to the prototyping phase.
As a reminder, to review a responsive building skin, it is dependent on four aspects as has been stated by Solla (2014). “A responsive building is based on four parameters: a) dynamic behaviour; b) adaptability; c) multi-functionality; and d) intelligent controls.” Dynamic behaviour is triggered by different sensors, i.e. camera’s, which is not elaborated on further. The assumption is made that techniques of electrowetting are capable of doing the previous different potentials, or in other words their adaptability is possible with the electrowetting technique. Then the next step is determining the multi-functionality of the electrowetting technique. This is dependent on two aspects: The first is questioning which aspects you would like to have combined; The second aspect is whether or not the mechanisms responsible for it are able to operate together or side by side. About the first aspect, there could be any reason to combine one of the potentials with the other, although some combinations are obvious. Combining light potentials with energy potentials is one of those. Comfort on the work place is only achieved if there is no excessive light and the temperature is right. Higher comfort levels are also achieved if your mood and health are at a right level. Combining this with energy or light aspects could give the façade a higher status. Another combination is between the lighting theme and the display theme. The desire is to have a visible screen in all lighting conditions, which means that either the screen is such that it is visible in every lighting condition, or the window is capable of creating the right amount of light.

Combining displays with main building functions such as lighting, shading and energy regulations is probably the direction façades are heading towards. The way shopping windows will function in the future is an example of this. Transparent display windows are keeping the transparency of the shopping street in tact and shopping will be pleasing again, because it would also have the features internet shopping does have now.

In order to use the electrowetting technique as an outdoors billboard, and being part of the full adaptive building skin, then it has to be in combination with comfort or energy related applications. This is possible, both the applications do have matching mechanisms. A real consideration however is the question of comfort reduction (i.e. too much or too few shading) if the electrowetting skin is used as billboard.

The optimization of PV cells is not really combinable, as it would would have an adverse effect on the efficiency. Personal routing is very good combinable with applications of the indoor and outdoor display.

5.9 Case studies

The following case studies are considered as a potential location for the electrowetting skin. The selection program is translating the preferences into possible application methods. The results can also show the option of considering another building skin instead of the electrowetting technique.

5.9.1 Ziggo Dome

The Ziggo Dome is a public building for concerts and events. 17,000-seat multi-use indoor arena in Amsterdam, the Netherlands. The building is covered with 120,000 LED fixtures, allowing the façades of the building to appear as a video screen on all sides. “It greatly influences the appearance of the city as an international cultural, economic and tourist centre” (Linders, 2013). If the skin of the Ziggo Dome have to be replaced, is electrowetting an option to be considered?
Electrowetting is no sufficient choice for the Ziggo Dome. Although it is possible to build the Ziggo dome façade with electrowetting, the façade is especially visible at night, and the inside of the building does not require daylight, which makes electrowetting a less obvious choice. Another reason not to choose electrowetting is because the Ziggo Dome does not require a high resolution, determined by the viewing distance.

5.9.2 Faculty of Architecture

The Orange Hall is taken as an example. The Orange Hall is currently dealing with highly fluctuating temperatures between the winter and summer period. As is done with other large glass façades, to prevent most of the problems, shadings were added, but this was at cost of the view.

The Faculty of Architecture is a very suitable building for an electrowetting skin. The building has a large glass façade on the South side of the building. Even the roof is a glass skin. Which has led to highly fluctuating temperatures and if not for the shading, the place would be unbearably hot in the summertime. All in all an ideal room to enrich with the electrowetting skin. Another reason is because the Orange Hall has flexible working places, which makes it the perfect spot for personal shading systems too. The large glass ratio enhances this.
6. Performance studies

One of the most promising applications as concluded from the previous chapter is its usage as shading or lighting method. The shading method looks more realistic than the lighting method (the one with the liquid prisms), therefore, the potential of electrowetting being a smart glazing is researched further. A smart glazing characterizes itself by being able to switch between different states of transparency. The switching method can be gradually or discontinuous. A performance study is done for the electrowetting skin as an gradual switching glazing. There were made quite a few assumptions at the start of the performance study, which is understandable considering the electrowetting technique is not yet used in the façade. The goal of this chapter is to research whether or not electrowetting is feasible as shading system based on its total energy consumption. The underlying movement is the consideration of other transparent displays as being used as smart glazing.

6.1 Model setup

In this performance study the goal is to compare the energy usage of a traditionally shaded room with an electrowetting skin that only uses the shades for the person in the room. This is application nr. 1 in chapter 4. The test-location will be a perimeter office with adjacent similar offices. The only outside facing wall is a full glass façade, with a glass percentage of almost 100%. The shading type will be compared with a reference building with traditional shading that is switchable between up and down. The electrowetting façade office has the same parameters, the difference is that is has differences in shading strategies. The shading provided by electrowetting will be a shading working within the glass.

6.1.1 Reference case

The reference building from Reinhart, Jakubiec, & Ibarra, (2013) is used. This reference case is particularly handy for smart glazings because of the large south wall façade and the depth of the room.

6.1.2 Office parameters

The analysis restricts itself to a max 4 person perimeter office with a south facing façade. The average heat accumulation of persons and equipment is 25 W/m². There are similar offices adjacent on every side of the office, which leads to adiabatic walls on every side. Except for south, this side is facing outdoors and has a 100% glass area. The office has available working hours from 8:00 until 19:00. The maximum amount of artificial light in the building will be 300W. The light is
switchable. The office has a size of 6x3.6x2.8 length width height. The heating set point is 21°C and cooling set point is 24°C.

6.1.3 Weather files
The weather in the Netherlands will be the base point. An average temperature of 12°C, an outside high temperature of 27 °C and the lowest temperature is set on -7.3 °C. During the winter period, the temperature outdoors will never be higher than the heating set point of 21°C, but that does not mean that the heater is always on. The room temperatures are also increased by people, equipment and lighting (artificial and solar).

6.1.4 Ventilation
Ventilation of the office is necessary, in both summer and wintertime. The room requires a minimum amount of 100 fresh air per hour, but when we simulate the reference office, this amount is too low. The mechanical ventilation has to be increased to 4 times to have a comfortable reference office whole year round. The office does not have windows that allow for opening, the perimeter office could be in a highrise too.

1. De reference case
2. Electrowetting skin

6.1.5 Glazing properties
In this paragraph the glazing properties of the electrowetting skin are determined by comparing it with other types of smart glazing. The graph shows a collection of data of smart glazings and static glazings (black dots) about their light transmittance. The amount of visible radiation(T-vis) through the glazing is plotted on the vertical axis versus the amount of total solar radiation (g-value) transmitted through the glazing on the horizontal axis. Glazings in the lower left corner are not letting pass any light, glazings in the upper right corner are passing all of the light. Very absorptive glazing, for example thermochromics are in the bottom of the graph and the reflective glazings are close to the physical limit of the g-value divided by the T-vis of 0.423 indicated with a grey striped line. (Light on the left side of the grey line is the energy of visible light, on the right side it is the energy of the heat radiation.)

Concerning electrowetting, the only certain values that are known are the expected variable visible transmission from 0% transparency up to 70% or even 90% in the future. Unfortunately just knowing the variable visible transmission range is not enough to calculate it. The required data to calculate it are the absorption coefficient (or reflection coefficient) and the transmission for both the part of the solar spectrum (visible and total). At the moment, only one out of four data known.

Moreover the g-value strongly depends on other factors, such as the U-value of the glazing (therefore the emissivity of the glass surfaces and the glazing cavity properties), and the boundary conditions (taken from standards). A hypothesis about the variability in the absorption and reflection is done and with that a range of possible g-values is calculated. The green area in the graph shows the expected zone in which the electrowetting skin assumable will operate. Because of its strong absorbing characteristics one would suspect it to be in the lower half of the graph, but concerning the fact is could be spectrally selective indicates it is in the upper part. Nevertheless, the electrowetting skin is certainly an interesting smart glazing whether or not its location in the graph. The graph is not an indicator for which type of glazing is better than another, but glazings of the same type are competitors. With more research on this subject it will become quite visible which glazings are the competing glazings of the electrowetting glazing.

6.1.6 Glare
Glare protection is necessary in both winter and summer situations, but the glare caused by direct sunlight is probably more common in the winter times when the
Design and performance studies

Performance studies

6.2 Performance results

Offices with 100% glass façades in the Netherlands are energy consuming. Our reference building confirms this. 1853 kWh energy usage during the winter period is spent on artificial lighting, the switching traditional shading and heating of the office. There are 41 hours in the period that should have been cooled, but the settings did not allow for it. The test façade did have the same settings (no cooling and 21°C heating set point) as the reference building, except it had no shading. The new shading type is described by a glass area that was reduced with 3%, done by reducing the ZTA & LTA value. The result of this is much more fluctuations in temperature, but also an energy reduction, it is only 973 kWh. The fact sun has a lower altitude. Excessive light in the summer is not primarily because of glare, overheating is the major part. The potential of electrowetting by creating local shades on the window is exactly what we need on the colder days. The assumption is made that the electrowetting technique is applicable on any glass façade (as if it is another layer of the glass, like a coating). The ideal solution is the window blocking the glare, but is not obstructing the view by its shades. To do this, the following method is used.

When there is a risk of glare is difficult to say. There are different forms of occurring glare. A difference in four types can be made. Glare caused by direct or by indirect light. Glare from light in your eyes and glare from light hitting your screen. Only glare by direct light hitting your screen will be discussed as this has only the sun as a variable. The screen is static and not moving, in contrast with your eyes. The reflection of sunlight could be from anything and will not be discussed here. The light rays that pass the façade and hit the screen are 3% of the total façade of 10.06 m². One screen.

Choosing the right reference building is of key importance, the results can change the feasibility of the entire concept. This also counts for the common parameters that are used, which became clear in the work of Lee and Tavil. “In hot and cold climates such as Houston and Chicago, electrochromic windows with overhangs can significantly reduce the average annual daylight glare index (DGI) and deliver significant annual energy use savings if the window area is large. Total primary annual energy use was increased by 2-5% for moderate-area windows in either climate but decreased by 10% in Chicago and 5% in Houston for large-area windows. Peak electric demand can be reduced by 7-8% for moderate-area windows and by 14-16% for large-area windows in either climate. Energy and peak demand reductions can be significantly greater if the reference case does not have exterior shading or state-of-the-art glass.” (Lee & Tavil, 2007) Of het dus werkelijk de potenties heeft als uit de resultaten blijkt. Voor stakeholders is het van belang. Daartegenover staat dat met dit nieuwe type zonwering, het resultaat wel zo significants anders moet zijn dan de huidige systemen.
that we see larger energy fluctuations only means that our 100% electrowetting glass is letting enough light pass that the building could be heated on it (in the winter period, the outside temperature is always lower than the desired inside temperature). The energy usage for those days for the shading cannot easily be calculated, and therefore will be ignored. Unfortunately, the results given by Orca cannot be filtered in energy demands by artificial lighting, cooling and heating, which makes this research in Orca fully unreliable and not comparable with any other studies.

The energy usage of the electrowetting has not been taken into account yet. If the shading is always active during the whole winter (211 days) for the occupancy hours (8), it uses 0.43W*211*8=729kWh. A total of 1702kWh, which means a difference to the traditional shade of only 151kWh. (Which sounds as if not feasible enough.) This is the most extreme case, it uses an electrowetting system that is always in an active mode, despite if glare protection is even needed. If another type of electrowetting is used, for example the bistability technique (which is more realistic if it is only used as a glare protection screen), than the difference is larger. In the case of bistable electrowetting, we assume every cell of the façade will be turned on and again turned off only once for every day. 0.43*211*2/3600=0.050kWh, which is neglectable. This means an energy reduction as given in the images, around 190% during the winter hours.

Another electrowetting technique is the inverse display, which means that a transparency state is obtained if no voltage is applied. In that case only 3% of the electrowetting façade is using energy for glare protection. The calculation: 0.03*729=22kWh, which is also neglectable.

6.3 Energy assumptions

The energy usage per unit of operating time of different types of mechanisms are compared in the graph above. The energy usage of a triple layer electrowetting skin will assumably be trice as much as a single layer electrowetting skin. The energy usage of the liquid prisms and lens method has never been made before, but if it contains three layers of electrowetting mechanisms than it will be comparable with the triple layer method. The bistable method is only using energy when it has to switch to another state. The bistable method is not a suitable method for video display or a reaction within subseconds. The graph is representable for video display applications or applications that require a response within subseconds, for example personal shading, this is indicated by the dark green bars. The graph is representable for a shading system that is tracking the sunpath and is responding on this every hour of a workday, indicated with the middle bars. Another type of switching speed that have been found is twice a day, turning on in the morning and turning of in the evening, indicated with the light green bars.
6.4 Conclusions

As we have seen from the results, it really depends on what kind of electrowetting mechanism is used. Different cases will be discussed in this conclusion. The worst case scenario is discussed first. This case represents an office building with a fully glass façade, in which the electrowetting layer is either not capable of reducing the light penetration or the electrowetting façade is continuously used as a display. Either way, there is no shading in the façade. This is a very unrealistic case during the summer period. Therefore, as a first conclusion, electrowetting is not energy reducing during the cooling days of the summer period, because then there is no way of using the electrowetting façade for other functions too. The electrowetting technique would be an addition to the shading system, no matter what type is used. The energy increase of the electrowetting layer is dependable of its usage.

The winter period is a different case. The need of having a shading system is less a necessity if it is used as an indoor temperature reduction device. The other reason of having a shade is for glare protection. Glare protection is only necessary when it appears. Cases for glare protection are: glare from direct sunlight hitting your eyes; glare from reflected sunlight hitting your eyes; glare from direct sunlight hitting your computer screen; glare from reflected sunlight hitting your computer screen. Every other light emitting device that has a lower intensity than the light coming from the sun is vulnerable for glare. Not every time direct light is hitting your eyes it causes glare. This is dependent on the direction the person is looking and this leads to an almost unmeasurable variable. The variability and the velocity of switching causes the trouble and therefore were not taken into account. The Orca energy performance focussed on glare protection that occurred on your screen from direct sunlight. A display is fixed at a location (and does not grow in size), which means that the part of the façade that has to function as a glare protection device is 3% for a façade of 10m2. The performance simulation has calculated the benefits of a shading device, made from electrowetting that is actively protecting a screen from glare. If the electrowetting façade is made with the same techniques as an electrowetting display and is always in the active state during the working hours, then the new shading system is only 151 kWh more economical. But, when another type of electrowetting system is used, the energy reduction can go up to 729 kWh. In other words, an electrowetting façade could potentially lead to almost two times a better energy performance during the winter times.
7. Trends & Prognosis

A structural changing trend in the façade industry is the media façade. Assumed is the increase in popularity of adaptive and/or responsive building envelopes too. The driving force behind this is the zero energy building strategy for 2020. For now, the striving zero energy building skins are in full development and only assumptions can be taken of how it will express itself in the coming years. This chapter is dedicated to determine the growth of interest in the subject and based on the trends give an indication of how electrowetting will manifest in the façade industry.

7.1 Subject interest

As electrowetting could be part of a responsive or adaptive system, the interest in those search terms is monitored. There are more definitions in use, varying from adaptable, adaptive, adjustable, dynamic, flexible, intelligent, kinetic, movable, moving, polyvalent, reconfigurable, responsive, retractable, smart, switchable, etc. Which makes it less easy

There is clearly a growing trend in the number of scientific publications (Loonen, Trčka, Cóstola, & Hensen, 2013). In 2010 R. Loonen published a selection of 100 different climate adaptive building skins, in which every example is unique. The year each idea, building or building component was published is set out in the graph. The graph shows an increase of interest in the subject, although it does not say anything about the market size of adaptive building skins. The disadvantage of this strategy is that it does not take the amount of installed square meters into account, something that can increase rapidly for subsystems and components (i.e. electrochromic glazing). Next to an increase in scientific publications, only since recently there are held conferences dedicated to the topic (Adaptive building envelopes, 2014; World sustainable energy days, 2015). This only confirms the assumption of a growing market/interest. However does this say anything about the application of adaptive façades in practice? There is a thin line between naming it an adaptive façade or still referring to a traditional façade, for example traditional venetian blinds can be called adaptive too, for the fact that they open and close gradually. The boundary between a sunshade and openable window and an adaptive façade is not clear. Dependent on this definition the market share ranges from 0,000001 and a few tens of percent (Loonen, 2015). Specific for switchable glazing various reports of market development and predictions are stating that by the thirties of this century smart glazing has reached a turning point. The growing awareness is the most obvious reason to believe that the smart windows will grow out of their niche.
Chapter 5 started with a selection process for the different electrowetting applications. An important part in the selection process was your own perception in how much value you gave to the different criteria. This value was primarily formed by your position, i.e. as architect, investor, public organ, user, etc. In the design process it is important to realise that the total façade value is determined by all four aspects. It not only means that every aspect needs some attention during the design process, but at a certain point a choice has to be made which party should be preferred. The façade value is both dependent on the demand side as the supply side and dependent on the strategic value versus the organizational value. The choice is different for every building.

Especially for smart glazings there are market value researches, but unfortunately they are not yet made public. The front pages are indicating a fast growth from now on, because they all believe smart glazings is finally coming out of the niche. “See our upcoming 2013 report on Smart Windows After many years of being no more than a niche, the smart windows market now seems ready to take off. NanoMarkets believes that several factors are combining to make this happen. The most obvious perhaps is that there is growing awareness.” Navigant Research forecasts that smart glass glazing units will grow to just over 2.7 million m2/29 million SF by 2022” (Navigant Consulting, 2015). “Indeed, IDTechEx Research estimates that the value of this market will reach at least $700 million in 2024” (Gonzalez, 2015) and a last source to add to the list: Smart Windows Markets: 2014-2021, (2014).

7.2 Market value electrowetting

Electrowetting’s value in the façade industry depends on several aspects: first there is the need for user wanting to have it; then there is the need for the investor who will see a drastic increase in the value of the façade by the implementation of electrowetting. For implementing electrowetting in the façade will add significant costs. In the instance that the entire façade will be used as a display, the costs will still add up to over 1000 €/m2. Fabrication is comparable to that of traditional LCD-screens, and production costs will be similar as well.

The user, marketing and its sustainability all influence the value of the façade. In the end, they determine the profitability of the façade. The figure shows the relation between the performance criteria and determining the façade’s value. There is an overlap between aspects and these aspects can also influence one another.
Important for the user is a good view to outside, a comfortable temperature balance during the day and every season, no glare or other excessive lights, the right lighting ratios.

Wat is belangrijk voor de gebruiker van het gebouw? Dat de gevel een goed zicht naar buiten toestaat; dat er een comfortabele temperatuurswisseling is gedurende de dag en ieder seizoen; dat de gebruiker niet afgeleid of verblind wordt door vervelende lichtinval; dat er zo min mogelijk gebruik wordt gemaakt van artificial lighting en mechanical ventilation; dat een electronische gevel leesbaar is voor verschillende doelgroepen en dat het een makkelijke gebruikersinterface heeft zonder laad-tijden. Voor de gebruiker (not the owner or company of the building) is het energieverbruik, aanschafkosten en efficiëntie minder belangrijk. De gebruiker ziet het graag zo gepersonaliseerd mogelijk en wil liever geen one-size-fits-all solution.

For the user (not the company or owner of the building), the energy use, purchase costs, and efficiency are less important. He prefers a personalized system, rather than a one-size-fits-all solution.

For branding the organization, it is important for the façade to stand out visually; images of logos and text are sharp and have vivid colors; and animated scenes can be played smoothly. Less important, to the organization, though low energy costs are and user comfort are of interest.

The sustainable value is characterized primarily by energy efficiency, and every part in the lifecycle is reusable. The façade is also multi-functional, adaptive to different environmental circumstances and has the possibility for the software to be upgraded.

For the financial value, life cycle costs carry much significance. The façade should earn itself back within a realistic time period. The cheapest method is not necessarily the best when a more expensive method leads to an increase in market value.

7.3 Software development

Electrowetting technology isn't optimal yet, but prospects are that it will improve greatly. The exact grade of transparency is yet to be seen, however it will be good enough to compete with other types of transparent display or electronic glazing. Development of the technology should prove worthwhile.

The other aspect is software development. The question which rises is whether or not the sensitivity and accuracy of the sensors can be sufficient; will the system be fast enough to process all the information and send it to the façade; will the façade be able to respond to changes in the environment quickly enough? The simple answer is yes. However, the truth is more nuanced.

As was discussed with the subject of blinding, the problem lies not with the principle of protection against bright sunlight, but with determining when a person experiences hindrance from too bright light. The direction of view, the amount of sunlight, and the position of the person in relation to the window all determine whether or not a person experiences glare. It's probably not possible to offer protection against all sorts of glare, other than specular light. The technology should be applied much in the same as how a polarizing filter can filter this type of light. The advantage electrowetting has over polarizing filters, lies in the amount of light which can still be transmitted after filtering out the direct light: 70 up to 90 percent, versus only 50.
The figure illustrates the possibility for architecture students and companies to incorporate a person into the design. Judging if a person experiences glare now becomes very realistic. The example shows the use of a Kinect, which can very accurately register one’s location, but can also monitor one’s field of view. For the first time in architecture it will become very clear when someone experiences glare and when he does not. This on its own can be a field of study. Another aspect which these days can be calculated by software is sensitivity for overheating, simply by registering body temperatures. Type of clothing and body language can be monitored through camera. This information is then linked to the façade, which in turn can adapt the translucency and/or the ventilation. The following figure shows how the body temperature of a static person is used to change the translucency of the façade.

7.4 Future vision

The electrowetting forecast can be divided in a few time periods. Firstly, the near future, this years forecast, with a extending tail in 2016, is the development of electrowetting billboards. The next breakthrough will probably be right before 2020 with the liquid energy façade. The reason for this forecast is a publication from the Wyss institute in the United States and the fact that for example the company Fluid Glass (Fluidglass, 2015) is doing practically the same thing, only in other dimensions. The liquid façade is presented as one of the applications in Chapter 4: number 10, thermal energy transport. On the short term the shopping industry should be of interest for the electrowetting skin too. In Europe, the confidence of the consumer has only been increasing the last couple of seasons (European Commission, 2015). This economic indicator has been a reason to applicate other types of transparent displays into shopping walls and in changing rooms (to try on similar clothes to the one you are trying on).

In the coming years it will be a challenge to enter speech for the electrowetting skin as shading device. The reason for this is partially because it will be a luxur-
8. Conclusions

This research focused on the finding of applications for the electrowetting technique. Electrowetting is a common method to move or change the shape of liquids in chemistry. Typical applications are the electro-meter, lab-on-a-chip, photography and displays. This last application has gotten some interest from architects, because the electrowetting displays is fast enough for video play, could be made paper thin (suitable for renovation projects) and should reach a transparency rate up to 90%. Electrowetting has the potential to be a smart glazing.

Problem definition
Smart glazings have become interesting since people realized that (office) buildings from the international style are not performing accordingly. There are various contradictions noticeable with regard to the expectations and the realization of the building envelope. Such buildings have to be as transparent as possible, although with a lacking eye for the environment. Smart materials and coatings are developed to protect us from this, although unfortunately they are still in their infancy. This search has developed into a discussion about the responsive building envelope. A responsive building should go hand in hand with environmental influences, and with that a responsive building envelope is multifunctional, adaptive, dynamic and intelligent. The abundance of multimedia façades do not qualify as a responsive façade, as they lack certain requirements; moreover, the view to outside is blocked by the screens.

The electrowetting display versus others
The focus of this thesis was on the research for an innovative display technique that could also be a responsive façade. Similar to the electrowetting technique are other transparent displays. One of the interesting differences is its colour gamut, which is CMY(K) for electrowetting displays. The consequence is a potential better view during daytime then RGB displays, which are better viewable at night. Electrowetting displays are therefore very interesting for a sustainable façade with regard to the prevention of light pollution, it does not require an external light emitting source.

Highly potential applications
There are many different ways to use electrowetting in the building envelope. According to the functions of a building skin, it could be of influence of the comfort (shading and lighting potential), energy (regulation and generation) and the architecture (media façades and display walls). Unfortunately, not every building function was combinable with another, this was due to the type of mechanism it had to work on.
Four distinguishable variations to the electrowetting mechanism were found; the bistable mechanism, a single layer mechanism, a triple layer mechanism and a method that uses a combination of liquid prisms and liquid cells. Concomitantly, every technique has a different energy expenditure. Some of the applications are more interesting than others when comparing the energy usage to the frequency a building function would be operated (secondly, hourly, monthly, etc.) at. Two types of applications stand out: the application as media façade and marketing/retail façade and the light regulation applications that are dealing with forms of excessive light forms. The media façade is highly consuming energy, this is not a sustainable solution. The excessive light reduction applications include glare protection, dealing with high contrasts and light directing systems. Their energy consumption will probably be smaller, because only a small part of the whole façade needs to be activated. It is less suitable, but still attractive as traditional shading, because covering the whole façade is comparable in yearly energy usage with the reference building. The energy performance showed it will be more energy consuming during the summer period and less energy consuming during the winter period.

Lifecycle
The lifecycle and production method of electrowetting displays is comparable with that of LCD screens. The advantage of this is that mass production is easier to execute, but the disadvantage is that electrowetting is another smart technique that is not as sustainable in production as it could/should be. Another drawback of the electrowetting skin is the production of large glass areas. This issue is currently being addressed by subdividing the panels into segments.

Display findings
If we would set out the distance to the display versus the size of the display, you will notice that only a very high resolution is needed for displays at a short viewing distance. A high resolution is more commonly desired indoors and low resolution displays are more suitable for outdoor usage, although there are some exceptions. The largest pixel size of an electrowetting display is ~1 mm. Due to this relative small size, electrowetting has greater potential for indoor usage and higher resolution displays. By combining multiple pixels, the complexion of installation is reduced, which makes it still interesting in the urban environment.

Market strategies
To mention one in many characteristics, the personal lighting and shading applications with a transparency rate between 0 and minimal 70% and the fact that it does not require an external light emitting source is of value for a highly competing marketing strategy. Compared with other types of transparent displays, electrowetting is one of the most sustainable. The reason not to choose for the electrowetting technique for the building envelope is because there seems to be a slight hold on the development for building skins. The last publications date from 2012, the reason is unclear. An investor should not choose to use electrowetting only as just a solar shade, its potentials as smart glazing are undermined. The solar shade should be in cooperation with an excessive light reduction application or as personal shading. Unfortunately, more research is required on both applications to visualize its energy performance. All that can said about it is, that it will be a significant reduction in energy usage and an increase in comfort due to less artificial lighting, less mechanical ventilation and more solar heating.

Forecast
The applications that will be arriving on the market soon are the billboard and the application of heat transport with connected micro-capsules to a heat exchanger. The relatively slow development of electrowetting has limited its position in the expanding highly competitive technology retail market. However, the building envelope market is embracing all smart glazings that are being developed (Favoino, 2015). Therefore, the light and shading regulation applications are very promising market wise. Only more research is required with regard to its behaviour towards daylight.
9. Recommendations

This chapter contains recommendations for further research in order to improve our understanding in the electrowetting technique and to expand our knowledge of electrowetting as a smart glazing.

Electrowetting as smart glazing
The actual sizes, shape and performances of an electrowetting skin are based on the implementation of the electrowetting displays. The quantitative research is not based on experiments with physical electrowetting glass. This should be the first step to determine further the characteristics of electrowetting. As of today, data of the g-value, visible transmittance, U-value, etcetera have not been published and have been estimated throughout the paper.

Mechanism
The distinguishable different mechanisms were optimized for separate functions. The bistable mechanism for indicators, the triple layer for displays and the liquid prisms and lens mechanism for light directing purposes and photography. The single layer mechanism should specifically be developed for the façade or shading system.

Material
The single layer mechanism is next to the bistable method a good solution for personal shading. The next step in this process is a material research and the optimization of the voltage levels versus the volumes of the liquids and/or vapour. Liquid and material selection is a necessary requirement for all applications. Another example is finding the right infrared absorptive dye or rather a reflective dye (if that even exists), this is a whole study on its own.

Building considerations
At the moment it is not certain what kind of influence and alterations an electrowetting façade must undergo to perform at certain types of buildings. There is a risk of freezing and a chance on overheating on sunny days. The proven functioning temperature range is between 0 °C and 60 °C. The problem might be solved with another liquid choice or the adding of anti-freeze.

Another building issue is the lighting effects. First of all, liquid lenses can create a focal point which potentially can start a fire. Whether this is true or not, has not yet been researched. Lenses do show the effects of dispersion and light bending, what this means for the buildings appearance needs some real considerations.

Maintenance
As with other screen types, the question still remains what should be done when
it has a death pixel. The current solution for all types of displays is a replacement. Display façades are more expensive to replace, caused by their larger dimensions. Unfortunately, this solution is not for the benefit of its sustainable value. The production process and recycle process needs a sustainable interference.

**Large area glass panes**
Subdividing large area glass panes should not be the final solution to solve the production problem. All in all, we live in a world that has to be bigger and brighter in every aspect. If subdividing is the answer, then the recommendation for further research focuses on the architectural impacts this has.

**Urban context**
Electrowetting as transparent display façade will be a whole new type of cladding in architecture. How it will influence the urban context has yet to be revealed.

**Software**
Performance research of smart glazings is limited by the software. There should be developed a calculating program that gives the energy levels in a room for different shading systems for the same window (think of personal shading glazings). The software is also limited in finding the chances on glare.


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fig. 20  logo brands


fig. 29  http://spie.org/sb6770.xml


fig. 33  http://www.onlineondeerden.shop.nl/blog/samsung-en-lg-smartphone-displays-goedkeuper-nieuwe-oled-technologie/

fig. 34  http://www.engadget.com/2012/08/30/samsung-22-inch-transparent-showcase-panel-eyes-on/


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Acknowledgements

Sincere gratitude is hereby extended to the following who have helped constructing this thesis. Thank you all very much for every input you have given.

My main mentors, Dr.-Ing. T. Klein and Ir. E.R. van den Ham

The enthusiasm of my external supervisor

My external advisors, H. Feil, H.E.E. van Asbeck and Dr. Ir. V. van Steijn

The very helpful men from the informatics design department at the faculty

My friends, family and fellow students, Yannick, Pasquale, Nick, Nico, Mark, Colleen, Ruud, Karin, JanC., Bas, Luuk, Reinier, Anne, Wendela and Ralf.
Appendix A

The images are recreated from an experiment in the late 1800s by Lippmann. A translation of this experiment is given in the appendix of Mugele and Baret (2005). The goal for this experiment was to change the surface tensions of the droplet. For the preparation you will need a metallic plate, some vaselin, a salt solution, voltage meter, cables and a high voltage regulator. The aluminium plate is greased with the vaselin for a nice insulating layer. As thin and flat as possible. The droplet is of a salt solution and was dripped on the plate. A metallic point of the cable is sticking in the droplet. Apply gently a voltage until the droplet changes its shape.
Appendix B Sugar water

A refractometer measures the extent to which light is bent (i.e. refracted) when it moves from air into a sample and is typically used to determine the index of refraction of a liquid sample. The refractive index is a unitless number, between 1.3000 and 1.7000 for most compounds. Before the refractometer existed the refractive index was measured with a sugar solution. This method is repeated in this appendix. The image shows a perspex plate with unknown refraction index. The flower card is only there to distinguish the effects. Three different sugar solutions are added on the perspex. The following images show that by turning the camera from a top view to a side view at one point the droplets will not be visible anymore. At first the left droplet disappears, this was just regular water. The middle droplet is also disappearing, but the last droplet seems to have the same refractive index of the perspex. The sugar solution was around 90% sugar. With the angle in which the picture was taken, is used to calculate the refraction index of perspex of 1.47. This was close to the actual refractive index of perspex: 1.495.
## Appendix C Input for the selection program ‘guess who?’

<table>
<thead>
<tr>
<th>Building function</th>
<th>Theme</th>
<th>Application</th>
<th>Location specifications</th>
<th>System and control methods</th>
<th>Climate</th>
<th>Display preferences</th>
<th>Other</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Orientation on the northern hemisphere</td>
<td>Façade section</td>
<td>Building height</td>
<td>Mechanism</td>
<td>Operation factor</td>
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<td>ground:upper:N/A</td>
<td>single:bistable</td>
<td>all</td>
<td>second:hour</td>
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<td>anti-glare solution</td>
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<td>transparent:N/A</td>
<td>ground:upper:N/A</td>
<td>single:bistable</td>
<td>auto</td>
<td>second</td>
</tr>
<tr>
<td>light shadings</td>
<td>luminance ratios</td>
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<td>transparent:N/A</td>
<td>ground:upper:N/A</td>
<td>single:bistable</td>
<td>auto</td>
<td>second:hour</td>
</tr>
<tr>
<td>light shadings</td>
<td>mood, health &amp; light therapies</td>
<td>all</td>
<td>transparent:N/A</td>
<td>ground:upper:N/A</td>
<td>single:bistable</td>
<td>auto</td>
<td>second</td>
</tr>
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<td>transparent:N/A</td>
<td>ground:upper:N/A</td>
<td>single:bistable</td>
<td>all</td>
<td>hour:day:season</td>
</tr>
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<td>Group shading</td>
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<td>ground:upper:N/A</td>
<td>single:bistable</td>
<td>all</td>
<td>hour:day:season</td>
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<td>ground:upper:N/A</td>
<td>single:bistable</td>
<td>all</td>
<td>hour:day:season</td>
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<tr>
<td>Energy</td>
<td>Thermal energy transport</td>
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<td>ground:upper:N/A</td>
<td>single:bistable</td>
<td>all</td>
<td>hour:day:season</td>
</tr>
<tr>
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<td>N/A</td>
<td>N/A</td>
<td>triple</td>
<td>auto</td>
<td>all</td>
</tr>
<tr>
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<td>north</td>
<td>opaque:transpar:outdoors</td>
<td>N/A</td>
<td>triple</td>
<td>all</td>
<td>all</td>
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<tr>
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<td>all</td>
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<tr>
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<td>all</td>
<td>all</td>
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<tr>
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<td>Privacy versus open for public</td>
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<td>opaque:transpar:outdoors</td>
<td>N/A</td>
<td>triple</td>
<td>all</td>
<td>all</td>
</tr>
<tr>
<td>Architecture</td>
<td>display architecture</td>
<td>north</td>
<td>opaque:transpar:outdoors</td>
<td>N/A</td>
<td>triple</td>
<td>all</td>
<td>all</td>
</tr>
<tr>
<td>Architecture</td>
<td>Personal routing</td>
<td>north</td>
<td>opaque:transpar:outdoors</td>
<td>N/A</td>
<td>triple</td>
<td>all</td>
<td>all</td>
</tr>
<tr>
<td>Architecture</td>
<td>choose technique other than electrowetting</td>
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<td>opaque:transpar:outdoors</td>
<td>N/A</td>
<td>triple</td>
<td>all</td>
<td>all</td>
</tr>
</tbody>
</table>
Appendix D settings for performance study

The settings to compare a traditional shading with the electrowetting only glare shading were put in Orca. The following images are print screens of the tabs for building characteristics in Orca.

fig. 77. Context tab: Netherlands; office building; calculate the winter period

fig. 78. Space tab: Square office; l:w:h 6000:3600:2800 mm; orientation: south

fig. 79. Walls: only wall 1 outer wall; max. glass area: 3400:2600; reference building glass type HR+; Switching shading system

fig. 80. Use own glasstype: electrowetting glass U:1,2, ZTA & LTA: 0,70, CF 0,05; with shading: ZTA & LTA: 0,68 (97% of 0,70)

fig. 81. Usage tab: persons 25W/m²; lighting 300W, switching; utilization hours: 8AM to 6PM

fig. 82. Natural ventilation: by grills & slits: standard 0,2 per hour; windows always closed

fig. 83. Installations: mechanical ventilation: optimized to 4x fresh air/hour, no recirculation; only heating, temperature set on 21 °C
Appendix E The Kinect for future designs

The X-Box, Kinect, iPhone, Oculus Rift, and much more will be making a difference in the design process of buildings. As they were intentionally meant to use for gaming and other interactive activities in front of your TV screen, they become interesting in architecture too. A virtual reality is what we have intended to build with physical models and virtual models. It is possible to add another dimension to it. Just awesome. The Kinect is used for this thesis too, to show you how easy it is to use tracking data from the camera into the design, to get a much more realistic image out of it. The original idea was to use Arduino and a robot too, to move parts of the electrowetting prototype. Unfortunately, electrowetting is too advanced to be built in your own office.

The images show a photograph of the Kinect with tracking sensors and a camera, the next image is the grasshopper model in which the tracking information is compared with the movement of the sun and the amount of lighting hours. The result is seen in the last image, this one shows a Rhino model of an electrowetting façade that is protecting the person from glare.

Fig. 84. The Kinect from the Xbox 360 for the design process

Fig. 85. Sun at a low angle: 3th of December, around 12:00 o’clock. The person is protected from glare.
Appendix E E-mail conversations

Van: F. Favoino (ff279@cam.ac.uk)
Verzonden: woensdag 13 mei 2015 11:07:50
Aan: Maaike de Haas (maaike.dehaas@hotmail.com)

Dear Maaike,

thank you for your email. Yes I could definitely be interested with the electrowetting technology, so please if you have some sort of state of the art for your graduation project, or some references, send it through so that I could have a more detailed understanding.

As far as the calculation of the g-value is concerned, unfortunately just knowing the variable visible transmission range is not enough to calculate it. The required data to calculate it are the absorption coefficient (or reflection coefficient) and the transmission for both the part of the solar spectrum (visible and total). Therefore at the moment you have just one of the four data you would need. Moreover the g-value strongly depends on other factors, such as the U-value of the glazing (therefore the emissivity of the glass surfaces and the glazing cavity properties), and the boundary conditions (taken from standards).

If you are able to retrieve some more data about the technology I could be able to help you out in calculating the g-value. In fact if you only have the visible and total solar transmission you could do some hypothesis about the variability in the absorption and reflection, and calculate a range of possible g-value. Knowing of the switching mechanism of this technology works could also help in elaborating these hypothesis.

Moreover just keep in mind that the graph I showed is not describing which technology is the better than another, because this is dependent of the context (such as type of building and occupation, climatic context, type and control of HVAC). Therefore it is only useful for a comparison in order to understand if the technology could compete with other adaptive glazing technologies, but it cannot say much about its performance when building integrated.

Best regards
Fabio

On 2015-05-12 14:27, Maaike de Haas wrote:
> I have become curious of your work since the façade conference in Luzern and I am using your graphs of g-value vs. T-vis to determine the potential of electrowetting for the façade. Electrowetting is a technique that could be the next generation transparent displays or it could be used as an adaptive glazing. It is my graduation topic at the TU Delft, faculty of building technology. I'm not sure if the technique is competitive enough against other adaptive glazing types, because I don't know those values.
>
> I remembered you were asking for more case studies at the conference, and maybe this is a long shot, but I hope you are able to help me by filling in some blanks about electrowetting.
>
> My knowledge is based on the information I got from the display industry and they state that the light transmittance can go up to a 70% transparency rate (in the future maybe 80%) and a minimum of 0% light transmittance. I believe they are talking about visible light.
>
> Maybe, you have been able to predict g-values/t-vis/u-values of certain materials/techniques by comparing it with all the other types, or maybe this is just a crazy idea. I am definitely interested in your answer.
>
> If you are interested in this topic and are able to help me with my research I'm happy to provide you more information about electrowetting!
>
> Thank you in advance,
> sincerely,
>
> M.I. (MAAIKE) DE HAAS
>
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> TU Delft | Faculty of Architecture
> T +31 (0)642418100
> E maaike.dehaas@hotmail.com
> A Oost-Indiëplaats 76, 2611 BT Delft

--

Fabio Favoino
Glass and Façade Research Group
University of Cambridge
The following mail conversation is with Roel Loonen from the University of Eindhoven. I was asking him about the monitoring of smart glazings. I was interested in his thesis: the 100th CABS overview and his pinterest page that he is still updating.

Van: Loonen, R.C.G.M. (r.c.g.m.loonen@tue.nl)  
Verzonden: donderdag 12 mei 2015 20:47:37  
Aan: Maaike de Haas (maaike.dehaas@hotmail.com)  

Beste Maaike,

Een interessante vraag, maar het is lastig om daar een pasklaar antwoord op te geven. Hierbij een aantal overwegingen:

- Zie de volgende link voor een overzicht (incl. jaartallen) van 100 CABS voorbeelden: https://dl.dropboxusercontent.com/u/9527295/RCGM_Loonen_CABS_Appendix.pdf. Dit overzicht stopt in 2010 en is dus niet echt meer actueel. Verder zegt het niets over bijvoorbeeld het aantal geïnstalleerde vierkante meters dat bij bepaalde concepten in de categorie subsystems & components (zoals bijv. electro-chroom glas) snel kan oplopen.
- Er zijn heel veel definities en benamingen in omloop: adaptable, adaptive, adjustable, dynamic, flexible, intelligent, kinetic, movable, moving, polyvalent, reconfigurable, responsive, retractable, smart, switchable, etc. Dit maakt het er niet makkelijker op.
- Waar ligt de grens? Wanneer noem je het zonwering of te openen raam, en vanaf welk punt wordt het een adaptieve gevel? Afhankelijk van deze definitie schommelt het marktaandeel tussen 0.000001 en enkele tientallen procenten.
- Adaptieve gevels spelen best een belangrijke rol in recente technology roadmaps van o.a. IEA, US DoE en de EU. Een extra bevestiging dat de trend niet dalend is?
- Wellicht vind je ook nog meer info bij relevante brancheorganisaties zoals VMRG, Romazo of ES-SO?

Hopelijk biedt dit wat aanknopingspunten.

Ik ben altijd geïnteresseerd in meer informatie en innovatieve ideeën over de toepassing van adaptieve gevelconcepten. Het zou fijn zijn als je me t.z.t. je afstudeer-rapport kunt toesturen (wanneer verwacht je klaar te zijn?). Mocht voor die tijd mijn input nog ergens nuttig van pas kunnen komen, dan kunnen we natuurlijk altijd bekijken wat de mogelijkheden zijn.

Groeten,
Roel
R.C.G.M. Loonen
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