The PolyArch potential

Finding the architectural and energetic potential of a responsive cholesteric liquid crystal glass coating for reflecting (parts of) the sunlight spectrum

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Graduation phase:	P5

Preface

Dear reader,

This report is the conclusion of my graduation research, conducted in the studio of Building Technology at the TU Delft. Starting with a theoretical background, which contains the research's relevance and the gained knowledge from literature studies, it continues with the new research that originated from this, which is subdivided in the investigation into possible applications, the simulation of one of them and the development of a proof of concept design based on this application. The conclusion contains recommendations for the coating development and its use in the design process. I want to stress the importance of the appendix, since this contains more detailed information about some of the chapters in the report such as the simulation description, as well as a number of enlarged images. At the end of the appendix, you will also find the reflection on the graduation process that is compulsory to complete the P5 phase.

The graduation is part of a research proposal by the TU Delft and the TU Eindhoven, called PolyArch. By this name I will also refer to the coating of which the properties and functionality are being investigated in this research. The whole research proposal is intended to run for at least two years, of which this graduation research is the exploratory, initial phase. Therefore, this document may also function as a knowledge base for future research on the PolyArch topic.

The report will present two architectural solutions for the implementation of the PolyArch coating on glass louvres, which may or may not be tilted in winter (more about this can be found in the simulation chapter). Simulation results are presented that are obviously not definitive yet, given the phase of this graduation project in the total research, but present various useful clues on the use of the coating and the direction of future research. To calculate the coating's transmission with any bandwidth or coating configuration, an Excel file has been created which can be used for future research as well. The basic method of this file has been presented in this report, the file itself has been included in the digital appendix, in which also the simulation files and consulted literature have been included.

Finally a remark about the research process, because due to unexpected circumstances at the end of my P2 phase, my graduation topic is shared by another student, Guido Lammerink. This has led to a cooperation until P3, which allowed me to broaden the scope of my research, but therefore also required several adjustments of the research that was proposed during my P2. Whenever I talk about researchers as "we", I refer to Guido Lammerink. It must be remarked that all the work in this report is original, unless references indicate otherwise.

Tom Bouwhuis

Image on front page: Impression of the architectural application of the PolyAch coating on glass louvres (own image).

Acknowledgements

In the process of researching the PolyArch coating I received professional support in many directions from various people, to whom I would like to express my gratitude for their role in conception of this graduation research.

First of all I want to thank my mentors Tillmann Klein and Eric van den Ham, and Guido's mentor Truus de Bruin-Hordijk for the motivation and critical feedback they gave during the entire process. The discussions we had as a group every two weeks ensured a continuous progression with a steady direction.

Secondly I thank Guido Lammerink for the many discussions we had about everything related to the application and assessment of the coating. Although the cooperation was unexpected, the results were certainly beneficial.

To Dick Broer and Michael Debije I want to express my appreciation for their explanation of the functionality of the coating, and for providing data that was required for doing simulation.

Furthermore, I thank Roel Loonen, PhD student at the TU/e, for answering several questions about the design of the simulation in TRNSYS, and helping to get started with the software.

Finally, I am thankful to Thim Zuidwijk, research engineer at the Optics group of the faculty of Applied Sciences at the TU Delft, for his enthusiastic cooperation with the invention and setup of a testing arrangement in which transmission of the coating samples could be measured.

Summary

Increasing interior comfort standard, rising energy prices, a tendency to use large glazed surfaces in architecture and growing environmental awareness are several important reasons for the use of sun shading. Ideally, a sunshade should sustain a comfortable interior climate by controlling the solar energy transmission through a window, with the smallest energy consumption possible, and at the lowest price possible. Until this moment, there has not been invented a sunshade which fulfils these requirements ideally. Interior shading devices and most glass coatings lack efficiency, while exterior shades face high maintenance costs.

This is why a research proposal is made to investigate the potential of a new kind of glass coating called PolyArch coating, which is based on liquid crystal technology. The coating can be switched on or off and is spectrally selective. Suitable applications need to be found, and their efficiency and architectural potential needs to be investigated. In this report, the energetic and architectural potential of the PolyArch coating on a specific application, namely exterior static glass louvres, will be elaborated on.

Other applications with a possibly high potential, that are worth further investigation are a direct application on the window glass, the application on ETFE cushions and the application on light weight constructions. The first mentioned application works by controlling visible and NIR light transmission separately, allowing optimising the optical quality of the window and the solar energy transmission. The second application is based on the light weight nature of ETFE cushions, and their high light transmission which in most applications inevitably calls for sun shading. The last mentioned application is based on the absorption of solar energy by a light weight construction like a roof structure, which may start to radiate heat to the interior once it is heated up. This is comparable to already existing switchable roofs, which can switch between white and black depending on the surface temperature.

The energetic performance of the coating as a reflector of solar energy is very good, and comparable to conventional venetian blinds even in the 60% ideal performance (to which it must be remarked that this 60% is more an indication of hierarchy between the coatings than an actual direct 40% worse transmission). The transmission of solar energy when this is desired is much worse however, because of the relatively low transmission of the glass louvres. There seem to be proper methods to improve this solar transmission in winter however, such as tilting the louvres to a horizontal position at the beginning of the heating season. The lighting energy requirement may be important for the PolyArch coating, since it can reflect solar energy while transmitting visible light, thus having an advantage over shading devices such as venetian blinds. The larger the influence of the lighting on the total energy consumption, the larger the advantage of using the PolyArch coating will be.

The architectural potential of the coating is large, since the glass louvres can become a permanent part of the architectural language while preserving the transparent nature of a glass facade when possible. When the coating is reflective, it could enhance the facade's geometry, but may also create patterns or even images on the facade. These images can be white or coloured, creating a seemingly endless possibility of combinations, able to act up to the architect's creativity.

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1. Introduction

1.1 Problem introduction

1.1.1 Societal and scientific relevance

The scientific and societal relevance of this research is directly related. Since the 1970's the interest in coating technology (and other ways to control solar transmission through glass) has assumed large proportions, with the oil crisis acting as a direct catalyst. Ever since, scientists have tried to find ways to make glazing more energy efficient. Partly because of professional interest, but surely stimulated by the societal need for the reduction of energy consumption.

The depletion of fossil fuels and the concern for the future of the earth and the next generations inhabiting it are of course reasons for this interest in less energy consumption, but also for those who care less about what effect their actions have on the world, the increasing energy prices will still be enough motivation to keep considering methods to reduce energy consumption.

The amount of energy that reaches the earth through sunlight is very large, as will be explained in more detail in the next paragraph. Since windows are inevitable in most building functions, this energy can easily enter buildings, providing free light and energy. Sometimes this energy is desired, but at other times it increases the cooling demand, resulting in higher energy consumption. Solar heat gain through windows is often the largest cause for the need for cooling (Selkowitz and Lampert, 1989). To make this effect worse, facades often display much more glass than what is necessary to create a well-lit indoor environment.

Figure 1: Although around 30% glazing would suffice to provide optimised natural lighting, architects often prefer larger glass areas. This shows the Post tower in Bonn, by Helmut Jahn(Sobek, 2013).

A window area that is 30% of the wall area would result into a light intensity of 500 lux on desk level for 76% of the annual working time. Increasing the windows to let in more daylight will not make the energy balance more efficient (Tzempelikos and Athienitis, 2007). However, this is based on the characteristics of the Canadian city Montreal, but since this city's latitude is almost the same as that of the Netherlands, the results will be similar. For the exact data however, simulated testing is necessary.

Several methods to control the transmission of solar energy have been invented, but very few are able to limit the transmission when it tends to cause overheating, and also allow this free energy to enter when the building needs to be heated. Up to now, no coating has been produced that can do this satisfactorily, so developing one that could would be a big step forward. It would create new possibilities for architects, who are not necessarily needing to integrate visible shading anymore. The maintenance costs for shading in high rise could drop drastically, and these are just some of the possible applications of a well developed PolyArch coating. The question is, will it be possible to develop such a coating, and if so, how efficient will it be compared to other coatings. That is why this graduation research is necessary, since it enables further research on this topic, being an exploratory investigation for the PolyArch research, which will continue for at least two years.

1.1.2 The solar spectrum

Sunlight that travels to the earth is emitted in a large variety of wavelengths. Since man was the one who categorised these wavelengths, they are depending on what is visible to the human eye. When ignoring irrelevant wavelengths like x-ray, gamma, microwave and radio, there are three types of wavelengths: visible light, shorter than visible light (UV) and longer than visible light (IR).

Visible light is defined as wavelengths from 380 nm (nanometres, or one millionth of a millimetre) to 780 nm. This goes from short wavelengths like purple and blue to larger wavelengths like orange and red. Shorter than 380 nm is called ultraviolet (UV). It can be seen in the graph below that the horizontal scale does not start at zero, but at 250 nm. This is because the wavelength of the shortest kind of UV light (UV-C) is filtered out by the ozone layer and therefore does not reach the earth's surface (Brennan and Fedor, 2001). Longer wavelengths than 780nm are called infrared light. The part of infrared light between 780 and 3000 nm is also called near infrared (NIR). Typical about the infrared part of the spectrum is the inconsistent line that represents the energy in this area that reaches the earth. The graph mentions the molecules that are responsible for filtering these wavelengths (Renckens, 1998).

The solar energy that reaches the earth through sunlight amounts to almost 1018 kW/h per square meter. More than half of this energy is radiated as infrared light (for the exact distribution, see the graph). A little less than half is radiated as visible light, and only a very small percentage reaches the earth as UV light. This means that when is coating is designed to reduce the amount of solar energy that is transmitted through a window, it is wise to first focus on the infrared light, and if necessary on the visible light as well (although this also has consequences that will be discussed later in this report). UV light does not have much influence, especially since most of it is already filtered by normal float glass.

UV light can be subdivided into three different groups, based on their wavelength: UV-C (100-280 nm), UV-B (280-315 nm) and UV-A (315-380 nm). Even though their energy level may not be as high as that of infrared and visible light, their importance for glazing coatings must not be underestimated. Only the latter two are able to reach the earth's surface. This part of the solar spectrum may not contain a large share of the total energy, but the damaging effect it can have on window coatings is considerable (Brennan and Fedor, 2001).

The shorter the wavelength, the smaller the chance that it reaches the earth's surface, because it is filtered out by pollution, clouds and atmospheric gasses. This is why the UV level that reaches the earth's surface is so much lower in winter, since the sun is low above the horizon so the path that the light has to travel is longer. The UV radiation that does reach the surface can cause damages to polymers in coatings, UV-B being more severe than UV-A. Each polymer has its specific critical wavelength. Radiation with a wavelength smaller than this criterion will deteriorate the polymer, radiation with larger wavelength will not have any effect (Brennan and Fedor, 2001).

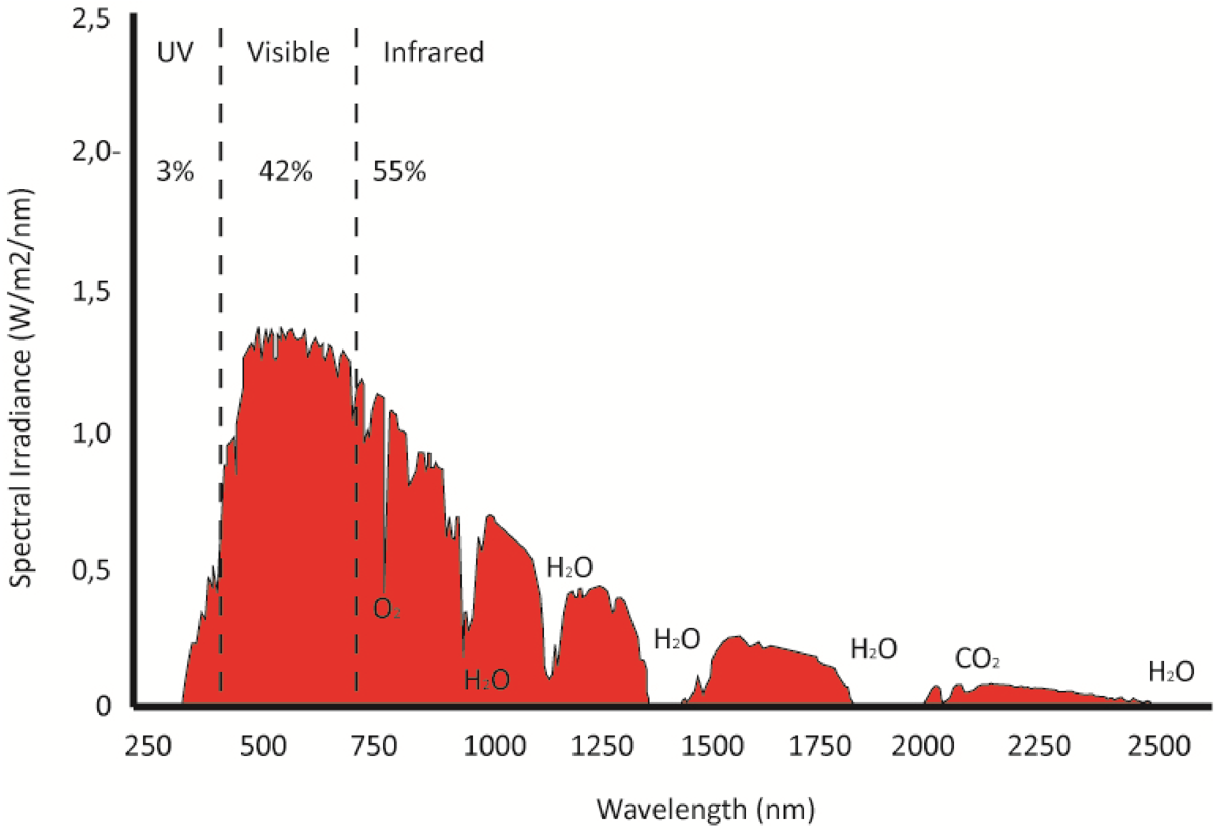


Figure 2: The distribution of solar energy that reaches the earth's surface. The graph includes the exact share each wavelength type has in the total solar energy. Own image based on (Rohde, 2007)

The selectivity index (SI) is the relation between light transmission factor T_{La}, which is the amount of (visible) sunlight transmitted, and the absolute solar energy transmission factor SET_a, which does not only include the visible light transmission but also that of infrared and ultraviolet light. A low SI usually means that much of the solar energy is transmitted by the window (i.e. if the visible light transmission is high), while a high SI indicates that much of the solar energy is blocked, because almost all the energy is transmitted in the visible part of the solar spectrum (Renckens, 1998).

Another, more common way to describe the heat transmission through a window is the g-value. This is the ratio of visible light to transmitted solar energy through a window. This is just an approximation however, because the g-value is calculated at near-normal incidence, while the transmission of glass changes with the angle of incidence. It is therefore more appropriate to work with angle dependent g-values, but this is not common practice (Kuhn et al., 2001).

To find the real transmission values of a glass type in order to calculate the angle-dependent g-value, there are a number of methods. For monolithic materials, it is possible to find the values for inclined irradiance using the refractive index of the material. With Fresnel's equation it is possible to find the other values with this refractive index. Once more than one refractive index are combined, for example in coated glass, this method is not valid anymore. For this purpose, models have been calculated for many different types of coating (Rubin et al., 1999). However, for the PolyArch coating this has not been done yet, so its angle-dependent g-value has to be determined differently.

Many ways to control sunlight penetration available, some more effective than others. A standard needs to be set to determine how well the PolyArch coating should perform and thus how much it may cost to be a competitive product compared to similar products.

1.1.3 Ideal coating

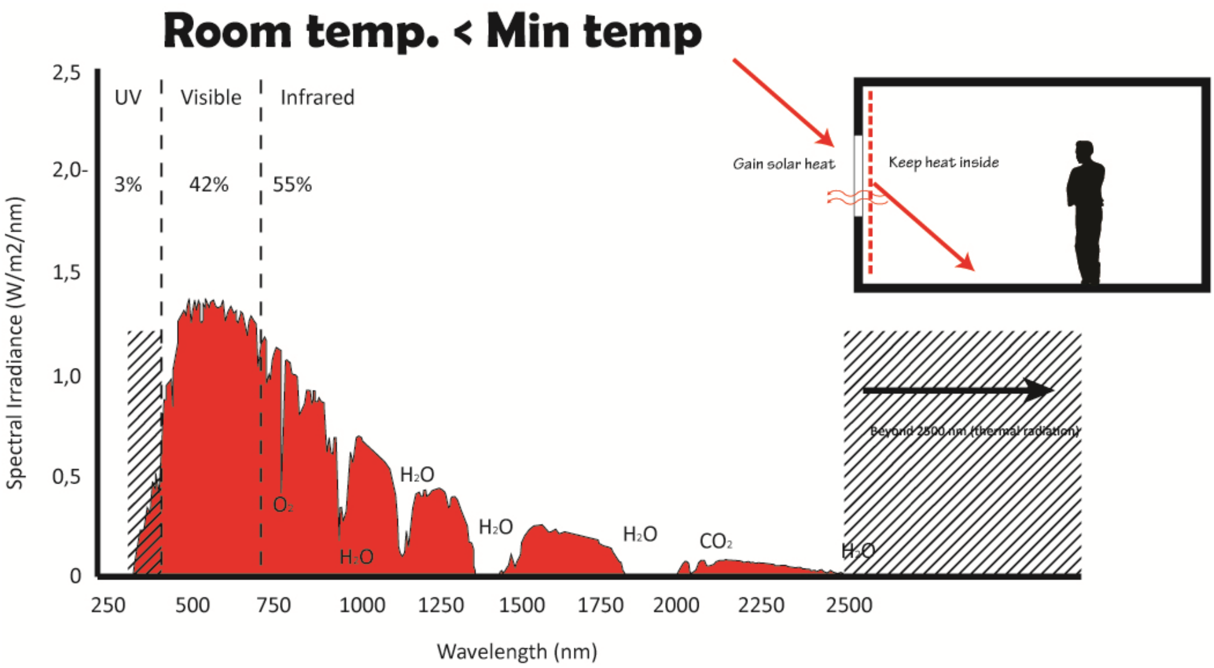


Figure 3: When the interior temperature is below the minimum allowed indoor temperature, the coating should enable heating by sunlight, so solar energy is transmitted, while thermal radiation is blocked so it will stay inside the room (own image.

Of course the perfect coating is the holy grail in coating technology. Although it may seem unrealistic that a coating is developed that actually is perfect, it is necessary to know what the highest goal is to know what the requirements are for a good or, if possible, for a perfect coating. What is ideal depends on the circumstances, and the situation that applies in this case is energy saving by controlling sunlight transmission through glass in a temperate climate. Such a climate means that at certain times, the coating should help to keep the building cool, while at other times it should facilitate heating of the space.

Each interior climate has an maximum (T_{max}) and a minimum (T_{min}) temperature, above or below which the room is considered uncomfortable. For the coating this means that when the interior temperature is below T_{min}, the coating should support heating of the room. Incident sunlight should be transmitted as much as possible, as this is a free source of heating energy.

Thermal radiation on the other hand, or blackbody radiation, caused by the fact that every object emits energy characteristic to its material properties and temperature, should be reflected back inside. Although it is unlikely that in such an occasion the exterior temperature is higher than the interior temperature, it should be noted that the inwards reflection of blackbody radiation should only take place when the outside temperature is lower than the inside temperature.

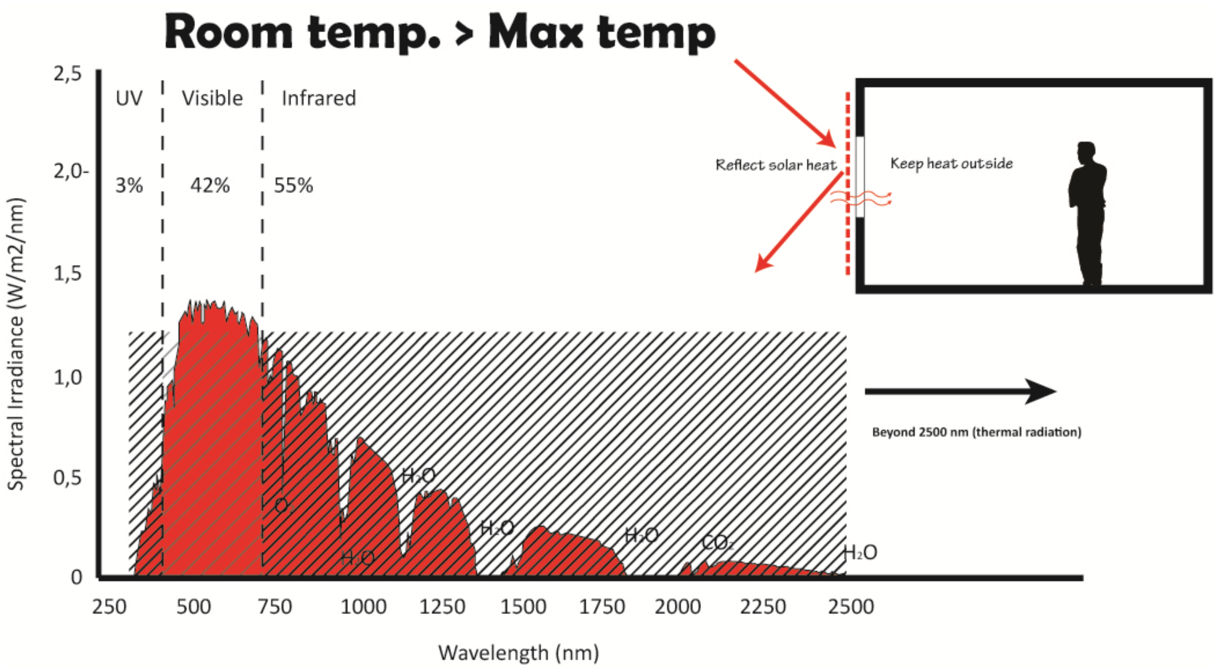


Figure 4: When the interior temperature is above the maximum allowed indoor temperature, the coating should prevent solar gain. Therefore NIR is reflected (and if necessary some of the visible light as well), but thermal radiation is transmitted so excess heat can leave the room (own image).

When the interior temperature is above T_{max}, the opposite should take place. Infrared radiation needs to be reflected, so it cannot heat the interior. Heat that is already inside, because of people working there, or because of equipment or lighting which produces heat, should be transmitted to the outside, but again only if the outside temperature is lower than the inside temperature. Otherwise the heat flow would be directed inwards.

When the room temperature is within the set boundaries, the coating does not have to 'act' to create a comfortable indoor climate. However, to avoid rapid undesired heat gain or heat loss, it would be wise to have the coating respond to the outside temperature even when the indoor temperature is comfortable. This would mean a heating scenario with a low outside temperature, and a cooling scenario with a high outside temperature. By doing so, the coating helps to prevent exceeding of the minimum or maximum temperature.

1.2 Research strategy

1.2.1 Research objectives

In conclusion, the problem that motivates this research is the critical use of energy. This raises the question whether the energy consumption in buildings can be reduced. In sunlight controlling coating technology, this can be done by reducing the combined energy needed for heating, cooling and lighting a building. Possibly the PolyArch coating can become a useful innovation that enables us to reduce the required energy significantly. Therefore we must know how well the PolyArch coating performs compared to other competitive coatings. This brings us to the main research question:

What is the energetic and architectural potential of the PolyArch coating in various heat-related applications, compared to competitive shading techniques?

To answer this question, several sub-questions are formulated here:

- What are suitable applications to use the PolyArch coating?
- What would be an adequate program to calculate the efficiency of the coating with?
- How would the coating be applied, considering the maximum bandwidth of the spectral reflectivity?
- What would a facade that uses this coating look like? (are there any implications that architects should take into account?)

The focus of the main research question is on five key points, which are 'energy', 'architecture', 'PolyArch', 'heat' and 'competitive'. 'Energy' and 'architecture' define the direction in which the potential will be sought. 'PolyArch' indicates around which specific coating this research revolves. 'Heat' means that only heat transmission will be taken into account for the energy calculations, rather than looking at daylight optimisation as well. 'Competitive' shows that the performance of the coating will be provided with context by looking at other products' performance.

1.2.2 Methodology

The research starts with a literature study to get familiar with the several coatings that are currently available in the field of architecture, with the chemical principles behind them, especially with the newly developed coating and its functions, and to compare their functionalities. Furthermore, I familiarise myself with the way in which the PolyArch coating works. The results are compiled in a brief but detailed overview of competitive coatings and the PolyArch coating, explaining common characteristics like the reasons for their (lack of) success and functional application possibilities.

This serves three purposes: firstly it enables the investigation of various applications of the new coating (for which understanding of its functioning is necessary), secondly it provides insight in which coatings that are already available are the closest related to the new coating, thus would form the competition and benchmark for the new coating (which is necessary to compare the new coating to in the computer simulation, because not every single coating can be tested and compared). Thirdly and lastly, the summarized literature will also form a knowledge base for further research that is part of the overall two year research proposal. This means giving a description of the available coating techniques to control sunlight penetration, including their benefits and drawbacks.

Figure 5: Scheme of the method of research that was pursued during this graduation. It also gives an outline of the main topics that were addressed during this research, namely the literature study, the benchmark definition (which was necessary to evaluate the eventual outcome of the research), the investigation into possible application (which will also be helpful for further research), the simulation and design (which made it possible to generate new knowledge from the consulted literature) and the conclusions that can be drawn from both of them. The arrows indicate the clear input of one topic for one of the latter topics (own image).

Since the technology to develop the PolyArch coating is available, but the dynamic coating has not been created yet, reasonable assumptions about the qualities of the coating can be made, but not much data is available yet. To improve this, a number of small tests will be conducted on coating samples in which additional data will be measured. The information that is available by these tests and earlier measurements is gathered and assessed. Nevertheless, this describes the current state of technology and not what will be possible in the near future, once the suitability of the coating may be proven. This means that an ideal situation has to be described, which represents the requirements the coating would have to meet to perform as good as it could possibly perform. The results of this definition have been described in the previous chapter.

The actual coating will most likely not be as good, but it is a good starting point for comparisons and calculations. If the coating will not perform significantly better than currently available coatings even in its ideal configuration, it is not likely that the actual coating will be able to render an important contribution to the control of sunlight penetration. However, if the ideal coating performs good enough, the maximum deviation from this ideal situation can be assessed. This is done by simulating the ideal coating, a coating that performs at 80% of this ideal coating (so is able to block 80% of the bandwidth that the ideal coating can block) and a coating that performs at 60% of the ideal coating.

After this is done, and with the knowledge that is gained through this literature research, suitable applications of the new coating are investigated. These applications cover a wide field of purposes, sometimes within the same coating, but are always applied in architectural facades. To find applications, the theoretical knowledge from the literature study is used to fuel a creative process in which methodically every need for heat or heat loss (including heat collection and heat storage) of a building is assessed to find whether this coating could contribute to that process (looking at various functions: the requirements of a swimming pool are very different from those of an office space, which are very different again from those of a large atrium).

The results of this brainstorm are categorised, partly to give a clear overview of the possible application directions that have been discovered, but also especially since my research topic is shared by Guido Lammerink, and we both need to focus on a specific research direction in order to let our results be complementary rather than competitive. Once the possible application are defined, their suitability is judged by means of a number of criteria that measure its assumed effectiveness and economic potential. This judgement is arbitrary since the effects and costs are not calculated or measured, but they are reasonably based on the knowledge that is available about the coating. Those applications that prove to have a high suitability will be selected for further, more detailed simulation.

For this purpose, a computer model will be built to simulate the effectiveness of the PolyArch coating compared to the currently available coatings in the found applications. For this purpose, a standard calculation model is generated in which every coating will be virtually tested under the same conditions. This means that a number of requirements has to be met before the simulation can take place. First of all, adequate simulation software has to be found. The aptness of the chosen software depends on the possibility to handle the angular and spectral selectivity of the coating in a design that originates from the selected applications, in adaptive way (meaning that the coating can be turned on or off, depending on an input that varies over time and comes from the model itself). Secondly, a standard model needs to be defined, which remains constant in all calculations. This is necessary to determine the effectiveness of the coating compared to similar shading devices, but also to put the calculation into context in general. In addition, the results from Guido Lammerink can be compared with mine, since he starts with the same input data.

The calculations will present the effectiveness of the coating, which is judged by the amount of energy that is required to control the interior climate. In this calculation, it may be necessary to focus on heating and cooling energy, and only make an assumption for the balance between lighting energy and insolation. At least the coating application in its ideal condition, in 80% and 60% of the ideal condition, and the currently available competitive product will be simulated, to find where the coating currently stands. By means of interpolation (or even extrapolation) the desired performance of the coating can be defined. The energy performance will be the most influential criterion, but other criteria like reliability or maintenance costs may influence the ranking if the differences between the different shading methods are small.

To illustrate the possible application in building practice of the coating as it is simulated, a small design is made which function as a means of visually interpreting the architectural potential of the coating application. It can therefore be seen as proof of concept design, which does not aim to provide a detailed and thoroughly reinvented facade design, but merely present a number of conceptual ideas that can fuel inspiration for other applications. It will also define architectural implications of the use of the coating.

An overall judgement will be presented in conclusions and recommendations for the continuation of the research project. These recommendations will be written, but also summarised in a conceptual design. This design is generic, and mainly serves to give an architectural example of the application of the coating. Finally, to complete the overall judgement, the potential triggers for the PolyArch coating will be evaluated, since they will influence the effectiveness and user friendliness, but also the costs and flexibility. Because there is no data available on these effects yet, the recommendations regarding the triggers will be conditional ("if this certain situation is possible, it would mean this for the choice of a suitable trigger") and based on the expertise of the developers at the TU Eindhoven.

2. Theory

2.1 Mechanical shading strategies

To prevent undesired heating-up of the building, various shading methods have been developed since the introduction of large glass surfaces in architecture. They can either be placed in front of the glass, behind the glass, or in plane with the glass. In this chapter I will briefly describe the benefits and drawbacks of interior and exterior shading, as an introduction to the following chapters about coatings, which are shading the room in plane with the glass.

Before explaining those strategies however, it is important to realise what kind of radiation may reach the window, especially since this has to be modelled in the simulation as well. Generally speaking, there is direct and diffuse radiation. Direct radiation occurs when there are no obstructions between the window and the sun. When these obstructions do occur, such as clouds or shading devices, the light is diffused and becomes omnidirectional. Direct and diffuse radiation can occur directly between the sun and the window, but may also take place as a result of reflection via the earth (ground reflection). This includes reflection via water, buildings and other objects (Renckens, 1998).

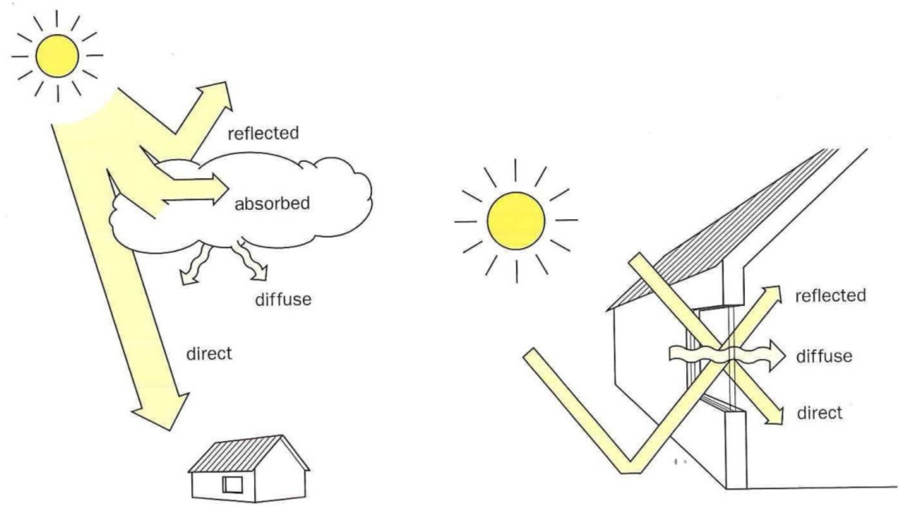


Figure 6: Sunlight reaches the window either directly, via reflection or after scattering by clouds. These three light directions ask for different shading methods (Renckens, 1998).

Of course the decision to find the most suitable shading device is depending on a large number of choices and fixed parameters. The orientation of the window determines the solar load, which imposes the urgency of shading, and also determines the sun path, by which the shading factor can be calculated. Outside geometries that may provide shade already, such as other buildings, trees or the building itself, will also influence the choice for a shading system. Furthermore, the degree of desired controllability is important, as well as the induced maintenance costs for a certain system. Finally, aesthetics and the type of glazing (and its operability) play a role(Renckens, 1998).

2.1.1 Interior shading

Interior shading is often manually operable shading that is placed on the inside of a room to control light penetration. Since solar heat has already entered the room once it reaches the shade, this way of heat control is less efficient than exterior shading. High reflectivity of the shade may reduce the difference, but shades will never perform as good on the inside as they do on the outside. This is why they often serve other purposes, such as darkening a room or reducing glare problems(Renckens, 1998).

Interior shades are more efficient when they are combined with a solar control glass (with a coating on the outer window pane) than in combination with a heat-mirror (with a coating on the inner pane). This is because the light that is transmitted through the window and is reflected by the shade, will be partly absorbed by the window because of the coating. In case of the solar control glass this is the outer pane, in case of the heat-mirror this is the inner pane, which means that in the former case less heat will be radiated into the room (Kuhn et al., 2001).

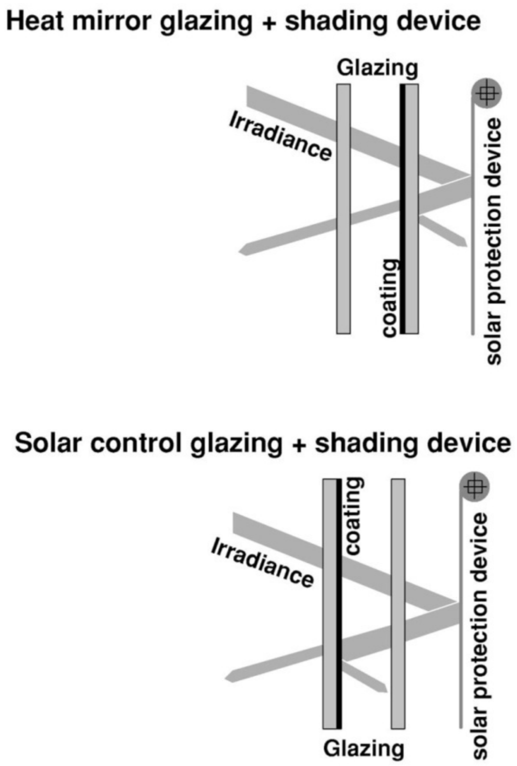


Figure 7: Internal shading works more efficiently with solar control glass than with heat-mirror glass, because with the former the outer pane absorbs most of the energy, while with the latter this happens to the inner pane (Kuhn et al., 2001)

Another reason why interior shades are less efficient than exterior shades is the heat accumulation between the shade and the window. This occurs with both interior and exterior shades, creating a radiant volume. Not only is the radiant volume in case of the interior shading already inside the room, but since it consists of air, it can cause a heat flow inside the room, which heats up the room air.

The big advantage of interior shades is that they are located on the inside of a building, which protects them from weather influences like wind, water and UV radiation. Because they are on the inside, maintenance and replacement is usually fairly easy and control can be done directly by hand. They have a smaller impact on the overall appearance of a building than exterior shades, but obviously need attention as well because they influence the appearance of the interior design.

2.1.2 Exterior shading

Exterior shades have existed for many centuries now, in many different appearances. The earliest forms perhaps being natural shades such as trees and other foliage, which over time were more and more replaced by mechanical shades. Because of their exterior position, they greatly influence the architectural appearance, which is why they need to be taken into account at an early stage of the design, also because of their structural implications. Although the prairie houses by Frank Lloyd Wright and the brise-soleils by Le Corbusier prove that exterior shades can very well be integrated into the architectural design, architects often disregards the necessity and potential of exterior shades for too long, which in many cases leads to design interventions after the damage has been done.

Exterior shades are available in many different systems, and also with many different controls. Some are static, while others are adjustable. These adjustable systems can either be manually or automatically operable, collectively or individually controlled and in general they have the great advantage over static systems that they can be adjusted to the sun's position, adding to their effectiveness. In general it is true that the shades need to be easily accessible, in order to enable replacements, cleaning and other forms of maintenance.

Various systems can be used, all with their specific benefits and drawbacks. This makes them often popular for certain applications and less favourable in others, although this may even be culture based. For example, in the Netherlands and Great-Britain the tendency to use exterior venetian blinds has been small, compared to other western and southern European countries. This may be because of the fact that such shading methods had been part of the building practice in those countries for centuries, while in the Netherlands and Great-Britain the need for those shades was not that urgent before the Modern movement (Jellema 4c).

External louvres are relatively efficient in controlling solar transmission, usually expressed in a low minimum g-value. Dark colours have a lower g-value than light colours, due to the high absorbance and low reflection of light. The low g-value also often implicates an obstruction of the view. This works in both ways however, so the shades can also be applied to ensure privacy. By tilting the louvres, the light penetration can be controlled. To improve the user comfort, this can be adjusted to the other interior lighting, and in addition it allows the user to darken the room (Jellema 4c).

Static louvres on south windows can improve the energy balance of a building not only in summer but on an annual basis as well. However, this is only valid for certain climates (the study which proved this was conducted in a Mediterranean climate) and obviously depends on the degree of insolation that applies to the specific window location (Datta, 2001).

Roller shutters provide full darkening of the room that lies behind, which this has both benefits and drawbacks. With foam filled profiles it is possible to have a small gap between the lamellae, in which perforations can be made that let through a little bit of daylight when the mat is stretched (but not lifted). Once all the lamellae are fully rolled down the gap closes again. Because the window is completely sealed off once the shutter is rolled down, it also serves as a protection against burglary, reduces heat loss and provides sound insulation. The lamellae are either made of aluminium or plastic. Plastic offers a better heat resistance and makes less noise when the shutter is in motion, while aluminium has a higher durability and larger mechanical resistance. For these reasons, nowadays factories are also producing lamellae which combine the strengths of both materials. Finally, due to the small distance between the window and the shutter, heat absorption that may lead to radiation needs to be avoided, which is why light colours are preferred over dark colours (Jellema 4c).

Fabrics can be an alternative for the abovementioned rigid shades, when light weight or lower costs are necessary. They can be applied either vertically or with projecting arms, but they are vulnerable to wind. They do not have enough mechanical resistance to function as a burglary protection, and often cannot darken a room as well as a roller shutter. The degree of diffuse transmission can be controlled by the thickness and pattern of the fabric. Another important point of attention for fabrics is weathering, which causes them to collect dirt and lose their colour. In addition, it must be noted that projecting blinds do not provide proper shading against sun from the sides (Jellema 4c).

Figure 8: Traditional awnings are closed from the sides, which significantly increases their efficiency (DBA Zonwering, 2013).

In traditional awnings, which are not retractable but are projected using an aluminium arm which rotates around a pivot point on the facade, the shade from the sides is provides as well, which makes them very efficient shades. The degree of light transmission cannot be controlled, and the room behind the shaded window will be considerable darkened. However, this kind of shading is almost exclusively used for residential buildings. For offices, the abovementioned retractable sunscreen is more popular (Jellema 4c).

Besides these dynamic shades, there are also various types of static shades. Their large advantage over dynamic shades is the lower maintenance requirements, because there are no moving elements in the shade that could break. Because of this, periodical cleaning usually suffices. This means of course that the shade needs to be accessible, but in general this is the case when the window itself can be reached for cleaning purposes (Jellema 4c).

Overhangs are a well known type of static shade, which do not obstruct the view to the outside and more or less transmit diffuse light, due to which daylight can light the room. However, due to their static nature, they cannot adjust to the sun's position. Therefore they are only dimensioned for the extremes at which they should be effective, and at other times they only provide a fraction of this effectiveness. It is however desirable that the southern sun is blocked when it is high in the sky, but transmitted when it is low, because this is an indication for the season and therefore can serve as a general way of determining the risk of overheating.

Overhangs can be found in many different shapes, both horizontally and vertically (in that case usually referred to as 'fins') and as an integrated part of the building or not. The building itself may function as a large overhang for lower windows, or as a fin for windows that are set back. In fact, creating a deep jamb already means an integrated overhang and fins around the window. Special other forms of overhangs include verandas and loggias, which have served for centuries to provide shaded walkways and patios, and inherently shade the rooms adjacent to this outside space.

Louvres are also sometimes applied as a static system, although they are usually preferred in a dynamic system because of the large darkening effect they have. When placed with some distance between the window and the shade, they are attractive shades however. Because the lamellae of the shade do not rotate nor retract, they can potentially be fitted with photovoltaic cells as well.

2.2 Coatings overview

2.2.1 Introduction

Glass is a product that has many advantages when used in architecture, such as the high transparency, durability and structural stability, but it is not a perfect material. For the colder climates this mainly concerns the low reflection in the far infrared part of the light spectrum, which causes energy losses via blackbody radiation. In warmer climates, it is the high transmission of near infrared light that causes an excess of undesired heat radiating into rooms, overheating them while not providing any benefits (Bräuer, 1999).

Many ways have been invented to compensate for the abovementioned and other deficiencies of glass. Some are shading devices, but many are applied directly onto the glass by means of a coating. These coatings can generally be subdivided into two different groups, which are static coatings and dynamic coatings. The former does not respond to any external stimuli, while the latter can change its properties when activated by certain conditions that are met.

In this chapter a brief overview of the currently available coatings will be presented. These will be only coatings that can be used to regulate solar heat penetrating through a window. Special attention is given to angular selective coatings, electrochromic coatings and thermochromic coatings, because they are closely related to the principles that apply to the PolyArch coating. Other coatings will be discussed in a more general way.

2.2.2 Static coatings

Metal coatings

As was mentioned before, glass does not reflect near infrared radiation very well. This is due to the high emissivity, which for normal glass is $\varepsilon = 0.85$. Coating the glass can reduce this ε significantly, and usually metals are found most suitable for this, although ITO coatings or doped SnO_2 would suffice as well. However, nowadays virtually only silver is used to create coatings with a low emissivity, so called low-e coatings. In case of silver, the emissivity of the glass unit can be reduced to 0.04 low-e coating (Granqvist, 1990). Of all insulation glazing units that are produced worldwide, 40% is coated with a silver based (Lampert, 2004).

There are two kinds of low-e coating, based on their intended use. One of them reflects most of the low infrared light, so called blackbody radiation, and is mostly applied to keep heat inside. Therefore sometimes it is also called a winter film. The other kind, the summer film, reflects a large share of the near infrared and high infrared light, meaning that it keeps out most of the infrared solar energy (Mohelníková, 2011).

The silver coatings are often encapsulated in an additional coating that prevents the silver from corroding and also prevents reflection and ensures good transparency (Bräuer, 1999). On its own, metal coatings would normally not transmit more than 50% of the visible light, because the transmission value depends on the thickness of the metal layer. There is a limitation to the thickness of the metal layer, because when trying to make the layer even thinner than that which transmits 50% of the visible light, the metal would cluster into small islands which strongly absorb the visible light. This is why additional, dielectric coating materials are used to increase the transmission value to 80% (Granqvist, 1990).

The figure below shows the materials that are most often used to dope (intentionally pollute a pure material to influence its characteristics) the coating of large glass surfaces. The reason for this is mostly economical, because when using magnetron sputtering, these metals can be applied to glass uniformly over widths up to 4 metres, without becoming too expensive (Bräuer, 1999).

Material	Index of refraction (550 nm)
SiO_2	1.46
Si_3N_4	1.95-2.05
SnO_2	1.95-2.05
ZnO	1.95-2.05
In_2O_3-SnO_2	1.95-2.05
TiO_2	2.35-2.55

Figure 9: The most used dielectric materials for doping metal coatings to enhance their transparency (Bräuer, 1999)

The reason why metal nanoparticles can absorb light waves is because an area of metal molecules has a large amount of free electrons circling around them, which can freely move from one molecule to the other. Certain wavelengths, those that are close to the natural frequency of the electrons, transform their energy into motion of the electrons, that collectively start oscillating when the 'right' wavelength irradiates the metal coating. This is called surface plasmon, and explains why metal coatings have a peak absorbance around a certain wave frequency (Paquet et al., 2009).

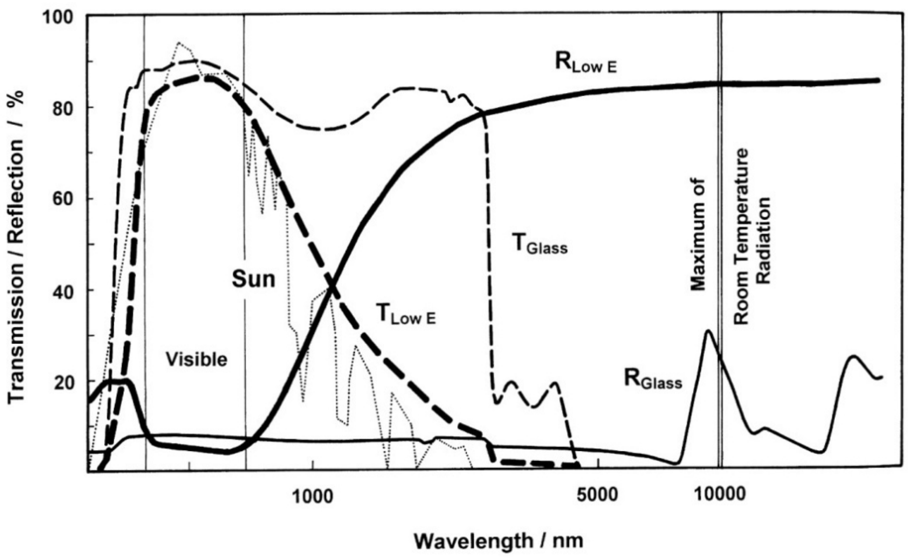


Figure 10: Reflection (lines with R show the reflection of a low e coating and of uncoated glass) and transmission (lines with T show the transmission for those products) values for light radiation of different wavelengths on a silver glass coating. It is clear that the reflection of this low-e coating starts roughly at 2500nm, so the far infrared, and continues over the entire far infrared. This coating is therefore a heat mirror(Bräuer, 1999).

The effectiveness of silver glass coatings related to radiation wavelength can be seen in the graph above. It shows that the reflection of infrared light is significant, especially in the blackbody radiation zone (>2500 nm). Because of this, the coating is usually applied on the inner pane of a double glazing unit, so it keeps the heat in as much as possible (Renckens, 1998). Generally, silver based low-e coatings provide an energy transmission reduction of 60-80% compared to clear float glass, which has a g-value of 0.87. The coating is placed inside the two glass panes as a measure of protecting the coating against mechanical and chemical damaging. It is also relatively common to apply this technique onto triple glazing units (Bräuer, 1999).

Another important aspects that explain the popularity of silver based low-e coating is the highly transparent, non-coloured appearance. However, depending on the thickness of the SnO_2-layer, which is used to encapsulate the silver, reflections in other colours can be expected. Besides, even when the glass is coated with silver particles, it can be recycled and reused for the production of float glass, while other metal coatings would pollute the fluids (Renckens, 1998).

Sol-gel coatings

Sol-gel coatings are not so commonly used in architecture, but since their application in certain circumstances may be economically viable and outperforming silver based low-e coatings, it is still discussed here. Different about the sol-gel technology compared to many other coatings is way the coating is applied, which is via spinning, dipping or draining (Klein, 2001). The process is quick and can be applied on the outside of a window without problems, also for bent glass and tempered glass (Nagamedianova et al., 2011).

The coating is made by applying the desired solution (hence the name sol-gel) of an alkoxide, water and a solvent to the glass. The metal inside the film reacts with the organic part of the alkoxide, creating an oxide skeleton over the glass. The coating is rigid, and can be densified using heat treatment. For application in architecture, wavelength selective films that reflect infrared radiation can be developed using transition metal oxides (Klein, 2001).

Compared to the common low-e coatings, the sol-gel coatings perform worse when UV light is concerned, but have a better performance considering the reflection of infrared light. This results in a significantly better light to solar gain ratio, which can be 15% higher than that of a sputtered low-e coating (which itself performs 14% better than a pyrolytic low-e coating). The transmission of visible light is more than 85% (Nagamedianova et al., 2011).

Semiconductors

Comparable to metal coatings with free electrons that are oscillated, semiconductors can provide spectrally selective coatings. These coatings are however not functioning because of oscillation, but because of the energy gap between the valence band (which is the highest occupied band of energy levels in a semiconductor) and the conduction band (which is the lowest band of energy levels). These energy bands are inherent to any semiconductor, and the energy gap is usually in the range of the energy of visible light. Electrons in the bands naturally want to move to a lower energy level, so when an electron in the valence band is excited by radiation, it moves to the conduction band, leaving behind a gap in the valence band. After a certain period, this situation is restored however, and energy is emitted. The amount of energy that can be emitted depends on the size of the semiconducting nanoparticle, thus so does the wavelength bandwidth that can be absorbed (Paquet et al., 2009).

Angular selectivity

Angular selective coatings have been developed since the late 1990's, and like the name implies they respond differently to critical angles of incidence than to other angles. This leads to different transparencies on either side of the glass on which the coating is applied: the most transparent side can be 45-60% transparent, while the least transparent side only lets 15-25% of the sunlight pass (Smith et al., 1998).

Angular selectivity means that when a light beam hits a surface under an angle θ, it behaves differently than the same light beam would behave under the same angle, but on the other side of the surface (-θ). This may address any kind of optical quality, but usually refers to transmission of light. Angular selectivity is caused by the transition of the light from one medium to the other, given that at least one of the media has an optical axis that is not perpendicular to the surface (Granqvist, 1990).

For several reasons angular selective coatings can be a smart idea. Firstly, in buildings people usually look out of the window in a fairly horizontal direction, but not as much to the sky. This means that transparency of the window in angles deviating from the horizontal line is less important than that perpendicular to the window surface. This can be applied to make the window efficiently less transparent, thus letting less light energy through (Granqvist, 1990).

Another reason to consider angular selective coatings is the fact that in summer, when the solar energy is undesired, the sun is high in the sky. In winter on the other hand, the sun is close to the horizon, and in those periods the solar energy is useful. Therefore one could say that the angle of incidence is related to the degree to which sunlight penetration is desired, making an angular selective coating an energy efficient measure. Keeping out direct sunlight in summer will also help to avoid glare problems, which improves the comfort level (Sullivan et al., 1998).

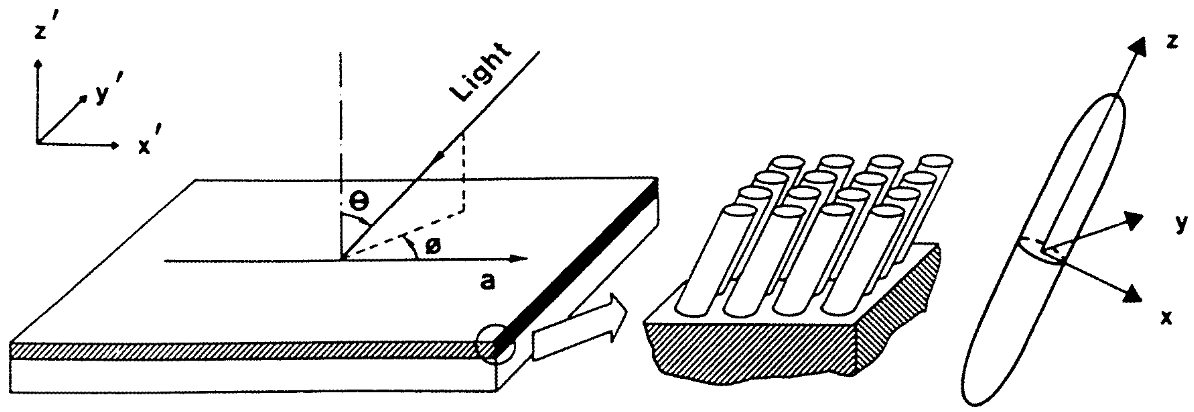


Figure 11: Elongated metal particles inside a thin film on the glass form a columnar structure that has a direction off the normal axis of the surface, causing different refractive indices from either side of the glass(Mbise et al., 1999).

All angular selective coatings are basically a columnarly oriented set of molecules looking somewhat alike with venetian blinds. Most of these coatings are metal based. The key principle behind these metal based angular selective coatings is the inclusion of elongated metallic particles, which are directed in such a way that their long axis is not perpendicular to the surface they are applied to. This results into different absorption of light over the surface area. Common metals for these inclusions are chromium, aluminium, titanium and tungsten (Mbise et al., 1999).

Trying to reduce the energy consumption caused by cooling by applying an angular selective coating may result in increased energy consumption for lighting. The efficiency of the angular selective coating depends on the location where it is used. In a sunny environment like Florida (USA) angular selective coatings may outperform spectrally selective coatings by 15%. Both of these coatings are also performing better than a normal wall without windows, when energy for lighting and temperature control are added up (Sullivan et al., 1998). Angular selective coatings are commonly produced in thin films which do not exceed the dimensions of 2.40 x 1.80 metres (Renckens, 1998).

Use of angular selectivity also implies the use of spectral selectivity, because the metal particles that are aligned in columns to absorb incident light function best when the wavelength that hits the particle is a little larger than the length of the particle. The effectiveness is reduced when the wavelength increases (Smith et al., 1998).

2.2.3 Dynamic coatings

Electrochromic coatings

Electrochromism provides a dynamic method to shade a transparent surface, using a low voltage of 1-3 V to induce a transformation from one extreme state into the other. Electrochromic windows can switch between a relatively transparent state (which means a transparency of approximately 80%) and a relatively opaque state (which lets through roughly 10% of the incident light). The given values are for a light wavelength of 550 nm, other values can be derived from the figure below. This shows that in the visible part of the light spectrum, the values for the darkened state reach a peak which averages around 20%, while in the infrared part there is almost no transmission of light (Bräuer, 1999).

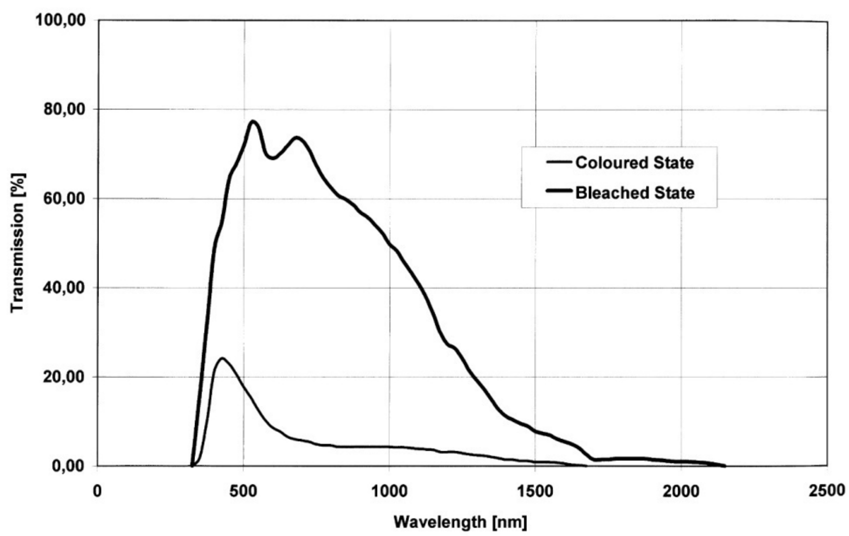


Figure 12: Transmission values of an electrochromic glass coating in relatively opaque and relatively transparent state (Bräuer, 1999).

ITO crystals (indium-tin-oxide), which are also used in liquid crystal technology, are used as a transparent conducting medium. This medium is located on the two outsides of a layered composition which usually consists of five layers. The next layers are an electrochromic layer, an ion conducting layer and an ion storage layer. The ion conducting layer has to be placed between the electrochromic layer and the ion storage layer, which can also be used as a second electrochromic layer (see diagram below). The use of the ion storage layer as a second electrochromic layer to enlarge the darkening effect will of course only function properly if one of the layers darkens under the influence of ion introduction, while the other darkens under the influence of ion extraction.

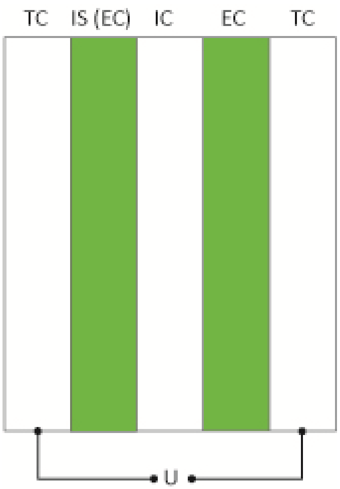


Figure 13: Principal layering of an electrochromic coating. On the outsides are two Transparent electrical Conductors (TC), followed by an Ion Storage layer (IS) which could also function as an Electrochromic layer (EC) and an Electrochromic layer, which are separated by an Ion Conductor (IC). Own image based on (Granqvist, 1990).

When a voltage is applied, ions (positively charged particles like H^+) are brought from the storage layer to the electrochromic layer, which darkens when the ions are introduced. Because of the fact that the central conductor that separates the storage and the electrochromic layer only lets ions through, an open circuit system is created. This means that ions do not return to their storage when the voltage is cut down, so the electrochromic layer remains darkened even without applying electric power, up until the current is directed the other way around and the ions are brought back to the ion storage layer (Granqvist, 1990).

The switch between transparent and opaque takes approximately 1 to 5 minutes. Because of the open circuit memory, it will stay like it is without continuous power supply, but this does not last eternally. Usually between 1 and 24 hours, the system is reset. This can go on for 10.000 up to even 1.000.000 cycles, leading to a expected lifetime of 5 to 20 years. The technology is not being applied for 20 years yet though, so this remains a prediction (Macrelli, 1998).

Another way of creating an electrochromic coating is by laminating two glass panes with a double layer coating (thus a transparent electrical conductor and an electrochromic/ion storage layer) together with a polymeric laminate that forms the ion conductor. This may be preferred in case of large glass area, because of its practicality and strength. In this case tungsten oxide (WO_3) is used as a cathode which strongly absorbs infrared light, combined with anodic hydrated nickel oxide (NiO_xH_y) which strongly absorbs visible light. Also in this case the peaks are around 80% (Granqvist, 1990).

A special kind of electrochromic coatings that deserves to be mentioned is the electrochromic coating with integrated photovoltaics. This pv should provide enough energy to operate the electrochromic window, eliminating costs for electricians and wiring. It is claimed to be more cost effective than regular electrochromic coatings when it is applied on windows that originally did not have an electrochromic coating (Benson and Branz, 1995).

Thermochromic coatings

In thermochromic coatings, the coating changes colour because of a change in temperature. This either causes a chemical reaction, or initiates a phase change of the material (Mohelníková, 2011). Important about this change is the critical temperature, which is the temperature at which the change in material properties takes place. Below this temperature, the coated window behaves like any other window, letting through all solar energy it would normally let through. When the temperature rises above the critical temperature however, the coating reflects the infrared part of the solar light (Parkin et al., 2008).

The transition in thermochromic coatings is called metal-to-semiconductor transition (MST), and can take place with a number of special thermo-transitive metal oxides. A common element that is used for thermochromic coatings is vanadium, or more specifically vanadium oxide (IV). The critical temperature of this material is 68 °C, making it the thermo-transitive metal oxide with the lowest critical temperature. To be useful in internal comfort regulating applications this is still far too high though. Therefore dopants are used to affect this temperature and bring it down to more reasonable temperatures (Parkin et al., 2008).

Several metals apply for this, and their suitability depends on their valence. High valence ions such as tungsten (VI) or niobium (V), which have an ionic radius larger than V^{4+}, tend to decrease the critical temperature of vanadium (IV), while ions with a smaller valence with an ionic radius smaller than V^{4+}, like aluminium (III) or chromium (III), increase the critical temperature (Parkin et al., 2008).

Large changes in reflective properties do have a downside, which is critical for the success of thermochromics: the transmission of light is negatively influenced by this, resulting in a need for extra interior lighting, which defeats the purpose of the flexible energy saving coating. Two ways have been invented to improve the visual light transmission, one of which is fluorine doping. However, this has proven to be unsuccessful because the transition between the transparent and the reflective state is blurred by this addition. The direct application of an antireflective silicon oxide or titanium oxide based film seems to be much more effective. The transmission of visible light should ideally be at least 55% (Parkin et al., 2008).

There are still some drawbacks which prevent the technology from being used at large scale however, the biggest one of them possibly being the colour of the film. They are yellow or brown now, which is undesirable. Using coloured glass or matching refractive indices of dopants could solve this problem, but this will be at the expense of the amount of transmitted daylight. Furthermore, the coating is not resistant against weathering. Therefore it must be applied inside a cavity (Parkin et al., 2008).

Some functioning thermochromic products have been produced so far, which show potential for the future, but not yet a serious attempt to claim a significant share of the world market (Lampert, 2004).

Other types of dynamic coatings

This section mentions several types of coatings that are not so commonly used in architecture, for various reasons (complicity, novelty, functionality, etc.), but are interesting topics anyway.

Photochromic glass

One kind of well known dynamic coatings that has not been discussed yet, is the photochromic coating. As the name implies, it changes colour under the influence of light. More specifically, colour centres in the glass are activated by shortwave radiation in the visible part of the spectrum and by ultraviolet light. The colouration, or darkening, of the glass can be undone under the influence of long-wave visible light radiation and short wave infrared radiation (Mohelníková, 2011).

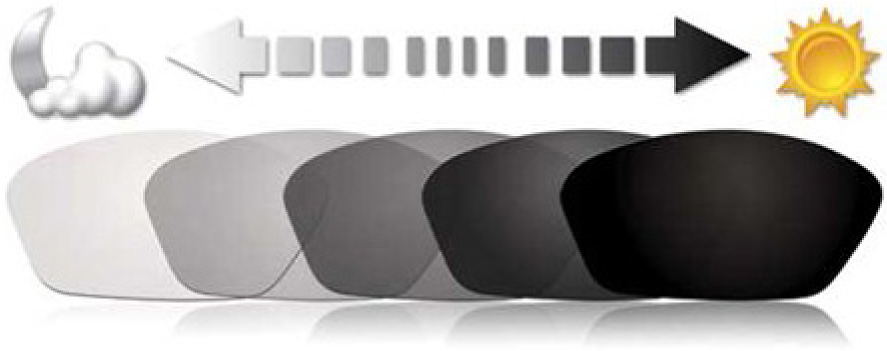


Figure 14: Photochromism is best known from its application in lenses for glasses, turning transparent lenses into sunglasses when the sun shines (Eyebuydirect.com, 2013).

Thermotropic glass

Thermotropic glass is comparable to thermochromic glass, but unlike thermochromic glass, which optical properties can change in quite varied ways, thermotropic glass can switch from transparent to translucent. The trigger to initiate this change is again heat. The mechanism is based on a number of special gels with different refractive indices that are contained between glass plates. When the temperature rises above a desired critical temperature (which has to be between 20 and 50 degrees Celsius), the gels break into nanoparticles, turning the transparent mass into a light scattering, white translucent volume (Mohelníková, 2011).

Gasochromic glass

The trigger in gasochromic glass is, unsurprisingly, gas. This is used inside a cavity between two glass panes, for example a tungsten oxide coating with platinum used as a catalyst. When exposed to hydrogen, the tungsten oxide turns blue due to a chemical reaction. This process can be undone with oxygen. Well execution is difficult and expensive, because the cavity has to be completely airtight, and an electronically controlled gas supply unit has to be connected to each cavity (Mohelníková, 2011).

Polymer dispersed liquid crystal (PDLC)

Polymer dispersed liquid crystals are a new technology that is based on liquid crystals that are fixated in a cured polymer matrix or an epoxy. The liquid crystal, that is placed in the polymer/epoxy like droplets without a uniform director, has a different refractive index than the material surrounding it, causing it to scatter light as it shines on it. However, when a low voltage is applied to the coating, the liquid crystals (which are dielectric and anisotropic) align with the current, causing the refractive index of the small liquid crystal droplets to become n_o, which is the smallest refractive index of the anisotropic liquid crystal (this will be elaborated on in the next chapter). Because the polymer/epoxy has a refractive index which is equal to n_0, the material becomes transparent (West, 1988) The power applied to keep the glass transparent is between 24 and 120 Volts or less than 20 W/m^2. Unlike electrochromic coatings, PDLC's do not have an open circuit memory, so the power supply has to be continuous to keep the window transparent (Lampert, 2004).

Figure 15: Polymer dispersed liquid crystals are used in some architectural applications, mostly those that are not requiring transparency, like roof lights such as this SwitchLite privacy glass (HowStuffWorks, 2013).

Suspended particle device (SPD)

The principle behind suspended particles is almost the same as that of PDLC's. Two conducting transparent layers on the outside provide, when switched on, an electrical field that aligns randomly oriented dipolar particles suspended in a polymer. This system does have a memory however, but is mostly used for displaying multiple colours in the same window, which is why it is mostly used for display purposes (Lampert, 2004).

2.3 Liquid crystal coatings

2.3.1 Introduction

Although the PolyArch coating is a new invention, liquid crystal coatings are not at all new. They are being developed since the late 1980's, originally for liquid crystal displays. Because for displays the same characteristics of transparency and light filtering are important as for window coatings, the technology was soon transferred to architecture (Bräuer, 1999).

Liquid crystals are called that way because they are in a phase between liquid and solid, which means that they can flow like and have the flexibility of liquids, but have the structural hierarchy of solid crystals. This combination of changeability and organised composition gives them unique qualities that cannot be found in other materials (van Oosten et al., 2009).

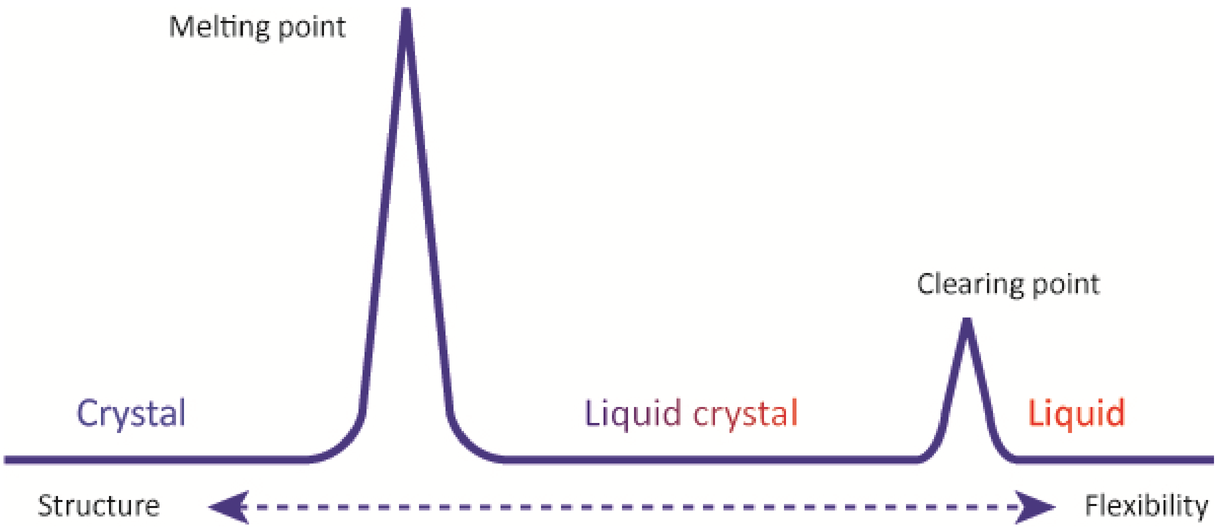


Figure 16: A liquid crystal has two melting point, the latter of which is called the clearing point. Between these two temperatures zones, the molecules have the structural hierarchy of a crystal, but the flexibility of a liquid (own image).

There are two kinds of liquid crystals, which are thermotropic liquid crystals and lyotropic liquid crystals. The former kind has two melting points and becomes a liquid crystal when the temperature reaches a value between those two melting points. Typical about these molecules is that they are often anisotropic. The latter kind of liquid crystals becomes a liquid crystal when solved into specific liquids. The PolyArch molecules are thermotropic(Broer, 2012a).

PolyArch coating is made of polymers. Polymers are increasingly popular because of the varied application possibilities. Polymers are usually made out of monomers, which can all have a different quality or function. Combining these monomers into a polymer means creating a molecule that has all these qualities together. In that way, monomers are comparable to building blocks which are used in building construction: some give structural strength, some give thermal insulation, others provide sufficient transparency and altogether they form a wall (polymer) which has all the desired qualities (Paquet et al., 2009).

2.3.2 Principle of PolyArch

The molecules that form the basis of the PolyArch coating are a combination of chiral (spiralling) monomers and nematic(directed) monomers. Chiral means asymmetrical, and its principle is understandable by the asymmetry between a left and a right hand. They are each other's mirror image, but cannot be placed on top of each other without rotation. Nematic means that all molecules, which are anisotropic (so they have a direction), are more or less aligned in one direction. The vector that represents the average direction is called the director. Note the difference between the nematic and the smectic phase: in the smectic phase the molecules are not only aligned in the long direction, but also in the short direction, which means that the molecules are aligned in a grid (Broer, 2012a).

When chirality and nematics are combined, a number of structurally ordered and directed layers exist on top of each other, in which each layer is rotated slightly relative to the layer below it around an axis perpendicular to the surface of the layer. This combination, which looks a bit like a helix but is not as strictly ordered, is called the chiral-nematic or cholesteric phase. The relative displacement of a layer from the ones below and above is the same, and determines the thread. The strength of the rotation can be adjusted (Broer, 2012a).

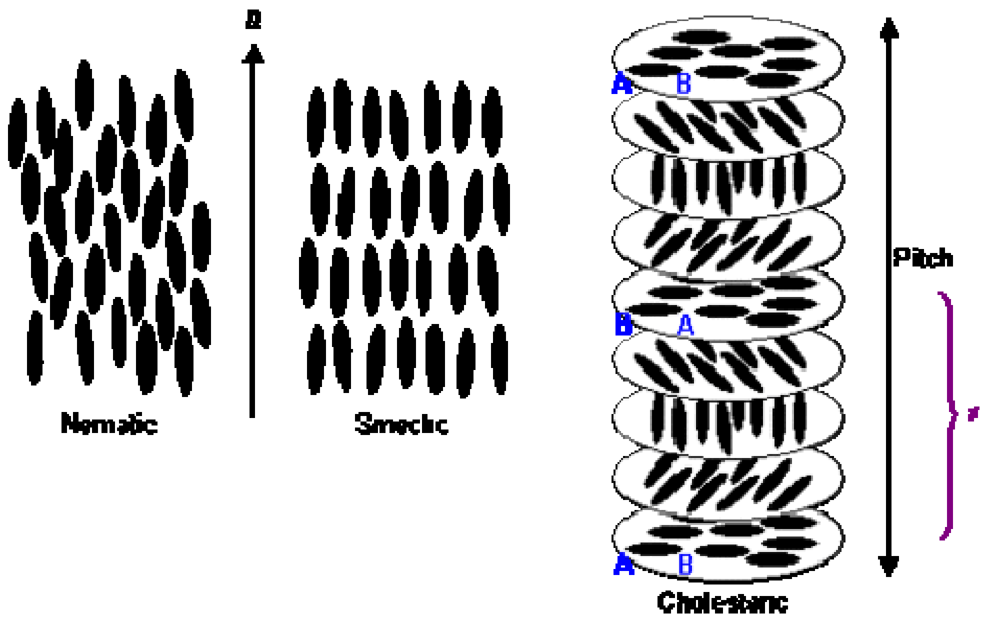


Figure 17: On the left the structural difference between nematic and smectic liquid crystals is explained in a simplified way. The diagram on the right shows a full pitch (rotation) of a chiral (helicoil) nematic liquid crystal, or cholesteric liquid crystal (Pressure Chemical Co., 2009).

The pitch is related to the reflection of light. When in chiral-nematic liquid crystals the wavelength of the incident light divided by the average refractive index of the liquid crystal is equal to the pitch, the light is reflected by the liquid crystal. See formula 1. This means that by changing the pitch, the reflected part of the solar spectrum is changed as well. Currently this flexible application of selectively reflecting liquid crystals is only possible when placed between two glass panes. This is because at the moment the liquid crystal is only flexible enough to change the pitch when it is in the low-molecular state, which means it is still a fluid and has to be contained in between something else. It is assumed however, that this technology will evolve in such a way that it will be available in hard coatings and foils as well (Broer, 2013a).

$$\frac{\lambda_0}{\bar{n}} = 2 \cdot \frac{p}{2} \rightarrow \lambda_0 = \bar{n} \cdot p$$

Formula 1: the relation between the light wavelength, the average refractive index of the liquid crystal (n) and the pitch of the liquid crystal (p).

The chirality of the polymer also influences the degree of reflection in another way, since light consist of left handed and right handed polarised waves, and the spiral of the polymer can only rotate either left handed or right handed. This means that half of the light is reflected, but the other half will be transmitted. Therefore a combination of a left handed reflecting coating with a right handed one is required for full reflection, or two right handed coatings with a half-lambda filter in between, which alters the rotation of the light (Broer, 2013c).

However, when two coatings with the same handedness are used and corrected with a half lambda filter, the transmission graph is distorted when the angle of incidence increases. This can be observed in the graph below, which shows that both the shape and the reflection peak are influenced negatively by the half lambda as the angle of incidence increases. This is due to the filter, which is not able to fully polarise the incident light at non-normal incidence.

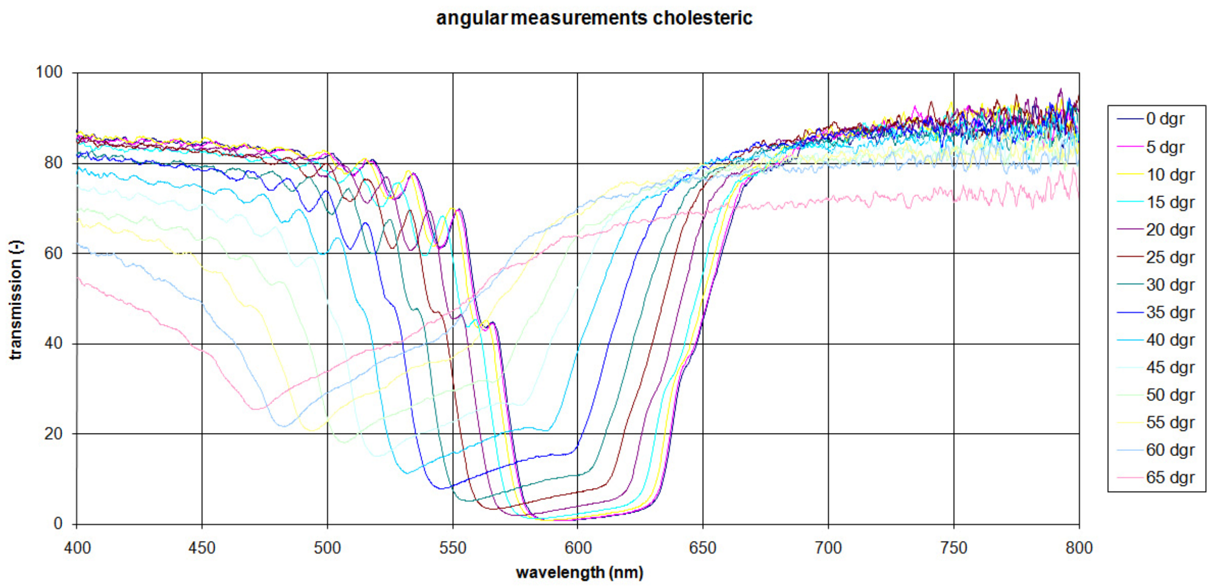


Figure 18: Transmission graph for a cholesteric liquid crystal which reflects at 580-630nm. The graph shows transmission values for two right-handed coatings, with a half lambda retarder in between to polarise the left handed light to right handed. It shows however that when such a retarding filter is used, the reflected part of the spectrum shifts to shorter wavelengths and the transmission increases once the angle of incidence increases. This is not the case when a left handed and a right handed coating are combined on normal floatglass(Debeije, 2007).

The coating works only as a reflector. This means that all wavelengths that are not reflected, will be transmitted to the substrate. Therefore, if the coating is applied on an opaque surface, in order to adjust its colour, the substrate must be light absorbant to prevent the light that irradiates the substrate after being transmitted by the coating from reflecting back and influencing the perceived colour.

When the coating is used to have a surface change colour, it is also important to bear in mind the transmittance of the substrate. When for example glass is concerned, the coating needs to reflect both left handed and right handed light, because otherwise the colour will be pale. Also, one should keep in mind that the reflection of light cannot be adjusted gradually while it is in place, but is either 50% (left or right handed) or 100% (both left and right handed). It would be possible to create a coating that can also be switched to intermediate states of reflection, but this would most likely become far too expensive (Broer, 2013c).

Depending on the trigger, the reaction speed of the switching varies. More chirality lowers the reaction speed up to several second. With light as a trigger, the response time would be possibly several minutes. Using heat as a trigger would be slightly faster, but still the reaction speed is in the order of minutes. Heat will the most likely trigger, but light, and eventually electricity too, should also become possible triggers. Also depending on the kind of trigger that is used, is the homogeneity of the coating 'operation', so whether the coating will show the same effect over the entire surface or whether it may be divided in separately operable zones (Broer, 2013a).

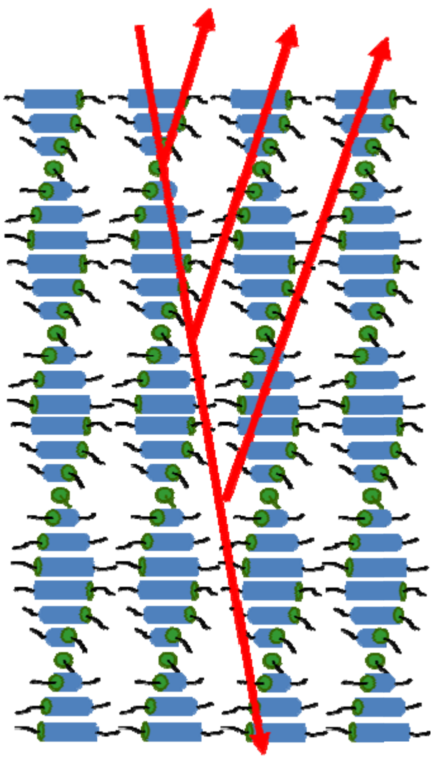


Figure 19: Selective light reflection in a cholesteric liquid crystal of those wavelengths that are almost identical to the pitch (Broer, 2012a).

All three triggers have advantages and disadvantages, making none of them stand out. A heat based trigger is the closest to the natural response of the liquid crystal, so it would be the easiest way of triggering the material. It is also directly related to the goal of the coating, which is temperature control (and because of that, energy saving). But, just like a light based trigger, a heat based trigger is hard to control. Light is also directly related to the source of the temperature control problem, but may compromise the visual quality when shadows on the glass cause uneven response of the coating. Electricity as a trigger would not have these problems, and it could be easily controlled by users or a control system. Using a control system would also mean that using the coating in another climate would only require adjusting the sensor settings. On the other hand, electrical triggering asks for electrodes and conducting materials that need to be integrated in the glass, increasing the costs and the energy required for the unit production (Liu et al., 2012).

In addition, the different triggers require a different chemical composition of the coating. The coating that has been described and investigated so far is one that responds to a heat trigger. For electrically controlled helices, an elastic helix is necessary, which also means that the coating becomes very flexible. Light responsive coatings require the inclusion of light sensitive components, which inevitably disturb the ideal order in the helix (Broer, 2013b).

The bandwidth of the reflected wavelengths is positively related to the bandwidth of the refractive indices, see formula 2. It is possible to change the size of the bandwidth of the reflected part of the spectrum by letting the chiral part of the molecule diffuse in another direction than the nematic part, because of which the difference in refractive indices increases. This is due to the anisotropic nature of the liquid crystals, which means that their refractive index parallel to their long axis (n_e) is larger than the refractive index perpendicular to the long axis (n_o) (Broer, 2013a).

$$\Delta\lambda = \lambda_0 \cdot \frac{\Delta n}{\bar{n}}$$

Formula 2: The bandwidth of the reflected wavelengths depends on the bandwidth of the refractive indices. If this difference increases, the number of reflected wavelengths increases as well.

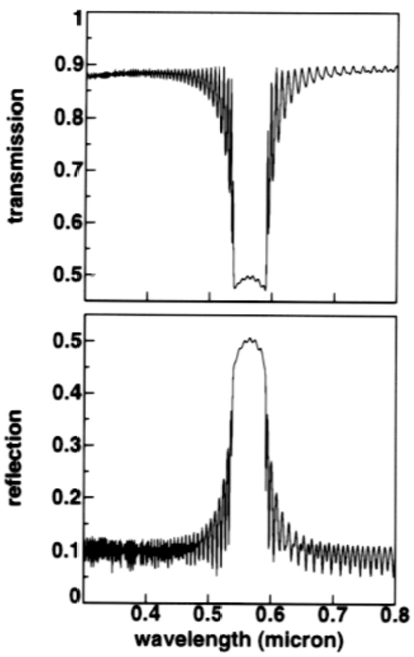


Figure 20: When the wavelength of the incident light is almost the same as the pitch, the light is being reflected. This results in a relatively accurately bordered bandwidth of very high reflection (Broer, 2012a).

This difference in refractive indices, or birefringence, can be chemically modified in such a way that the reflected bandwidth normally can vary between 20 and 100 nm. With a special modification of the chirality, making it gradually decreasing, this can be increased up to several hundreds of nanometres. Theoretically, the reflected bandwidth is infinite. However, with an increasing bandwidth, the likeliness of errors in the polymer increases as well. In addition, the coating thickness grows and the price rises. The same result can be achieved by stacking layers, but so far both methods are more easily applied in static coatings than in dynamic, changeable coatings (Broer, 2013c).

Applying a gradient to the pitch also implies a larger coating thickness. Normally, at least 10 rotations are required for adequate reflection. This means that to reflect a light wave of 2000nm – which means a pitch of approximately 2000/1.5 = 1250nm – a coating thickness of at least 12.5 mu is required. However, since in a gradient pitch not every part of the polymer reflects the same wavelength, the coating has to be thicker to make sure that the polymer makes enough rotations for each wavelength. There is a maximum to this thickness, due to price and the molecular order in the liquid crystal that may be lost in a too thick layer. However, this will not become a problem shortly (Broer, 2013c).

A special way of implementing the liquid crystal would be to use it as a pigment, meaning that the axial orientation is replaced by random orientation of each polymer. Because of this, the angular dependence can be eliminated, making this way of application very promising. Also, reflection of left handed polarised light and right handed polarised light can be combined in one layer. On the other downside, the random orientation would mean a large variation in refractive indices. The transition between these indices results into a decreased transparency, expressed in a white haze. It is very difficult to tune all refractive indices effectively enough to reach full transparency. This way of reflection would also mean that the coating does not reflect specularly anymore, but in a diffuse way (Broer, 2013c).

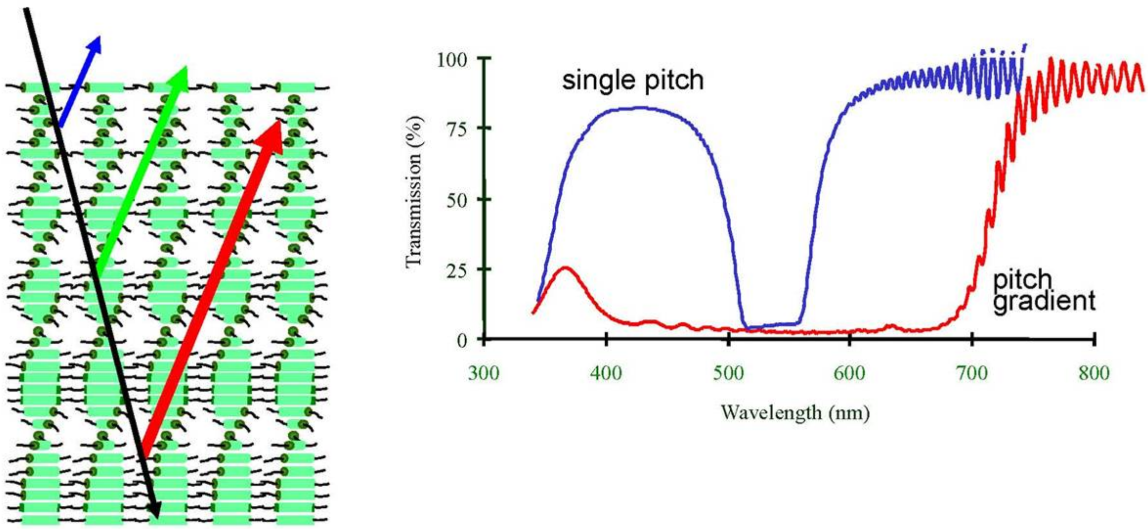


Figure 21: By introducing a gradient in the polymer pitch, the reflected wavelength varies over the chiral axis, resulting in a larger reflected bandwidth (Broer, 2012b).

2.3.3 Potential

The PolyArch coating is based on reflection of light, and does not absorb light. It has a minor influence on the transparency of a window, because of the transition between two media with different refractive indices. This is the case with virtually any addition of material, like converting double glazing into triple glazing and so on, and the effect is small (Broer, 2013a).

Moreover, the only limitation to the scale of the application of this coating is the size of the glass itself. In addition, the coating could be relatively cheap. The static coatings with these principles are available at around €7,50/m^2. For the dynamic coatings there is no indication of a price yet however, because this greatly depends on the willingness of sponsors to invest in this technology (Broer, 2013a).

When ignoring the UV part of the spectrum (because there is little energy in this area and it is already mostly absorbed by normal float glass), the visible, NIR and infrared part of the spectrum can be dealt with by a dynamic coating or a static coating. Many coatings have been discussed already, which are flexible in one or more of those (visible, NIR, IR) areas. In fact, out of all the possible combinations of flexible and visible coating possibilities, only two options have not been developed yet: a coating that is flexible for visible light and NIR, and a coating that is flexible for all three kinds of light. The PolyArch coating would be such a coating, that is flexible for reflecting or transmitting all three kinds of light (Lampert, 1992).

In theory, every wavelength in light could be reflected, at any bandwidth. When fully developed, this means that the coating on the window can be directly adjusted to the outside situation, thus always following the best strategy to save energy, for heating, cooling and lighting.

2.3.4 Challenges and limitations

In principal, the chiral axis (around which the 'helix' of the liquid crystal rotates) is situated perpendicularly to the surface of the substrate. However, while the liquid crystal should be fully transparent, but light does not irradiate the substrate at normal incidence but under an angle, a part of the light is being reflected anyway. This is inherent to its function as a Bragg's reflector, which causes a so called blue shift (because the shift occurs towards the blue part of the light spectrum). This can be seen in the graph on the following page, which shows the transmission of the coating without any substrate. This is particularly relevant when the reflecting coating is situated directly on the border between visible and NIR light (780nm), because although the coating will reflect ideally at normal incidence, it will start to reflect part of the red light as well when the angle of incidence increases.

This means that the light that enters the room behind the window is not white, but (slightly) coloured. With small angles, this effect is marginal, but when taking the whole azimuth of the sun into account, the colouration becomes significant. This means that the pitch needs to be adjusted to the new angle of incidence, because the projected wavelength will be shorter. This requires a flexible coating of course (Broer, 2013a).

Another option is to optimise the angle of the chiral axis by tilting it away from the normal axis. Obviously, sunlight is not likely to hit a glass surface exactly perpendicularly. Placing the chiral axis between the expected extrema in the time the room behind the glass is used may reduce the problems with coloured light. This will not rule out all problems however, especially since its intended period of functional use will most likely be at one of the extrema, namely summer, when the sun is at its highest. One might consider different coatings for differently orientated facades, because this also limits the difference between the extrema.

The effect of this blue shift is investigated into more detail in this report, and it is shown that choosing strategic locations for the coating (provided that the reflected bandwidth is large enough) will be sufficient to avoid uncomfortable light colouring.

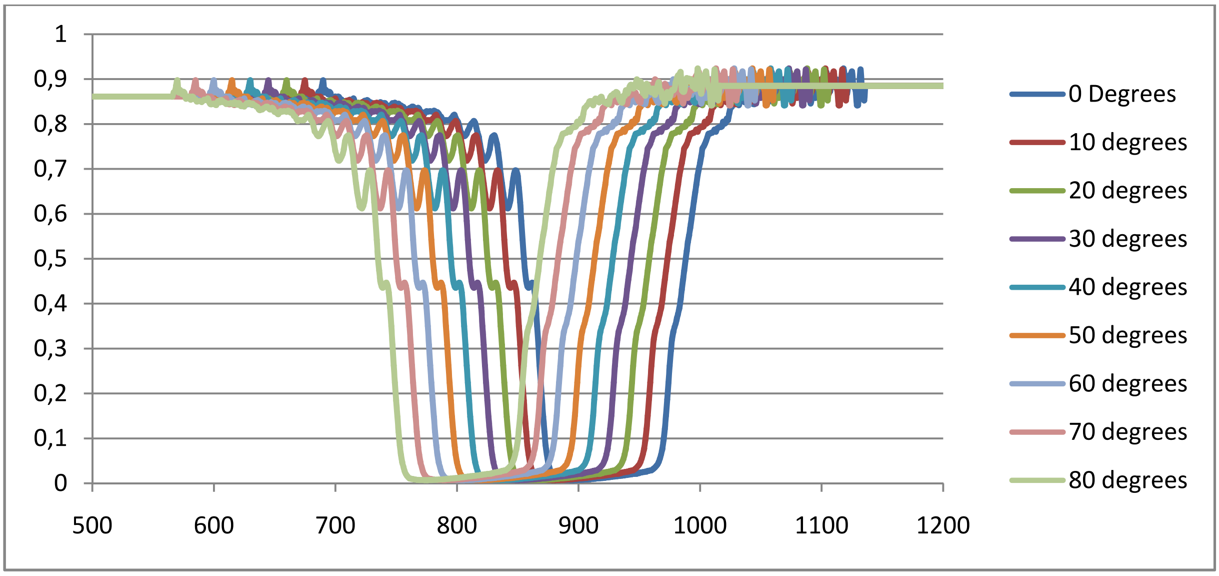


Figure 22: The blue shift of the reflection peak as a result of an increasing angle of incidence. This graph is an approximation based on the assumption that the shape of the graph is not influence by the angle of incidence and a blue shift of 15nm per 10 degrees. This assumption was made after deliberation with Michael Debije (researcher at TU/e) because the only available data shows transmission values on a half lambda filter (own image).

UV light also forms a risk factor for the PolyArch coating, because it causes the liquid crystals to slowly degrade. Much (but not all) of this effect can be prevented by using a good UV filter. Also the use of radical scavengers may help, as they can prevent chain degradation (Broer, 2013a).

Like in any liquid crystal display, the liquid chemical substance that is the basis for the dynamic coating is a potential health risk when it escapes the seclusion of the glass. Breaking the glass could therefore be dangerous (apart from the possible mechanical damage this might cause). The static coatings can be used without risk (Broer, 2013a).

Finally, it can be seen that the transmission of the coating outside the reflection peak still reaches 5-15%. This would become problematic when several coatings are combined, and the reflection values of these coatings are to be combined. However, with accurate optical coupling this effect, which is causes by transitions between varying refractive indices, can be eliminated. The same goes for the combination of the coating with glass, which also has a different refractive index but can be coupled optically. This means that outside the reflection peak, it is reasonable to assume that the transmission is the same as that of the glass used as a substrate. With a layered coating, an in between layer should provide the required coupling, while the binder should be able to do so when the coating is applied as a pigment(Broer, 2013b).

2.4 Coating applications

2.4.1 Possible applications

The PolyArch coating is a coating that can be applied to many different substrates, not just glass. Therefore, there are many different possible field in building to which it can be applied. During several brainstorm sessions with Guido Lammerink, we invented as many different applications as we could think of. The list of these applications is included in the table related to the following paragraph, which is also included in Appendix E.

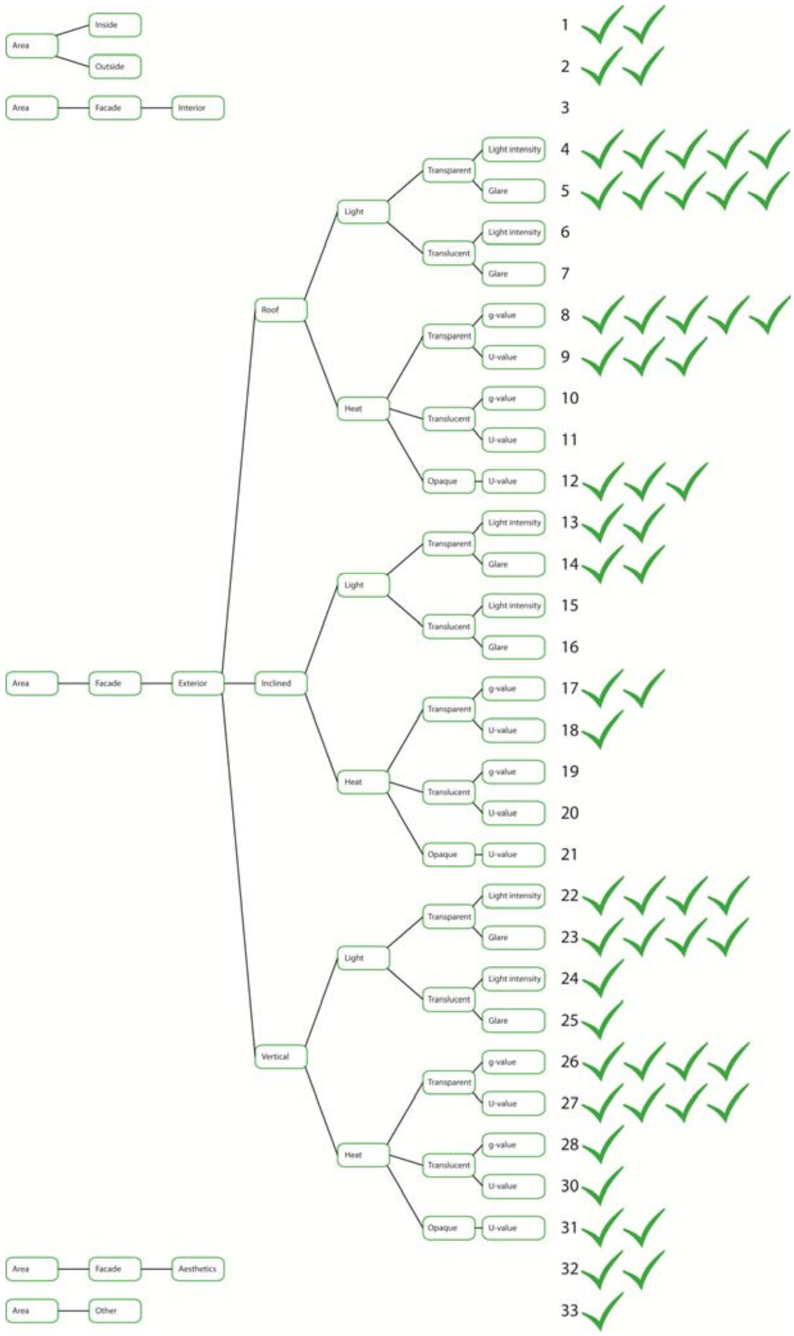


Figure 23: Combining all parameters gives a list of all possible coating application areas. This list can be applied to each building function (own image).

We considered all kinds of parameters that might lead to different kinds of use for the coating, such as the area where the coating would be applied (inside, outside or on the facade), whether the coating would be applied to the interior or the exterior of a facade, where in the building it would be applied (the roof, a vertical facade or an inclined facade), whether it would serve to reflect heat or light, whether the surface that it will be applied to would be transparent, translucent or opaque, whether it would influence the light intensity, the U value or the g value and finally in what building function the coating would be applied (office, residential, industrial or educational). Then there were the remaining categories, which are aesthetics and 'other', that cannot be placed in any of the abovementioned categories.

As a starting point, we created a tree diagram in which all parameters would be combined with each other. The aim of this was to make sure that the resulting list would give an overview of all possible combinations. This would give direction in the brainstorm, and also allow us to categorise the proposed applications in one or more categories. This tree diagram can be found on the previous page, and also in larger dimensions in Appendix E.

The small v's behind each category indicate the number of times that one of the applications we invented fitted into that category. The applications can be, and often were, placed in multiple categories. What we learned from this was that the initial subdivisions were not accurate enough, since most applications could fit into multiple categories and some categories were not used at all. The non-used categories were all related to translucency, which lead to the decision to eliminate this parameter from the final tree diagram. Also, the applications did not seem to vary much between building functions, the main difference was in the performance requirements. Therefore we decided not to differentiate between building functions either. Furthermore, the inclined facade did not render different results from the vertical facade, so this category was also left out in the final diagram. Finally, we prioritised between important (energy related) parameters and less important parameters (such as aesthetics and less influential applications).

The result of this evaluation can be found on the following page, and again in Appendix E. It shows that the focus of our categorisation is on the facade, and that we have distinguished integrated systems and added systems. With the former we mean applications directly on the facade, such as a coating on the window, while the latter refers to systems that are connected to the facade, such as a shading overhang. This subdivision is mainly because of the fact that we both have chosen the same research topic and that neither of us was comfortable with completely abandoning the formerly chosen research direction. Therefore we created this division in which the focus was still on the application of the coating on a facade to reduce the undesired energy transmission through transparent facade elements. Additionally, we aimed to use the same simulation conditions to make our results comparable. Other possible subdivisions, such as new building versus renovation, educational versus office function or transparent versus opaque facade elements, did not meet all these requirements.

The light green box in the diagram shows the parameters with lower priority. These are factors that both of us need to keep in mind at all times, and which may influence the overall performance of the system when combined with other applications, but will most likely not render significant results individually. As was mentioned above, the subdivision between integrated and added systems was made to distinguish between Guido's and my research, which is why the focus of this report will be on added systems, since this is the direction I chose to follow.

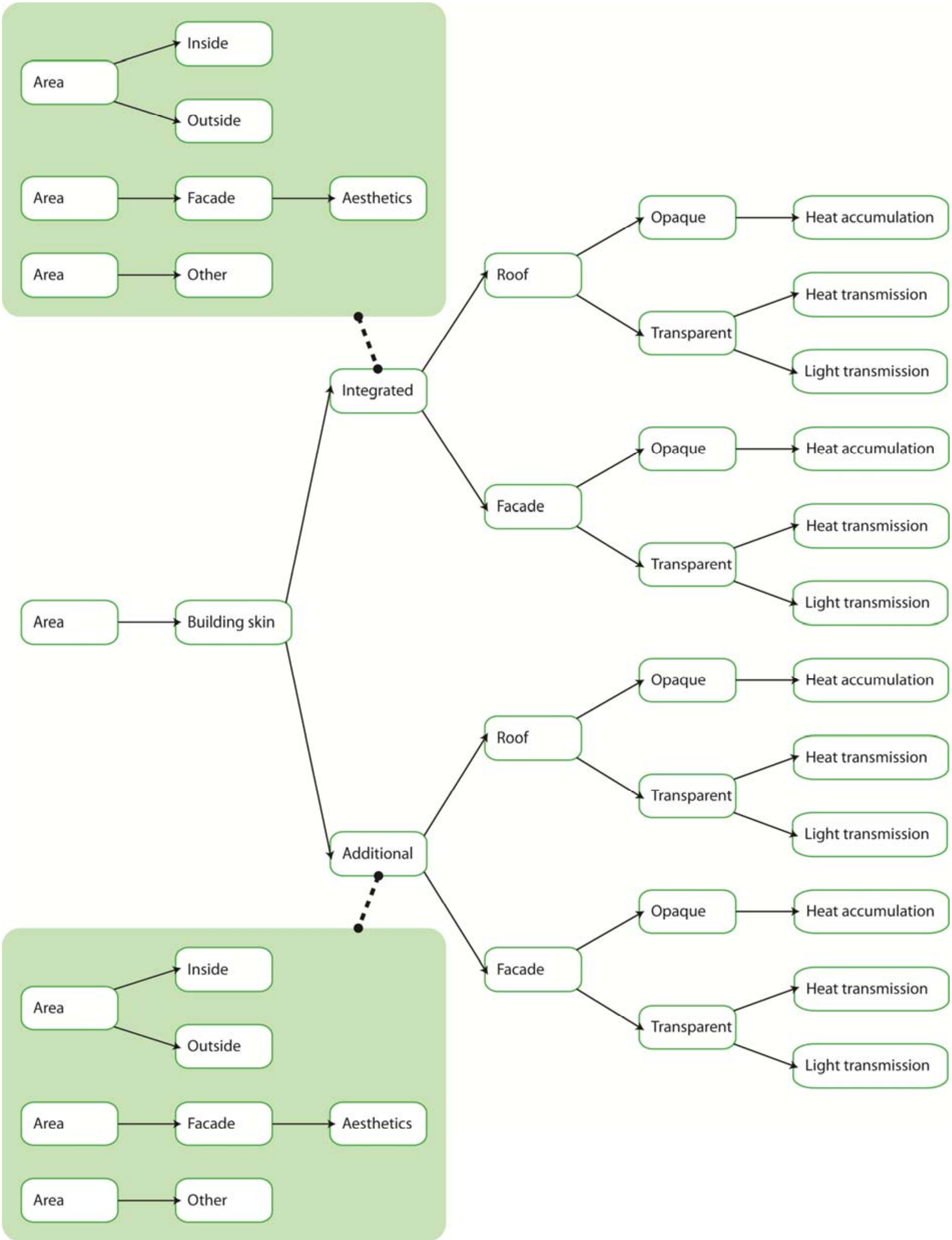


Figure 24: Revised tree diagram to categorise the possible coating applications. The light green boxes indicate parameters with lower significance, judged by their expected influence on the overall reduction in energy consumption (own image).

2.4.2 Review of potential

Once the set of possible applications had been established, their potential had to be determined. This was done by a small number of selection criteria, three of which focused on the principal effect it could induce, and two others based on the economic potential. The reason for this is that the coating has to be both functional and profitable to be interesting for further development. For the effectiveness, its potential to control energy transmission, light transmission and aesthetics was judged. The economic potential considered the ease of application (since a coating may be very functional, but if radical measures have to be taken to apply it, the potential decreases significantly) and the number of interesting markets on which the application could be introduced. A market becomes more interesting when the investment capital increases.

The applications were divided into a category with a large expected potential, one with a moderate expected potential and one of which the potential was assumed to be small. The judgement was based on the expected effect for each criterion, for which the application could be awarded one or two plusses, or in case of no expected potential a zero. Once a zero has been assigned in either one of the economy related criteria, the potential was assumed to be small, since investment capital is critical for the development of the coating. Although this way of assignment is obviously arbitrary, it is justified by the fact that no exact data is available on the possible effect of the coating in any application whatsoever, making a reasonable assumption the best possible evaluation. An alternative would be to obtain data for each application, but this would be too time consuming and exceeding the scope of my research.

The top part of the comparison table is included in this paragraph. It shows the applications which we expect to have the highest potential, both functionally and economically. Since the intended use and reasons for reaching the conclusion are described in the table, I will not go into more detail regarding those descriptions. Again, the full comparison table can be found in Appendix F.

COMPARISON OF SUITABILITY OF VARIOUS COATING APPLICATIONS

Number	Application	Description	Selection criteria					Comment	Conclusion
			Significant effect?			Economically interesting?			
			Energy	Light	Aesthetics	Easily applicable	One/more interesting market(s)?		
1	ETFE Foil	Control of solar radiation in ETFE cushion without inflatable parts	++	+	+	++	+/++	ETFE foils now have problems with controlling solar heat. The advantage is that they are light weight, so a lightweight solar screen is a high potential.	LARGE
2	Darkening glass	Making parts of the glass opaque by applying the coating as a frit or window shape	++	+	+	++	++	Darkening may influence the light level badly, but it can be applied to virtually any glass facade (especially interesting for offices) and the level of opacity can vary.	LARGE
3	Controlling NIR transmission glass	Reflecting NIR and possibly also a little visible light to control heat transmission on windows, glass roofs and atria	++	++	+	++	++	Effects can be large, and invisible. Wide range of applications, especially offices.	LARGE
4	Compensate lack of heat accumulation	Prevent heating of the building by reducing the absorption of heat in visible light and NIR, or the other way around, on roofs and light weight constructions	++	0	-/+	+	++	Application on the roof may be difficult due to the commonly used roofing materials, but the effect on heat accumulation may be significant. Only heat application though.	LARGE
5	External shading	Fixed horizontal/vertical glass panes on the outside next to the window that can be darkened to provide shading. Can work with a cantilever or louvres, the latter also on the roof	++	++	+	++	+/++	Could work just like the darkening glass, but remains efficient when the window is opened and also allows view outside. External panels are not widely used though, but not difficult to implement either.	LARGE

Figure 25: This table shows the top part of the full comparison table that can be found in Appendix F. It lists all the invented applications that we considered to have a high potential regarding their effectivity and economical attractivity (own image).

For both the integrated application and the added system application of the coating I invented a number of applications. Apart from the rather obvious application directly on glass, I came up with three possibilities which may have a large potential, firstly darkening the glass (by means of a pattern, frit or areal division), secondly preventing the heating-up of light weight constructions by controlling the reflection of heat in NIR and visible light and thirdly the reduction of insolation by means of overhangs, vertical fins and louvres. Since the control of heating-up of a contruction is not related to heat transfer through transparent parts of a facade, this application remains a recommended use for the coating, but will not be investigated further. All of these applications are described more detailed both in the table above and in Appendix F.

The darkening of glass may be an effective shading method, and more efficient than only controlling NIR. To not obscure the view to the outside, one may consider a pattern that only darkens a part of the glass, or divide the window in areas of which some can be darkened while others cannot. Additionally, modifying the sensitivity of the triggers may enable the user to control the degree of shading gradually (e.g. by letting some coated surfaces switch to the reflective state at 19 degrees Celsius, some more at 21 degrees, even more at 23 degrees, etc.). One must always be aware of the increased glare risk in such a patterned application, because reflecting surfaces close to transmitting surfaces may cause uncomfortable light intensity ratios.

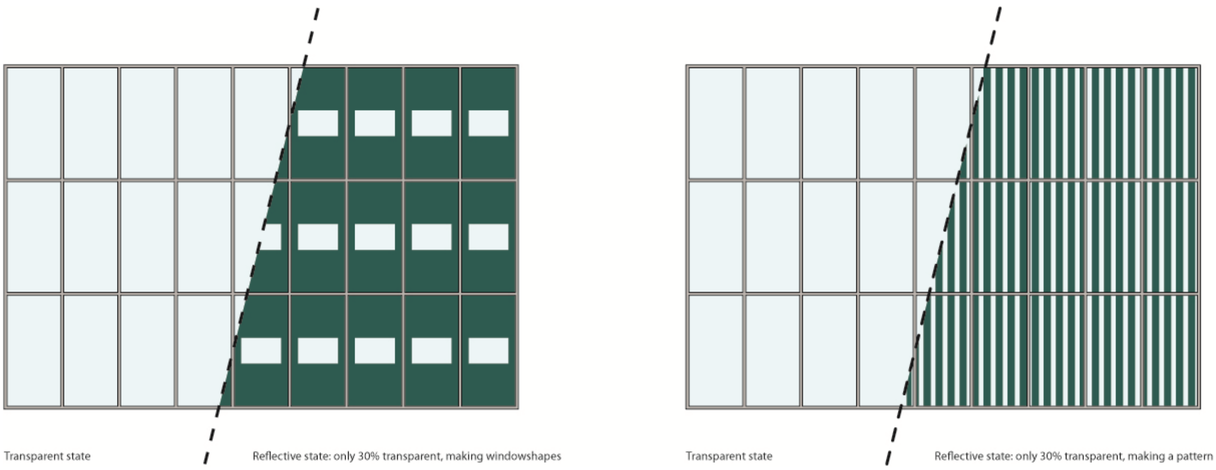


Figure 26: These diagrams show some of the possibilities of reflecting visible light too on some parts of the glass. One must keep in mind that when some colours are selected in the visible light, instead of reflecting all of it, the colour will be change when observed at different angles (own image).

Coating the glass directly will however be an example of direct implementation of the coating, while my focus is on added systems. For this, the louvre system, as well as overhangs and vertical fins, form a good example. In this case, the coating would be placed on a glass cantilever or louvre system, of which the transparency can be adjusted. The reflection will take place in both the visible and the NIR light.

These applications have the advantage of not compromising the view to the outside, which means they can be switched to a fully opaque state without making the room behind them uncomfortable. Also an important advantage of louvres and overhangs is the fact that even while the windows are opened, the coating remains in place and will function as a heat reflector. In that sense, they approach movable exterior sun shading, while eliminating the extra maintenance that is needed for movable parts.

Downsides of such a system, compared to placing the coating directly on the glass are for example the fact that especially overhangs do not always shade the entire window. This means that the efficiency of the coating decreases. Also reflection of light on the shading device must be considered, since via this reflection heat that is blocked initially may enter after all. With respect to the coating, this would mean that specular reflectivity would be less desirable compared to diffuse reflection. Pollution may also form a greater risk in this case than it does with ordinary opaque shading, since dirt will reduce the transparency of the fixed transparent shading. Therefore, proper cleaning must be facilitated in the design.

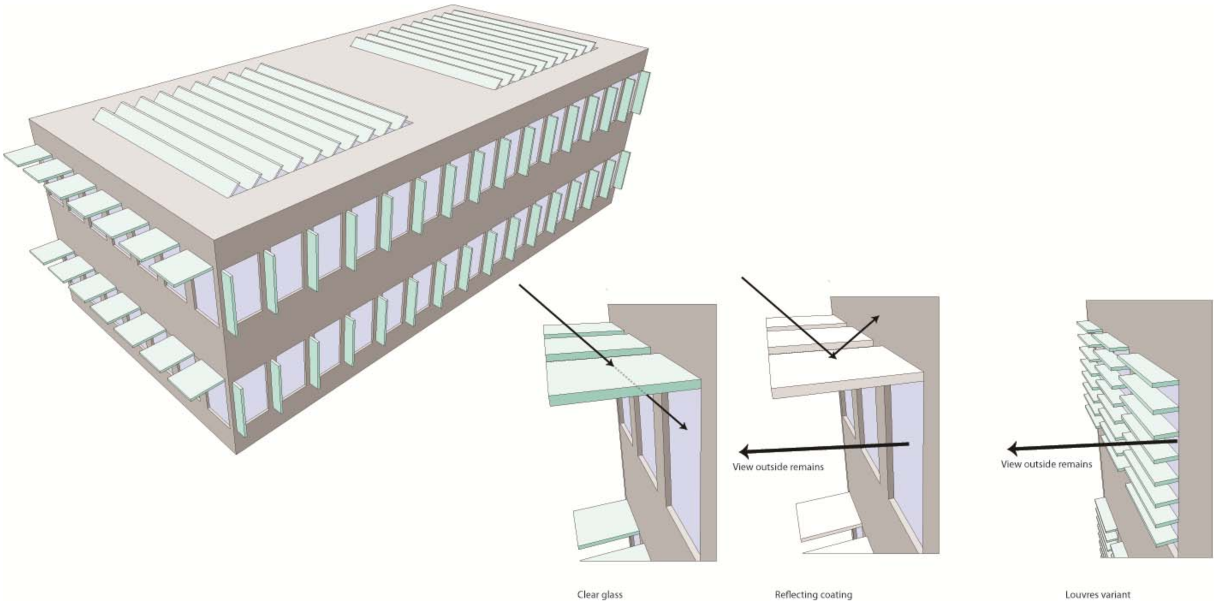


Figure 27: Example of coating application in external added shading devices. It shows overhangs, vertical fins, roof shades and louvres. All can be switched from a transparent to a reflective state (own image).

2.4.3 Further considerations

To assess the abovementioned applications, it is necessary to first obtain some additional knowledge. In this paragraph I will discuss the energy distribution of the far infrared and its relevance for the coating applications, I will describe the ideal ratio between opaque and transparent façade elements form an energy point of view, I will explain the choice of dimensions for the overhangs and vertical fins and conclude with colour appreciation through the coating.

Far infrared energy

The reflectivity of the coating could in principle also work with thermal energy wavelengths. This means that the coating could be used for example to 'activate' thermal mass. In summer, the coating would not be reflecting, so the thermal mass would absorb heat energy, but in winter the coating could be reflective, making sure that no energy is wasted on heating the building mass (irrelevant if the building is used continuously though).

However, this requires two things: a sufficiently small bandwidth in which the coating can be reflecting to make sure it can be efficient, and a sufficiently large amount of energy concentrated in thermal heat waves. The graph below shows that this is not the case, making the reflection of wavelengths in the thermal part of the spectrum unattractive.

First of all, the thermal energy does not have a peak quite as large as the solar energy, despite the fact that the scale of the two peaks is different: the thermal energy graph is magnified 20 times compared to the solar energy graph. This means that the energy that can be controlled in the thermal part of the spectrum is insignificant compared to the solar energy.

Furthermore, the horizontal scale is logarithmic. It starts at 2500 nm and continues until 50µm. This is more than 20 times as wide as the solar spectrum, which is a major drawback considering the limited reflection bandwidth of the coating. In general, that means that using the PolyArch coating to control thermal energy reflection will not be efficient.

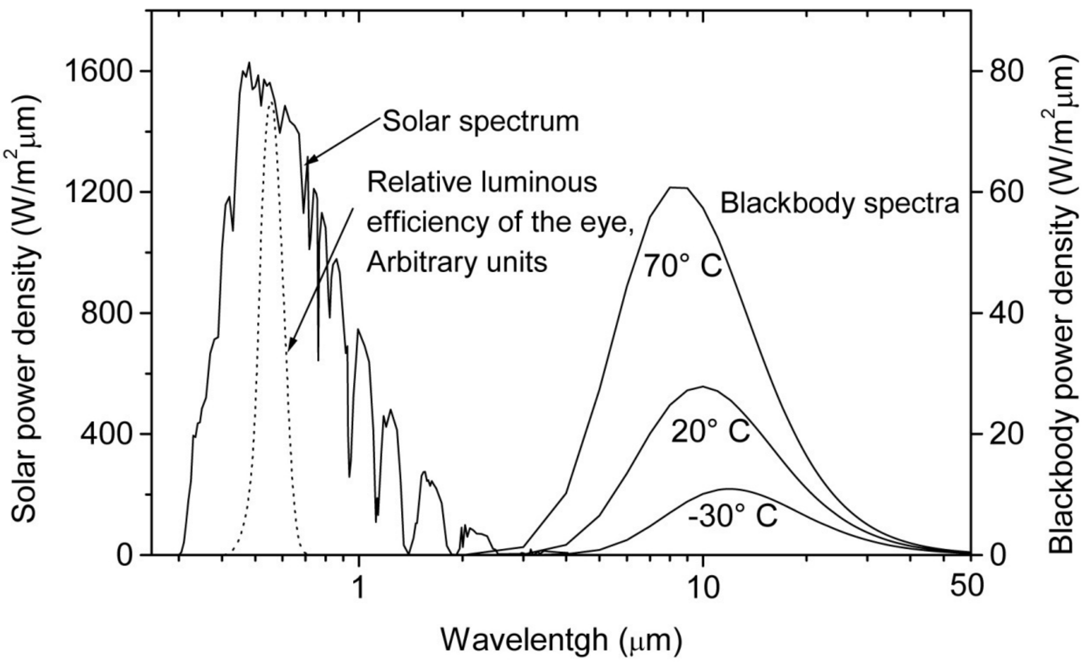


Figure 28: The energy that is stored in the thermal part of the spectrum is far less than the energy in the solar spectrum (note the differently scaled axes). Also, the bandwidth over which this energy is distributed is far bigger than that of the solar spectrum (Karlsson, 2001).

Ideal window area (with respect to interior light levels)

Research has proven that there is an optimum between the energy that can be saved by using natural lighting instead of artificial lighting, and the energy that can be saved on cooling by keeping sunlight outside as much as possible. Since the amount of sunlight is known (given a clear sky), the ideal ratio of transparent and opaque facade elements can be calculated. Of course, the actual window size cannot be adjusted so easily, but the g-value can by means of e.g. a coating, and this will principally have the same effect.

The ideal window size depends on a number of factors, which are different for every building and every room. First of all, the location of the building has a great influence. Obviously, not only the amount of solar energy that will reach the building is higher in central Africa than in northern Canada, but also the appreciation of this energy will differ. In Africa, it will soon be considered undesired heat, while in Canada it may be welcome for both light and heat. This automatically means that in tempered climates, the ideal window area in winter may be very different from the ideal area in summer (Ghisi and Tinker, 2005).

Secondly, the orientation of the windows influence the ideal size. This is of course related to the orientation, because the sun path is different for each geographical location, meaning that the energy that reaches the window on a certain facade orientation changes as well. In general, facades which receive the least energy can have the largest windows. This is also shown in the table below, which shows that the north facade can have the largest windows for a building in Leeds, while the west facade (and slightly less, the south facade) allows for much smaller windows (Ghisi and Tinker, 2005).

Thirdly, the proportions of the room matter for the ideal window size and its energy saving potential. Small rooms and rooms that are wider than deep receive a relatively large amount of sunlight per floor area. However, the energy consumption in narrow, deep rooms is smaller. This means that receiving high levels of daylight may be advisory with regard to user comfort, but for energy consumption reduction a large room which is rather deep is better (Ghisi and Tinker, 2005).

Ideal window area for Leeds, England (% of the room facade area)																				
K	2:1				1.5:1				1:1				1:1.5				1:2			
	N	E	S	W	N	E	S	W	N	E	S	W	N	E	S	W	N	E	S	W
0.60	16	11	10	7	19	12	11	7	16	16	11	7	18	20	11	8	23	20	14	9
0.80	18	12	11	7	20	13	11	7	18	17	12	7	21	21	12	9	26	21	14	10
1.00	19	13	11	8	21	14	12	8	20	17	12	8	24	22	13	10	29	23	15	11
1.25	21	13	11	8	23	15	12	8	23	18	13	9	27	24	14	11	32	25	17	12
1.50	23	14	12	9	25	16	12	9	26	20	14	10	31	25	16	12	36	27	18	13
2.00	27	16	13	10	28	19	13	10	31	22	15	11	37	28	18	14	43	31	20	15
2.50	30	17	14	11	31	21	14	11	37	24	17	13	44	31	20	15	50	35	22	18
3.00	34	19	14	12	34	23	14	12	42	26	18	14	51	34	22	17	58	39	25	20
4.00	41	22	16	14	40	28	16	14	53	31	21	18	65	40	27	21	72	47	29	24
5.00	49	25	18	16	47	32	17	17	64	35	24	21	79	46	32	25	87	55	34	29

Figure 29: Ideal window area for the English city of Leeds. The K value represents the room size, 0.60 being a small room and 5.00 being a large room. The ratios represent the width to depth ratio, 2:1 being a wide, shallow room and 1:2 being a narrow, deep room. The ideal glass percentage increases when the room size increases and when the room becomes narrower. The north and east facade allow for larger window areas than the south and west facade. N.B. These values are only representative for the interior light level and do not take other building physical aspects like insulation into account(Ghisi and Tinker, 2005).

Overhang dimensions

The dimensions for projecting shading devices depends on a number of parameters. First of all, the location of the building, because this determines the sun path. Secondly, the orientation of the window determines how well a shading device can cast a shading on the window. This generally means that a horizontal overhang is used for south orientations, while east and west facades are most efficiently shaded with vertical shading fins. The window orientation can be expressed as the window azimuth, which is the angle between south orientation and a line perpendicular to the window. Perfect south facades have a window azimuth of 0 degrees, east and west facades have a window azimuth of 90 degrees and for north facades this is 180 degrees. Finally, it is important to know in how many sections the shading device is divided. A horizontal overhang can also be designed as a louvre system for example, which means a smaller projection and moreover a smaller unshaded window area(O'Connor et al., 1997).

The overhang and vertical fins are typically static shading devices, which means that they cannot adapt to changing angles of incidence. Therefore, the critical month and time must be determined, and from that the desired angle can be derived. As a rule of thumb the month September is often used, with 10 am for the east facade, noon for the south facade and 3 pm for the west facade.

To find the minimum projection dimensions, the following formula can be used for horizontal overhangs:

$$h = \frac{D \cdot \tan(solar\ altitude)}{\cos(solar\ azimuth - window\ azimuth)}$$

In this formula, the solar altitude and solar azimuth are location dependent. The window azimuth has been described above, h is the height of the shadow and D the depth of the overhang.

For vertical fins, the following formula can be applied:

$$w = D \cdot \tan(solar\ azimuth - window\ azimuth)$$

In this formula, w represents the width of the shadow, and D the depth of the vertical fin. One must keep in mind that these dimensions are minimum requirements.

Month	22 December		21 March/ 23 September		21 June	
Time	Azimuth	Altitude	Azimuth	Altitude	Azimuth	Altitude
4					127	2
5					116	10
6					105	18
7			78	9	94	27
8			66	18	82	37
9	41	5	52	26	68	45
10	28	10	36	32	50	53
11	14	13	19	36	28	59
12	0	15	0	38	0	61
13	14	13	19	36	28	59
14	28	10	36	32	50	53
15	41	5	52	26	68	45
16			66	18	82	37
17			78	9	94	27
18					105	18
19					116	10
20					127	2

Figure 30: Solar azimuth and altitude in the Netherlands, in all seasons, at all times (BK Wiki, 2010).

Colour rendering

Because the reflectivity of the coating is depending on the angle of incidence not only with regard to the degree of reflection, but also regarding the reflected wavelengths, it is important to know how much of the red light can be filtered without disturbing the white balance of the light. The reason for this is the fact that a lot of energy in the solar spectrum can be found at the division between visible and NIR light, at 780. Therefore it would be desirable to place a coating directly from that point over the NIR, because it could control a lot of heat without visible effects. However, when the angle of incidence changes, the reflection bandwidth shifts up to 100nm to the shorter wavelengths, meaning that a part of the red light is reflected as well. The transmitted light will therefore become slightly bluer.

The question is how much of the red light can be reflected before the blueness of the light becomes uncomfortable. To know that, it is first of all important to know that the human eye is not equally sensitive to all wavelengths of the visible light. Its sensitivity is displayed in figure 28 in what is called the ‘human eye sensitivity curve’, which shows that the highest sensitivity can be found around 555nm. Towards the NIR and UV, the sensitivity radically decreases. Because of the insensitivity near the extremes, the spectrum of visible light can also be taken from 380 to 720nm (Christie, 2001).

Still, our eye can also adapt to the colour of the light. For two colours which are not too different, like daylight compared to fluorescent lamps, the eye can adjust its sensitivity to perceive both colours as the same white. This process is called chromatic adaptation, and works because the eye, which senses colour with the cones on the retina, has three types of those cones, all sensitive to a slightly different bandwidth of the visible light. There are S, M and L cones, and their sensitivity can change independently from the others. For example, when light is slightly bluer than completely white light, the sensitivity of the S cones (short wavelengths) becomes slightly smaller compared to the M and L cones. The light then still appears to be white (Fairchild, 2005).

However, chromatic adaptation only works with light that differs only in a very small degree from white light. Beyond that point, colour will be perceived. To determine whether this is disturbing or not, the Colour Rendering Index (CRI) can be calculated. The exact way to do this is described in the European norm EN-410. The outcome will be a number between 20 and 100, and provides insight in how well the colour can be used to identify or match colours. When the CRI is between 60 and 80, the colour quality is moderate, which means that it is suitable for industry and some school/office functions. A CRI between 80 and 90 is better, and allows accurate colour judgement. Therefore, it is suitable for e.g. offices, school, homes and hotels. Only for functions like colour mixing, exhibitions and medical examinations a CRI above 90 would be required (Low Energy Architecture Research Unit (LEARN), 2013).

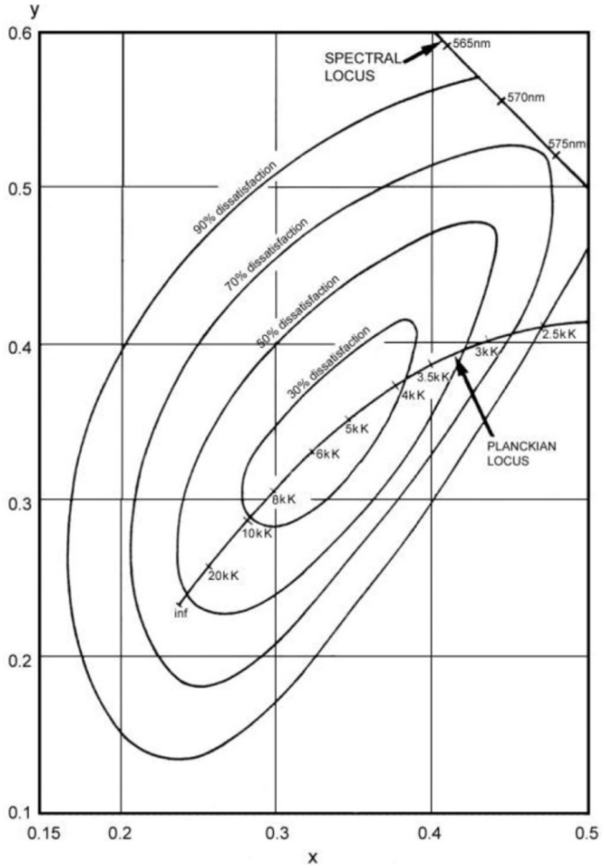


Figure 31: Planckian locus in the CIE 1931 chromatic diagram. A correlated colour temperature (CCT) between 4000K and 10000K will mean that less than 30% of the people finds the colour discomforting(Boyce, 2003).

Also the correlated colour temperature (CCT) can be used to predict whether a colour is perceived to be comfortable. This method is based on the colour of a perfect blackbody. A blackbody radiates a predictable colour at a certain temperature, and therefore there is a direct relation between the temperature of the object and the corresponding colour. To match colours of other objects, this is used as an objective method of comparison. All colours of a radiating blackbody can be calculated with Planck's law, and when included in the CIE chromatic diagram they represent the Planckian locus. The colour that most closely resembles the colour at a certain intersection with the Planckian locus is the CCT at that point (Boyce, 2003).

Daylight is defined to have a CCT of 5500K. The fragment of the CIE chromatic diagram of 1931 below shows the relation between this CCT and the Predicted percentage dissatisfied (PPD). This is not accurate enough yet, but gives an indication of what colours are perceived to be uncomfortable. As long as the CCT remains between 4000K and 10000K, the PPD will be smaller than 30%(Boyce, 2003).

3. Simulation

3.1 Software selection

3.1.1 Requirements

The complex functioning of the coating was reflected in the list of demands that we composed for the simulation software. There was not a single software package found that was able to meet all requirements, so in the next paragraph a comparison will be made to explain the software choice. First I will describe here the requirements that the simulation ideally should meet:

- Adaptive simulation. The coating responds to a certain trigger; either light, temperature, electricity or something else. Regardless of what initiates this trigger, this means that the reflection state of the coating will change depending on the circumstances. When the simulation would only take into account a coating state that is either 'on' or 'off' for the entire simulation, the adaptive potential could not be simulated.
- Trigger flexibility. Directly related to the previous requirement is the need to model a certain trigger value into the simulation. The possibility to introduce such a value is inherent to adaptive simulation, but the number of different types of triggers is relevant for the trigger comparison. Even though I may not be analysing this in great detail myself, this may be valuable for further research, when my simulation model can be expanded or used otherwise to find the best trigger.
- Angular dependence. The coating responds very differently to radiation that irradiates it under a large angle of incidence compared to normal incidence. It would invalidate the simulation results if this would not be taken into account in the simulation. Even though most measurements for glass g-values are commonly done only for normal incidence, this is incorrect but justifiable because the reflection behaviour of glass is known. The PolyArch coating responds in the exact opposite way, which makes it necessary to consider the effects of a changing angle of incidence.
- Geometry flexibility. Since the coating is not only applied directly on glass, but also on other geometries such as overhangs, louvres and ETFE cushions, there must be a way to integrate this kind of objects in the simulation, to make the different simulations comparable and as exact as possible.
- Daylight. Since the degree of shading will have an influence on the light level inside, and therefore on the necessity to use artificial lighting, the simulation should be able to use the artificial lighting energy and the cooling energy as an input to always find the optimum between those two, determining whether the coating should be reflecting or transmitting.
- Variable comfort standard. To get a relevant result, the simulation must be able to implement the changing comfort standard that are known for users in models such as Fanger's thermal comfort model (1970)and preferably also the for thermal adaptation adjusted model by Brager and De Dear(1998).
- Ease of use. The simulation program will probably be new, so it will take some time to learn how to work with it. The shorter this time is, the more time there will be for doing simulations, which makes this a critical criterion with respect to the short time that is available for doing the simulation.

- Output. The comparison between the different shading methods will be done using the energy consumption that is needed to keep the interior comfortable. Therefore, the simulation software must be capable of calculating and outputting the desired heating and cooling loads.

This will automatically call for a simulation program that is capable of doing quite detailed calculations. However, it must be noted that the level of detail in the outcome may not be representative for the accuracy of these values, since the input data is still very much susceptible to change, because the technology is not fully developed yet. The input is therefore an estimated performance, rather than an exactly measured performance.

It is therefore not correct to say that a detailed calculation gives exact outcomes, but would be more sensible to acknowledge the fact that the simulation of this coating is complex, and that therefore a detailed calculation is needed to provide a foundation for estimations. An even more detailed calculation, which is outside the scope of this research, would be able to give exact outcomes, provided that the inputs are definitive values.

3.1.2 Comparison

Based on a quick review of options, there were three simulation software packages that seemed to be suitable for the simulation of the energy transmission control by the PolyArch coating. These were Matlab/Simulink, TRNSYS and DesignBuilder. They all have certain advantages and disadvantages, due to which there initially was not a single best choice. There was no program available that was able to meet all the requirements I mentioned in the previous paragraph. In that case there are two main possibilities: revising the demands on the simulation, in order to simplify the simulation without rendering its outcome insignificant, and expanding the capacities of the simulation software. The latter would consume a considerable amount of time, which is why the former method should be applied beforehand in order to determine whether the model can indeed be changed without compromising the level of detail in too large a degree (Loonen, 2010).

Before explaining more about the reconsideration of the simulation, I will briefly introduce the three abovementioned simulation software packages, describing their benefits and drawbacks.

Matlab/Simulink

Just like TRNSYS, Matlab/Simulink is modular software, which connects small components. In this way, Simulink is the graphical editor which is comparable to the TRNSYS simulation studio, and Matlab is the text editor which is comparable to TRNEdit. Matlab is based on matrices, in which all nodes between calculation elements are defined and connected. This means that the number of formulas increases exponentially when the number of nodes increases, with as a result an increasing chance to make mistakes. There is however a high degree of transparency, which allows the user to adjust the simulation calculation themselves, provided that they have an expert knowledge of the software (El Khoury et al., 2005). This transparency also makes Matlab/Simulink an interesting option if the intended simulation exceeds the capacity of TRNSYS (Spoel, 2013).

Because of the modular setup of Matlab/Simulink, there is the possibility to add, replace or remove certain components from the calculation. Simulink, which is used parallel with Matlab, provides the possibility to do dynamic calculations with the matrices in Matlab. However, when the matrices that are integrated in the model are time dependent, this will cause problems which can be solved by either splitting the model into several submodels, or by using a different programming language like C or Fortran. The latter is the standard software used in TRNSYS, for this reason(El Khoury et al., 2005).

Although Matlab primarily is not appropriate for complex general purpose simulations like multizone buildings, there is a possibility to make use of a large variety of available toolboxes, like Simbad, which is a software system that facilitates connections between separate zones. However, due to the non-specialised nature of the software, the window model in Simbad is rather abstract compared to the detailed, angle dependent output which is used for TRNSYS simulations (El Khoury et al., 2005).

TRNSYS

On the one hand, just like Matlab/Simulink, the TRNSYS software is based on a modular system of components, which can be connected to one another in order to create a simulation model. This flexibility based on its components, which are each specialised on a specific part of the building simulation and based on well-established evaluation guidelines such as ASHRAE and DIN, is its great strength (Wetter and Haugstetter, 2006).

On the other hand, TRNSYS is procedural software, unlike Matlab/Simulink, which is equation based. TRNSYS consists of two main elements, which are the kernel that executes all calculations, and the library of components that offer these calculations. The user only works with the components, which are also called Types, and can be connected to each other via the text editor TRNEdit, or via the graphical Simulation Studio. Every type has its individual functionality and use, translated into relevant calculation methods. The great advantage of this is that the user does not need to insert and connect all relevant formulas themselves, but merely has to connect the outputs of one component to the inputs of one or more other components, thus eliminating a large chance of errors due to inaccuracy. The downside of this system is the lower degree of freedom in making the model, because not all formulas which are used for the calculation can be accessed, which sometimes results in the need for special combinations or workaround methods, which can be redundant and inaccurate (Wetter and Haugstetter, 2006).

Other strengths of TRNSYS are the extensive documentation on the use of the software – both in a manual and in comments for each input, parameter, etc in each component, which describes what the purpose of this specific variable or parameter is –and the possibility to connect the TRNSYS model to numerous other data and simulation programs, among which are Matlab and Microsoft Excel (US Department of Energy, 2011).

In comparison to Matlab, TRNSYS has the benefit of being especially developed for architectural application, while Matlab serves many other purposes. Therefore TRNSYS can offer much more detailed models which are specific for architecture(Spoel, 2013).It is possible for example to import a window input file from the Window program, in order to take into account accurate angular dependent reflection and transmission data for both the visible light and NIR light, specific to a certain window composition.

Also the calculation in TRNSYS can be executed much quicker than it can be done in Matlab/Simulink. When the accuracy of a TRNSYS model is increased from one time step an hour to eight time steps an hour, the calculation time doubles. For a similar Matlab/Simulink model this would take three times more time (Wetter and Haugstetter, 2006).

Regarding the proposed Matlab/Simulink plugin Simbad, which makes Matlab/Simulink more building related, also solar radiation calculations are more accurate in TRNSYS than in Matlab/Simulink.(El Khoury et al., 2005). One major drawback of TRNSYS is the impossibility to calculate light intensities, since it only takes thermal energy into account. This means that optimisation between light intensity and cooling energy is impossible. Another weakness may be that the software does not assume standard values for the simulated building, which means that the user is required to have detailed knowledge about the building (US Department of Energy, 2011).

DesignBuilder/EnergyPlus

DesignBuilder is the graphical interface of the dynamic thermal simulation software program EnergyPlus. This means that not DesignBuilder, but EnergyPlus will perform the calculations. The biggest advantage of DesignBuilder is the high-quality interface, which enables easy input of geometrically relatively complex models. Because of this interface, it is fairly easy to learn how to work with the software, which makes it very suitable as an educational and communicational instrument, to develop a better basic understanding of how certain building physical situations work (Wasilowski and Reinhart, 2009).

DesignBuilder can calculate with various building physical factors, such as the ventilation speed and amount, thermal energy transmission through structures and light levels and lighting energy. Apart from that, there is a possibility to introduce several kinds of standard sunshades, such as louvres and overhangs, which can be adjusted to personal demands up to a certain level.

However, DesignBuilder was not created for complex and special projects. It offers a number of standard inputs for each simulation parameter (e.g. wall composition, glass type, sunshade, etc.) from which the user can make a selection, but which cannot be replaced by a detailed personal input specific to the design. It is possible to use an adaptive thermal comfort model. All this combined makes the software very suitable for a quick insight into the building physics of a regular building, but for special applications this software is hardly useful.

In addition, EnergyPlus, and because of that DesignBuilder as well, is not suitable for adaptive calculations. There is a possibility to use EnergyPlus EMS, which offers the possibility to model large EnergyPlus systems and also allows the user to influence what happens with the simulation while it runs, but this requires much more additional research to understand the functioning of this software (Tindale, 2013).

3.1.3 Selected software

It was shown in the comparison in the previous paragraph that DesignBuilder is an interesting tool for preliminary results and quick insight in standard principles, but its relatively low flexibility makes it inadequate for very specific calculations which are needed for the simulation of the PolyArch coating.

This leaves the choice between Matlab/Simulink and TRNSYS. Although Matlab/Simulink may in principle be the right choice based on the potential of the software, TRNSYS was preferred because it required less time to create a model, less time to understand the principles behind the model, and because it offered in general more accurate calculations when building simulations are concerned. This means that the ease of use, which is expressed in many ways when TRNSYS is compared to Matlab/Simulink, prevails over the possibility to optimise the lighting energy. With regard to the complex geometries, difficulties would be present in either of the remaining software packages.

3.2 Model description

3.2.1 Standard office

As was mentioned in the introduction, the model will be based on a standard office that is the same for both Guido's and my calculations. The choice for an office was induced by the strict thermal comfort demands and the large investment potential in this sector. To define this standard office, all relevant parameters were defined in advance. They were collected from a number of different sources, each of which is mentioned after the concerned value. The main sources were the reference office provided by Agentschap NL and the reference database made by ISSO.

$R_{c,facade/Floor}$:	3.5 m^2K/W (Agentschap NL, 2012)
$R_{c,roof}$:	4.0 m^2K/W (Agentschap NL, 2012)
Window frame:	Aluminium (Agentschap NL, 2012)
Glass type:	HR++ (Agentschap NL, 2012)
Window area percentage:	50% (Agentschap NL, 2012)
g-value glass standard:	60% + internal shading (Agentschap NL, 2012)
Ventilation rate:	n=2 (balanced ventilation)(Agentschap NL, 2012)
Heat and cold generation:	HR-107, T_{in}> 55°C (heat pump) (Agentschap NL, 2012)
Lighting:	9 W/m^2, daylight switch + presence detector (no light fixture ventilation) (Agentschap NL, 2012)
Tap water:	Electrical boiler (Agentschap NL, 2012)
PV cells:	No (Agentschap NL, 2012)
Solar collector:	No (Agentschap NL, 2012)
Infiltration:	Infiltration rate standard office = 0.25. $q_{v,10,kar}$ = 0.3 $dm^3/(s\ m^2)$ (litres per second per square meter of used area) (ISSO digitaal, 2010d)
Reflection of internal walls:	50% (Stichting Kennisbank Bouwfysica, 2009)
Reflection floor:	20% (Stichting Kennisbank Bouwfysica, 2009)
Reflection ceiling:	70% (Stichting Kennisbank Bouwfysica, 2009)
Reflection roof material:	Black: 10-20% White: 70-85% (Provincie Utrecht, 2010)
Reflection façade material:	Concrete and brick: 5-15% Aluminium: 50-60% Light wood: 30-50% Dark wood: 10-30% (Stichting Kennisbank Bouwfysica, 2005)
Internal mass of room:	Average weight = 50-120 kg/m^2 (façade and floor = concrete, hallway separation wall = brickwork, internal walls = covered insulation material) (ISSO digitaal, 2010e)
Ventilation:	At least 1 $dm^3/s\ m^2$, minimum of 10 dm^3/s per room (ISSO digitaal, 2010c)

Air change rate:	Minimum 1dm^3/s m^2→ 69.084 m^3/h →n = 1.33/h (derived from room dimensions) → reference from Agentschap NL is higher → n=2 if occupied, n=1 if unoccupied
Humidification:	30-50% humidity (<6%PPD) or 25-60% humidity (<10%PPD) (ISSO digitaal, 2010f)→ 50% humidification for simulation
Air supply temperature:	Outside air + 70% heat recovery
Power of heating/cooling installation:	Depending on interior climate
Internal heat production:	Person: 130W→ metabolic rate = 1.24 MET Laptop: 30W Printer: 50W *5% operation time*number of persons using it (ISSO digitaal, 2010g)
Specific gains:	3.3 W/m^2 (equipment only, calculated with 2 laptops and 1 printer)
Sun shading:	Functions automatically at $q_{z,s}$ = 250 * g-value or $q_{z,s}$<300W/m^2 (total incident radiation)→ not relevant for coating application
Occupancy:	2 persons
Occupancy rate:	80% (ISSO digitaal, 2010a) weekdays from 08:00 – 18:00.
Heating and cooling time:	06:00 – 18:00 (ISSO digitaal, 2010b)
Ventilation time:	07:00 – 18:00 (ISSO digitaal, 2010b)
Vacations:	No
Room height:	2.7 metres
Room width:	5.4 metres
Room depth:	3.6 metres
Room area:	19.44 m^2
Room volume:	52.488 m^3

The diagram on the following page summarises the most important values from this table.

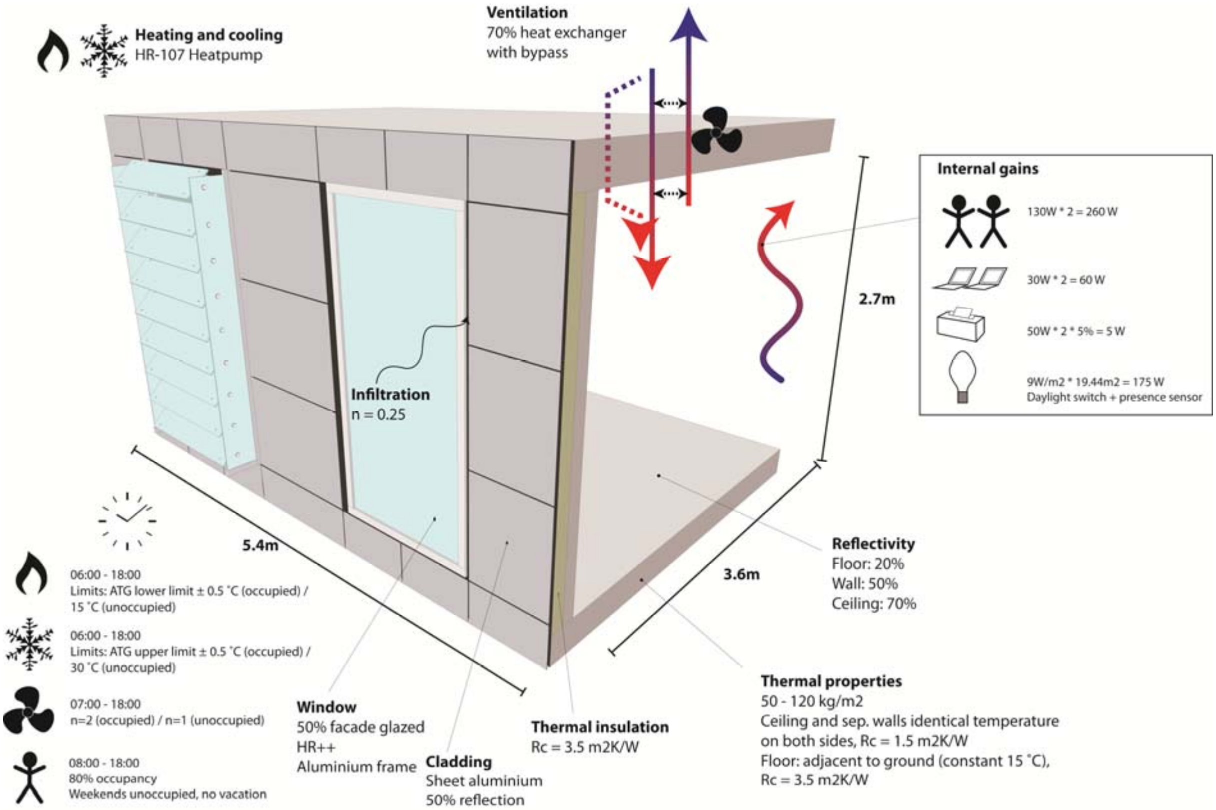


Figure 32: Schematisation of the properties of the standard office as it was used for the simulations. Not every property listed in the table above is included in this scheme, only the most important ones (own image).

3.2.2 Method of simulation

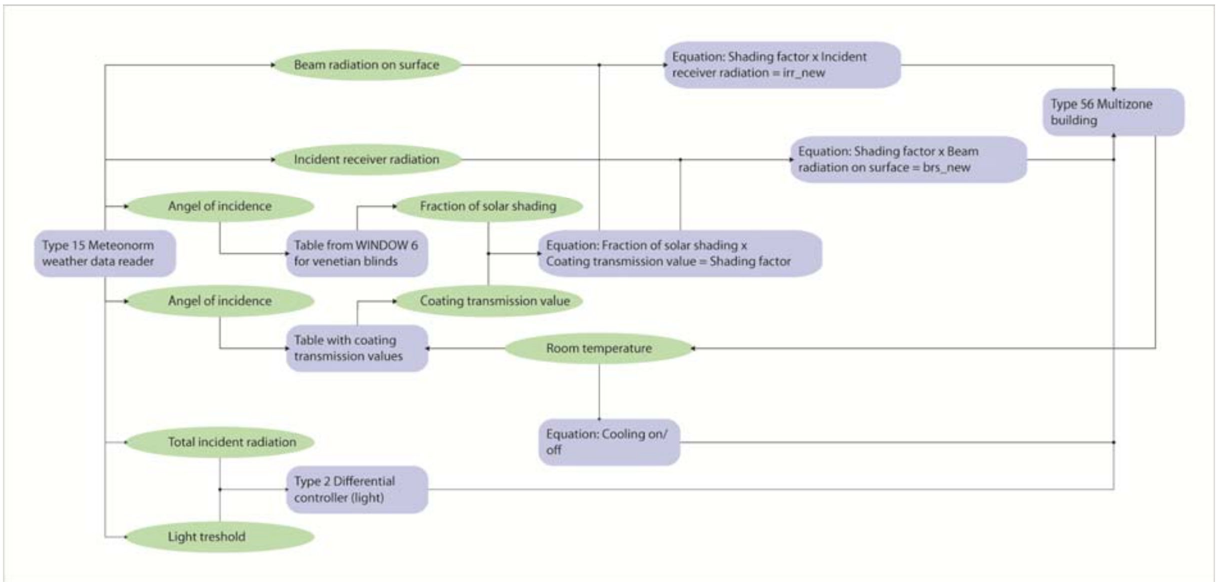


Figure 33: Flow diagram showing the simplified principle behind the simulation. A larger image is included in Appendix D, where also a more detailed description of the simulation model can be found (own image).

The scheme above shows the principle behind the simulations that will be done to evaluate the potential of the PolyArch coating when it is applied on louvres or an overhang. The middle section shows that a weather data file provides the angle of incidence of the solar radiation, which will be used to determine the corresponding g-value and the corresponding coating transmission value.

These two will be multiplied to find the corrected shading factor. By multiplying this outcome with the total irradiation and the direct beam radiation respectively, both coming from the previously mentioned weather data file, new radiation values corrected for the shading are calculated, which are used as an input for the building type. This calculates the indoor air temperature, which can be used again as an input to determine whether the coating should be on or off, and whether the cooling should be on or off. Finally, there is a separate route for the lighting, which collects its radiation data from the weather data file, and makes a continuous loop to determine whether this requires the lights to be on or off.

Nothing in this simulation model is standard in TRNSYS, apart from the weather data files and a part of the radiation equation. The required input for the Multizone building has been derived from an automatically (via an integrated wizard) generated shading model, which has then been modified to use the PolyArch shading instead of the predefined overhang. Almost all components contain either equations and lookup tables in Excel, or equations specific Equation components, none of which are standard in TRNSYS. The largest advantage of TRNSYS in this simulation was to connect all equations and perform a dynamic adaptive simulation, which could create an input for the standard Multizone building component in which the desired outputs were generated.

A more detailed description of the simulation model, as well as the text files that were generated by the simulations, can be found in Appendix B. Here you can find examples of the Excel lookup tables that were used to find the correct transmission values for the coatings and venetian blinds, as well as a lookup table for the reference temperature for the ATG, that will be explained in more detail in the next paragraph.

The simulations that will be performed are first of all the above described simulation for a louvre system and for an overhang, of which the latter will be compared in opaque state with the standard overhang calculation (which is always opaque) to validate the chosen calculation method. The table of coating transmission values will be modified to also calculate the 80% and 60% performance outputs.

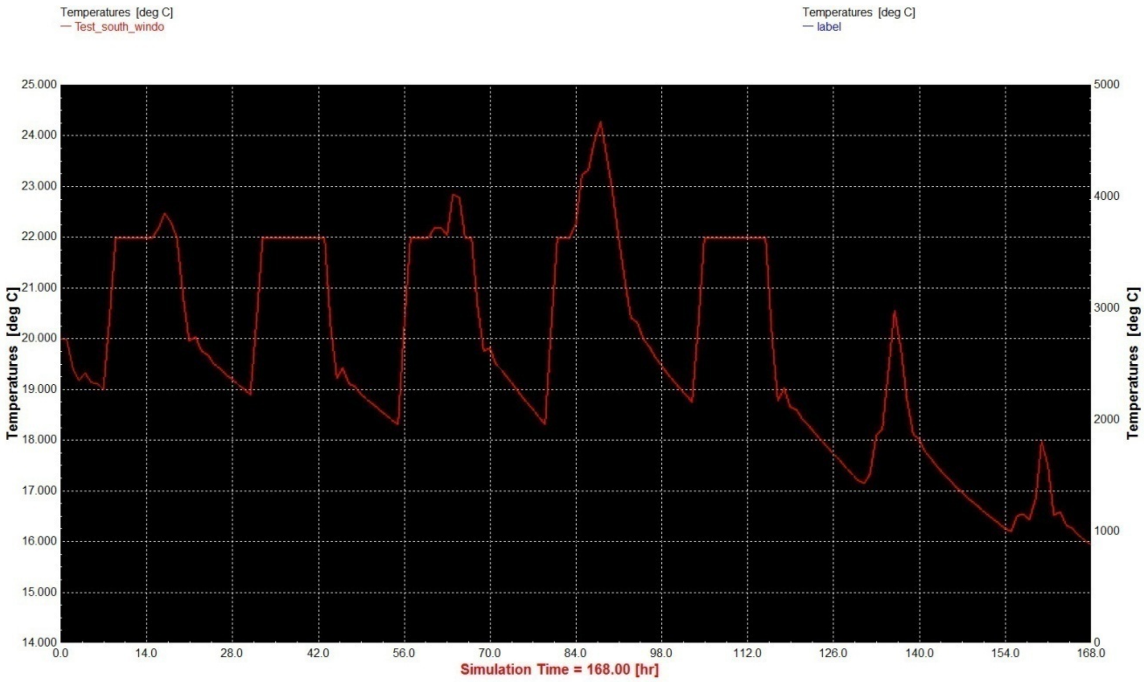


Figure 34: The temperature for a non shaded office with a window area of 50% and cooling (no heating) installed. The calculation was performed for the first week of January, and shows that the cooling installation is not able to control the temperature at all times, in contrast to the situation for the west facade (own image).

For the windows, a south orientation was chosen. As was mentioned describing the ideal window area, both the south and the west orientation impose a high risk of overheating on the building. A small simulation in TRNSYS was performed to determine which one of them causes the highest overheating risks. It shows that when the same conditions are applied, the cooling system is able to control the temperature to a steady 22 degrees, but when the windows are oriented towards the south, the temperature exceeds this 22 degrees at some times of the day.

In addition, the lower temperatures are a few degrees lower on the west facade than on the south facade. For these reasons, a simulation for the south facade was preferred over a simulation of the west facade, because the shading potential for this orientation proved to be slightly larger.

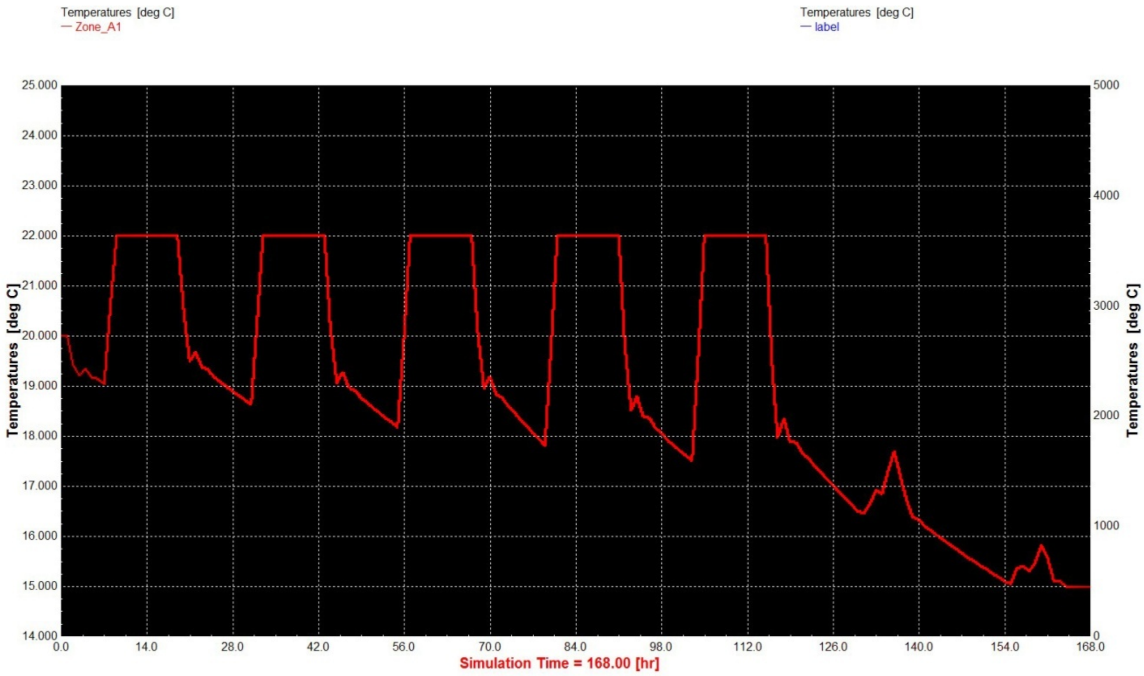


Figure 35: The temperature for a non shaded office with a window area of 50% and cooling (no heating) installed. Apart from the difference in maximum temperatures, the minimum temperatures on the west facade are lower than on the south facade (own image).

Control strategy

Two common practice control strategies are firstly controlling based on the level or irradiance and secondly controlling based on the indoor temperature. It is important to consider the influence on the energy consumption of irradiation in winter, which is why the latter control strategy proves to be more adequate. Although the irradiation does function as a means to predict an increase in room temperature, it is not necessarily true that this increase is undesired. Therefore it is more appropriate to consider the room temperature itself, since this determines the number of hours in which overheating takes place (van Moeseke et al., 2007).

The chosen accepted indoor temperature is chosen to be variable, according to the Dutch ATG, which translates to Adaptive Temperature Limits. In this model, the perceived comfortable temperature depends on the weighted average outside temperature over the past four days. At an offset of this ideal comfort temperature, there are boundaries within which 90% of the users would still feel comfortable, and similarly for 80% and 65% of the users. In this simulation, the 90% standard is selected, because this is most applicable to the high standards in office buildings. The ATG also includes a correction for buildings with natural ventilation, but since this is not relevant for the simulated office building, the effects of this are not further discussed here.

3.2.3 Possible inaccuracies

A computer simulation is always a representation of reality, regarding only some aspects. For that reason, computer simulations will always be an abstraction, despite the level of detail some software packages display.The degree of abstraction determines the level of accuracy in the model, meaning that if certain variables are not taken into account, the model will become less accurate. In addition, the simulation will only calculate values for certain time steps, and no matter how small these steps are, in no simulation will they be continuous. However, leaving out certain variables or taking slightly larger time steps will also mean that the simulation model becomes less complex, which results in more comprehensibility and faster calculation. It is always necessary to find the right balance between accuracy on the one hand, and comprehensibility and calculation time on the other hand(Clarke, 2001).

Some of the inaccuracies are inherent to the software that is selected for the simulation. The effect of the proportions of the opaque parts of the overhang and louvres(the glass fittings and support construction) is not taken into account in the simulation. Although there is a small difference in projected shadow depending on the angle of incidence onto these opaque parts, the difference will most likely not be large enough to be worth the effort of modelling this slightly changing projected shadow. This is because the elements are slender, and in most cases do not have a large projection from the facade.

Furthermore, the sun shading in TRNSYS is not spectrally selective. This means that the program assumes a roughly equal distribution of the light between the visible and the NIR part (Loutzenhiser et al., 2007). This would not be a problem if the window's values for transmission of visible light and transmission of NIR were approximately equal, but if this is not the case, e.g. in a low-e coating, the simulation will assume a too high reflection of solar heat by the combination of coatings. This problem is illustrated in the diagram below.

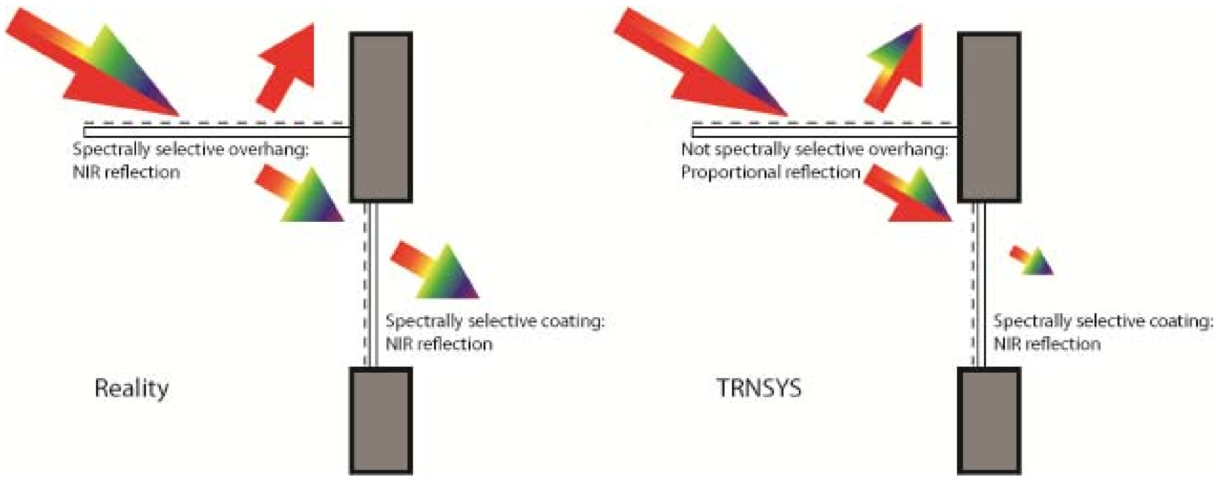


Figure 36: Spectral selectivity inaccuracy in TRNSYS. On the left is shown what happens in reality when a spectrally selective coating on a glass overhang is combined with a spectrally selective window coating: the overhang filters out the NIR radiation, transmits the visible light, rendering the window coating obsolete due to the absence of NIR radiation in the incident light. However, since TRNSYS cannot take into account spectral selectivity of the overhang, it will work with a proportion of the energy that will be reflected (for NIR reflection, this means 55% of the energy will be reflected), assuming that the 45% of transmitted light still contains both visible and NIR light. When only considering the energy, this is correct, but since the window coating filters the NIR radiation as well, it will reflect some of the presumed transmitted radiation, again approximately 55%. This means that the combination of the two coatings reflects a too large share of the incident light.

In addition, the PolyArch coating is not effective in the far infrared part of the light, so in order to simulate a realistic application of the coating without too much heat loss, it had to be combined with a low-e coating. There are two types of these low-e coatings. One of them is called heat mirror and this reflects mostly far infrared, the other one is called solar control glass and is also reflective in the NIR part of the spectrum. Since the PolyArch coating is also effective in the NIR, it is essential that the chosen low-e coating has as little effect in this part as possible, because otherwise the effect of the switchability would be much smaller. To this end, Pilkington K-glass was chosen for the simulation, since this is a very effective heat mirror but marginally influential in the NIR light. The difference between this K-glass and a conventional low e coating (solar control glass) can be seen in the two images below. Here it can also be seen that although the K-glass coating transmits most of the NIR light, the reflection does start before the end of the NIR, so the effect of the PolyArch coating might be reduced in this part of the spectrum. Nevertheless, this effect will be small, since the energy contained in this part of the spectrum is very small.

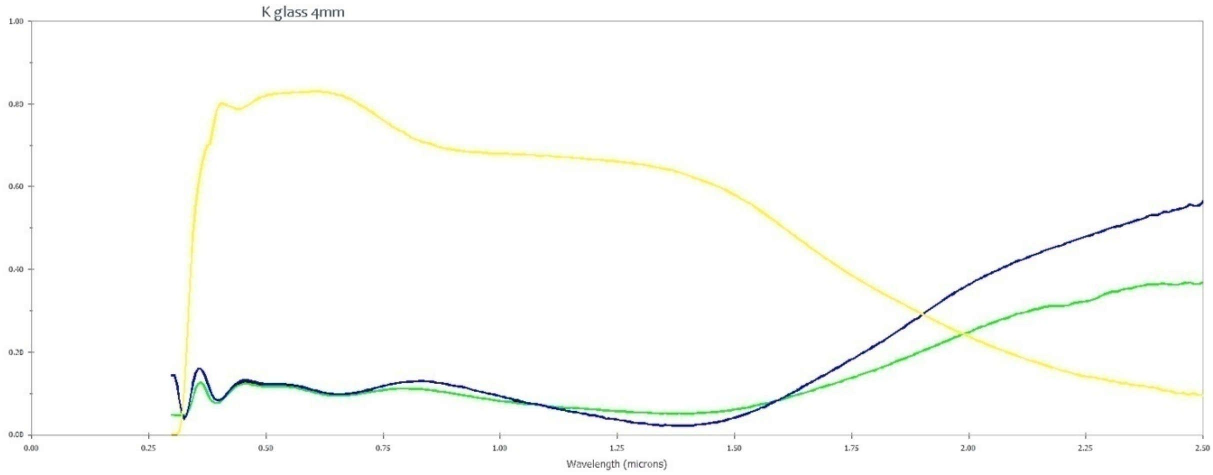


Figure 37: The transmission and reflection graph for K-glass in the solar spectrum. The yellow line represents the light transmission, the blue line the reflection at the front and the green line the reflection at the back of the glass. On the x-axis the wavelengths are distributed showing the entire solar spectrum. The graph shows that although the transmission of the glass decreases towards the far infrared light, the energy transmission in the NIR is still fairly high for a low e coating (own image).

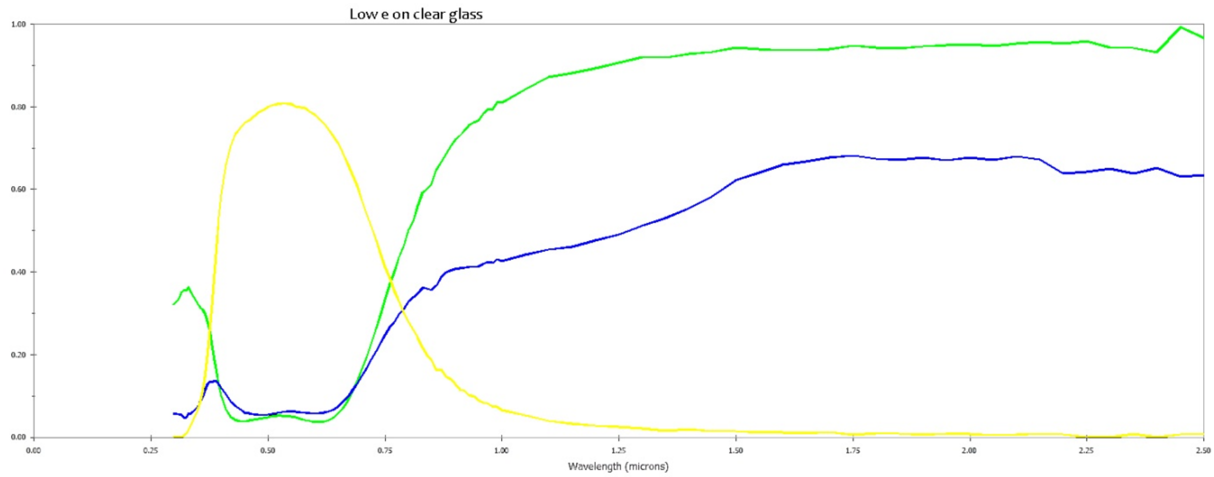


Figure 38: The transmission and reflection graph for a low e coating on clear glass in the solar spectrum. The yellow line represents the light transmission, the blue line the reflection at the front and the green line the reflection at the back of the glass. On the x-axis the wavelengths are distributed showing the entire solar spectrum. The graph shows that the light transmission of the low e coating is very much focused on transmitting the visible light and reflecting all other sorts of radiation. The performance in the far infrared is similar to that of the K-glass (own image).

An option to solve this problem is to use a variable window ID. This means that the window that is used for the simulation is depending on an input value from the simulation. The Adaptive Temperature Limits could function as an input in this case, because between the upper and lower limit, the shade will be spectrally selective, while outside these limits, the shade will either be fully reflective or fully transparent. Since problems caused by double spectral selectivity will only occur when both the louvres and the window are spectrally selective, the window can continue to have a low-e coating in the simulation, apart from the moments in which the temperature inside is comfortable, because in that situation the louvres will be spectrally selective.

In that case, the window will be exactly the same, just without the low-e coating. It must be remarked in addition that the louvres only switch to a spectrally selective state from 1 June to and including 30 September, because outside that period its function of preventing overheating while the indoor temperature is still comfortable will most likely not be helpful. However, even in this summer period, heating was required in the test simulations, because the absence of a low e coating on the window when the louvres would become spectrally selective resulted in an energy loss that influenced the results far more dramatically than the incorrect reflection of 50% (roughly the NIR – visible ratio) of 10% (the related part of the NIR light) of the light. Therefore the K-glass was chosen to be the most suitable compromise between thermal insulation and NIR transmission.

Another abstraction is found in the transmission values of the coating, which are not calculated for each specific angle, but for intervals of angles. This means that the transmission value will be slightly off in most cases. Furthermore, there is an impossibility to calculate the effect of reflected radiation that will reach the room via the shading device. For both louvres and overhang this will be relevant, especially in case of a specularly reflecting coating on a reflective glass surface. By implementing the reflection in the g-value input this is compensated for to some degree, but the full effect cannot be taken into account.

Also the transmission of the combination of the louvres and coating is not entirely accurate. This is because the transmission that is calculated for the venetian blinds consists of a part directly transmitted radiation, a part diffusely transmitted radiation (from reflections between the louvres) and a part emitted radiation (after absorption by the louvres). This is what happens in real life too, so it should be calculated like that, but since transparent louvres may behave differently than opaque louvres and result into a different ratio between the different kinds of transmission it is not by definition correct to correct for transmission through the opaque part of the louvres as is done in the simulations. Especially when looking at specularly reflecting coatings, the reflections between the slats may influence the total transmission. This is an abstraction that had to be made to combine angular dependent coating transmission data with an angular dependent venetian blind transmission, and when considering diffusely reflecting louvres this effect will not be so large.

Another important aspect that presents a difficulty in the calculation is the optimisation between artificial lighting energy and cooling energy required as a result of transmitted daylight. It would be interesting to see whether the effect of making the interior light intensity a trigger for the reflectivity of the coating would result into significant energy consumption reductions. It has already been proven that responsive light switches enable users to cut a large share of their energy consumption, since artificial lighting is generally responsible for approximately 30% of an office’s energy use. This is controlling the artificial lighting based on the light level inside, switching it off (partly) when the daylight provides enough light already. The best performing systems save up to 65% of the lighting energy, so it is evident that the energy consumption reductions in this optimisation are significant (Franzetti et al., 2004). It would be interesting to see how much a optimisation between the shading and the cooling energy could contribute to saving energy as well. It may be more difficult to control in reality due to the more difficult control of the shading compared to controlling artificial lighting, but in simulations this is not a problem yet.

Greek research has already indicated the existence of this optimum (Tzempelikos and Athienitis, 2007), but the exact optimum is varying over time. In another case, two identical full-scale test offices were monitored to find the energy saving potential of optimisation between daylight level and operable venetian blinds. It presented possible savings of 7-15% on cooling energy and 19-52% on lighting energy for a slat inclination of 45° (Lee et al., 1998). Although the latter study is not fairly recent and the glass area that was used was very high (virtually 100%, due to which the results for other applications may be slightly less high), this is why simulating the influence of turning on and off the shading properties on the energy balance would be interesting to see the maximum potential of this optimisation, but this is not possible with the software that is currently available.

Finally, since TRNSYS does not offer a possibility to measure the light intensity accurately, only very rough estimations can be made for this. This requires additional software that is not taking into account angular dependence, so the results would have a large margin of error. This uncalculated potential is an important inaccuracy in the calculation of the energy that can be saved by the application of this coating.

3.3 Data completion

3.3.1 Sample testing

Since the transmission data that could be extracted from the graph that was provided by the TU/e was not complete – the angle of incidence did not exceed 65 degrees – it was necessary to complete these data before we could perform a simulation. To this end, a test arrangement was set up at the faculty of Applied Physics, by which it would be possible to measure the transmission values of the coating.

However, the tests did not work out as they were intended, because the testing facility was not advanced enough to measure the spectral transmissions accurately. One reason for this was the absence of a spectrophotometer, or preferably a goniophotometer, due to which a workaround measurement had to be designed that was not as accurate as the other measurement devices. Another reason was the absence of a light source that was strong enough to let enough light reach the sensor, because of which some results were not trustworthy anymore since the light level became too low.

The most important results from the testing were qualitative results from a diffraction grating (which were for visual illustration of the principle of the coating, rather than a contribution to the simulation) and conclusions about where the measurements went wrong, which may be beneficial when further testing will be conducted. A more detailed description of the exact chosen procedure for the testing, the abstraction that were imposed by the availability of material and the results and conclusions that can be made from them can be found in Appendix A.

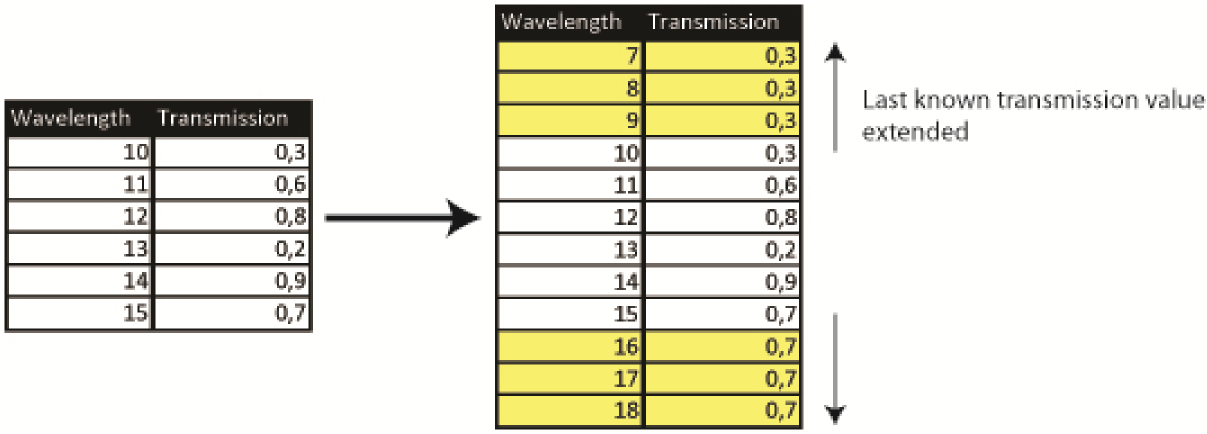
In addition it must be remarked that the data that was provided by the TU Eindhoven was not worth completing, because the transmission values were only valid for application of two coatings with the same handedness on a half lambda retarder. This will not be the case for application in building practice, and since this has radical implications for the transmission values, only the transmission of normal incidence could be used for simulation purposes.

3.3.2 Data approximation

To complete the data in such a way that they would be useful for simulations, four things had to be done. First of all, the graph only shows the transmission values for a small part of the spectrum, namely from 400 to 800 nm. Therefore the graph should be extended, to find the transmission values for the entire solar spectrum. Secondly, the data that was provided was only valid at normal incidence, so the other angles of incidence had to be approximated. Thirdly, the bandwidth of the reflection peak had to be adjusted, in order to create a bandwidth that is more realistic to be used in the building practice. Fourthly and finally, it had to be possible to find the transmission values if multiple layers of the coating are combined. Illustrations in this section are only about the principle behind the step and do not represent actual values, because when this would not be done, thousands of values had to be displayed, which would affect the intelligibility.

Extending the transmission graph

The available data goes from 400 to 800 nm, while the solar spectrum (of radiation reaching the earth's surface) starts at 280 nm and continues up to 2500 nm. This means that data outside the graph had to be estimated for the missing wavelengths. Since the transmission values on the right of the reflection peak remain constant for the last 100 nm, it was assumed that this would remain the same for the following wavelengths. A similar phenomenon was observed on the left of the reflection peak, where the transmission values remained constant after reaching a value that is approximately 10% lower than the value they have on the right of the reflection peak. So if e.g. the graph for 30 degrees remains constant at around 85% on the right of the reflection peak, it remains constant on the left of the reflection peak from a transmission value of 75%.



Wavelength	Transmission
10	0,3
11	0,6
12	0,8
13	0,2
14	0,9
15	0,7

Wavelength	Transmission
7	0,3
8	0,3
9	0,3
10	0,3
11	0,6
12	0,8
13	0,2
14	0,9
15	0,7
16	0,7
17	0,7
18	0,7

Figure 39: The provided data was extended in both directions by assuming the first and the last known value to remain constant. More about this is explained in the text (own image).

Assumptions for off normal incidence

The provided transmission data were, as was mentioned above, only valid for normal incidence, due to the distortion of reflection caused by incomplete polarisation of the incident light by the half lambda retarder. This meant that the transmission values for angles of incidence up to 80 degrees had to be approximated.

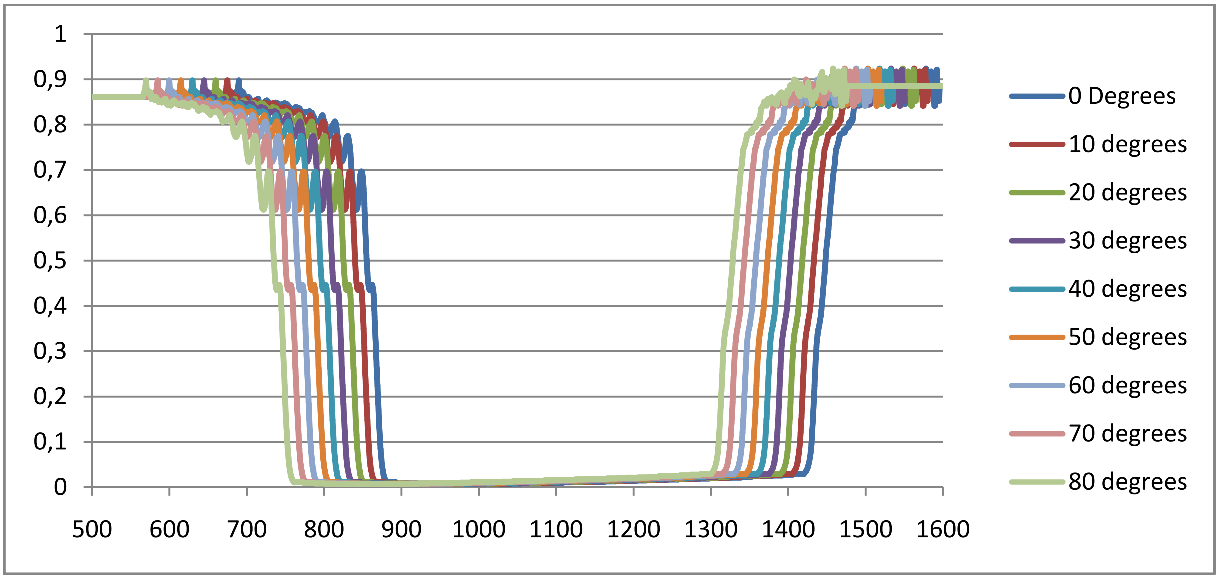


Figure 40: The approximated transmission data for the coating only, when it is already stretched in order to represent a 500nm reflection bandwidth (own image).

To do so, the blue shift of the reflection peak was still taken into account, since this was not determined by the substrate but inherent to the coating composition. This blue shift was considered to remain constant, shifting the graph 15 nm to the shorter wavelengths for each increase of 10 degrees of the angle of incidence.

The reduction in reflection, which can be observed in the provided data as the angle of incidence increases, is however caused by the inaccuracy of the half lambda retarder, so this is not used in the approximation of the transmission data of the coating only. This means in fact that the performance of the coating dramatically improves. The same goes for the shape of the transmission graph, which seemed to change in the provided data when the angle of incidence increased, but was again caused by the retarder. Therefore, there is no change of transmission graph shape in the approximated transmission data anymore, the graph of normal incidence is simply copied.

Increasing the bandwidth

The provided data shows a bandwidth of around 40 nm, while one of several hundreds of nanometres is required to be effective as a shading coating. Therefore the graph was stretched at the reflection peaks, until the reflection peak had the desired bandwidth. For each angle of incidence, the starting point of this stretching was chosen slightly different, because of the blue shift, which causes the reflection peak to vary as well. The stretching starts at the left bottom of the reflection peak for each angle of incidence, and continues for 40 nanometres regardless of the angle of incidence. The stretching of the graph was done by increasing the interval of the wavelengths in the reflection peaks, because of which the transmission value was not available anymore for every wavelength.

Wavelength	Transmission
7	0,3
8	0,3
9	0,3
10	0,3
11	0,6
12	0,8
13	0,2
14	0,9
15	0,7
16	0,7
17	0,7
18	0,7

Wavelength	Transmission
7	0,3
8	0,3
9	0,3
10	0,3
11	0,6
12	0,8
22	0,2
32	0,9
42	0,7
52	0,7
53	0,7
54	0,7

Interval between wavelengths increased

Figure 41: Starting from the left bottom of the reflection peak, the wavelength interval was increased, due to which larger wavelengths corresponded to the original transmission values. As a result, the graph was stretched while the data remained controllable (own image).

The most accurate approximation of the values in between these intervals would be to interpolate, but since the intervals were relatively small (e.g. an increase of 1 to 12.5 nm for an increased bandwidth of 40 to 500 nm), the transmission values did not vary radically, it was not considered worth the large amount of manual labour required to perform the interpolation for each interval. Instead, these values were assumed to remain constant over the interval.

Wavelength	Transmission
107	0,3
108	0,3
109	0,3
110	0,3
111	0,6
112	0,8
122	0,2
132	0,9
142	0,7
152	0,7
153	0,7
154	0,7

Wavelength	Transmission
112	0,8
113	0,8
114	0,8
115	0,8
116	0,8
117	0,8
118	0,8
119	0,8
120	0,8
121	0,8
122	0,2
123	0,2

Assumed constant values in between interval boundaries

Figure 42: The values of wavelengths in between the interval boundaries were assumed to remain constant, although interpolation would provide more accurate data. However, the potential benefits were outweighed by the extra effort it would take, as is explained more thoroughly in the text (own image).

Combining coating layers

Since the coating would probably applied in multiple layers instead of one, to be able to control the transmission of visible and NIR light individually and because of the large required bandwidth to cover the entire solar spectrum, it was necessary to find the transmission values of the combination of layers. This would not simply be one layer with a larger bandwidth, because the shift of the graph creates an overlap of reflected wavelengths. This means that for certain wavelengths, the transmission values had to be combined.

Wavelength	Transmission
7	0,3
8	0,3
9	0,3
10	0,3
11	0,6
12	0,8
22	0,2
32	0,9
42	0,7
52	0,7
53	0,7
54	0,7

Wavelength	Transmission
107	0,3
108	0,3
109	0,3
110	0,3
111	0,6
112	0,8
122	0,2
132	0,9
142	0,7
152	0,7
153	0,7
154	0,7

Wavelengths corrected for desired reflection peak

Figure 43: The wavelengths corresponding to the transmission values were corrected to make sure that the reflection peak would start at the desired wavelength, simply by adding the required number to the original wavelength (own image).

In the setup chosen for the simulation, four bandwidths were used (both consisting of two coatings, one for left handed light and one for right handed light) with a constant bandwidth of 500 nm. They start at 380, 880, 1300 and 1950 nm. These values were chosen to make sure that almost the entire solar spectrum would be covered, also considering the dips in the solar spectrum causes by particles in the air, resulting in very low energy levels at certain wavelengths. One of the coatings also has an overlap (the second coating continues until 1380 nm while the third coating already starts at 1300 nm), this was chosen to occur in that part of the NIR light that contains the highest amount of energy, in order to be render the highest effect.

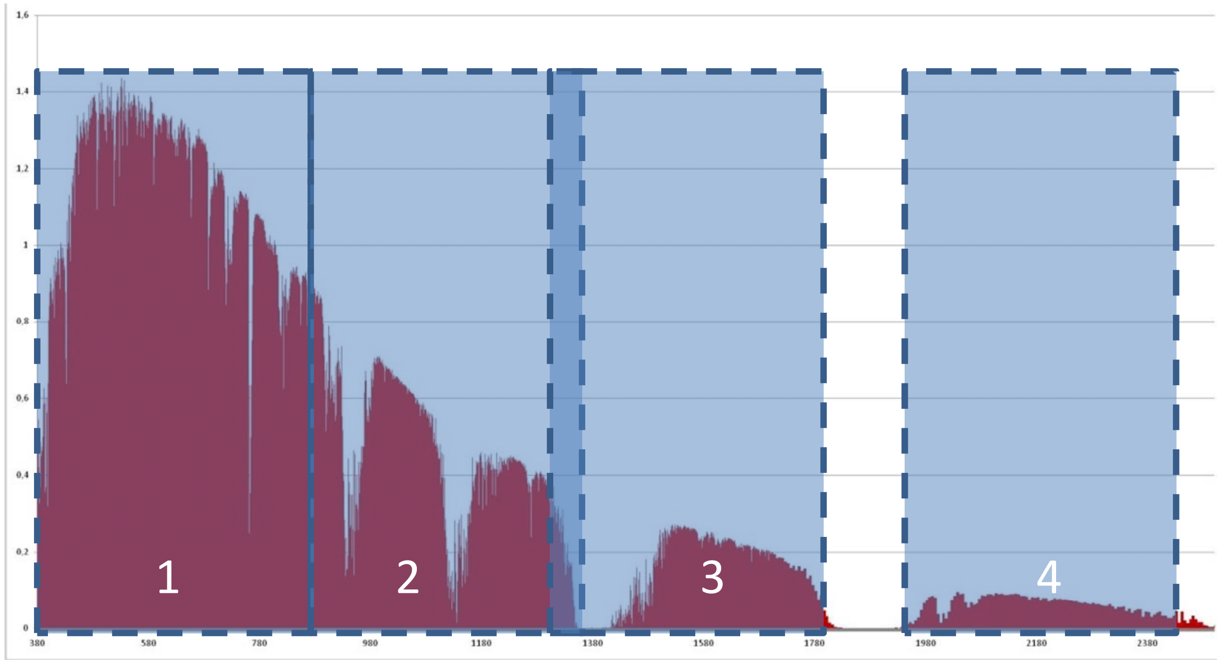


Figure 44: Graphical representation of the coating configuration, showing the solar spectrum with the solar energy on the y-axis and the wavelength on the x-axis. The initial simulations were performed with four coatings of 500nm wide, starting at 380, 880, 1300 and 1950 nm (own image).

The combination of layers means that the provided data had to be converted to the desired wavelengths, because of which a correction was introduced that shifted the left (starting) point of the reflection peak to the right or to the left, depending on the desired start of the reflection peak. The other wavelengths were corrected correspondingly. Another correction was made for transmission values below 380 nm, because glass will not transmit UV light, thus the coating will not be able to induce any effects in this region.

Because the coating will not be used in isolation, but applied on a glass surface, the reflection of the glass had to be taken into account. The transmission of glass varies for each angle of incidence, and is different for each wavelength. A division has been made between visible and NIR light, and for angles of incidence increasing in steps of 10 degrees at a time. These transmission values were multiplied by the corresponding transmission of the coating (taking into account the angle of incidence and whether the corresponding wavelength is part of the visible or the NIR part of the spectrum) to get the transmission value of the combined system. Multiple glass layers can be used, in which case the multiplication is repeated automatically.

It is also possible in the created Excel file to turn coating layers on or off, apart from adjusting their reflection starting point. When the coating is turned off, this means that it is assumed to be 100% transparent, which is different to shifting the reflection peak to another wavelength area. The difference is caused by the blue shift in this case, because the transmission outside the reflection peak is again assumed to be 100% due the optical coupling that is described in chapter 2.3.4. Only the second filter is not corrected to 100% outside the reflection peak, because this layer will always be present and represents the transmission of the total of coupled layers, whether this is a number of four or just one coating layers.

Finally, the Excel file allows the user to switch the reflection of a coating between single handed and double handed. This would be useful especially in the visible light, when a compromise needs to be found between energy reflection on the one hand, and view to the outside and daylight transmission on the other hand. The provided transmission data is valid for double handed reflection, so a conversion had to be made here as well. In an ideal situation, the left handed reflection is responsible for 50% of the light, and right handed reflection for the other 50%.

This means that the transmission value of a double handed reflection is equal to the average value of both transmission values. To calculate the transmission value of a single handed coating, one simply replaces one of the transmission values by 100%. That means that if a double handed reflecting coating exists for example out of two coatings that reflect 80% (i.e. 20% transmission) of the light at a specified wavelength, the corresponding single handed reflecting coating would have a transmission value of (20 + 100) / 2 = 60%.

Coating control

Desired bandwidth	500

Number of glass layers	1

Filter	Start	End	ON/OFF	Single handed?
1	380	880	on	no
2	880	1380	on	yes
3	1300	1800	off	yes
4	1950	2450	off	no

Angle of incidence	Transmission value
0	12,60%
10	12,86%
20	13,06%
30	13,22%
40	13,23%
50	12,88%
60	11,74%
70	9,10%
80	4,30%

Figure 45: Screenshot of the Excel file to approximate the coating's angular dependent overall transmission values. It shows the possibility to adjust the coating bandwidth, to adjust the number of glass layers on which the coating is applied (including the possibility to change the selected glass), to select the starting points of each coating layer, to vary from 0 to 4 coating layers by turning them on or off and to choose whether the reflection is single handed or double handed. It outputs overall transmission values for the entire solar spectrum, which after a minor adjustment could also be converted to T_{vis} and T_{sol} (but this was not done here becauase it was not necessary for the simulations) (own image).

3.3.3 Global radiation transmission for coating

The calculation in TRNSYS requires the input of direct solar radiation in combination with the incident global (or total) radiation. Since the transmission data provided is only relevant for direct radiation, an assumption has to be made for the transmission of diffuse light, and subsequently an assumption for the transmission of global radiation.

A generally accepted method to predict the transmission of diffuse light is to look at the transmission of the glazing at an angle of incidence of 60 degrees (Duffie and Beckman, 1980). This is valid for most glass systems. Although the coating may very well respond differently than glass, more detailed calculations require an extinction coefficient and coating thickness, to determine the transmission for each angle of incidence, which would be a too complex process to do manually.

The combination of direct and diffuse light form the global radiation, but since the proportion of the former two depend on for example the cloudiness of the sky, it would not be accurate to presume a general fraction of diffuse or direct light. The fraction of solar is therefore calculated each time step in TRNSYS, and used to calculate a weighted average of the diffuse transmission and the direct transmission, which is the global transmission.

3.4 Simulation results

3.4.1 Simulated cases

To assess the energetic performance of the PolyArch coating, a number of simulations has been performed. Most of these simulations are using the PolyArch coating, while two are made for comparison to conventional shading methods (low e and venetian blinds). The PolyArch coating simulations generally have the same coating layout (apart from the 250nm simulation), which is calculated with the previously mentioned Excel transmission calculation file. This file and the configuration of the coating layers over the solar spectrum have been described in more detail in chapter 3.3.2.

The four coatings have been configured in such a way that their reflection peaks (of 500nm) are placed over the peaks in the solar spectrum. Their peaks start at respectively 380, 880, 1300 and 1950 nm. To illustrate this, the following images corresponding to all the simulated cases show the transmitted solar energy in all used coating configurations. For each of them, one graph represents full reflection and the other one the 'half reflective' state, which is used in certain periods when the indoor temperature is comfortable. The half reflection is created by switching off the coating that is functional in the visible part of the spectrum. In addition, a graph is shown which represents single handed light transmission. In these graphs, the influence of a 12mm glass substrate has been taken into account (except for the 3mm case, in which 3mm glass thickness is used).

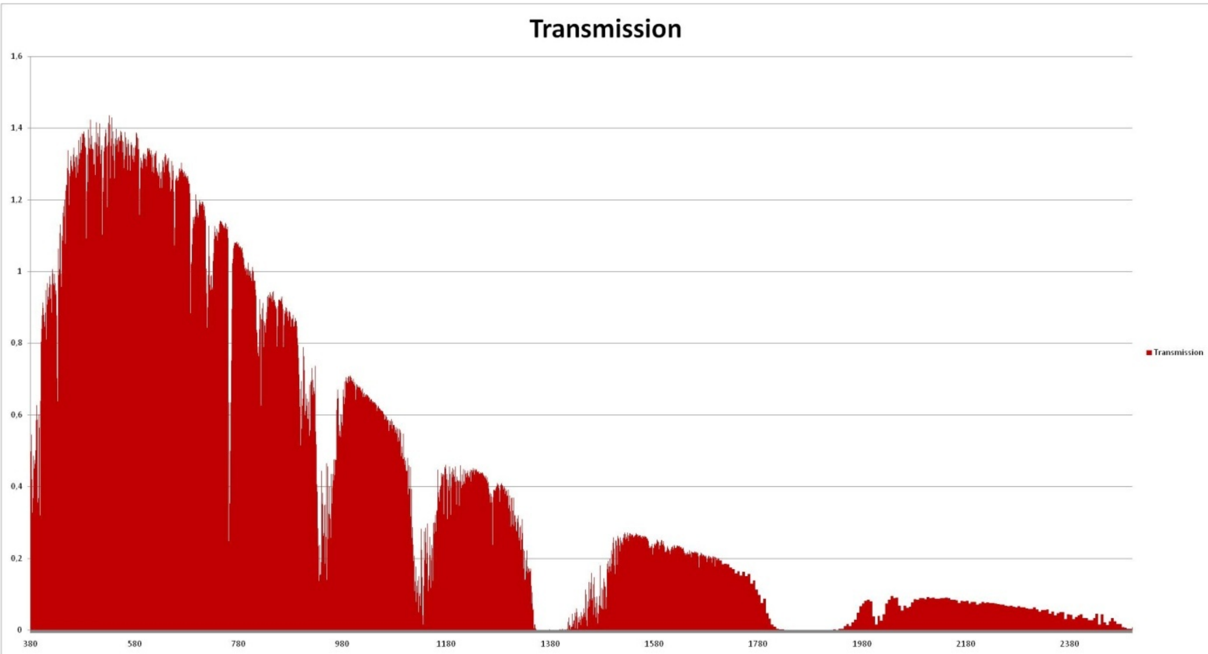


Figure 46: The energy contained in the normal solar spectrum, so representing a transmission of 100%. It shows the light wavelength on the x-axis from 0 to 2500nm, which is the entire solar spectrum, and the transmitted energy on the y-axis in W/m^2 * nm (own image).

100% PolyArch

This is the ideal situation in which all four layers are in place. The reflection of this configuration is practically 100% in the fully reflective state. The half reflective state is identical, apart from the fact that the first coating, which covers the visible light, is turned off. This leads to an overall transmission that is nearly 35% higher than that of the fully reflective state.

Angle	Transmission		
	Glass	Coating	Half
0	0,699	0,006387	0,395438
10	0,698	0,006423	0,387373
20	0,695	0,006494	0,378157
30	0,689	0,006634	0,367705
40	0,676	0,006819	0,353451
50	0,648	0,007019	0,330824
60	0,587	0,006916	0,29016
70	0,463	0,005857	0,216636
80	0,251	0,003081	0,103942
90	0	0	0

Figure 47: Transmission values of a 100% ideal coating. The "Glass" column represents the transmission values for a non reflective state, the "Coating" column represents the transmission values of the reflective state and the "Half" column represents the transmission values for the reflective state in which visible light is still transmitted, which is used to prevent overheating in summer (own image).

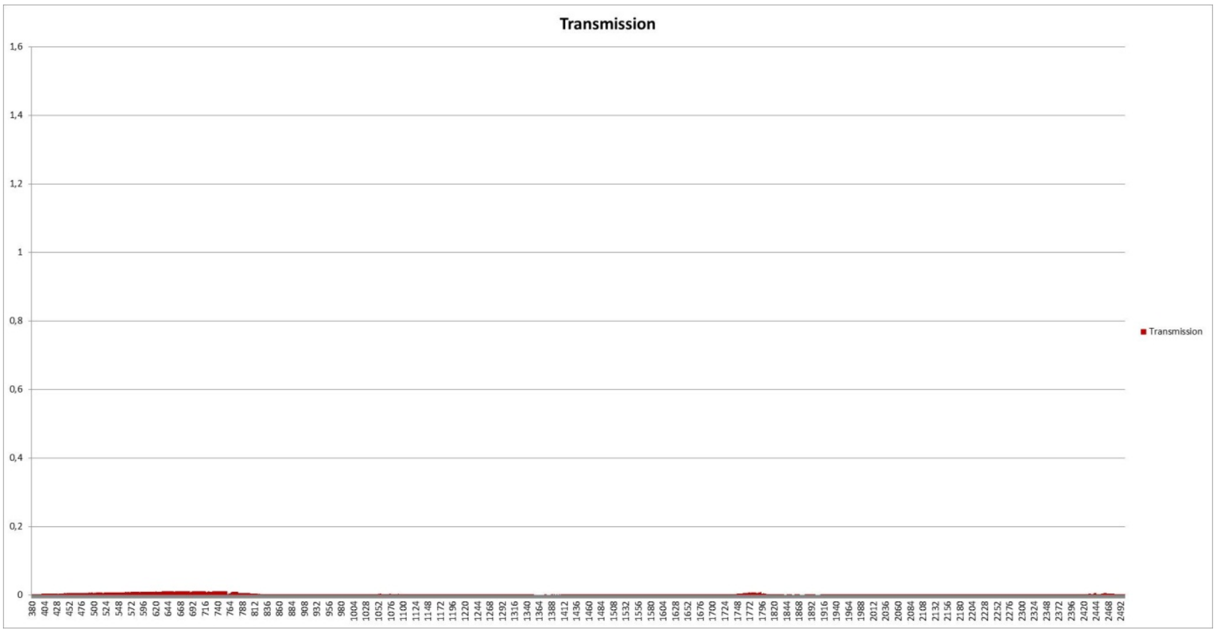


Figure 48: Transmission of a 100% performing coating. It shows the light wavelength on the x-axis from 0 to 2500nm, which is the entire solar spectrum, and the transmitted energy on the y-axis in W/m^2 * nm. This 100% performance means that the coating performs ideally, and all four coatings are present (own image).

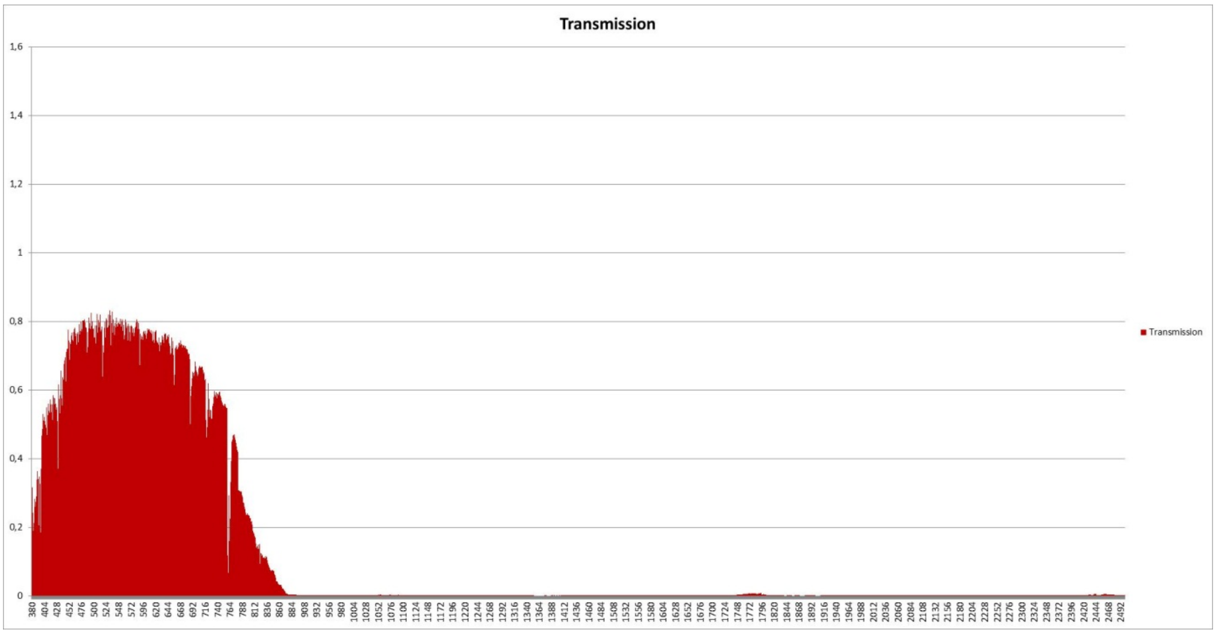


Figure 49: Transmission of a 100% performing coating, but in the half reflective state. It shows the light wavelength on the x-axis from 0 to 2500nm, which is the entire solar spectrum, and the transmitted energy on the y-axis in W/m^2 * nm. This half reflective state means that the last three coatings are turned on. The difference between this transmission state and the previous (fully reflective) one is that in this situation the visible light is transmitted (own image).

60% PolyArch

The 60% case refers to a performance at 60% of the original coating. This name does not indicate however that the coating transmits 40% more light, but that the last two coating layers (layer number 3 and 4 in the image in chapter 3.3.2) are absent in the simulation.

	Transmission		
Angle	Glass	Coating	Half
0	0,699	0,06489	0,453941
10	0,698	0,065317	0,446267
20	0,695	0,065169	0,436832
30	0,689	0,064585	0,425657
40	0,676	0,063083	0,409715
50	0,648	0,059915	0,383721
60	0,587	0,053276	0,33652
70	0,463	0,040501	0,251279
80	0,251	0,019016	0,119876
90	0	0	0

Figure 50: Transmission values of a 60% ideal coating. The “Glass” column represents the transmission values for a non reflective state, the “Coating” column represents the transmission values of the reflective state and the “Half” column represents the transmission values for the reflective state in which visible light is still transmitted, which is used to prevent overheating in summer (own image).

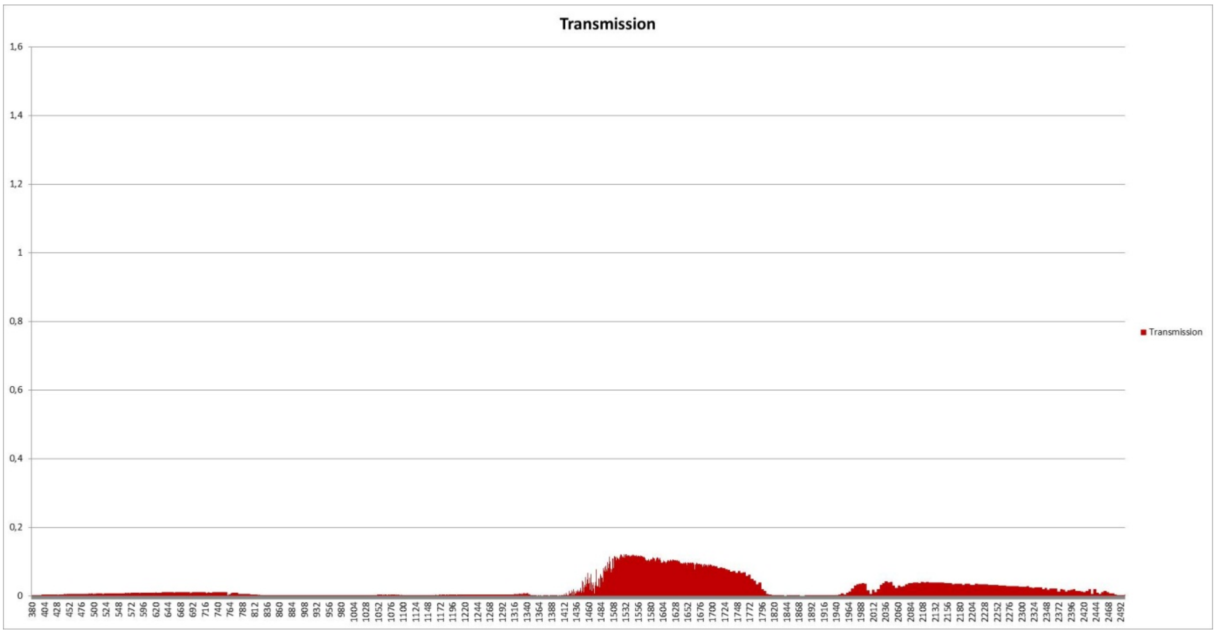


Figure 51: Transmission of a 60% performing coating. It shows the light wavelength on the x-axis from 0 to 2500nm, which is the entire solar spectrum, and the transmitted energy on the y-axis in W/m^2 * nm. This 60% state means that the first two coatings are turned on, but the latter two are not present (own image).

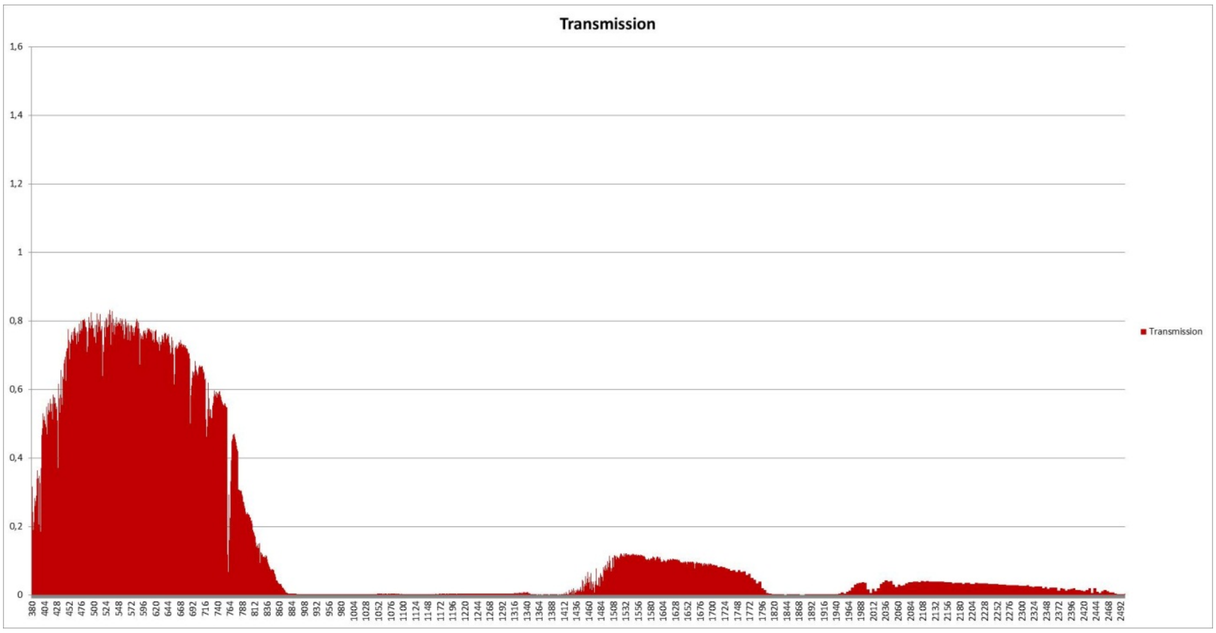


Figure 52: Transmission of a 60% performing coating, but in the half reflective state. It shows the light wavelength on the x-axis from 0 to 2500nm, which is the entire solar spectrum, and the transmitted energy on the y-axis in W/m^2 * nm. This half reflective state means that only the second coating is turned on. The difference between this transmission state and the previous (fully reflective) one is that in this situation the visible light is transmitted as well (own image).

Initially there was also an 80% case in which only the last coating layer (number 4) was absent, but since the differences between these cases and the ideal 100% case turned out to be very small (there is only a small share of the solar energy in the last 500nm, and the performance in this area is also compromised by the low e coating on the window glass), the 80% case has been excluded from the final simulations.

In the transmission graphs can be seen that in the fully reflective state the largest part of the solar energy is still reflected, being the visible light and the first 600nm of the NIR light. In the half reflective state this is reduced to only the first part of the NIR light.

250nm PolyArch

Angle	Transmission		
	Glass	Coating	Half
0	0,699	0,167147	0,549971
10	0,698	0,170943	0,543852
20	0,695	0,17442	0,535704
30	0,689	0,177867	0,524384
40	0,676	0,179484	0,506538
50	0,648	0,176594	0,475923
60	0,587	0,162462	0,419333
70	0,463	0,126591	0,314699
80	0,251	0,059932	0,149915
90	0	0	0

Figure 53:Transmission values of a 250nm case coating. The “Glass” column represents the transmission values for a non reflective state, the “Coating” column represents the transmission values of the reflective state and the “Half” column represents the transmission values for the reflective state in which visible light is still transmitted, which is used to prevent overheating in summer (own image).

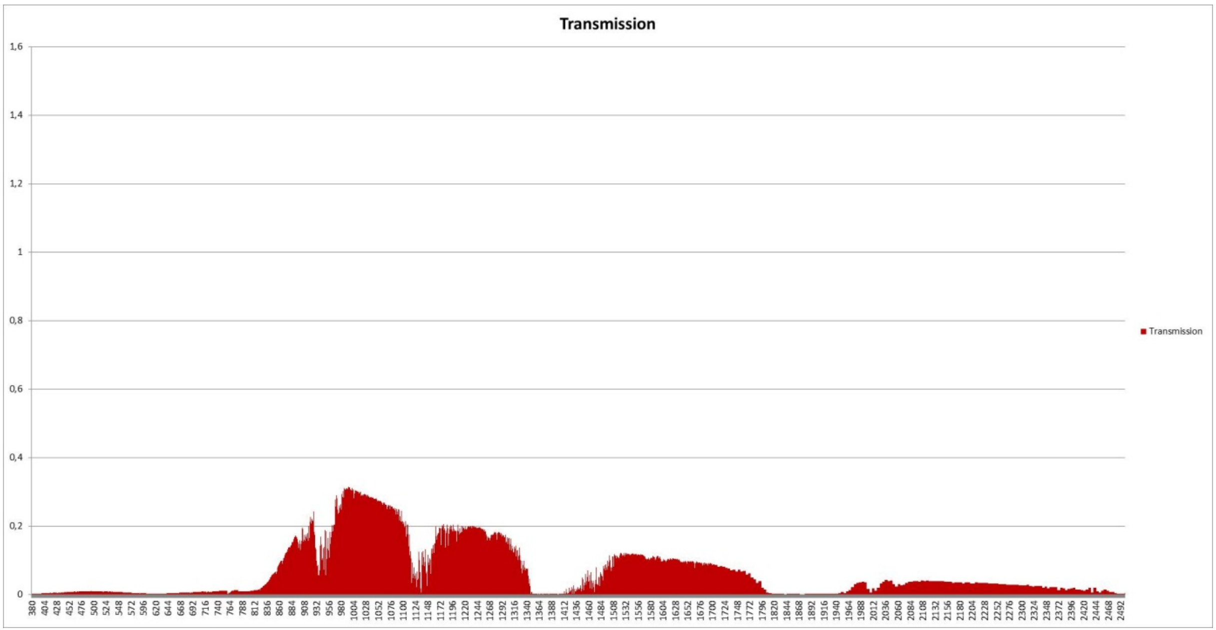


Figure 54: Transmission of a 250nm coating. It shows the light wavelength on the x-axis from 0 to 2500nm, which is the entire solar spectrum, and the transmitted energy on the y-axis in W/m^2 * nm. This 250nm configuration means that the first two coatings of 250nm are turned on, but the third one is off and the last one is not present (own image).

Because the differences between the 100% case and the 60% case (and initially the 80% case, which is described under the 60% case) are small, another simulation case a bit further away from the ideal coating has been simulated, to be able to make reliable extrapolations. In this case, the first normal 500nm coating is replaced by two coatings of 250nm (thus creating the same reflection peak with twice as many coatings) and the other 3 normal 500nm coatings are absent. In the half reflective state, only the first 250nm of the NIR light are covered. This means that in the fully reflective state, the entire visible light (but not more than that) will be reflected, and in the half reflective state only the first 250nm of the NIR light will be reflected.

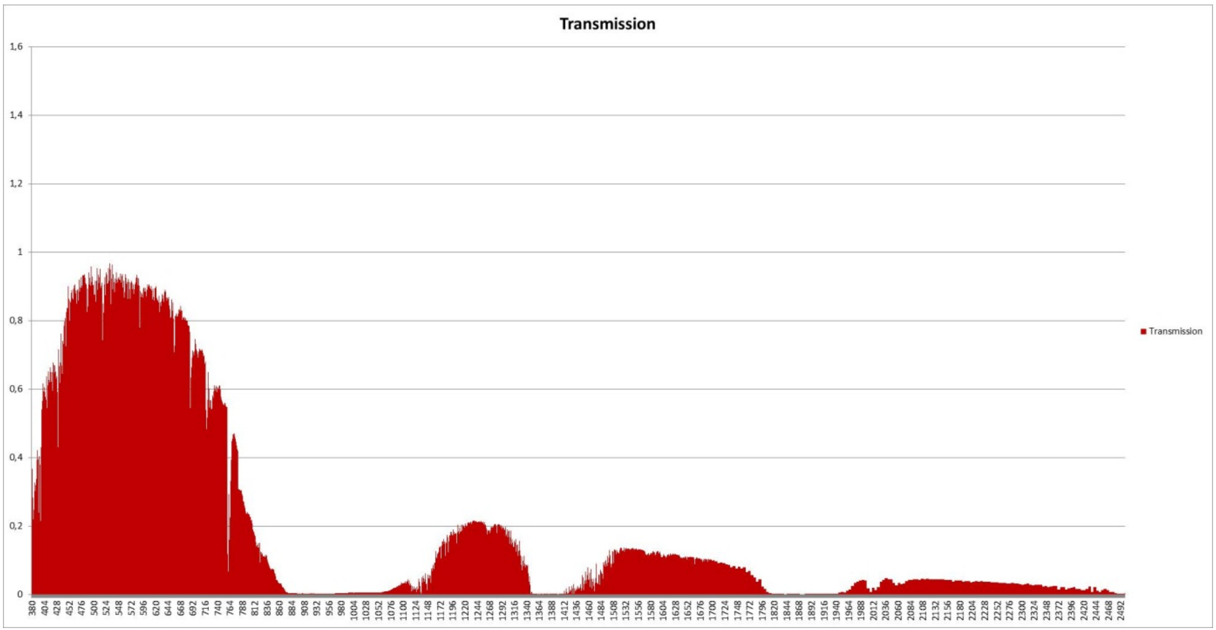


Figure 55: Transmission of a 250nm coating, but in the half reflective state. It shows the light wavelength on the x-axis from 0 to 2500nm, which is the entire solar spectrum, and the transmitted energy on the y-axis in W/m^2 * nm. This half reflective state means that only the third coating is turned on. The difference between this transmission state and the previous (fully reflective) one is that in this situation the visible light is transmitted as well, but the first part of the NIR light is reflected (own image).

No coating

	Transmission		
Angle	Glass	Coating	Half
0	0,699	0,699	0,699
10	0,698	0,698	0,698
20	0,695	0,695	0,695
30	0,689	0,689	0,689
40	0,676	0,676	0,676
50	0,648	0,648	0,648
60	0,587	0,587	0,587
70	0,463	0,463	0,463
80	0,251	0,251	0,251
90	0	0	0

Figure 56:Transmission values of a No coating case. Since there is no coating present, every column contains the same transmission values, namely those for 12mm uncoated glass (own image).

This situation was simulated to compare the best performing coating (100%) to the worst performing coating (no coating), to see what the influence of the coating is on the total energy consumption. In this situation, the transparent state which is presented in the previous simulation cases (with only the transmission of the glass louvres) is copied to the columns where in those simulations the reflective and half reflective state used to be, so the simulation is entirely the same apart from the fact that the indoor temperature does not affect the transmission of the louvres anymore.

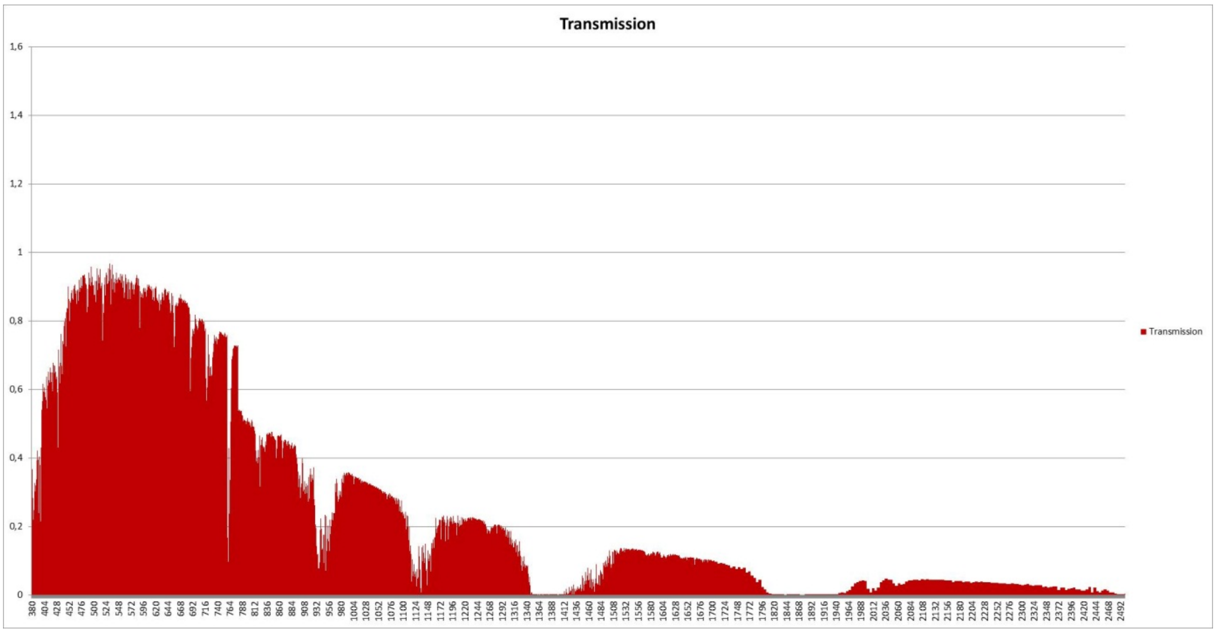


Figure 57: Transmission of the glass louvres without a coating. It shows the light wavelength on the x-axis from 0 to 2500nm, which is the entire solar spectrum, and the transmitted energy on the y-axis in W/m^2 * nm. This No coating configuration means that the only thing influencing the solar transmission of the louvre system is the glass itself (own image).

Therefore, the transmission graph is almost identical to the solar spectrum, with as the only difference that the peaks in the graph will be less high. In the presented graph there is also a drop in transmission observable after the visible light (i.e. from 780nm), which is caused by the different transmission values of the glass for visible light and NIR light.

Venetian blind

The venetian blind case is used to indicate the currently ultimate performance of a shading device, which, due to its larger difference between the ultimate reflection state and transmission state, should always perform better than the PolyArch coating on glass louvres with regard to energy consumption for climate control. Because a venetian blind is very flexible since the louvres cannot only be let down and pulled up, but also tilted once they are let down, a number of combinations is simulated during the year. Which of these combinations is chosen depends on the time of year and the indoor temperature.

In a summer situation (from 1 June to 30 September), normal 45° inclined opaque louvres are used in a warm situation. In a comfortable situation, the reflection and absorption of the 45° inclined opaque louvres are halved to mimic a situation in which the louvres are in front of the window, but somewhat more horizontal. In a cold situation, the louvres will be contracted and the total transmission will be 100%.

In a winter situation (1 November to 28 February), the same 45° inclined opaque louvres will be used for a warm situation. In a comfortable and cold situation however, the louvres will be contracted to make the transmission 100% again. In the days between summer and winter (1 March to 31 May and 1 October to 31 October), an additional louvre configuration with horizontal louvres is used for the comfortable situation, which transmits more light than 45° inclined louvres, but less than no louvres, thus creating a compromise between summer and winter.

Angle	Transmission		
	Blind up	Blind down	Half
0	1	0	0,5
10	1	0	0,5
20	1	0	0,5
30	1	0	0,5
40	1	0	0,5
50	1	0	0,5
60	1	0	0,5
70	1	0	0,5
80	1	0	0,5
90	1	0	0,5

Figure 58:Transmission values for the representation of a normal venetian blind. The values of 1 and 0 indicate that the louvres are either fully transparent or fully reflective. The half in this case literally represents a half transmission of the incident light on the opaque part of the slats (own image).

Low e coating

The low e coating represents a fairly well performing conventional coating shade, which due to its static nature cannot perform as good as a dynamic coating such as the PolyArch coating. This simulation is used to put the results of the PolyArch coating into context. For this simulation, a low SHGC low e coating (or solar control glass) without additional colouring of the glass is chosen, with a transmission of visible light of 65.9% and a transmission of NIR light of 26%, leading to a g-value of 0.333. The U-value of 1.29 W/m^{2}K is a little lower than that of the glass used in the other simulations, but this is inevitable when selecting a solar control glass instead of a heat mirror.

3mm glass PolyArch

Because the glass that is used for the louvres is fairly thick to be able to make a stiff and safe laminated louvre, the transmission of the glass louvres is limited even when the coating is fully transparent. This means that in winter, a part of the solar energy is always kept outside, even when this would actually be desired. To judge the influence of the thickness of the louvres, another simulation with the 100% case is performed, but this time using glass louvres of only 3mm thickness. This thickness is unrealistically thin, but serves only to determine what effect decreasing the glass thickness would have.

Angle	Transmission		
	Glass	Coating	Half
0	0,86	0,007916	0,461984
10	0,86	0,007939	0,451064
20	0,859	0,008034	0,439602
30	0,855	0,008246	0,427877
40	0,847	0,008643	0,418118
50	0,827	0,009095	0,393631
60	0,78	0,009537	0,360936
70	0,669	0,009201	0,300656
80	0,42	0,006378	0,182235
90	0	0	0

Figure 59:Transmission values of a 3mm case coating. The "Glass" column represents the transmission values for a non reflective state, the "Coating" column represents the transmission values of the reflective state and the "Half" column represents the transmission values for the reflective state in which visible light is still transmitted, which is used to prevent overheating in summer (own image).

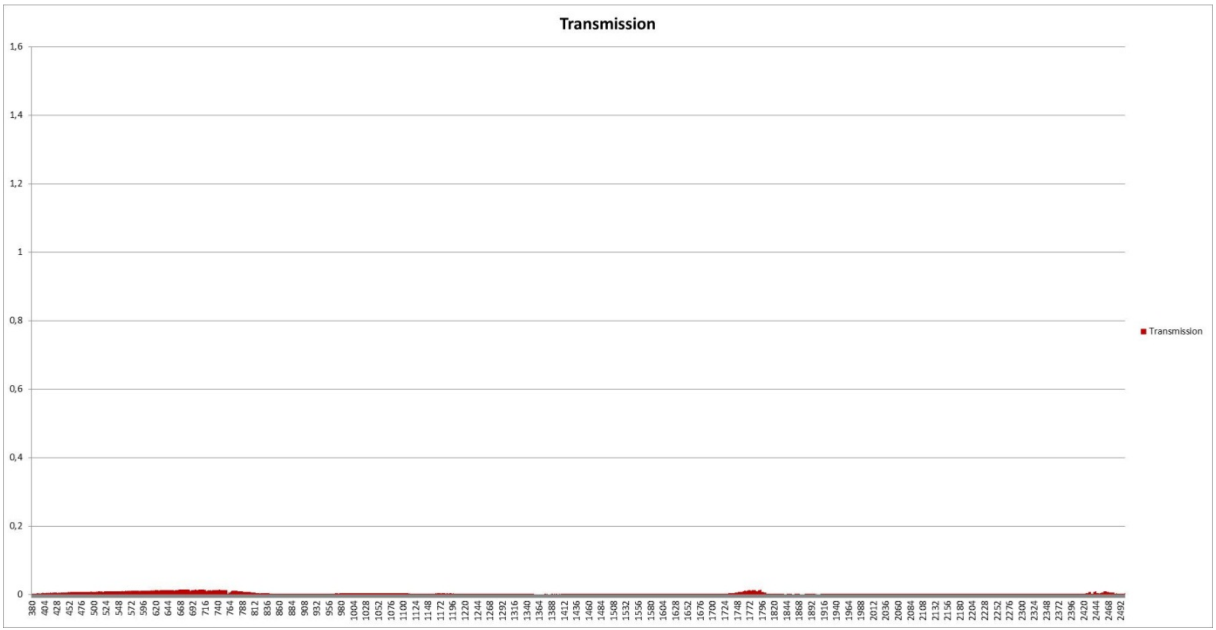


Figure 60:Transmission of a 250nm coating, but in the half reflective state. It shows the light wavelength on the x-axis from 0 to 2500nm, which is the entire solar spectrum, and the transmitted energy on the y-axis in W/m^2 * nm. This half reflective state means that only the third coating is turned on. The difference between this transmission state and the previous (fully reflective) one is that in this situation the visible light is transmitted as well, but the first part of the NIR light is reflected (own image).

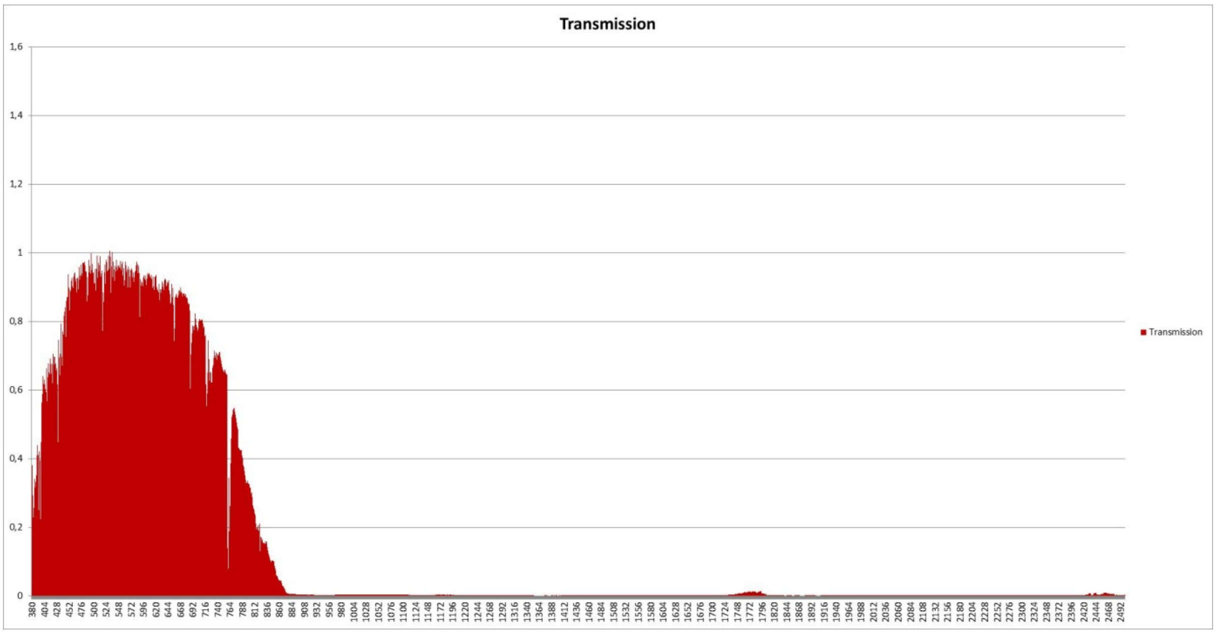


Figure 61: Transmission of a 100% case coating, but this time on thinner glass (3mm instead of 12). It shows the light wavelength on the x-axis from 0 to 2500nm, which is the entire solar spectrum, and the transmitted energy on the y-axis in W/m^2 * nm. The coating configuration is identical to that previously presented at the 100% case (own image).

100% PolyArch with horizontal louvres in winter

As was mentioned in the previous paragraph, there is potentially a lot of solar energy wasted in winter because of the louvres transparency. Another possibility would be to tilt the louvres once in the beginning of every winter to a horizontal position. This way, there would still be no need for engine operated systems which require a lot of maintenance, because the tilting of the louvres can be scheduled at the same time as the cleaning of the windows and louvres, which is necessary anyway. The possibility to keep out heat decreases significantly though, especially since the sun is mostly close to the horizon in winter, so horizontal louvres offer a very limited projected shading surface. Whether this would lead to a cooling need in winter, and if so, whether this can be compensated by a decreased heating load is to be found out with this simulation.

100% without half reflective state

In the ideal coating, a half reflective state is used to prevent overheating in summer (active between 1 June and 30 September). The functionality of this half reflective state has been described before in this chapter, but its influence on the energy consumption had not been specified exactly yet. Therefore a simulation was performed which was identical to the 100% case, apart from the half reflective state, instead of which the normal transparent glass was used.

The influence of the half reflective state is illustrated in the following two images, showing the indoor and outdoor temperature, the ATG limits and the required cooling energy. It most clearly shows the difference in required cooling energy, which is much lower when the half reflective state is used in summer, because this is created to prevent overheating by reflecting the NIR also in the comfortable state. This also leads to a single heating need once, after a long cold period outside (approximately 12 degrees on average for almost an entire week).

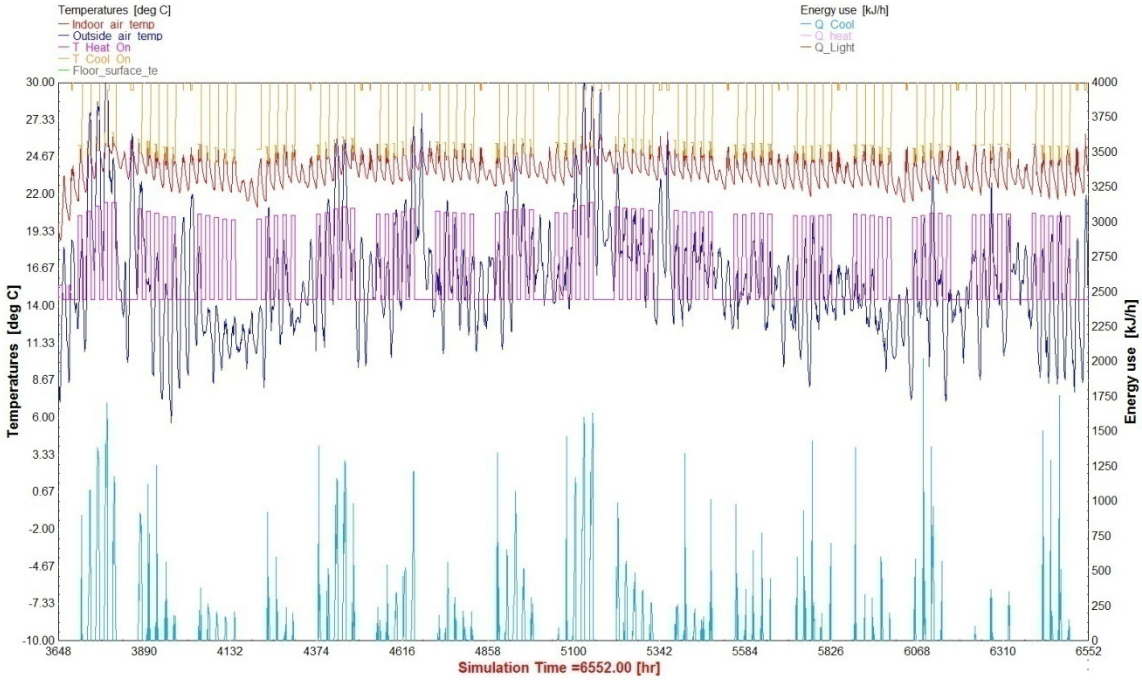


Figure 62: The summer situation for the 100% case without the half reflective state that should prevent overheating. It shows in dark blue the outside temperature, in red the indoor temperature, in orange the upper ATG limit and in purple the lower ATG limit (temperatures in degrees Celsius, left y-axis), and in light blue the energy required for cooling (energy in kJ/h, right y-axis). Compared to the situation with a half reflective state, the larger need for cooling in this situation is evident (own image).

Figure 63: The summer situation for the 100% case with the half reflective state that should prevent overheating. It shows in dark blue the outside temperature, in red the indoor temperature, in orange the upper ATG limit and in purple the lower ATG limit (temperatures in degrees Celsius, left y-axis), in pink the energy demand for heating and in light blue the energy required for cooling (energy in kJ/h, right y-axis). Compared to the situation without a half reflective state, much less cooling is needed, since the room tends to overheat only when the temperature peaks. In general, the room temperature is lower than in the situation without the half reflective state (own image).

As was mentioned in the introduction of this chapter, each coating layer actually consists of two coatings, because light is circularly polarised. Half of it is left handed polarised, the other half is right handed, which simply means that their rotation around the axis of movement is exactly opposite to each other. In all simulations both handednesses of polarised light are reflected simultaneously, but to give an impression of what the transmission would be when this were not the case, another graph is included here that illustrates single-handed reflection over the entire solar spectrum.

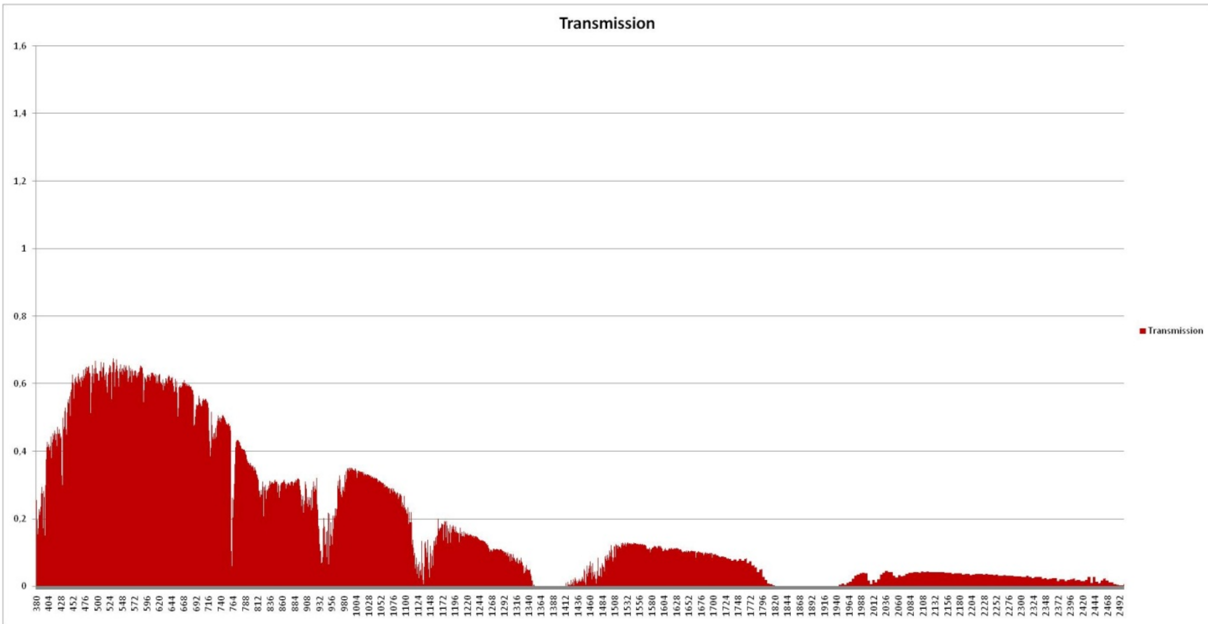


Figure 64: Transmission graph of a 100% performing coating, but reflecting only one handedness of light. This type of coating has not been used in the simulation, and is only presented for a better understanding of the influence of selective circularly polarised light reflection. It shows the light wavelength on the x-axis from 0 to 2500nm, which is the entire solar spectrum, and the transmitted energy on the y-axis in W/m^2 * nm(own image).

3.4.2 Simulation results

For each situation a calculation is made for the energy that is needed to cool, heat and light the space until a comfortable working environment is created. The results of these simulations are presented in the table below, and worked out in the graphs in this paragraph. Because the energy demand for heating and cooling is relatively low, the results for heating and cooling are also presented separately (without the lighting energy), because the energy requirement for lighting now dominates the total energy demand. Since this is most likely due to assumptions that were used for the simulation such as the location of the office inside the building and the glass percentage of the facade, the results are not generic, but do give an impression of the proportional differences between various simulated cases for the energy demand. The heating and cooling demand gives a reasonable indication of these ratios when this energy demand would be dominant, while the addition of lighting energy shows that the PolyArch might have a performance that is even better than that of a venetian blind.

	Heating	Cooling	Lighting	Total h+c	Total	
100%	887,74	157,96	1028,92	1045,69	2074,61	MJ/year
60%	885,95	208,99	1072,89	1094,93	2167,82	MJ/year
Venetian 1	576,49	254,28	1439,05	830,77	2269,82	MJ/year
Venetian 2	674,06	95,23	1439,05	769,29	2208,33	MJ/year
Low e	1100,83	511,35	586,28	1612,19	2198,47	MJ/year
250 nm	883,13	245,95	940,09	1129,08	2069,16	MJ/year
No coating	794,26	1287,82	791,53	2082,08	2873,61	MJ/year
3 mm glass	757,11	179,62	980,28	936,73	1917,01	MJ/year
100% Hor	702,89	244,24	1084,36	947,13	2031,48	MJ/year

Figure 65: Energy consumption for all simulated cases in MJ/year. Two venetian blind cases have been simulated, the first one being a fairly rigid case that only switches between inclined louvres and no louvres, while the last second one works with inclined louvres, increased transparency of the inclined louvres, horizontal louvres and no louvres. Although the total energy of these cases does not vary much, the individual energy demands for heating and cooling indicate that the simplification of the venetian blind as such may be too large, and more refinement is required to obtain optimal results, since a more flexible model should approach the true performance of a venetian blind with its scala of transmission values more accurately (own image).

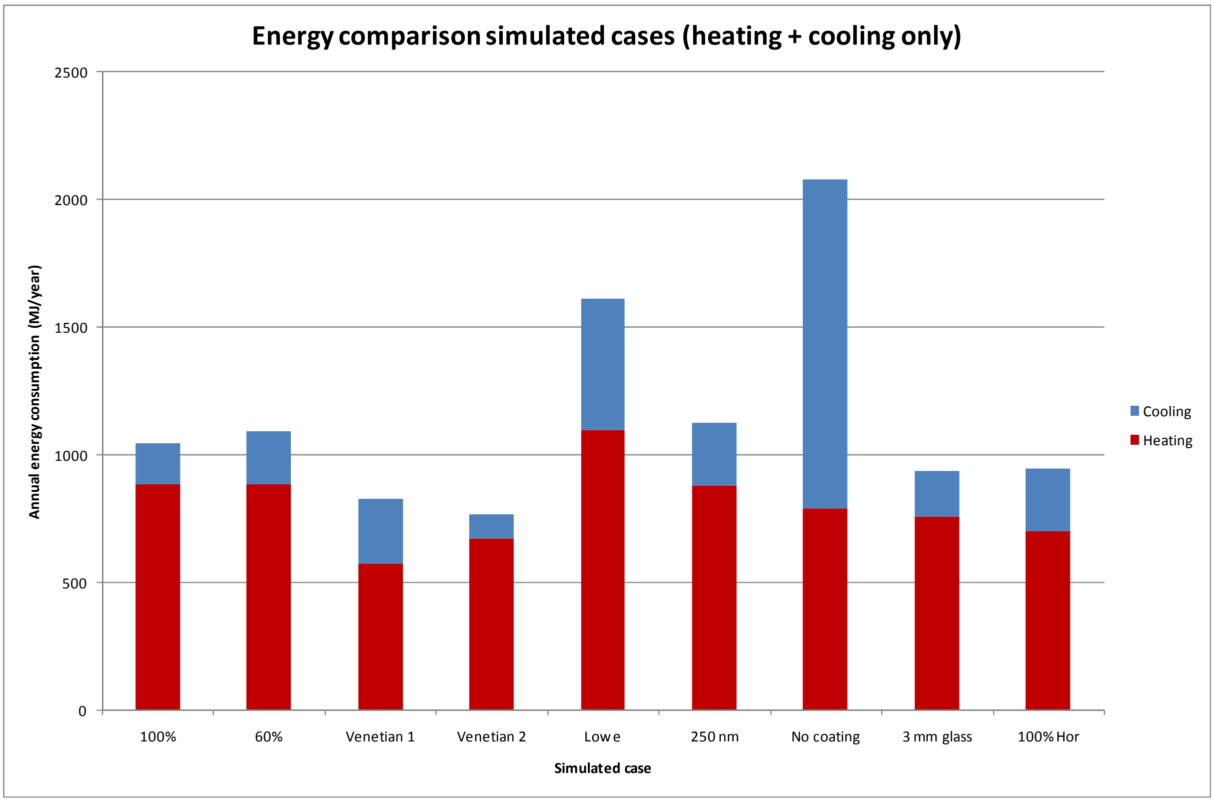


Figure 66: Graphical representation of the results in the previous table for heating and cooling only. On the x-axis, all simulated cases are presented, while on the y-axis the annual energy consumption for the entire room is presented in MJ. The meaning of these results will be elaborated on in the following paragraph (own image).

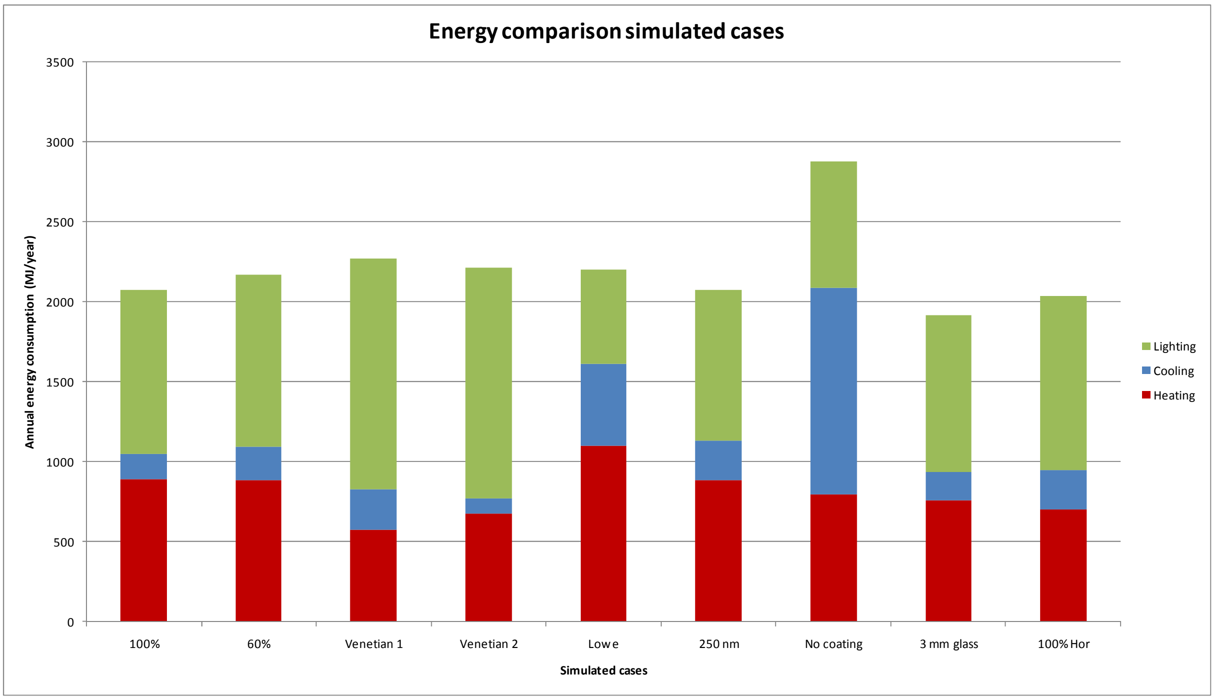


Figure 67: Graphical representation of the energy consumption including the energy demand of lighting. On the x-axis, all simulated cases are presented, while on the y-axis the annual energy consumption for the entire room is presented in MJ. The meaning of these results will be elaborated on in the following paragraph (own image).

The results presented in the previous graph are however absolute energy demands, meaning that this is the energy required to keep the room comfortable. Because the energy for heating and cooling is generated using a heat pump, the efficiency of this energy generation is higher than that of the lighting. Usually a heat pump has a theoretical Coefficient Of Performance (COP) of 4-4.5, but in reality this is slightly lower, in the range of 3-3.5. This is why the results in the next graph are corrected for a COP for heating and cooling of 3, resulting in an even greater dominance of the lighting energy.

Because these ratios are entirely depending on the method of energy generation, and mostly interesting from an economical point of view, all other graphs only present the absolute energy demand of the office and not the required energy to produce this energy. After all, if the electricity for lighting were generated using photovoltaics on the building while the heating energy is produced using natural gas, the proportions become entirely different.

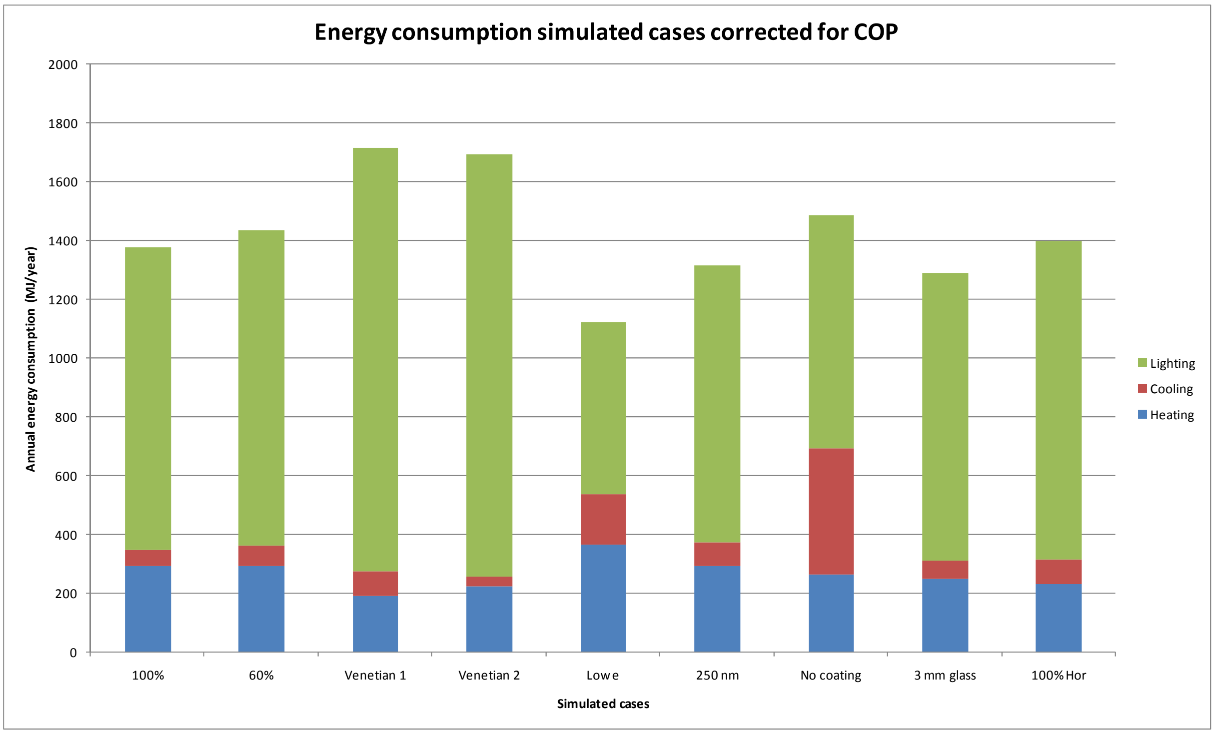


Figure 68: Graphical representation for all simulated cases, showing the energy required to produce the demanded energy. The used COP for heating and cooling is 3, while for lighting it remains 1. This results in a even greater domination of the lighting energy demand. The proportions are only relative though, due to the great dependence on the method of energy generation, and are only presented here to give an indication of the influence of different COP's (own image).

To give a better understanding of the distribution of the heating and cooling energy over the year, the following graphs present the monthly energy consumption. This shows more clearly in which season the heating demand is high, and in which season the cooling demand is high. This performance is of course very much depending on the year that is chosen for the simulation.

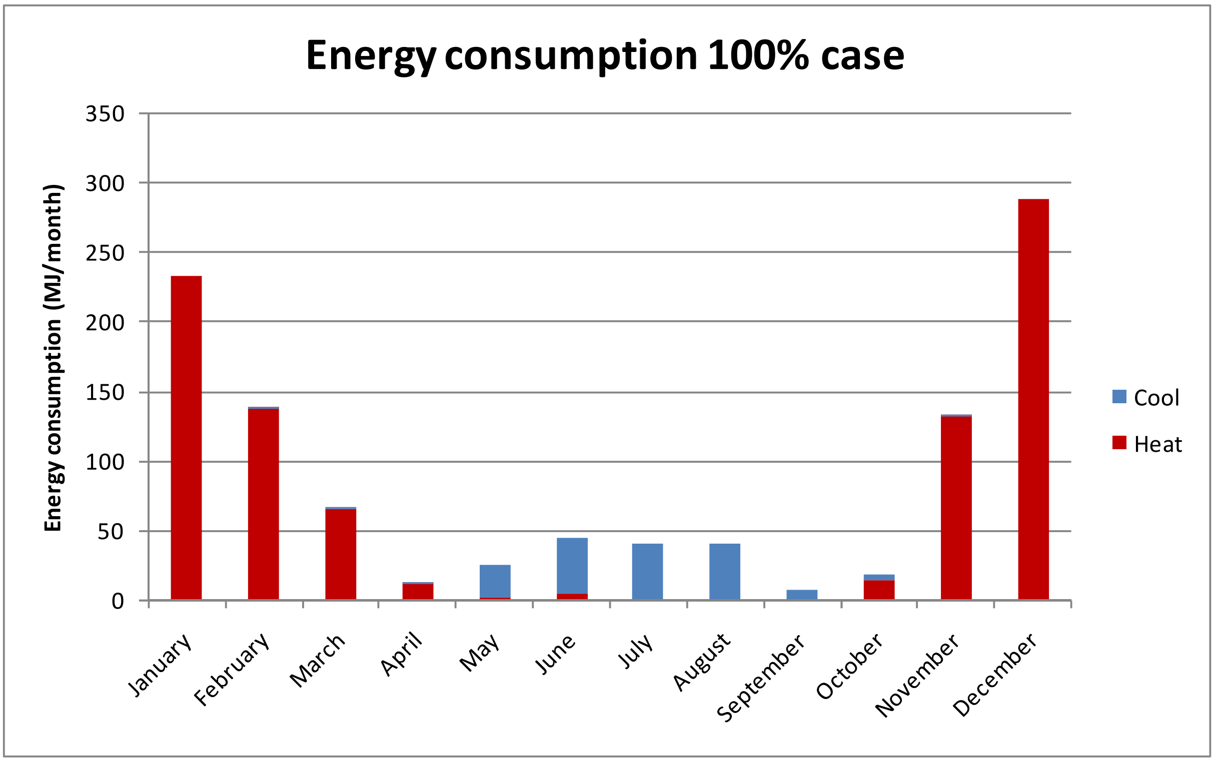


Figure 69: Monthly energy demand for heating and cooling in MJ/month for the entire office, when this is simulated in the 100% case. The pattern of heating and cooling is consistent with the expected need for heat in winter and need for cold in summer. Only one small bit of heating is needed after a cold period of a week in June (own image).

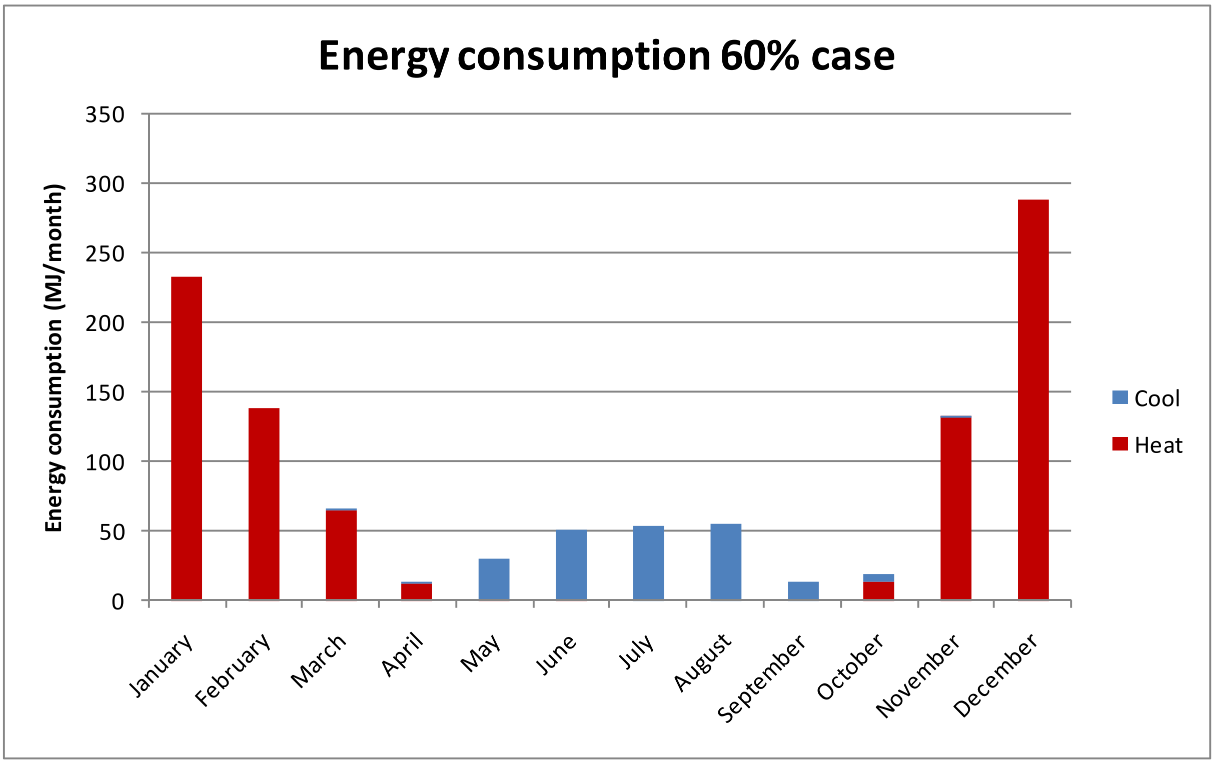


Figure 70: Monthly energy demand for heating and cooling in MJ/month for the entire office, when this is simulated in the 100% case. The pattern of heating and cooling is consistent with the expected need for heat in winter and need for cold in summer. The cooling need in summer is slightly larger than in the 100% case (own image).

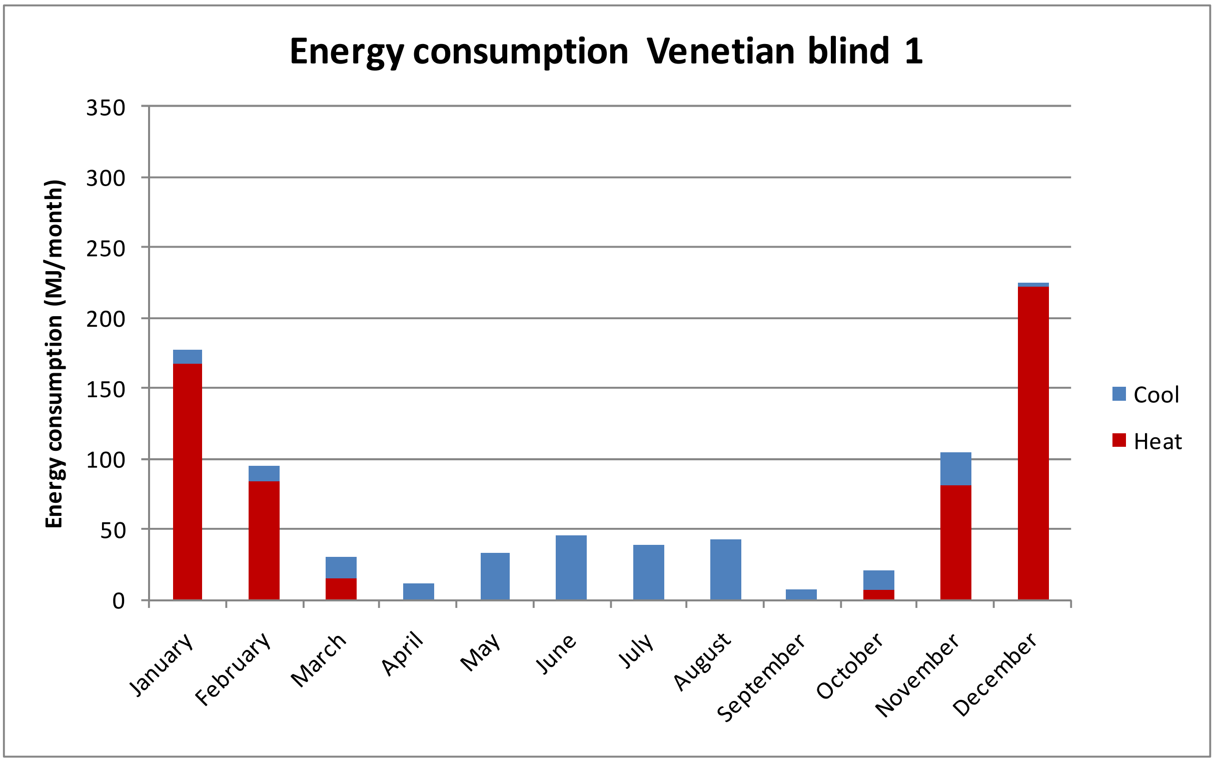


Figure 71: Monthly energy demand for heating and cooling in MJ/month for the entire office, when this is simulated in the more rigid venetian blind. The pattern of heating and cooling is consistent with the expected need for heat in winter and need for cold in summer. However, in winter there is also a need for cooling sometimes, which is explained in the discussion of results (own image).

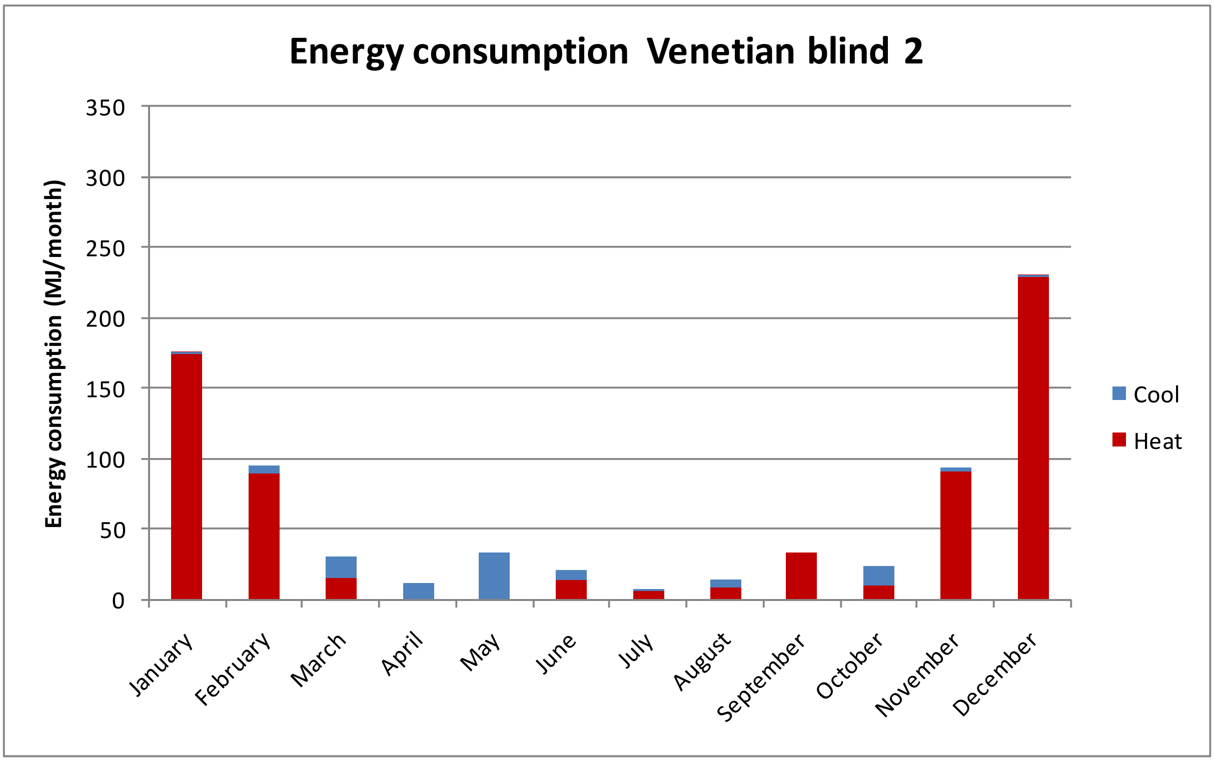


Figure 72: Monthly energy demand for heating and cooling in MJ/month for the entire office, when this is simulated in the more flexible venetian blind. The pattern of heating and cooling is consistent with the expected need for heat in

winter and need for cold in summer. However, in winter there is also a need for cooling sometimes, which is explained in the discussion of results (own image).

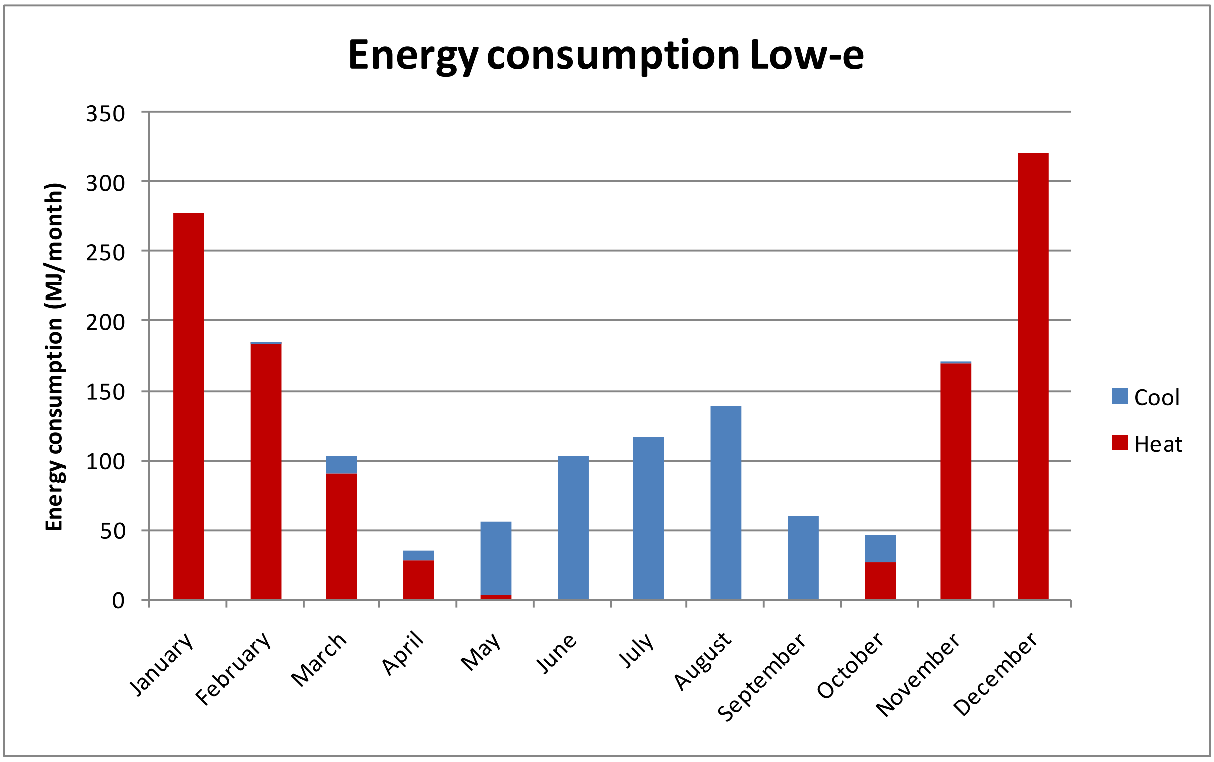


Figure 73: Monthly energy demand for heating and cooling in MJ/month for the entire office, when this is simulated with a low SHGC low e coating. The pattern of heating and cooling is consistent with the expected need for heat in winter and need for cold in summer. Both the cooling and the heating demand are (much) higher than that of the PolyArch coating cases and the venetian blinds (own image).

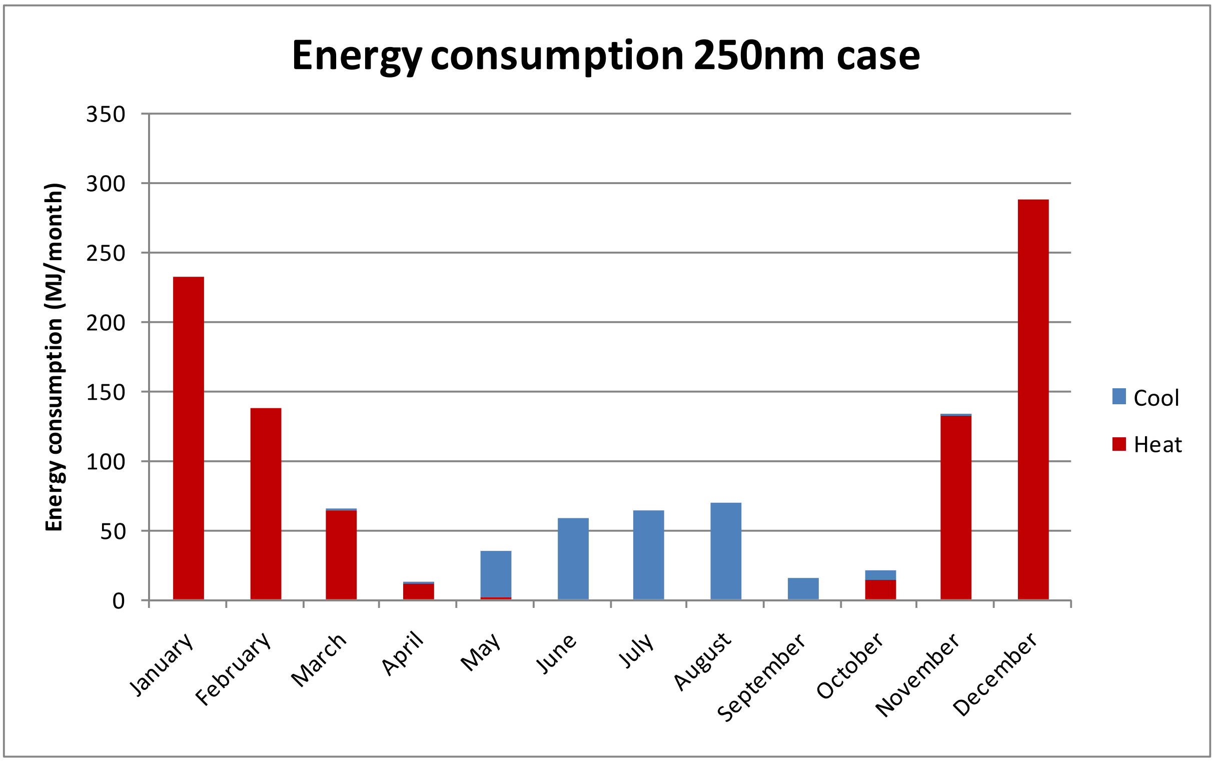


Figure 74: Monthly energy demand for heating and cooling in MJ/month for the entire office, when this is simulated in the 250nm case. The pattern of heating and cooling is consistent with the expected need for heat in winter and need for cold in summer. The cooling demand is significantly higher than that of the 100% case (own image).

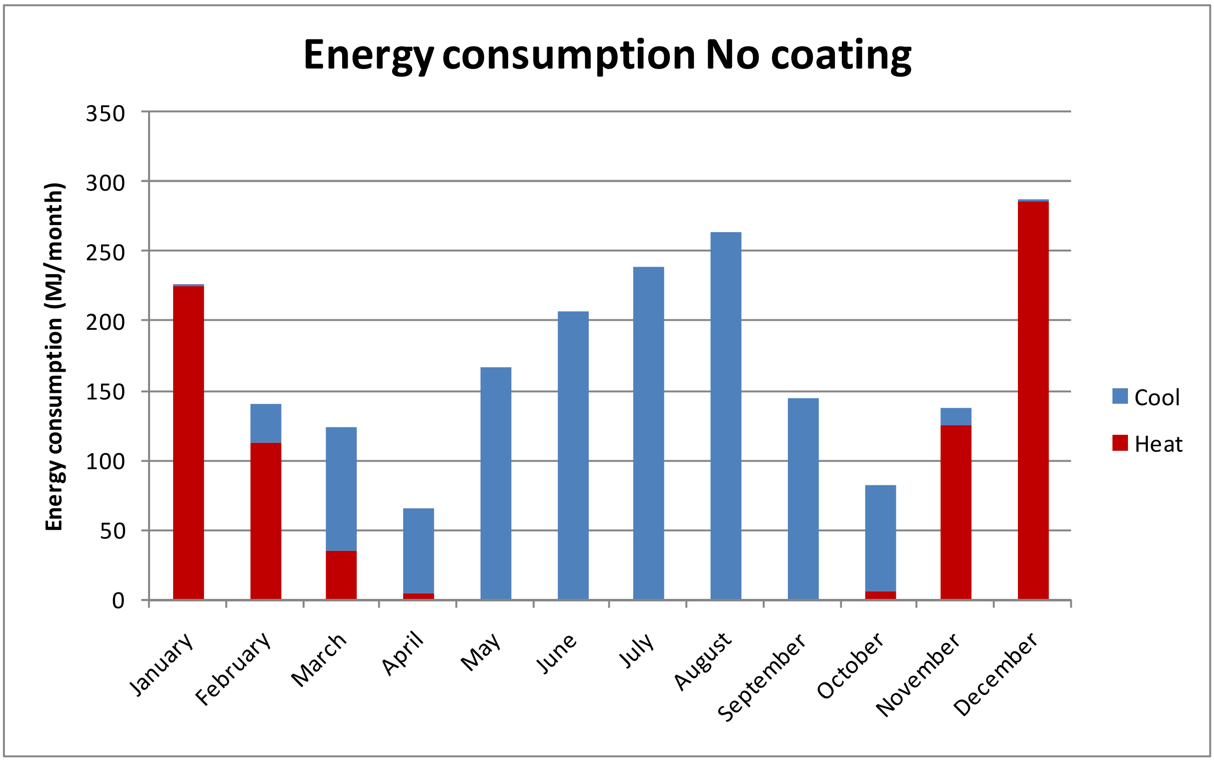


Figure 75: Monthly energy demand for heating and cooling in MJ/month for the entire office, when this is simulated in the No coating case. The pattern of heating is consistent with the expected need for heat in winter, but cooling is needed almost all year. The cooling demand is significantly higher than that of the 100% case (own image).

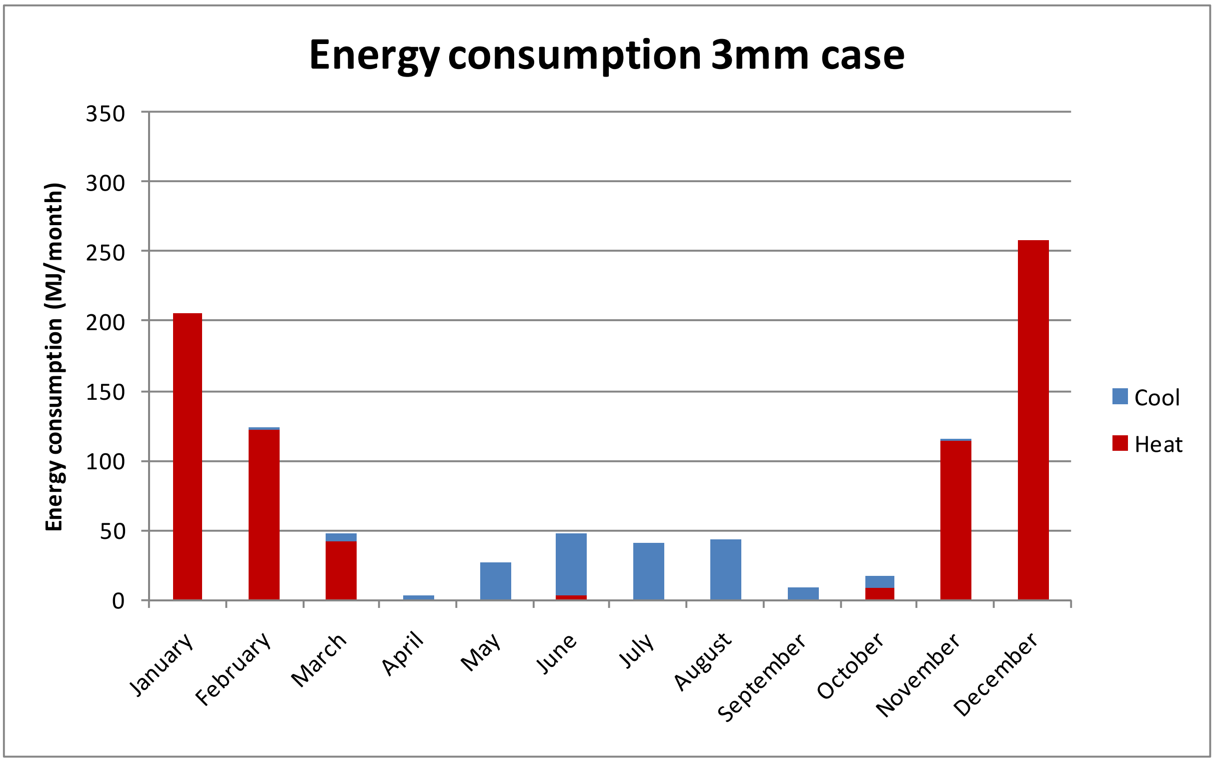


Figure 76: Monthly energy demand for heating and cooling in MJ/month for the entire office, when this is simulated in the 3mm case. The pattern of heating and cooling is consistent with the expected need for heat in winter and need for cold in summer. The heating demand is significantly lower than that of the 100% case (own image).

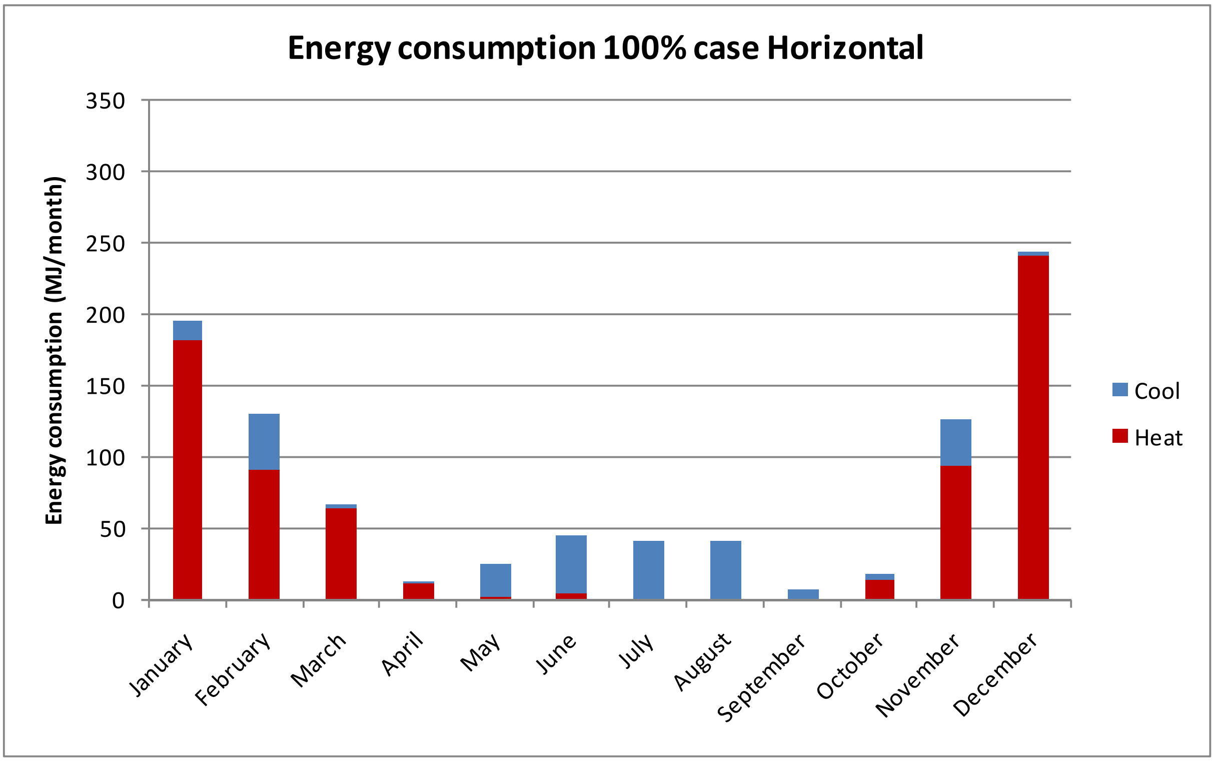


Figure 77: Monthly energy demand for heating and cooling in MJ/month for the entire office, when this is simulated in the 100% case with horizontal louvres in winter. The pattern of heating and cooling is consistent with the expected need for heat in winter and need for cold in summer. The heating demand is significantly lower than that of the 100% case, but in some winter months, cooling is needed as well (own image).

Output images from TRNSYS have not been included in this report because the annual results have so many fluctuations that the differences between the graphs can only be observed digitally by switching quickly between graphs. For this reason, they have been included in the digital appendix of this report, in which also the TRNSYS simulation model, the Excel files and the consulted literature have been included.

3.4.2 Discussion of results

The energy demand for heating and cooling shows a predictable distribution. The 100% case performs only marginally better than the 60% case on cooling, and similar on heating. This is because the reflection of the 100% is slightly better, but the transmission of both cases when heating is needed is determined by the same glass louvres. This is proved again by the results of the 3mm case, which has a reflection that is almost identical to that of the 100% case, but a transmission of the glass louvres that is more than 10% higher. This results in an almost identical cooling demand, but a heating demand that is almost 15% lower.

The same goes for the 100% case in which the louvres are moved to a horizontal position at the beginning of the heating season. It shows a heating reduction of more than 20%, but cannot reach the same cooling load, because the horizontal louvres transmit the solar energy in winter very well when this is desired, but also when shading is actually desirable, thus being much less effective as a shade.

On the other hand, when the glass is kept the same, but the coating transmission is altered, this does indeed leave the heating demand the same but changes the cooling demand, as can be seen in the 250nm case. This case has a much lower reflection than the 100%, leading to an increase in cooling demand of more than 50%. Remarkable is that in the No coating case, the heating demand decreases with 10%. This happens mostly in the months February, March and April, in which there is also a relatively high cooling demand, which is not present in the 100% case.

This can be explained by the fact that also in the heating season, the sun occasionally is intense enough to require cooling. When the glass is coated, the coating prevents overheating before cooling is needed, while on the uncoated glass the room can heat up until cooling is needed. During weekdays there is only half a degree difference between the setpoint temperatures for the coating and the cooling, but in the weekend the coating is still controlled by the ATG (since this only requires potentially extra energy for the operation of the coating, which is marginal) while the cooling system starts to work only at 30 degrees. This means that when the solar load on the facade is high, the temperature during the weekends will stay lower in the coated situation than in the uncoated situation. This leads to higher overall temperatures in the weekends en beginning of the week, which influences both the heating and cooling demand.

The low e coating performs worse in both the heating and the cooling aspect, compared to the 100% case. The energy needed for cooling is twice the cooling need of the other coated situations, but since the cooling loads are low in general this needs to be put in perspective. It is relatively easily explained though, since the transmitted light in summer is much higher than in a situation with a dynamic shading device, thus resulting in a larger cooling demand. The real issue of a static coating is displayed in the heating load however, because it continues to keep heat out in winter, resulting in a large increase in heating demand.

The high transmission value at all times does however also mean that the energy required for lighting the office is by far the lowest of all. For venetian blinds, this energy requirement is more than twice as high, because the reflection of solar energy is always reflecting visible light. This is also the reason why the PolyArch coating examples are in between these two extremes, since the PolyArch coating is operating with a half reflective state in which the visible light is still transmitted, and because the glass louvres in some cases prevent overheating already, due to which the need for reflecting visible light is avoided.

When only looking at the energy demand of heating and cooling, the venetian blind performs very well though. Both venetian blinds display a significantly lower combined heating and cooling energy consumption. The more rigid version shows however a larger cooling demand than the 100% case, which is mainly caused by the fact that the transmission of the blinds when the blinds are up is 100%, while the 100% case always has the glass louvres in front of the window, which transmit only around 70% of the light at most. This also means however that the sun can be used more efficiently as a heating source, leading to a much lower heating demand. The more flexible version of the venetian blinds uses a decreased reflection instead of no reflection when the indoor temperature is comfortable, which decreases the cooling demand. It also uses (a different kind of) decreased reflection in the summer though, which prevents overheating so efficiently that a small amount of heating is needed at some periods.

All results, but especially those of the venetian blind, have to be observed with careful consideration of the abstraction of the simulation model though. There are many variables in the simulation for which a certain value or range of values had to be chosen, or a method of abstraction had to be applied in order to allow simulation, which may or may not have an influence on the final result. These uncertainties have already been described in chapter 3.2.3 in more detail, but it needs to be stressed again that e.g. a different location in the building (with more extreme boundary conditions than the office that is simulated now, which is enclosed by offices with identical thermal conditions as the simulated office at all sides) or a different weather file may have a large influence on the final result.

This would also put the lighting energy more in context, since this usually accounts for roughly 20% of the building's energy, but in this simulated scenario is often half of the required energy. This can (at least partly) be explained by the fact that the energy demand for heating and especially for cooling is very low in the simulated cases. A hand calculation to validate the outcomes is presented in the following paragraph. In different scenario's, the energy demand for heating and cooling may be larger, thus reducing the proportional influence of the lighting energy. Therefore it is not said that the PolyArch coating performs better than a regular venetian blind. After all, it would be a peculiar conclusion to state that a low e coating performs better than a venetian blind, even though it may be true given the situation that is simulated.

Even though no definitive conclusions can be drawn from the results, there are some things that can be learned already. First of all, it seems safe to say that the reduction of heating energy is controlled by the glass transmission (confirmed by the 3mm and 100% horizontal case), and the reduction of heating energy is controlled by the coating quality (confirmed by the 100%, 60% and 250nm case). Furthermore, the absence of a PolyArch coating in the last 1000nm of the solar spectrum does not seem to have a large impact on the total transmission and energy consumption. This is partly due to the small amount of solar energy in this part of the spectrum, but is certainly also caused by the fact that the static (heat mirror, K-glass) low e coating on the window, that is necessary to obtain a reasonable U-value, starts to become reflective in this part of the spectrum. With a 500nm bandwidth, not much worse coatings can be produced, so it is interesting to see where the limit is in decreasing the bandwidth, since the coating with half the bandwidth and a smaller amount of active coating layers (the 250nm case) is still fairly efficient.

Also the influence of the lighting energy becomes clear in these simulations. Although the amount of lighting energy compared to heating and cooling energy seems out of proportion in these simulations, they do indicate an important difference between the venetian blind and the PolyArch coating, i.e. the fact that the PolyArch coating can reflect spectrally selectively. This could save a lot of lighting energy at times when the building does not need drastic shading. In these simulations, the effect of single handed reflection in the visible light (meaning that half of the light would still be transmitted) has not been studied yet. This and the spectral selectivity may very well present an opportunity to (partially) compensate the energy difference in heating energy.

With regard to the heating energy, it also seems plausible that tilting the louvres once every heating season to a horizontal position will reduce the heating energy enough to induce a energy consumption reduction, even though it also leads to a need for cooling at certain times. It is interesting to see whether there is an optimal position of the louvres at which both the heating and cooling energy are minimised.

3.4.5 Validation

Since the energy demand for cooling is very low, a hand calculation was performed to verify the outcome in a basic way. Obviously, this is a very rough assumption, but it gives an indication about whether the outcome is in the correct range. The calculation has been performed for a summer situation (150 days) with an uncoated glass louvre (g-value of 0.65), because with this type of sun shading the variety in g-values (between reflective and transmitting shading device) can does not have to be integrated in the calculation. A distinction between day temperature and night temperature is made, the former lasting from 10am to 8pm, the latter lasting from 8pm to 10am. The ventilation has a ‘quick’ modus during the day (from 7am to 6pm), at which the air change rate is 2, and a ‘slow’ modus at other times (from 6pm to 7am), at which the air change rate is 1. The infiltration rate is at all times 0.25.

The calculation considers a simple energy balance between incoming and outgoing energy. For the incoming energy, internal heat and solar energy transmission are calculated. For the outgoing energy, this is energy transmission through the facade and ventilation. The difference between the two energy sums (given that the incoming energy is larger than the outgoing energy) is the cooling energy demand.

Incoming energy

Internal gains

15 W/m^2, 20 m^2 → 15 * 20 = 300 W

150 days/year, $^5/_7$ week (5 days a week), 8 hours/day → 150 * $^5/_7$ * 8 = 857 hours

300 W * 857 hours = 257.1 kWh

Solar energy

200 W/m^2 (corrected for clouds, brightness differences etc.), 7 m^2 glass, SHGC = 0.65 * 0.75 (g-value of the window) = 0.49 → 200 * 7 * 0.49 = 686 W

150 days/year, 10h/day → 150 * 10 = 1500 hours

686 W * 1500 h = 1029 kWh

Total

257 + 1029 = 1285.8 kWh

Outgoing energy

Transmission through facade

U-value = (1.5 + 0.3)/2 = 0.9 W/m^{2}K (average of opaque facade and window glass), facade area = 14.6 m^2 → 0.9 * 14.6 * ΔT = 13 W/ΔT

Day temperatures: 150 days/year, 10 h/day → 150 * 10 = 1500 hours

13 W/ΔT * 1500h = 19.5 kWh/ΔT

Night: 150 days/year, 14 h/day → 150 * 14 = 2100 hours

13 W/ΔT * 2100h = 27.3 kWh/ΔT

Ventilation

Quick modus: n = 2 + 0.25 = 2.25, V = 52 m^3 → 120 m^3/h

$$\frac{120m^3/h}{3600\ s} \cdot 1200 \frac{J}{kg * K} \cdot \Delta T = 40\ W/\Delta T$$

Day temperatures: 150 days/year, $^5/_7$ week (5 days a week), 8 h/day → 150 * $^5/_7$ * 8 = 857 hours

Night temperatures: 150 days/year, $^5/_7$ week (5 days a week), 3 h/day → 150 * $^5/_7$ * 3 = 321 hours

Slow modus: n = 1 + 0.25 = 1.25, V = 52 m^3 → 65 m^3/h

$$\frac{65m^3/h}{3600\ s} \cdot 1200 \frac{J}{kg * K} \cdot \Delta T = 21.7\ W/\Delta T$$

Day temperatures: 150 days/year, 2h/day + 150 days/year, $^2/_7$ week (2 days a week), 8 h/day → 150 * 2 + 150 * $^2/_7$ * 8 = 643hours

Night temperatures: 150 days/year, 11h/day + 150 days/year, $^2/_7$ week (2 days a week), 3 h/day → 150 * 11 + 150 * $^2/_7$ * 3 = 1779 hours

Day temperatures: quick hours + slow hours = 857h * 40 W/ ΔT + 643h * 21.7 W/ ΔT = 48.3 kWh/ ΔT

Night temperatures: quick hours + slow hours = 321h * 40 W/ ΔT + 1779h * 21.7 W/ ΔT = 51.4 kWh/ ΔT

Total

Day temperatures: 19.5 + 48.3 = 67.8 kWh/ ΔT

Night temperatures: 27.3 + 51.4 = 78.7 kWh/ ΔT

Cooling energy requirement

Given a ΔT_{day} = 0 °C and ΔT_{night} = 10 °C

150 days/year, 24h/day → 150 * 24 = 3600 hours

Energy balance: 1285.8 kWh – 78.8 kWh/ ΔT * 10 °C = 499 kWh

499 kWh / 3600h = 139 W → 6.93 W/m^2

The currently used cooling power in this situation is 5.1 W/m^2, so the cooling power from the simulation is in the same range as the outcome of the manually calculated energy balance.

4. Design

4.1 Design introduction

4.1.1 Purpose of design

The design that is presented in this section of the report is not a final design, showing the best application of the coating in the application that I have tested. It is more a tool to give more insight in the tested application and the architectural consequences this might have. It is intended to stimulate the imagination of designers that may implement this kind of application in their design, by offering a way in which it may be used.

The design recommendations that will be presented in the following chapter are very important for that reason. They give a number of tips for designing with the coating, which are based on what is now possible, but also on what may be possible in the future. They do not only address the designed application, but also other types of application.

4.1.2 Design criteria

This design serves as a proof of concept design, so it intends to illustrate the research and simulation process with an architectural application possibility. For this reason, the design is made for a small office (with the properties of the standard office as it is described in chapter 3.2.1) in the Netherlands. The focus of the design lies on shading, since this is the focal point of the entire graduation research. A technical solution to implement the coating in the way that is proposed in the simulation is presented, in which the technical aspects are given priority, without disregarding the aesthetics however.

The reason for this is the fact that a generic design is considered more valuable than a specific design for one building, because the purpose of this design is to give fuel for thought to designers which may consider using this coating. In a design in which aesthetics are dominant, this is more difficult because these are much more depending on the vision of the architect and therefore are much more project specific than technical requirements. To complete the design and also avoid disregarding the aesthetics too much, 3D renders are presented in which ideas for the implementation of the louvres are offered.

For this reason, and due to the illustrative function in which the simulated environment had to be represented, the choice was made to design a new building instead of implementing it on an existing building. This meant that the design was made for a 50% glazed facade. However, many offices have curtain wall facades, which is why another design was made in which the implications of the larger amount of glass and the fewer connection points are presented. This is not simulated, but offered as extra information about the possible application of the coating.

4.2 Design

4.2.1 Design context

In architecture, glass louvres can be applied both in a flexible and in a static way. Dynamic louvres find their prevalent application in ventilation systems, in which the louvres control the passing airflow. In such a way, the louvres are in fact automatically operated windows. They are commonly fitted with either an aluminium frame or aluminium clips on pivots. The latter is also executed in polypropylene sometimes, in order to avoid discomfort caused by rattling of the system(Watts, 2011).

Figure 78: On the left, Clay 2928 in Buenos Aires by Dieguez Friedman. It effectively shows the possibility to emphasise horizontal lines with the large glass louvres. On the right, the Palmas Altas Campus for Abengoa in Sevilla, designed by Rogers, Stirk, Harbour and partners. It shows the body tinted glass which can be used to provide shading, while leaving the view to the outside intact. In this project however, the choice for glass was not made because of the transparent nature of the material, since the louvres were applied horizontally and separated per floor.

Apart from this application, glass louvres are also occasionally used as a shading device. In this case, the glass is often coated with a static coating, usually body tinted darkening. However, this is often not enough for adequate shading, so the louvres are often combined with a loggia or walkway. Examples in architecture can be found in both sunny environments, like Buenos Aires and Sevilla, and in less sunny environments like Amsterdam and Toronto.

The selection of designs presented in this paragraph shows some of the features and possibilities that are inherent to the application of glass louvres. First of all they present a strong architectural language, which can be used as an instrument by the architect to enhance their design. Furthermore, glass can be applied both in a transparent, a translucent and an opaque way, in which its shading qualities increase, but the material experience is not compromised. Visual quality through the louvres can remain intact, and still they can offer effective sun shading.

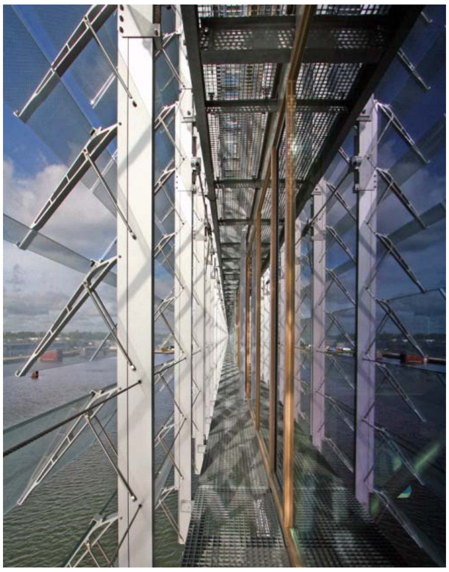


Figure 79: On the left Kraanspoor in Amsterdam by OTH architecten. These louvres are operable, and do not only control the sunshading but also the airflow through the facade. On the right, the proposal for the Union station transit in Toronto by Zeidler partnership architects. This shows that even for certain large scale applications, glass louvres can be an appropriate shading technique and possibly even be the only required facade.

For optimal shading, static glass louvres are normally tilted 45 degrees. The choice of glass system depends among other things on the scale of the project. For safety reasons, the louvres are normally laminated to avoid pieces of glass falling down the facade when an element breaks. In some small project, normal float glass may suffice as well however. In both instances, both single and double glazing can be used (Watts, 2011). In addition, toughened glass is often used instead of normal float glass.

The dimensions of the glass are limited, depending on the manufacturer. AGP offers louvres with a maximum dimension of 1500x500mm (length x width), for 12mm thick laminated toughened glass (AGP Group, 2013). Colt provides more detailed data, distinguishing between shading systems with and without an additional support structure. They have a maximum width of 350-600mm (regardless of the presence of an additional support structure) and a maximum length of 2500-3300mm (1800mm without an additional support structure) (Colt, 2013).

4.2.2 Design description

The selected application of the PolyArch coating was to use it on a glass louvre system. In this way, it would function more or less like retractable louvres, without the issue of mechanical failure. This would be the case since the transmission of the coating could be brought back to almost zero if it is turned on, because of which the glass louvres on which it is applied suddenly become opaque. If the coating is turned off, the glass remains transparent. Although this will have slight implications for the visual quality, the view to the outside is almost entirely ensured.

For safety reasons, laminated toughened glass is used. The toughened provides extra mechanical resistance, while the lamination ensures that no pieces will fall down the facade when the louvre happens to break anyway. In addition, the glass has a low iron content, to avoid the usual green lines on the glass's edges. This is done to enhance the perception of transparency when the coating is transmissive, and keep the colour of the louvre uniform when the coating is turned to the white reflective state.

The louvres have to be fitted on a support structure to hang them in front of the window. In the case of the facade with large opaque surfaces, a glass fin was chosen to connect the louvres to. It is supported on the bottom by an aluminium frame to avoid bending moments in the plane of the glass caused by the eccentric connection of the louvres. Resistance against strong winds has not been calculated, but similar examples with operable louvres have already been built, such as Macquarie apartments in Sydney, designed by Renzo Piano.

Figure 80: Macquarie apartments in Sydney, designed by Renzo Piano. For optimal transparency, the glass louvres are connected to a support structure consisting of glass fins (Wilson Property Agents, 2013).

Another important reason to choose for glass fins on the sides, even without their function as a support structure, is the possibility to apply the coating on these fins as well, and in that way also control solar transmission on the east and west facade.

For a curtain wall, this is less necessary because since the louvres are located directly next to each other, adjacent louvres project a shadow on the window where a gap would exist if the louvres were to be applied individually. Because of this, no structure on the side is required, which means that the aluminium support is the only necessity. Per floor, the aluminium supports are connected to an aluminium strip, which is connected to the mullion on the top and bottom. The supports do not interrupt the continuing line of the louvres, which offers architects a way to optimally use the louvres as a means to emphasise on the horizontal lines.

4.2.3 Design recommendations

This paragraph describes the way in which designers should approach the coating when they intend to design with it. It offers some tips regarding the design that is presented in this section, but also concerning other kinds of applications. It also pays attention to future developments that can be expected, and the consequences this may have on architectural design.

Design related recommendations

To avoid green lines in the glass, the use of low iron glass is recommended. In addition, laminated glass is suggested with regard to safety issues.

Applying the coating on glass fins on the side of the louvre system will improve the shading properties slightly on a south facade, and radically on an east or west facade. These glass fins can be used as a support structure for the louvres as well.

Keep in mind the maximum dimensions of the louvres when designing the facade grid in case of a curtain wall facade, to avoid the necessity of a secondary support system in front of the glass.

Other recommendations

When the coating is applied directly on glass, several setpoint temperatures can be used on the same window. This creates zones, by which the transparency of the window can be regulated more or less gradually. The application can be in straightforward rectangular surfaces, but also in organic patterns. If the zones indeed respond to different temperatures, the patterns could gradually evolve into a growing and shrinking pattern, or perhaps even an image that becomes visible and disappears when the zones are activated.

A special feature of the zoning could be the creation of these images, either for shading purposes or fully artistically. This can be done both in a white/transparent mode and in a coloured application. It would also be possible to create coloured images on the facade that only appear when the temperature exceeds a certain limit. The potential of such images can be seen for example in thePlace in Sunderland, where Kathryn Hodgkinson created an artistic image on glass louvres.

Coloured reflections on glass will not be as bright as coloured reflections on opaque materials, since light from the other side of the glass disturbs the perceived colour. To avoid similar disturbance of the perceived colour when incident light is reflected off opaque materials, the use of light absorbing materials is recommended when the coating is applied on an opaque surface and intended to reflect a colour. Applying a black paint underneath the coating may be enough for this.

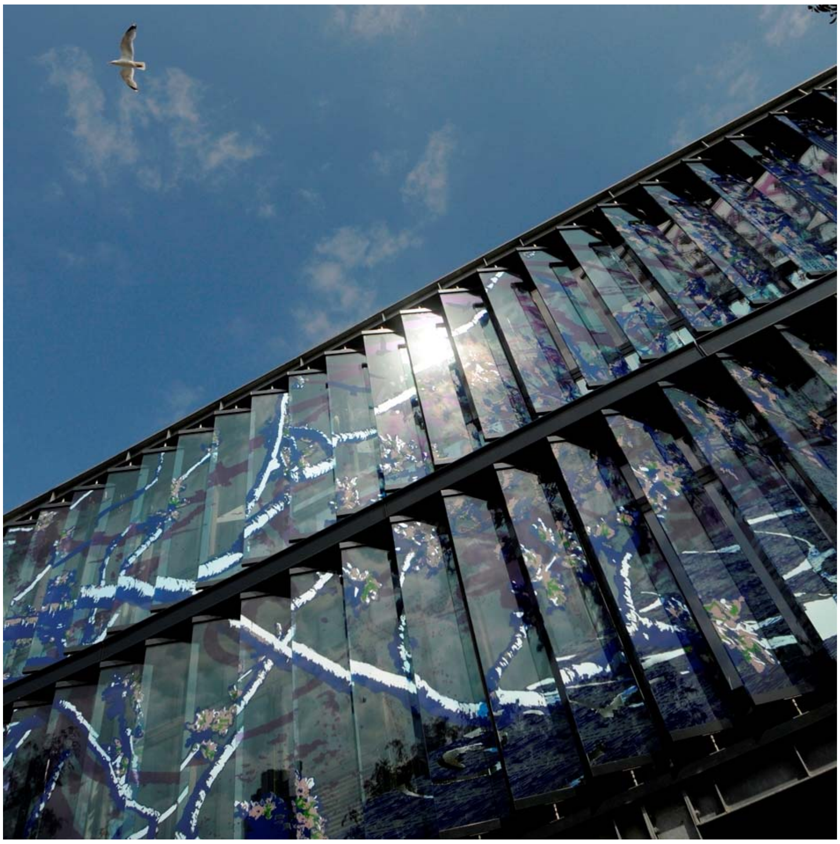


Figure 81: These operable vertical glass louvres for 'thePlace' in Sunderland were produced by Levolux and designed by local artist Kathryn Hodgkinson. The special pattern shows an interesting artistic approach towards louvres, one that may give the PolyArch coating another dimension(Levolux Limited and Levolux A.T. Limited, 2012).

Future development

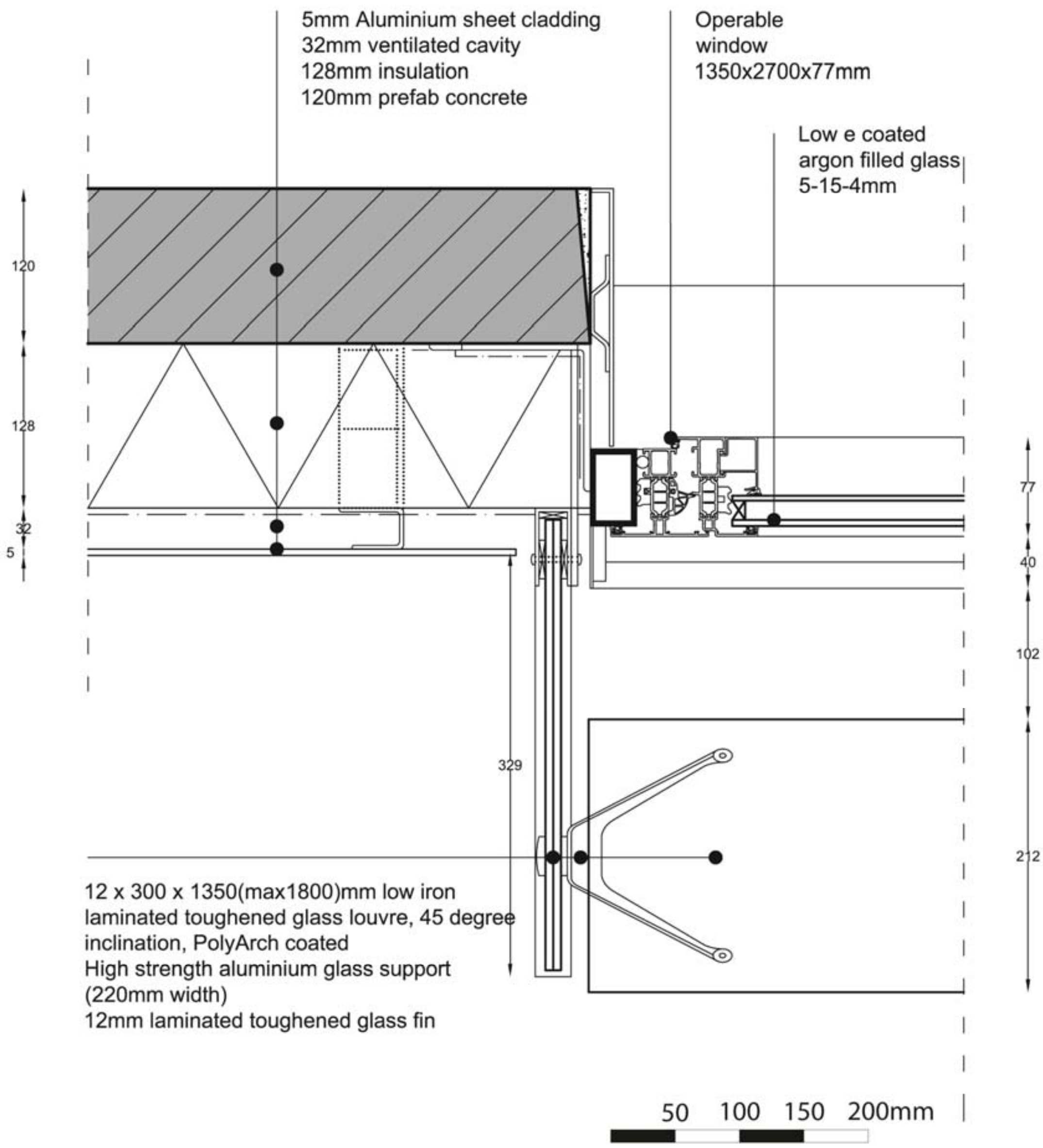
A slight shift in reflected colours will still occur with the coating as it has been described so far. However, if the coating would be applied in a pigment in which chiral axes are orientated randomly, the colour would remain constant, regardless of the angle of incidence (or observation). This may be important for certain artistic expressions, but the reduction in transparency caused by a white haze must be considered.

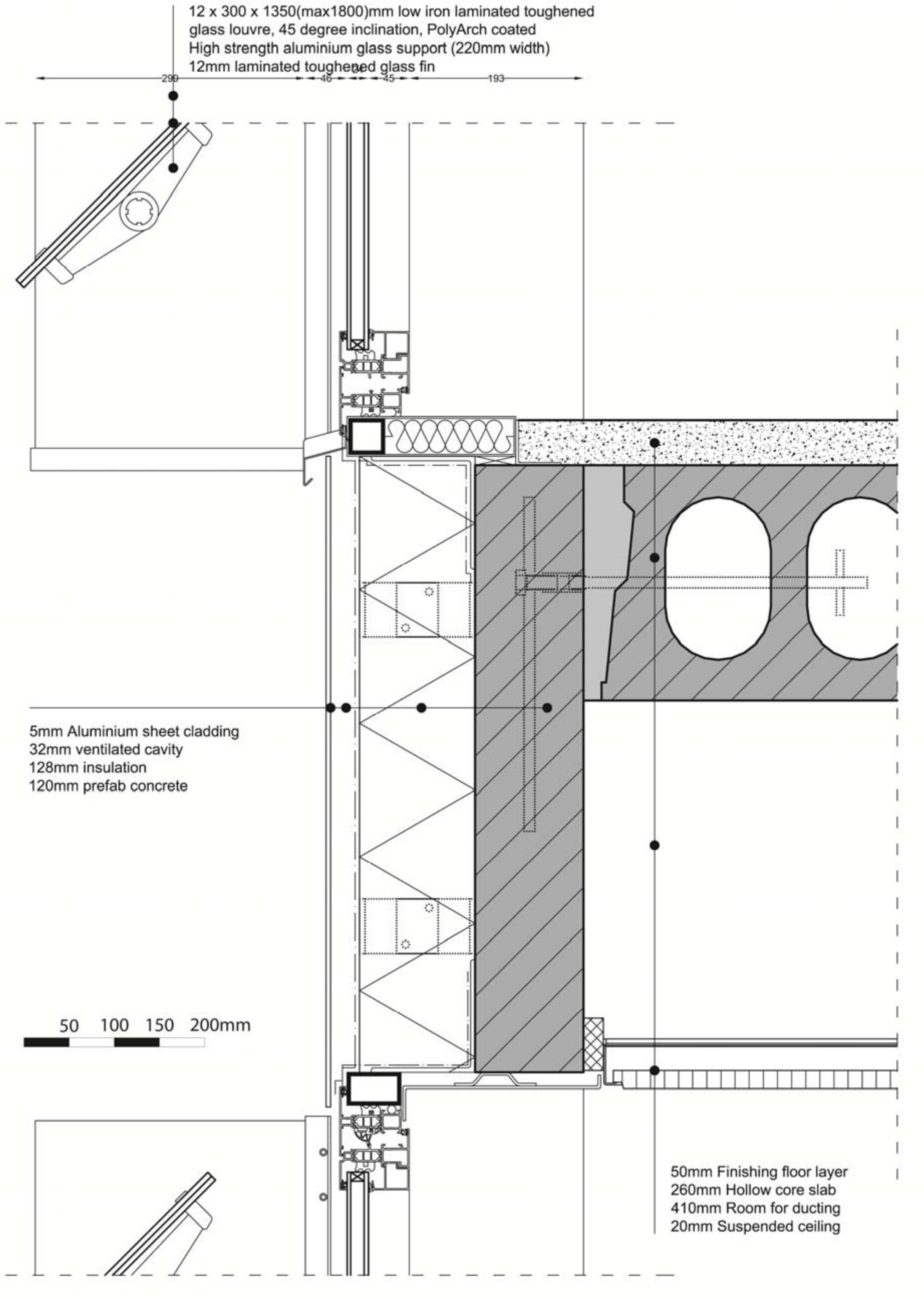
Large bandwidths caused by a pitch gradient, up to several hundreds of nanometres, were already assumed for this design, although they still need more development. If the currently more common small bandwidth would be considered, architects would have to be aware of a large amount of coatings, which may cause reduced transmission if errors in the optical coupling would occur, and in addition require an advanced operating system if the coating would be triggered electrically.

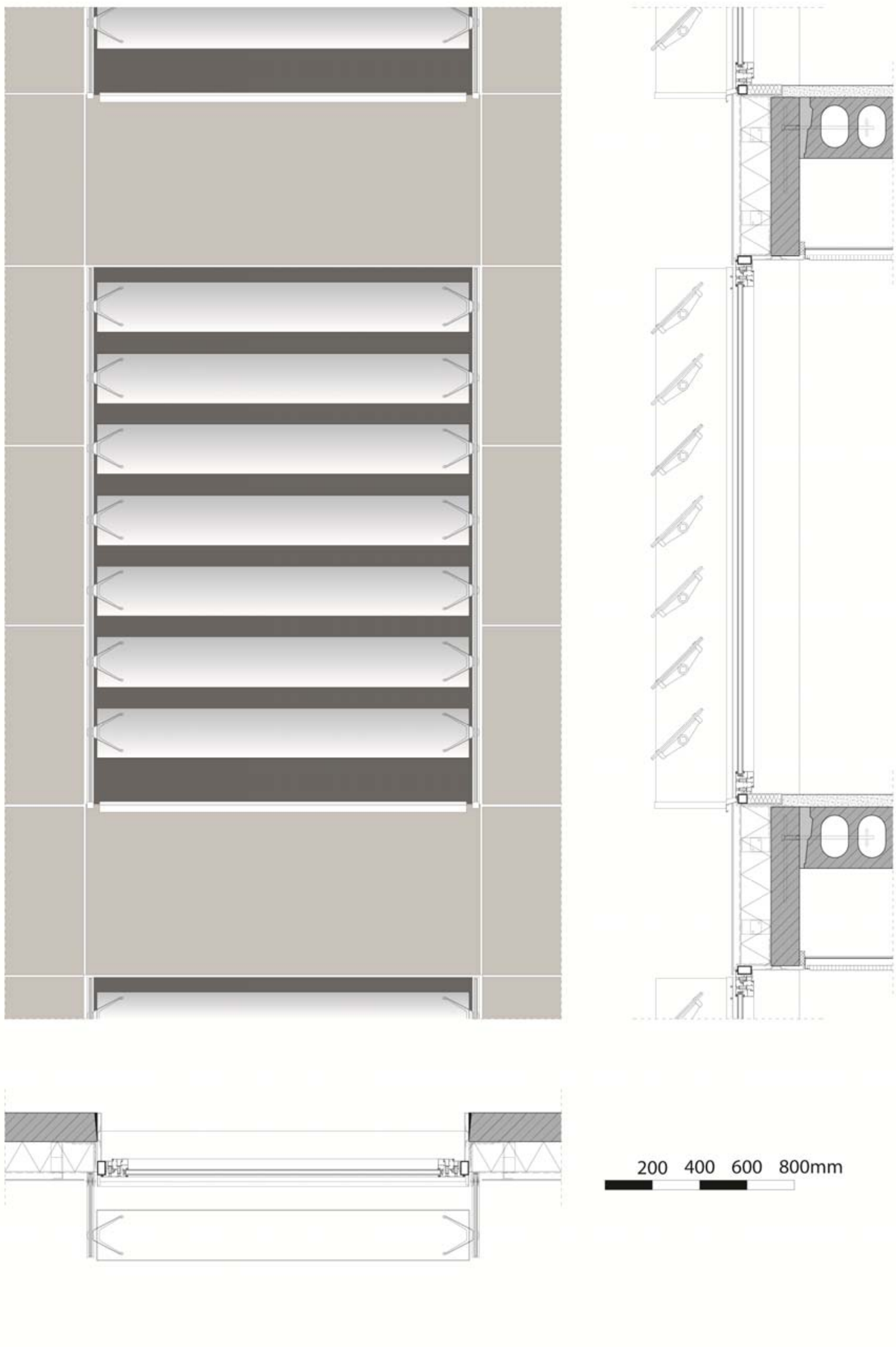
4.3 Drawings

4.3.1 Normal facade

These drawings show the connection of glass louvres to a normal facade, in which approximately 50% of the facade is glazed. The louvres are connected to a glass fin, which is connected to the prefab concrete with a steel profile. All louvre connections are essentially static. Only for the curtain wall facade also an operable louvre system has been drawn, although the application of such a system more or less defeats the purpose of using the PolyArch coating. The images show a horizontal detail, a vertical detail and finally a 1:20 facade fragment. The images may not be to scale, but a scale bar is provided on each drawing.

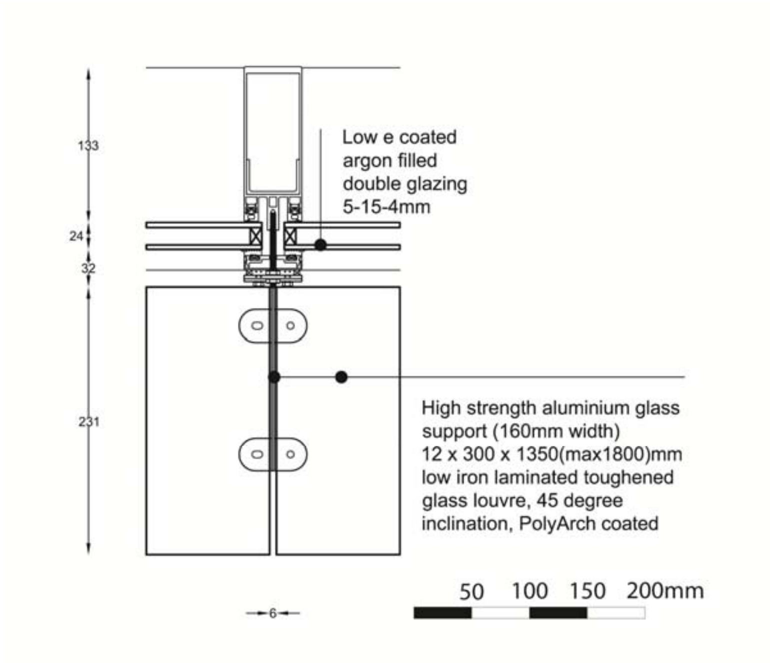


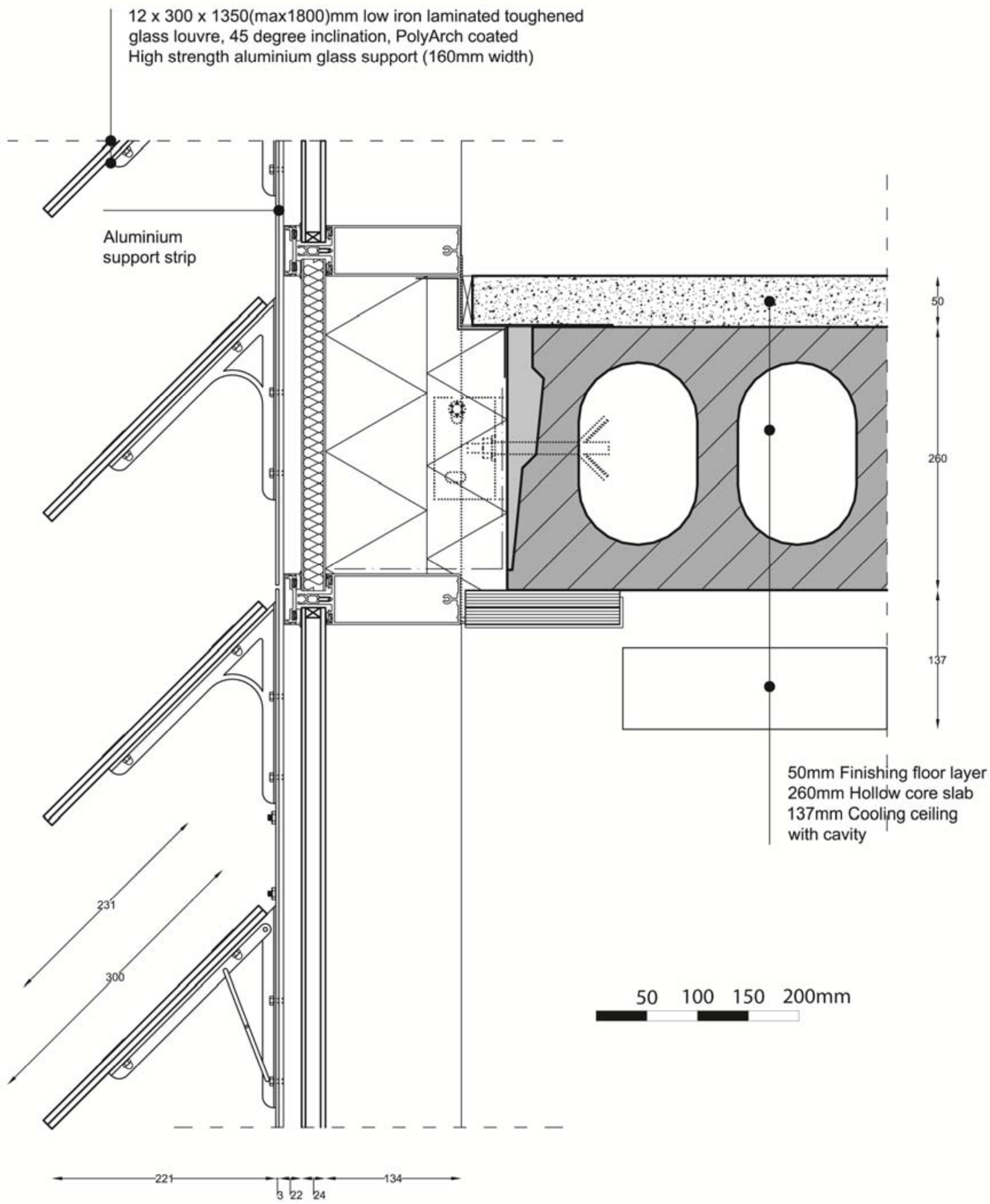

12 x 300 x 1350(max1800)mm low iron laminated toughened
glass louvre, 45 degree inclination, PolyArch coated
High strength aluminium glass support (220mm width)
12mm laminated toughened glass fin
299
46
45
193
5mm Aluminium sheet cladding
32mm ventilated cavity
128mm insulation
120mm prefab concrete
50 100 150 200mm
50mm Finishing floor layer
260mm Hollow core slab
410mm Room for ducting
20mm Suspended ceiling


200 400 600 800mm

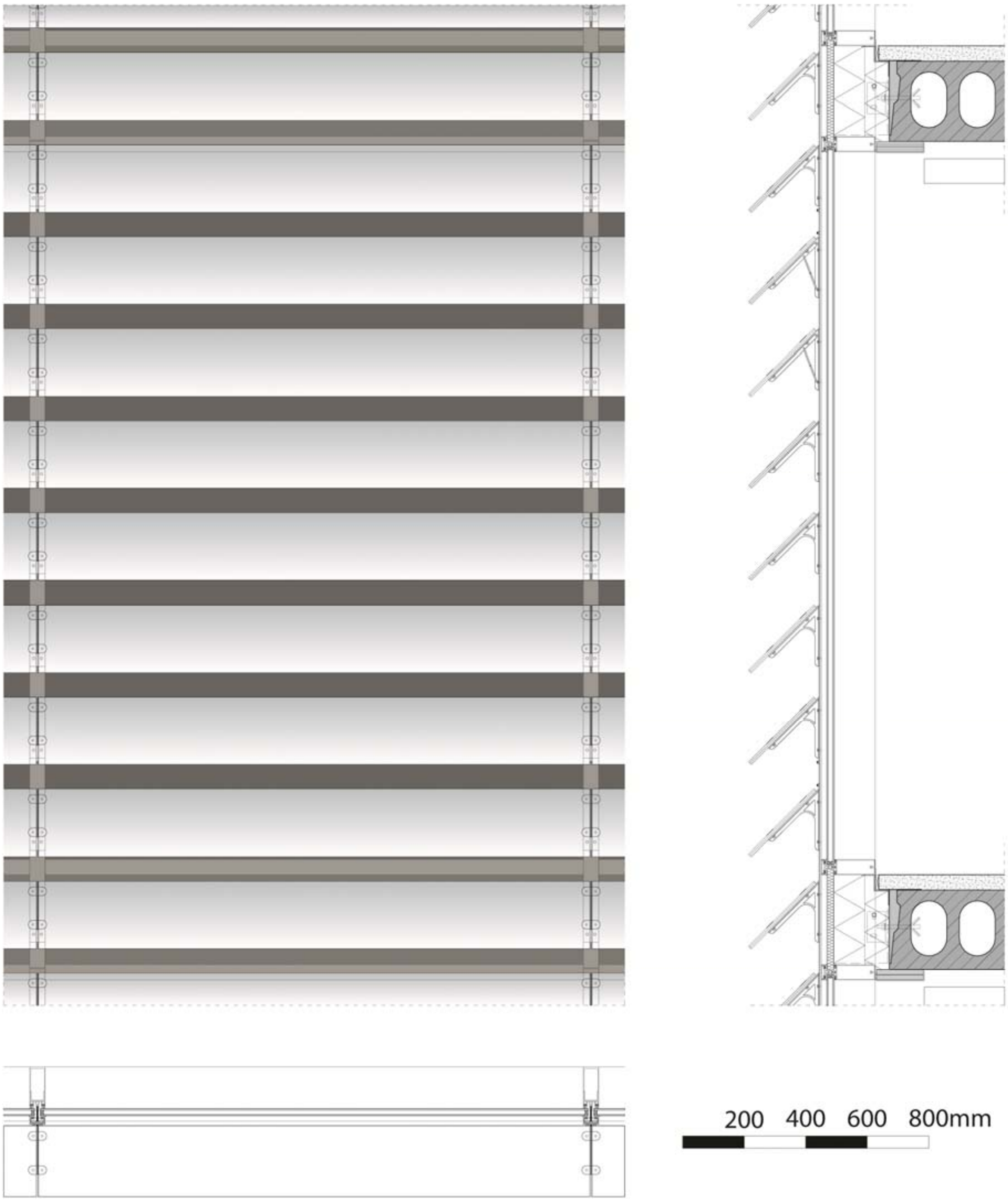
4.3.2 Curtain wall facade

Although this type of facade has not been simulated, drawings are provided for a curtain wall facade as well due to the commodity of this facade type. Although mechanical problems caused by moving elements are one of the main reasons why the PolyArch coating should be implemented, the vertical detail shows louvres in the top of the facade which are moveable, in order to have the possibility to use them as a light shelve. Again a horizontal detail, a vertical detail and a 1:20 facade fragment are shown. These drawings may not be to scale, but a scale bar is provided on each drawing.





12 x 300 x 1350(max1800)mm low iron laminated toughened glass louvre, 45 degree inclination, PolyArch coated
High strength aluminium glass support (160mm width)
Aluminium support strip
50
260
137
50mm Finishing floor layer
260mm Hollow core slab
137mm Cooling ceiling with cavity
231
300
50 100 150 200mm
221
3 22 24
134


200 400 600 800mm

4.4 Visual impressions

Louvre dimensions

With most manufacturers, the maximum width of glass louvres is 500mm. However, the glass louvres in the design are only 300mm wide. The choice to make the was mostly driven by aesthetical considerations, since transmission values do not depend on the dimensions but the proportions of the shading device. Large louvres do however mean that more weight has to be supported by the glass supports, which automatically calls for larger dimensions in the supports too. Large louvres may also be more problematic to handle by maintenance workers when one of them needs to be replaced, but they also create a much bolder image. This may be desired or not, depending on the project, but personal preference combined with the abovementioned motivation made the smaller louvres the right choice.

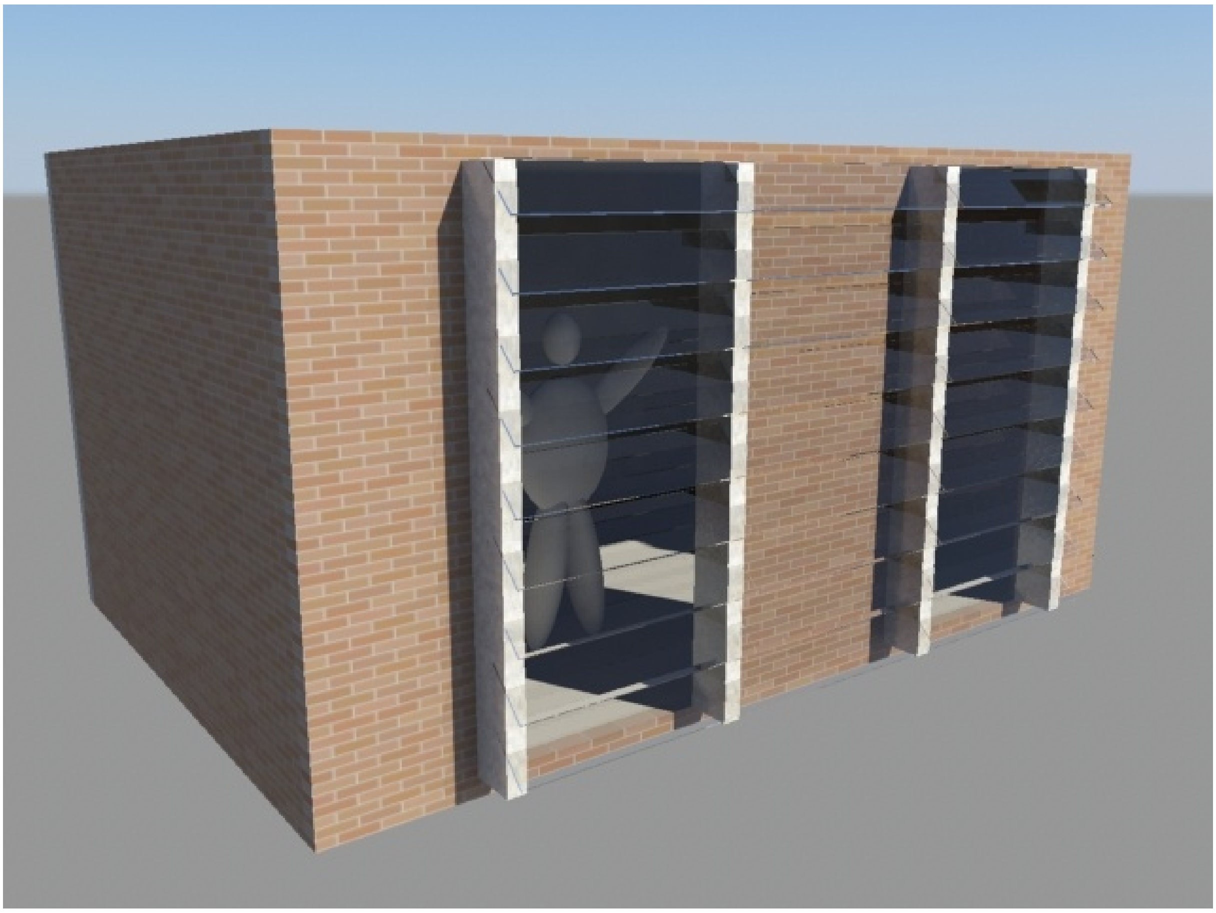


Figure 82: Glass louvres of 300mm wide on a single office cube, in the configuration as was simulated in this research (own image).

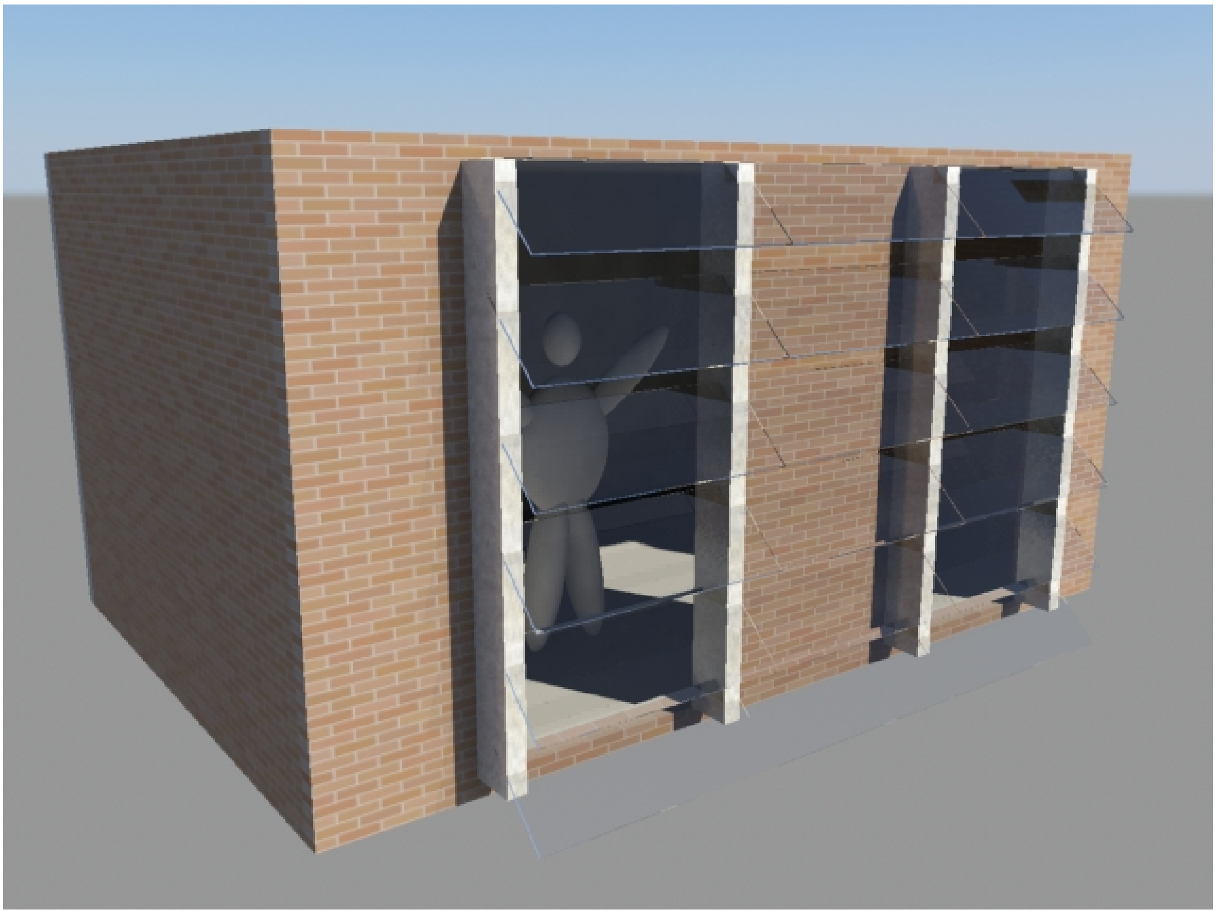


Figure 83: Glass louvres of 500mm wide on a single office cube, in the configuration as was simulated in this research (own image).

Simulated situation

The following images are intended to illustrate the simulated architectural situation. They are directly based on the design details for a normal facade presented in the previous chapter. The image do subsequently show the louvres in transmitting state, in a state in which the louvres themselves reflect but the supporting glass fins remain transparent and a state in which both the louvres and the fins are reflective. The reflection of the coating is either specular (mirror-like) or diffuse, and since the entire visible part of the spectrum is coated, all colours are reflected equally. Because the efficiency of the louvres would be compromised drastically when the louvres were specularly reflective, the renders show a diffuse reflection of the environment.

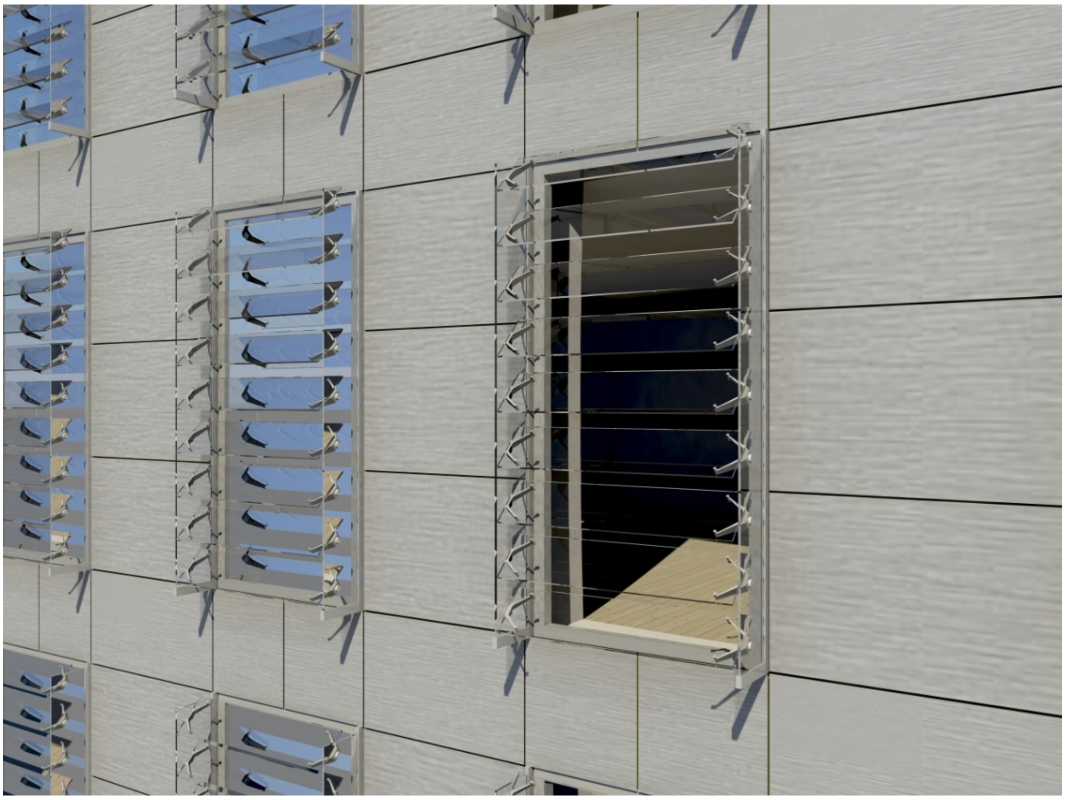


Figure 84: The glass louvres in fully transparent state. Only the aluminium glass supports remain clearly visible, apart from which the view is almost unobstructed (own image).

Figure 85: Fully reflective louvres provide a large degree of shading (own image).

Figure 86: By applying the reflective coating not only on the louvres, but also on the supporting glass fins, the transmission of light through the edges of the louvres can be eliminated as well, making the system almost completely reflective and entirely reflective to direct beam radiation above a critical angle of incidence (own image).

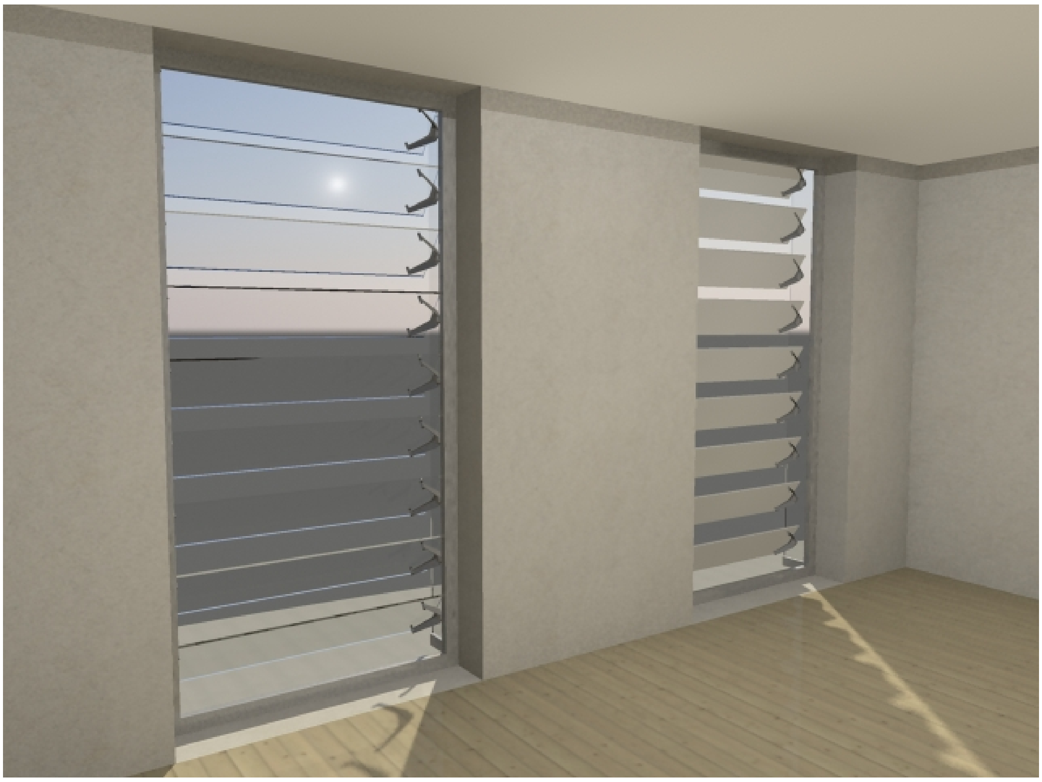


Figure 87: This render shows the difference between a shaded louvre system and a transparent louvre system from the inside. Also the effect of the gap on the sides that is inherent to the use of venetian blind is visible, which is why applying a coating to the glass constructive fins may be wise (own image)

Curtain wall facade

Although this type of design was not simulated, an impression of its appearance and some possible applications have been given for a curtain wall as well, because of the fact that this kind of facade is used a lot in office buildings. The renders are again directly based on the details that have been presented in the previous chapter.

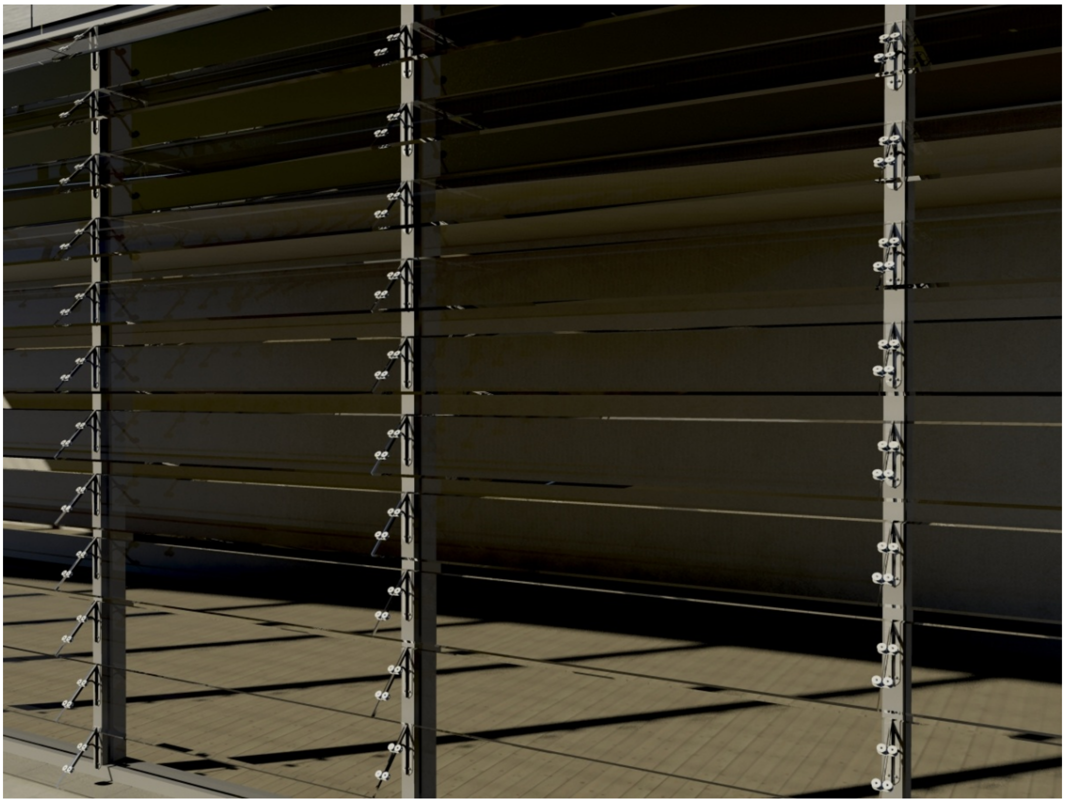


Figure 88: Curtain wall with PolyArch coated louvres in transmitting state (own image).

Figure 89: Curtain wall with the same louvres in front of it as in the previous image, but this time with the PolyArch coating in reflective state. It shows the potential of the louvres as a horizontal accentuation, when the supports are applied properly (own image).

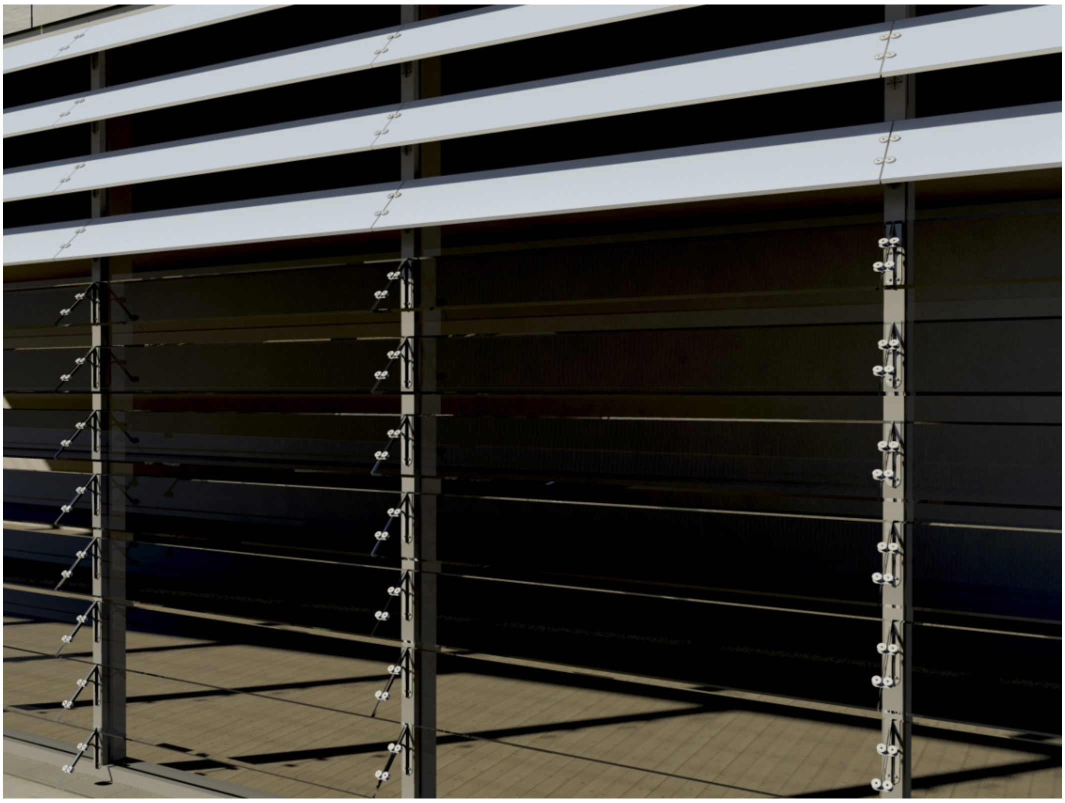


Figure 90: Variant on the previous two applications, showing a local reflection which still allows for a direct connection with the outside, while shading the top of the facade completely (own image).

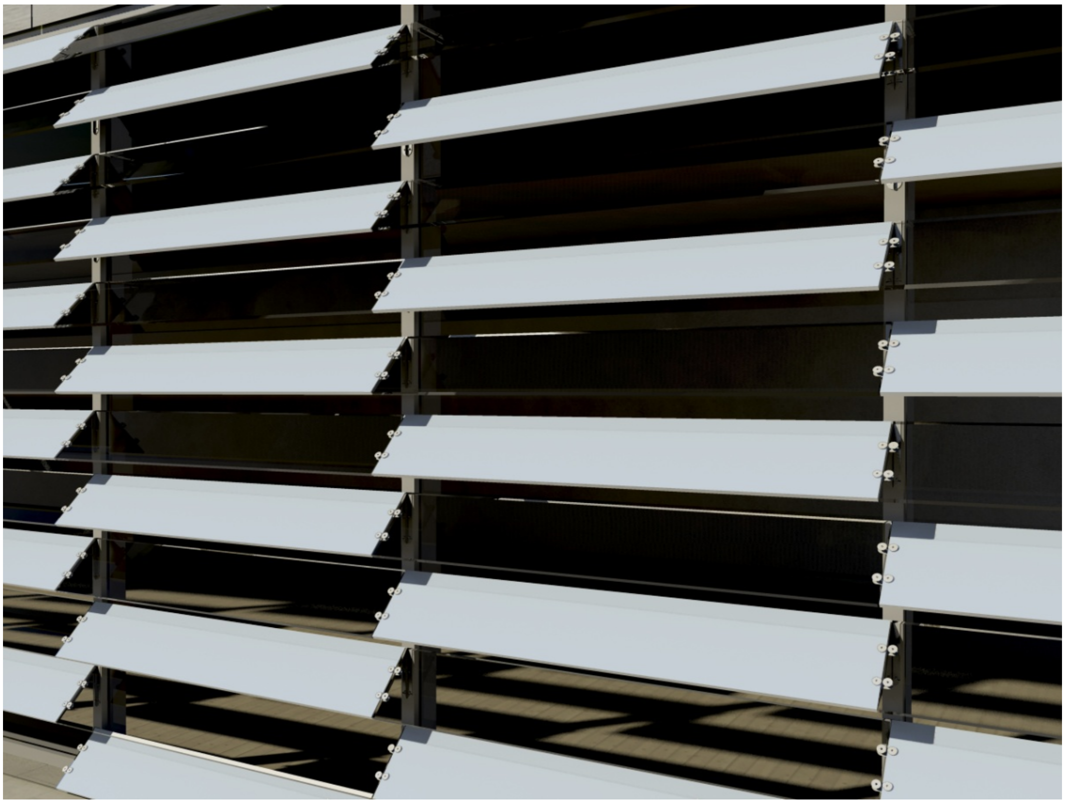


Figure 91: Another variant showing a checkerboard layout of the reflective louvres. If necessary, the other louvres may be turned to a reflective state as well. This checkerbord is just one way of showing the possibilities of creating an optimum between transparency and shading (own image).

Overall perspectives

These images show the application of the glass louvres on a full building scale. The curtain wall louvres are reflective on the top only, while for the normal facade some louvre systems are reflective while others are not. In real life, this may depend on the function of the room and its occupancy.

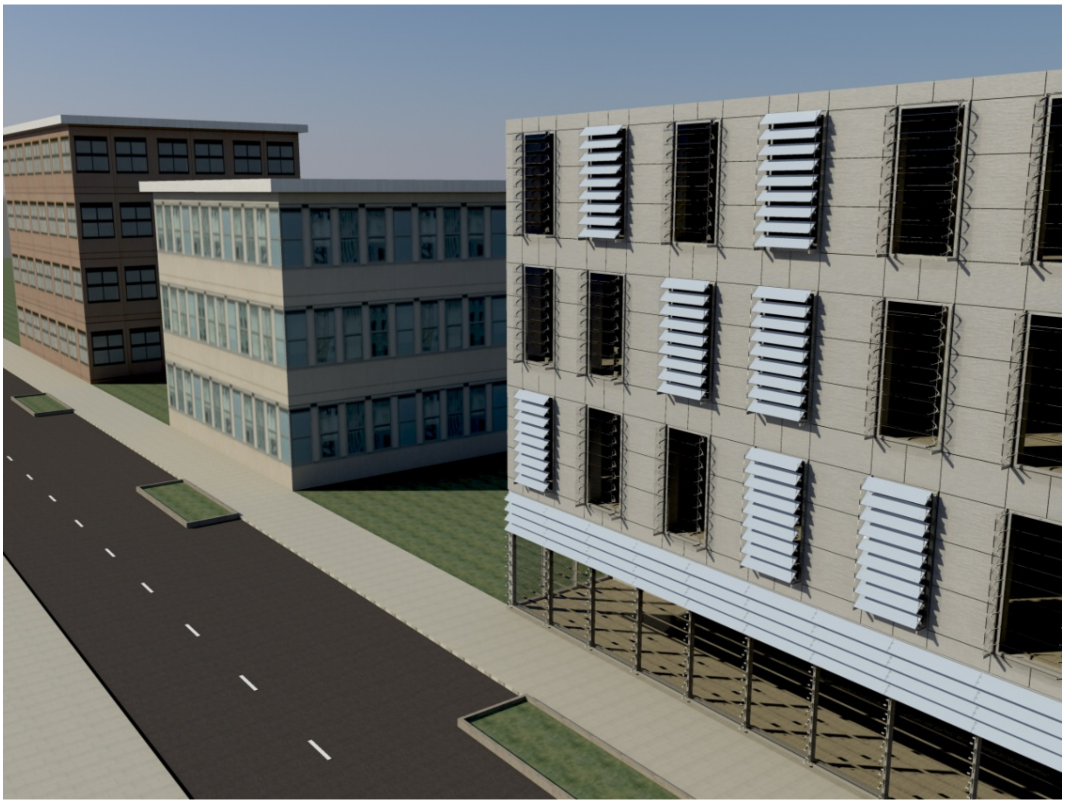


Figure 92: Overview of the glass louvres, on some of which the PolyArch coating is reflective, and on others transmissive (own image).

Figure 93: Overview of the glass louvres, on some of which the PolyArch coating is reflective, and on others transmissive (own image).

5. Conclusions

5.1 Conclusion: coating assessment

In this chapter, an answer will be given to the research question and its sub questions. This question, which can also be found in the first chapter, is defined as follows:

What is the energetic and architectural potential of the PolyArch coating in various heat-related applications, compared to competitive shading techniques?

To answer this question, several sub-questions are formulated here:

- What are suitable applications to use the PolyArch coating?
- What would be an adequate program to calculate the efficiency of the coating with?
- How would the coating be applied, considering the maximum bandwidth of the spectral reflectivity?
- What would a facade that uses this coating look like? (are there any implications that architects should take into account?)

Firstly the architectural part of the coating's potential will be reviewed, combined with remarks on the coating application in a more technical way. After this the building physical review is presented, in which the energetic potential is discussed. In both cases a comparison will be made between the PolyArch coating and competitive shading methods.

A conclusion that does not belong to any of the abovementioned categories is the fact that this graduation research has resulted in the generation of an Excel file which allows for fairly elaborate approximations of coating combinations, extensions of bandwidths and configurations of the reflected bandwidths. This file cannot be described entirely in this report, because the vast amount of data and the references in the used formulas would be unintelligible, but it is available for use for further research. It needs to be supported by test measurements however to gain reliability.

5.1.1 Architectural evaluation

From a practical point of view, the coating has a large potential especially in architecture with sloped or curved facades. In this type of geometries, conventional shading devices such as venetian blinds face difficulties or even impossibilities. When opening and closing a shading device can be controlled by turning a coating on and off, either on a fixed transparent shade or directly on glass, these mechanical problems can be avoided. The same goes for application on high rise buildings, where avoiding mechanical problems with conventional shading devices requires more costly solutions than in low rise buildings.

For good functionality, the glass on which the coating is applied must remain as clean as possible, in order to not compromise the transparency of the shading device when the coating is not reflecting. This is necessary to ensure optimal transmission of solar energy when this is desirable due to a low indoor temperature.

Aesthetically, the angular dependence of the coating must be considered, because an increasing angle of incidence results into a change in reflected wavelengths. Since the blue shift of the coating is approximately 15nm per ten degrees increase in angle of incidence, the total blue shift is roughly

120nm. That means a shift from dark red to orange, or from orange via yellow and green to blue. This is a considerable change of colour, which may be utilised by architects as an aesthetic instrument, but can also lead to undesired change of the perception of the design. To avoid this, a continuous reflection bandwidth from 380 to 880 nm has to be ensured.

It is recommended to continue in the NIR part of the spectrum with a reflection bandwidth similar to that used in the visible light part, since a bandwidth of 500nm enables covering the large peaks in the solar spectrum without unnecessarily covering drops in this spectrum. For optimal configuration of the coatings, the start of each coating layer should be at respectively 380, 880, 1300 and 1950 nm. This creates an overlap at the largest peak in NIR light, which ensures full reflection of this energy if necessary. One must keep in mind that each of these layers should consist of one coating that reflects left handed light, and one coating which reflects right handed light. It is not recommended to use a half lambda retarder in order to be able to use two right handed reflection filters, since the reflection graph is compromised drastically when the angle of incidence increases.

In this research, only one possible application has been investigated. However, there are at least three other applications with a high potential, which deserve attention: application directly on glass (reflecting in either or both the visible and NIR light), application on ETFE cushions and application on light weight constructions to control their up-heating, thus compensate for their lack of thermal mass. Other possible applications which now seem to be less likely to render large effects, but may be suitable for certain specific fields of application, or perhaps after more elaborate investigation turn out to be more successful than anticipated, have been listed in the table of applications, which can be found in Appendix F. This table includes a short review of the potential of each application, considering its energetic and economical potential, presented in a grading system which is supported by a written explanation.

It is necessary to look at the other high potential applications as well in order to draw a more general conclusion about both the architectural and energetic potential of the coating, since this report presents results for only one application. It shows that in this field, the potential is indeed high, but investigation of other applications may either support this conclusion and make it more reliable, or prove it wrong for other applications and make it of less potential, generally speaking.

5.1.2 Energetic evaluation

The PolyArch coating is a very good reflector, leading to relatively good results with regard to the cooling energy demand. However, it's performance when applied on glass louvres is also influenced by the low light transmission of the 2x6mm glass louvres, a thickness that is needed for safety reasons. This leaves room for improvement, because the heating energy demand can be reduced when the light transmission in winter can be improved. One way to do this that might be efficient is to tilt the glass louvres to a horizontal position once every year, at the beginning of the cooling season.

The 60% case and 250nm case show that when compared to the 100% case, the results are still fairly good, especially for the 60% case. This means that not the entire solar spectrum needs to be covered to achieve good results. This is partly because the solar energy per nanometre is concentrated around the visible light, and decreased towards the far infrared. Therefore the last part of the solar spectrum has little influence on the total transmitted energy. Another important factor is the fact that a low e coating is necessary to reach an acceptable U-value of the glass, because this cannot be achieved with noble gasses in the glass cavity alone. The most ideal low e coating reflects the far infrared and transmits all visible and NIR light, because these last two areas are the areas where the PolyArch coating has its influence. Therefore, a heat mirror needs to be combined with the PolyArch coating instead of a solar control glass, because the latter would compromise the efficiency of the PolyArch coating.

Another important conclusion is the fact that the lighting energy may be a field where the PolyArch coating could have an advantage over conventional venetian blinds. This is however not inherent to its use on glass louvres, but originates from its possibility to reflect spectrally selectively and the possibility to reflect single handed (although no evidence for the latter conclusion is presented in this report, since this opportunity has not been investigated). This may reduce the energy demand for lighting, and although the influence of lighting energy is in general less dramatic than in the simulated cases, it usually still is around 20% of the energy demand of a conventional office.

Finally, with regard to the triggers, it must be remarked that all simulations that are performed with a PolyArch coating presume it to work with an electrical trigger. This is because the reflectivity is controlled by the indoor temperature, rather than any condition that is directly connected to the louvres, which makes a sensor based control system necessary. Also for using adaptive temperature limits, an electrical control system is required.

The efficiency of a system that is controlled by the indoor temperature is, according to the literature, the most effective, but this has not been tested in the simulations. It would require a different simulation model to find whether blocking radiation based on the amount of incident radiation would be able to control the indoor climate well enough both preventing overheating in summer and preventing reflecting desired heat in winter. Especially the latter seems unlikely because the coating cannot distinguish by itself whether the heat is desired or not, although the glass temperature may give some feedback about the season. Also, since overheating occurs in winter as well, there may be a maximum allowable solar transmission above which sunlight needs to be reflected at all cases, since the solar heat has a major impact on the incoming part of the energy balance. How it works below that maximum remains uncertain until simulations on this topic have been performed.

Since the influence of the response time has not been measured because this would demand too much from the simulation (because of the small time step, which would lead to very long simulations), it is not possible to determine whether any of the triggers should be favoured, but because all triggers respond fairly quickly (within minutes) none should face problems with this, since quickly switching between reflective and transmitting state will most likely cause discomfort.

5.1.3 Simulation evaluation

The simulation of the coating's performance has been a critical element in this graduation research. There are lessons to be learned from this simulation, both positively and negatively. First of all concerning the chosen software, TRNSYS proves to be rather easy to learn and provides most of the desired features that were required for a sufficiently accurate simulation. It remains problematic however that when faced with difficulties or problems, little direct support is possible. The online forum provides some help, but cannot aid as much as an experienced tutor could. This is also partly caused by the use of predefined types, which are the only way to perform the complex calculations within the time available, but of which the functioning is not always entirely clear. By using many custom made components, this has been avoided as much as possible however.

The largest difficulty of simulating in this research has been to find the right level of detail. On the one hand, making a detailed simulation may seem not very useful, since the coating still is in development and not much is certain about its qualities. However, there are many variables that all have a certain margin of error inherent to their uncertain nature. A not very detailed approach of these variables may seem legit when they are observed individually, but when the margins of error are combined, the overall deviation may render the results unreliable. Since there is no way of telling the deviation of a less detailed simulation without first performing a detailed simulation, effort was made to make the simulation as accurate as possible, even though some variables are still subject to change in the future.

The conclusions of this report, especially those based on the simulations, need to be considered carefully however. Although great effort was put into creating a generic situation, the results of a more extreme case may provide more general information than the apparently safe situation that is prescribed in documentation.

5.2 Recommendations for coating development

Because of blue shift that is a result from the angular dependence, a large bandwidth has to be ensured, and if this is not possible, the angular dependence must be eliminated. This can be done with using the coating as a pigment with randomly orientated chiral axes, but more research into the possibilities of this kind of coating has to be done, because for example the white haze may be undesirable, either energetically, aesthetically or because of the user's comfort.

In addition, it is advisable to perform adequate measurements with the coating on architecture related products such as window glass and ETFE, instead of a half lambda retarder, to observe and measure the consequences of applying the coating on glass with a certain bandwidth. To do this, several configurations of coating layers that could be expected in architecture, such as full NIR reflection but visible light transmission, full reflection of all light, or transmission of all left handed light and reflection of all right handed light, ought to be measured. This needs to be done preferably with (near) industrial accuracy, to be able to perform more accurate simulations after obtaining data for the effect of optical coupling, combination of coating layers in general and the use of large reflection bandwidths.

For observational purposes, plastic substrates may be preferred over glass substrates because of the possibility to bend the material, which easily makes the effects of angular dependence visible. For measurements however, glass substrates are a better choice, because the material's rigidity results in more accurate results when aligning or fixating the substrate.

More research into the assessment of possible triggers has to be done, in order to find whether the higher costs of electrical triggering may be worth the effort, or are a waste of time and energy. In the current simulations, direct response was assumed for the entire time step, although dead bands were taken into account. This is not in the least due to the fact that a time step of several seconds would increase the simulation time so dramatically that either more calculation power is required or the level of detail is outweighed by the practical benefits. Another decision method needs to be developed in that case, possibly based on theoretical considerations about the performance and difficulties of triggers in other applications.

5.3 Recommendations for further research

This research has been the basis for further research, for which some recommendations will be made in this chapter. First several individual remarks on the extension of knowledge and practical aspects of the research will be made, after which the proposed continuation of the research is described.

To study the effects of colouration of the light by a blue shift on the border between visible light and NIR light on the user comfort, colour rendering may be studied. This calculation method provides more insight in the accepted deviation from white light for several building functions. The calculation method is described in the European Standard EN 410. More theoretical background can be found in “Human factors for lighting” by Peter Boyce (2003).

Furthermore, for future transmission measurements of the coating, the use of a xenon lamp is recommended to represent the solar spectrum (Gessel et al., 2005). Measurements should be done preferably with a goniophotometer, but at least with a spectrophotometer.

For more detailed information about responsive liquid crystal coatings, the work of Timothy White and Timothy Bunning at the Wright Patterson laboratory should be reviewed, since they work at the top of their field. This may provide a better understanding of the limitations and possibilities of the coating, also in fields that are not currently being researched in Eindhoven.

Then some recommendations for the direction of further research will be named here. First of all, the simulations that have been performed in the scope of this research do not include the effect of daylight optimisation. The integration of the interior light level into the simulation model should be investigated, to find the possible energy savings when not only the average ideal window area is considered, but the window area can be varied dynamically over time to match the ideal window area depending on outside conditions and geographical location.

In addition, the effects of glare and the protection against this discomforting phenomenon should be observed, since the coating may not only serve as a means to save energy but also to increase the user comfort. For daylight optimisation matters, the Intelligent Lighting Institute (ILI) in Eindhoven may be consulted, since this specialises in daylight optimisation and exploring new ways of daylight transmission control.

Furthermore, other applications can be investigated. Not much attention has yet been given to applications on the roof, nor have applications on opaque surfaces been investigated in much detail. There lies great potential in these areas however, which is why simulations and design solutions for these and other application areas, that can be found e.g. using the categorisation tree diagram presented in this research, are worth doing.

Also the architectural desires need to be explored in further detail. Some suggestions have been presented in this report, but since the beauty of architecture is at least partly subjective, a broader field has to be explored to find whether a general opinion can be subtracted from it. This can be done for example via interviews, or a survey, among current and future architects and people working in the facade industry.

Apart from the architecture, the potential of the coating has to be funded more thoroughly in at least two directions. Firstly, the financial benefits of the coating need to be mapped, in order to be able to determine the maximum costs of the coating development. To this end, the theoretical expenses for several applications have to be calculated, after which the feasibility of the coating needs to be assessed. Since this will lead to a comparison of shading with the PolyArch coating, the lifetime of the individual shading devices must taken into account as well, since in case of e.g. glass louvres the static nature of the shading device may be beneficial with respect to the maintenance costs, but the extensive use of glass may be a drawback when breaking glass becomes a significant issue.

Secondly, the energetic performance of the shading device must be calculated more thoroughly, since the reason for developing the PolyArch coating is not only based on financial motives, but also originates from the desire to reduce energy consumption (which is still often coming from fossil fuel) to create a better environment. To give a realistic prediction about the total energy costs, also material costs such as embodied energy need to be taken into account.

Finally, the validation of the simulation model needs to be conducted more thoroughly. Although the greatest possible care was taken to ensure the absence of flaws in the model, concise scientific validation could not be performed yet. After all, simulation software is a representation of reality, which means that assumptions are made, and it must be verified that these abstractions do not divert the results to much from realism. Judkoff describes three possible validation techniques, each with their respective benefits and drawbacks: software-comparisons, analytical study of the model and empirical comparison (Judkoff, 1988). The last method has been attempted to implement, but due to insufficient test methods this failed to provide reliable data.

Analytical validation is only useful for simple problems in which the correct outcome is known in advance, so this kind of validation is not applicable to the detailed and unpredictable problem that is described in this report. Nevertheless, a small manual calculation is presented that gives an indication about the correctness of the outcome of the cooling energy calculation for one simulated case, but this is not a full validation of the model. Computer simulations in several programs have as a great advantage over the other two that they are relatively easily executed. Despite their ease of execution it was not possible to create multiple simulation models in different programs, due to the difficulty of finding suitable programs and other considerations that have been described more detailed in the simulation software chapter.

Moreover, with validation through computer simulations there is no way to determine which computer program performs the best calculation, it can only increase the likeliness of accurate results by reaching similar results via different programs. It does not provide a true standard which indicates the validity of the simulation, but merely a possibility to determine whether the simulation performs within acceptable deviation from other programs. What is acceptable is arbitrary however, since one deviating program from three other programs with similar results does not necessarily mean that the one different program gives the least trustworthy results, since this program might have certain features which are not present in the other software programs, which make it more suitable for the desired calculation than the others. A thorough understanding of the functioning of all used software tools is therefore required.

Empirical analysis does provide a truth standard however, albeit only up to a certain degree, since inaccuracies in the measurements may result into inaccuracy in the obtained data as well. In addition do empirical analyses usually cost a lot of money, which is why they are not standard procedure.

With regard to the simulations, there are a few things that are very important to investigate. Firstly, the standard office that is used for the simulations in this research appears to be a rather safe situation. More extreme cases with more glass, different floor areas or with a different orientation (west facades for example are more difficult to shade adequately) may present a more realistic ratio between heating/cooling energy and lighting energy.

Secondly, the horizontal position of the louvres in winter seems to work efficiently for the reduction of heating energy demand, but simultaneously increases the cooling demand in winter due to the decreased shading efficiency. It would be interesting to see whether there is an optimum for this inclination of the louvres in winter, to find out what the minimum sum of heating and cooling energy is in winter.

Architecturally, it would also be interesting to see if there are other methods in which the louvres' light transmission in winter could be improved effectively, but with a simple measurement that does not require an engine based operating device. Two methods (thinner glass and tilting the louvres semi-permanently) have been presented in this report, but other methods may be present.

6. Literature

6.1 List of literature

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Appendix

A. Sample testing

This chapter describes the measurements of the coating samples in a more elaborate way than was needed in the report. Since the tests did not render quantitative results, the most valuable part of this description is the documentation of the followed procedure, since the motivation for performing certain tests can provide extra information for following tests, as can the method of testing.

A.1 Motivation for testing

In our simulations we preferred to take the angular selectivity into account, as we were well aware of the large influence this has on the reflectivity. However, the data we were provided with only offered transmission values until an angle of incidence of 65 degrees. For the following angles up to 90 degrees, there was no data available. This made it not possible to calculate the diffuse reflection, nor to simulate the correct reflection values for each angle of incidence, without making rough estimations based on not much more than gut feeling.

The lack of scientific approach in this estimation encouraged us to find our data in a different way, which is why we inquired for a number of samples which we could test ourselves. This way we could complete the data we received, and at the same time validate our measurements with those data. We also asked for some specific samples for visual analysis.

A.2 Sample description

The samples we asked for were all of the size 5x5 cm. The bandwidths we were interested in exceeded the standard 75nm in most cases, which is why some samples had to be subdivided into a number of stacked sequential layers. We did not receive all the samples we asked for, mostly because the time the research group in Eindhoven had for the preparation of the samples was limited; those we did not receive are marked with an (*):

- A sample with a reflection peak at 555nm, reflecting both left and right handed light, with a glass substrate. Since the highest sensitivity of the eye is at 555nm, we liked to see a sample reflecting in this part of the spectrum because we reckoned the angular dependency would be best visible in this area. With this sample we can also do our measurements for transmission values to complete the data we received from the research group in Eindhoven.
- (*) A sample with a reflection peak at 555nm, reflecting both left and right handed light, with a plastic substrate. The purpose of this sample would be to compare the properties of the coating on glass to that of a coated plastic. The reason for this is the interest in the application of the coating on ETFE.
- A sample that reflects the NIR light, starting its reflection at 780, so directly at the division between visible light and NIR. The coating reflects both left and right handed light and has a bandwidth of at least 200nm. The purpose of the coating is to observe and measure the influence of the reflection wavelength shift to shorter wavelength, to see whether the reflection of the longest wavelengths in the visible light will result into an uncomfortably coloured light transmission or not. The sample we received however started reflecting at 880nm instead of 780, which made measurements of the reflected red light irrelevant. Also, the reflected bandwidth was only 150nm (two layers), while the shift in wavelengths occurs

over at least 100nm but the decreased transmission may even be observed over 200nm, so the full effect could not be seen. This influence is small however, because the wavelengths that will now be transmitted after all are hardly visible.

- (*) A sample reflecting the whole visible light, so from 380nm to 780nm, either left or right handed. This sample was originally intended to do our measurements with, because in real applications for thermal energy transmission control the coating will most likely not be applied to reflect single colours but the visible light, in order to have the transmitted light remain white. Now we need to make assumptions for our simulation. In addition, we were interested in whether the stacking of layers had any visible consequences.
- Finally we asked for a sample in which the coating was applied without chirality. This represents the coating when it is turned off, so with full transparency.

A.3 Test method

The abovementioned sample which blocks the whole visible light was preferred to measure the transmission through the coating. This would also give us an idea about the performance in the NIR light, since a coating that is good enough to cover the whole NIR part of the spectrum is currently not realistic. This was not possible however, so we measured with the sample which has the peak of its reflection at 555nm.

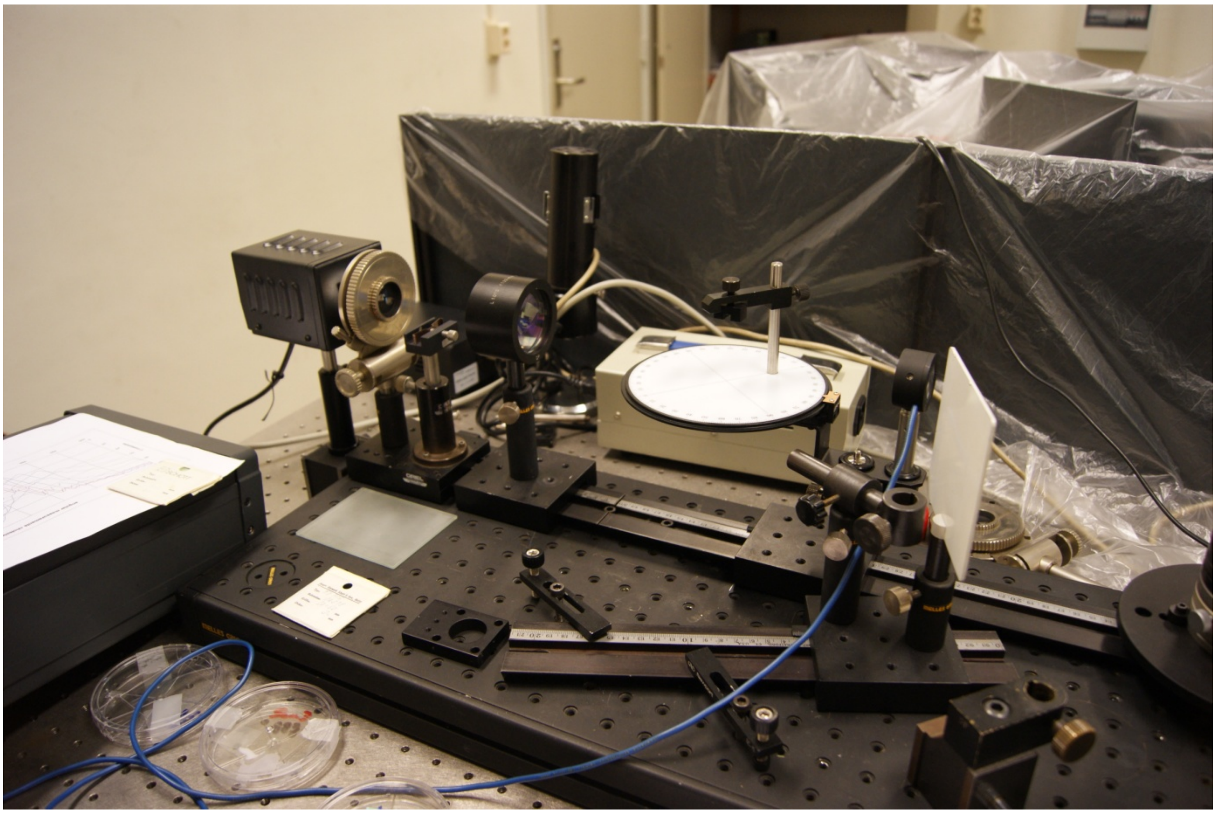


Figure 94: Test arrangement for angular dependent spectral transmission tests. From left to right connected to the rail: the halogen light source, the diaphragm, a holder for the spectral filter, a collimator, the protractor with the sample holder and finally the sensor which is connected via the blue wire to the photometer (photo by Guido Lammerink).

The goal of the measurements was to complete the angular dependent spectral data which we already had, so we preferred to use goniophotometer, which is a spectrophotometer that can measure at different angles. Since this device was not available in Delft, we wanted to use a spectrophotometer, but this also turned out to be not possible. Therefore we worked with a slightly less accurate method to approximate the transmission values at different wavelengths, using a photometer.

This device measures the intensity of the light that irradiates the connected sensor. It assumes however that all the irradiating light has the same wavelength, and corrects the light for that wavelength. Therefore it has to be readjusted for each specific wavelength we wanted to measure. The light source we could use was a normal halogen light, to which we added a spectral filter. By means of this filter we were able to somewhat regulate the wavelengths we used. This does affect the accuracy of course, because the filter transmits at least a bandwidth of approximately 25 to 30 nanometres. These bandwidths can vary slightly from filter to filter, and also obviously have a peak and not a perfectly perpendicular reflection graph.

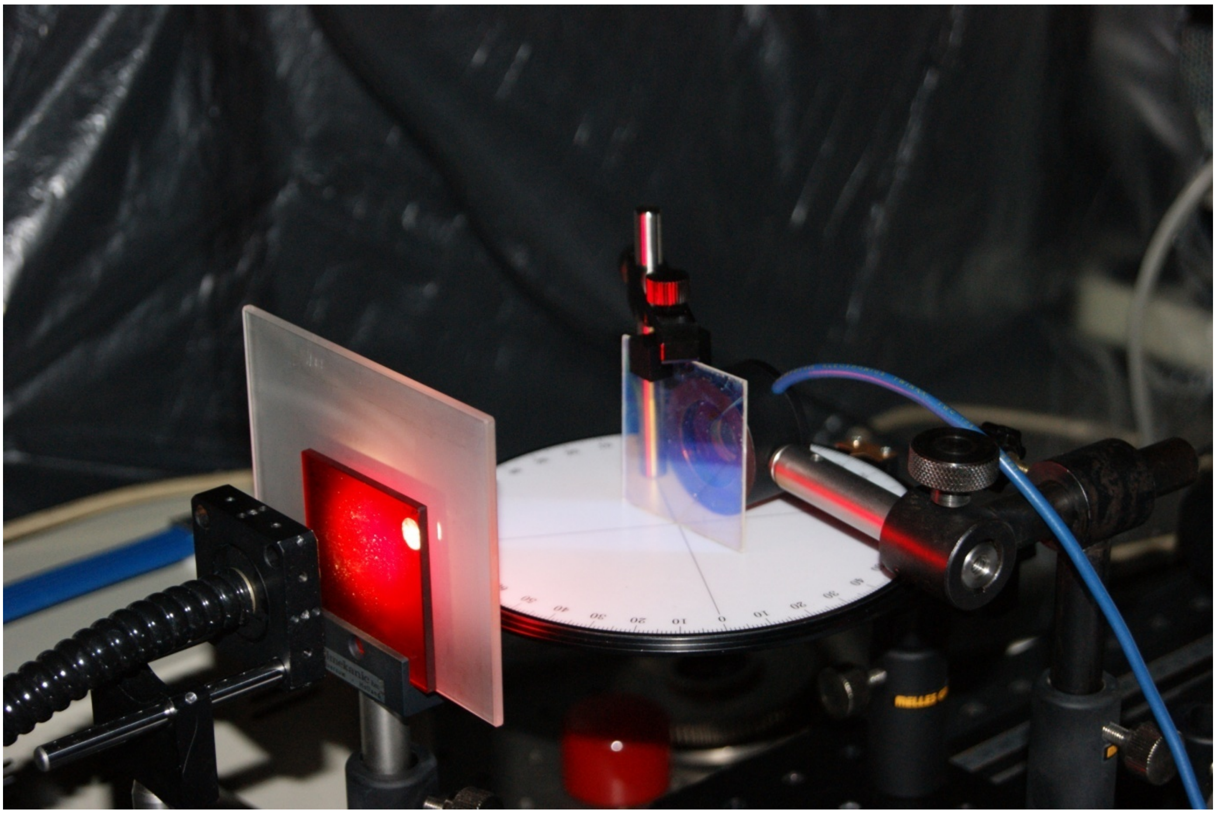


Figure 95: For the diffuse light measurements, the arrangements was modified: the collimator and diaphragm were not needed anymore, the light source could be replaced by a more powerful, but less collimated light source, a translucent glass pane was placed between the filter and the sample and the sensor was placed directly behind the sample to reduce the influence of reflected light (photo by Guido Lammerink).

By rotating the sample we were able to control the angle of incidence, which we measured using a protractor. Before each measurement series we had to take into account the ambient light, by calibrating the photometer to a 'zero'-value for the light level in that situation. Since the output values of the photometer are always relative values, we measured the transmission of the system without the sample in it as the 100% transmission value, to compare the values of the sample with that value to find the relative transmission. For each angle we did two measurements, to decrease the chance of measuring errors. By changing the filters for the light between 410nm and 720 nm we intended to approach the spectral graph we already had, to be able to make an estimation for the in-between values.

The diaphragm was used to control the amount of light coming from the light source, to make sure that at all cases all the light would reach the sensor, even when it was deflected by the rotation of the sample. This would ensure comparability of the light intensities. However, because the sensor is circular and the light beam approximately square, there may still have been a slight error here when the projected beam was shifted due to refraction in the rotated sample. For the same reason a collimator was used after the filter, which combines three lenses to create a parallel light beam towards the sample and the sensor.

To be able to compare our calculated values for diffuse light transmission to measured results, in order to validate them, we repeated the measurements I described above, but with a translucent glass pane between the sample and the filter and without rotating the sample. Again a measurement was done without the sample to define the comparison value, and one with the sample to find the transmission at a certain wavelength.

Additionally, we used the diffraction grating to visualise the effect of rotation on the transmitted wavelength. This device is a jagged mirror with 1200 lines per millimetre, because of which it separates the wavelengths in its reflection. The reflection can therefore show a shift in transmitted wavelengths. For both the sample with a reflection peak at 555nm and the one with a peak at 880nm we performed this test, which is only qualitative, so with observations instead of measurements.

A.4 Test results and conclusions

It must be remarked that a low light value automatically means that the influence of measuring errors – as a result of errors in the arrangement of measuring devices, personal mistakes or inaccuracy of the equipment – will increase. In general, a minimum of 10 µm is required to let the results have significance.

In addition, it proved to be impossible with the equipment we had to obtain reliable results for angles above 75 degrees, because from that rotation angle the sides of the sample started to project a shadow on the sensor, disturbing the results. This could be solved by measuring with a (much) wider sample.

Directed light																
Degrees / Filter	410nm (K1)		450nm		480nm (K3)		480nm (K3)*		550nm (K4)		600nm (K5)		630nm		720nm (K7)	
Calibration (without sample)	4,8	-	2,2		13,7	-	32,9	-	83,9	-	143,8	-	282,1	-	60,3	-
0	2,9	2,9	1,9	1,9	9,1	9,2	26,0	26,1	67,9	68,1	125,3	125,3	257,4	257,4	53,0	53,0
10	2,9	2,9	1,9	1,9	8,8	8,8	25,7	25,7	68,3	68,2	125,2	125,2	257,0	257,0	52,8	52,8
20	2,9	2,9	1,9	1,9	8,3	8,3	25,2	25,2	69,4	69,3	125,4	125,4	256,7	256,7	52,8	52,8
30	2,9	2,9	1,9	1,9	8,0	8,0	24,9	24,9	70,8	70,8	125,2	125,3	255,8	255,9	52,5	52,5
40	2,8	2,8	1,8	1,8	8,4	8,4	25,4	25,4	71,5	71,6	124,3	124,3	253,9	253,9	52,0	52,0
50	2,7	2,7	1,7	1,7	9,3	9,4	25,9	25,9	70,5	70,5	121,4	121,4	249,0	249,0	50,8	50,7
60	2,4	2,4	1,6	1,6	9,6	9,6	24,8	24,8	66,4	66,4	114,3	114,2	236,2	236,2	47,7	47,7
70	1,7	1,7	1,4	1,4	8,4	8,4	20,4	20,4	56,2	56,1	96,4	96,3	202,2	201,7	40,1	40,1
75	1,2	1,2	1,2	1,2	7,0	7,1	16,1	16,0	46,1	45,9	79,7	79,6	167,0	166,8	33,1	33,1

* Second filter

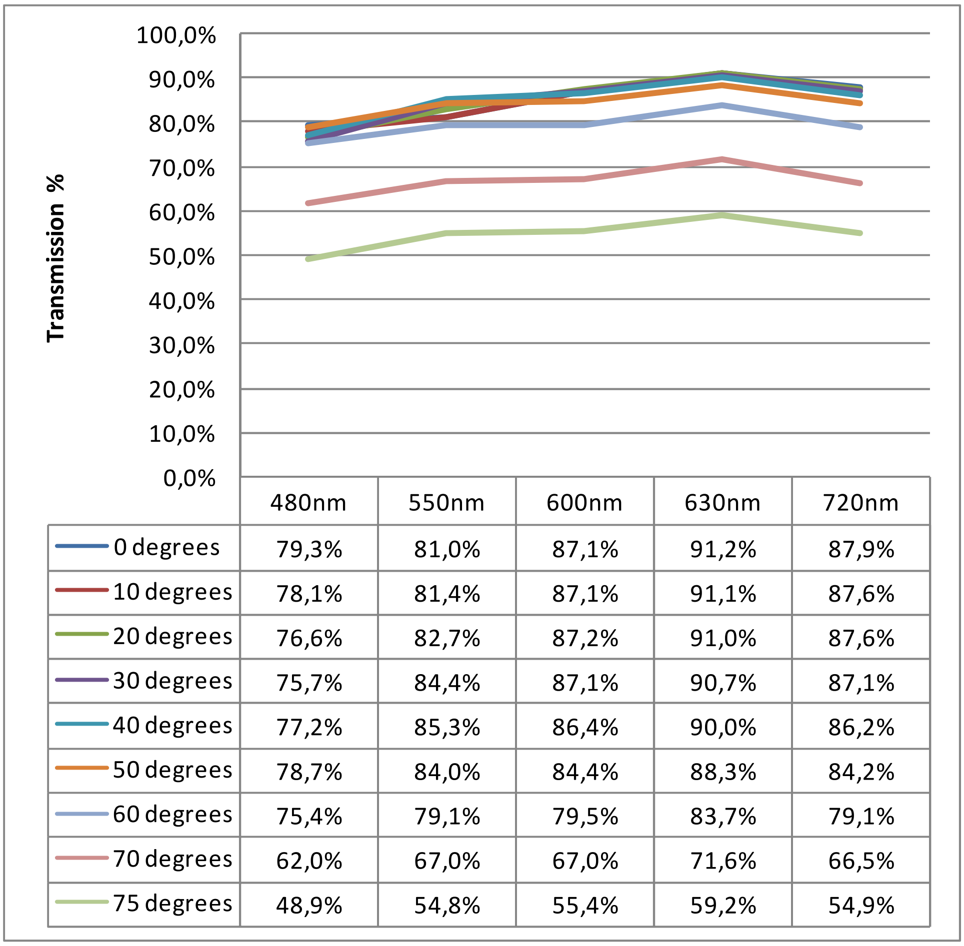
Figure 96: The light intensities at different angles of incidence, with different light filters. The first three colums show values below 10µm, which are not reliable due to their low overall light level (own image).

Finally, the results from the diffuse measurement show such a large variation that they cannot be assumed reliable. This is probably due to the impossibility to rule out the effects of reflection from surrounding objects, after the diffusing translucent plate spread the light. Although placing the sensor as close to the sample will have reduced this effect, it cannot be excluded without another separation between the sensor and the environment.

Interpreted results																	
Degrees	Filter	410nm (K1)		450nm		480nm (K3)		480nm (K3)*		550nm (K4)		600nm (K5)		630nm		720nm (K7)	
		Average intens.	Relative transm.	Average intens.	Relative transm.	Average intens.	Relative transm.	Average intens.	Relative transm.	Average intens.	Relative transm.	Average intens.	Relative transm.	Average intens.	Relative transm.	Average intens.	Relative transm.
0		2,9	60,4%	1,9	86,4%	9,2	67,2%	26,1	79,3%	68	81,0%	125,3	87,1%	257,4	91,2%	53	87,9%
10		2,9	60,4%	1,9	86,4%	8,8	64,2%	25,7	78,1%	68,3	81,4%	125,2	87,1%	257	91,1%	52,8	87,6%
20		2,9	60,4%	1,9	86,4%	8,3	60,6%	25,2	76,6%	69,4	82,7%	125,4	87,2%	256,7	91,0%	52,8	87,6%
30		2,9	60,4%	1,9	86,4%	8	58,4%	24,9	75,7%	70,8	84,4%	125,3	87,1%	255,9	90,7%	52,5	87,1%
40		2,8	58,3%	1,8	81,8%	8,4	61,3%	25,4	77,2%	71,6	85,3%	124,3	86,4%	253,9	90,0%	52	86,2%
50		2,7	56,3%	1,7	77,3%	9,4	68,6%	25,9	78,7%	70,5	84,0%	121,4	84,4%	249	88,3%	50,8	84,2%
60		2,4	50,0%	1,6	72,7%	9,6	70,1%	24,8	75,4%	66,4	79,1%	114,3	79,5%	236,2	83,7%	47,7	79,1%
70		1,7	35,4%	1,4	63,6%	8,4	61,3%	20,4	62,0%	56,2	67,0%	96,4	67,0%	202	71,6%	40,1	66,5%
75		1,2	25,0%	1,2	54,5%	7,1	51,8%	16,1	48,9%	46	54,8%	79,7	55,4%	166,9	59,2%	33,1	54,9%

* Second filter

Figure 97: Interpreted results of the tests. For each spectral filter the left column shows the average value of the two measurements, while the right column shows the ratio of this number to the calibration test value (own image).



	480nm	550nm	600nm	630nm	720nm
0 degrees	79,3%	81,0%	87,1%	91,2%	87,9%
10 degrees	78,1%	81,4%	87,1%	91,1%	87,6%
20 degrees	76,6%	82,7%	87,2%	91,0%	87,6%
30 degrees	75,7%	84,4%	87,1%	90,7%	87,1%
40 degrees	77,2%	85,3%	86,4%	90,0%	86,2%
50 degrees	78,7%	84,0%	84,4%	88,3%	84,2%
60 degrees	75,4%	79,1%	79,5%	83,7%	79,1%
70 degrees	62,0%	67,0%	67,0%	71,6%	66,5%
75 degrees	48,9%	54,8%	55,4%	59,2%	54,9%

Figure 98: A graph showing the transmission values for the reliable test values. These results do not at all approach the values that are shown in the data we already had. This renders the data obtained in these measurements unreliable (own image).

There are a few conclusions to be drawn from these results. Firstly, the light levels through the two filters for the smallest wavelengths show too small overall intensities to be reliable, which is why they have been eliminated from the results for the final graph. In addition, there is one filter for wavelengths around 480nm which shows the same deficiency, but since we had two of these filters and the other one showed better results, we were able to include this wavelength in our conclusions.

However, the results from the tests do not approach the values that were already known from earlier tests. There is no appreciable peak in the graph, nor does the transmission first decrease and then increase varying over the angle of incidence. Therefore, the transmission values for 70 and 75 degrees cannot be transferred to the known data from the other graph. Whether this is due to the quality of the samples, the quality of the testing facilities, the quality of the performed tests or another variable that has not been accounted for remains to be investigated.

Diffuse light															
Test	Filter	410nm (K1)		480nm (K3)*		550nm (K4)		600nm (K5)		630nm		720nm (K7)		Vis. Light	
Calibration (without sample)		26	27	123	123	184	192	234	245	507	524	192	200	828	832
Normal diffuse		24		63		78,3		200	203	469		190	197	660	664

* Second filter

Figure 99: The measurements for diffuse light show a large variation in the measured values, which kept changing during the measurement. The documented values are the upper and lower limit of this fluctuation. Because of the large change, the results lose their reliability (own image).

The diffuse tests show even larger variation in the results, unsurprisingly considering the reflection possibilities that were not prevented in the testing arrangement we used. For this reason, they will not form reliable validation for calculations of diffuse light. There were results however that were valuable, albeit not quantitatively but qualitatively.

These are observations from the diffraction grating, which displays all the transmitted visible light wavelengths next to each other. This clearly shows that at normal incidence, the green light is reflected, but when the sample is rotated, the reflection moves to the smaller wavelengths. A similar test was conducted for the infrared sample (880nm) to see whether it would start to reflect red light at a certain angle of incidence, but although there was a reduction in intensity observable for the red light, the same was true for the green and blue light. If there was a difference in the change of intensity between these colours, it was too small to perceive.

There were also some observations possible from the received coatings without using any testing facilities. Firstly, the coating that reflects NIR shows that a margin of 100nm is sufficient to prevent discomforting light colouring caused by the shift in reflected wavelengths. Obviously, this is just a preliminary assumption, because the observed sample was rather small, not perfectly produced and most importantly, not measured. Testing of a good sample will provide more insight in this, as it allows to calculate the colour rendering index.

Secondly, the substrate on which the coating was applied without chirality proved that, unsurprisingly, the coating is indeed invisible without chiral doping. Of course there is no reflection without a rotated axis, but there are also no unexpected side effects caused by the inclusion of polymers on the substrate.

Finally, a general observation can be made regarding the substrate material. For observing angular dependence, plastic substrates are found more convenient than glass substrates, as they can be bent and in that sense show all expectable angles of a facade in one glance. For measurements on the other hand, glass substrates prove to be more stable in the sample holder and are more useful for this purpose.

Figure 100: The diffraction grating reflects the transmitted wavelengths apart from each other. This shows that at normal incidence, there is hardly any transmission of green light, but as the angle of incidence increases, the reflection shifts to the smaller wavelengths (own image).

B. Model description

This chapter contains a description of all components that are used in the simulation. It describes the relevant settings and connections, and if necessary shows the setup of the component visually. The order of description roughly follows the simulation steps, but since there are many interconnections and loops, this is not always possible.

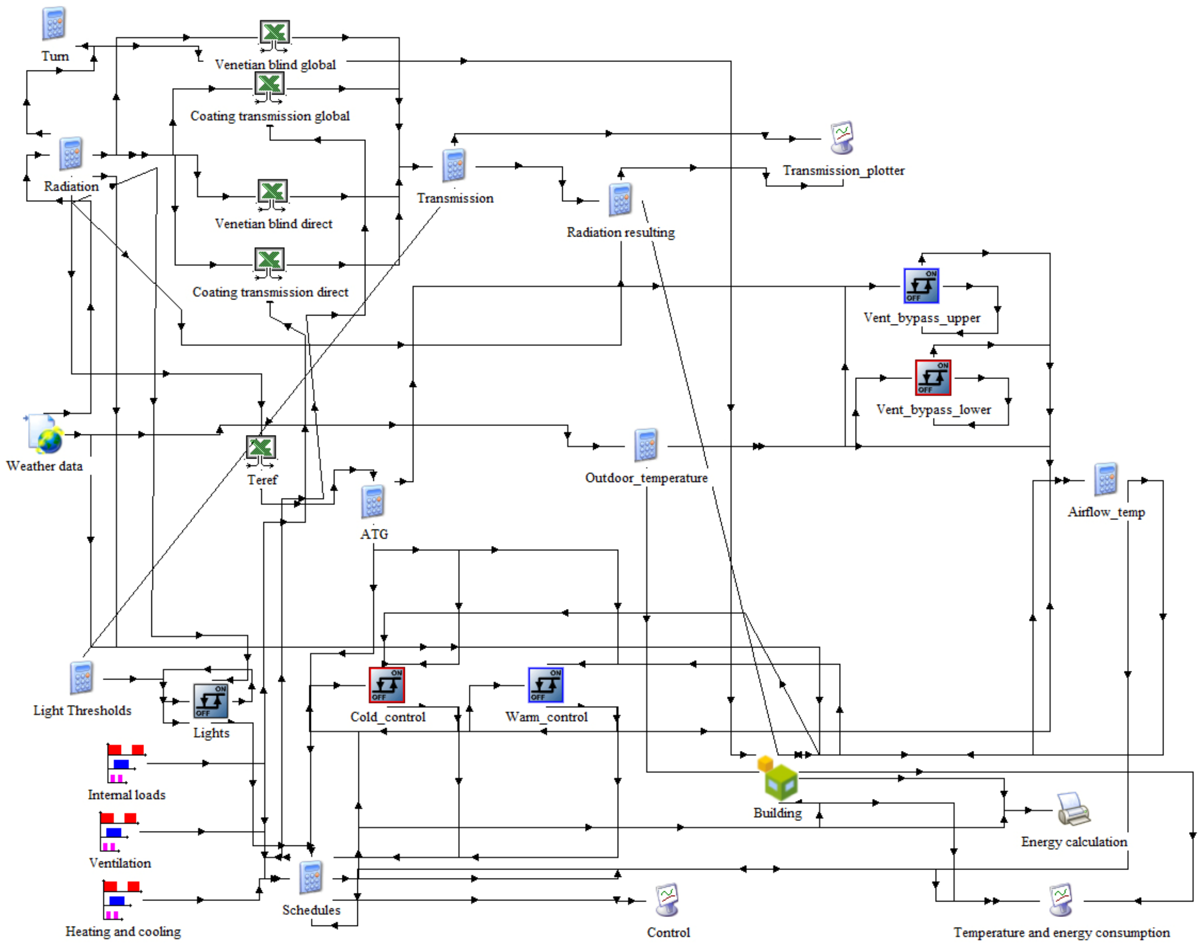


Figure 101: Setup of the simulation model in TRNSYS. It is ordered from left to right, with in the top the Excel files representing the shading device, leading to transmission equations. On the bottom left the schedules for occupation and climate control are ordered, and in the middle the ATG calculation leading to the controls for both the shading and the climate control can be seen. The green icon represents the Multizone building component, in which the energy and temperature calculations are performed, and on the very right the output components can be seen (own image).

B.1 Weather file

The weather data that were used were correct for Amsterdam, and were imported from the EPW weather file database. All relevant weather data like the ambient dry bulb temperature, solar azimuth, zenith and radiation were extracted from this file. The EPW weather file is specifically made for EnergyPlus simulations, and derived from TMY-2 weather files. TMY stands for typical meteorological year, since it contains parts from different years to compile a reference year that contains all kinds of weather, while keeping the average values intact. This is because some years may be hotter than average while others are colder, which would influence the results. However, taking an average of many years (which is what happens with databases such as Meteonorm) makes it difficult to assess the performance of the simulated aspect at a specific extreme situation, since these are flattened out in average years. The difference between these two types (EPW and Meteonorm) is shown in the images below.

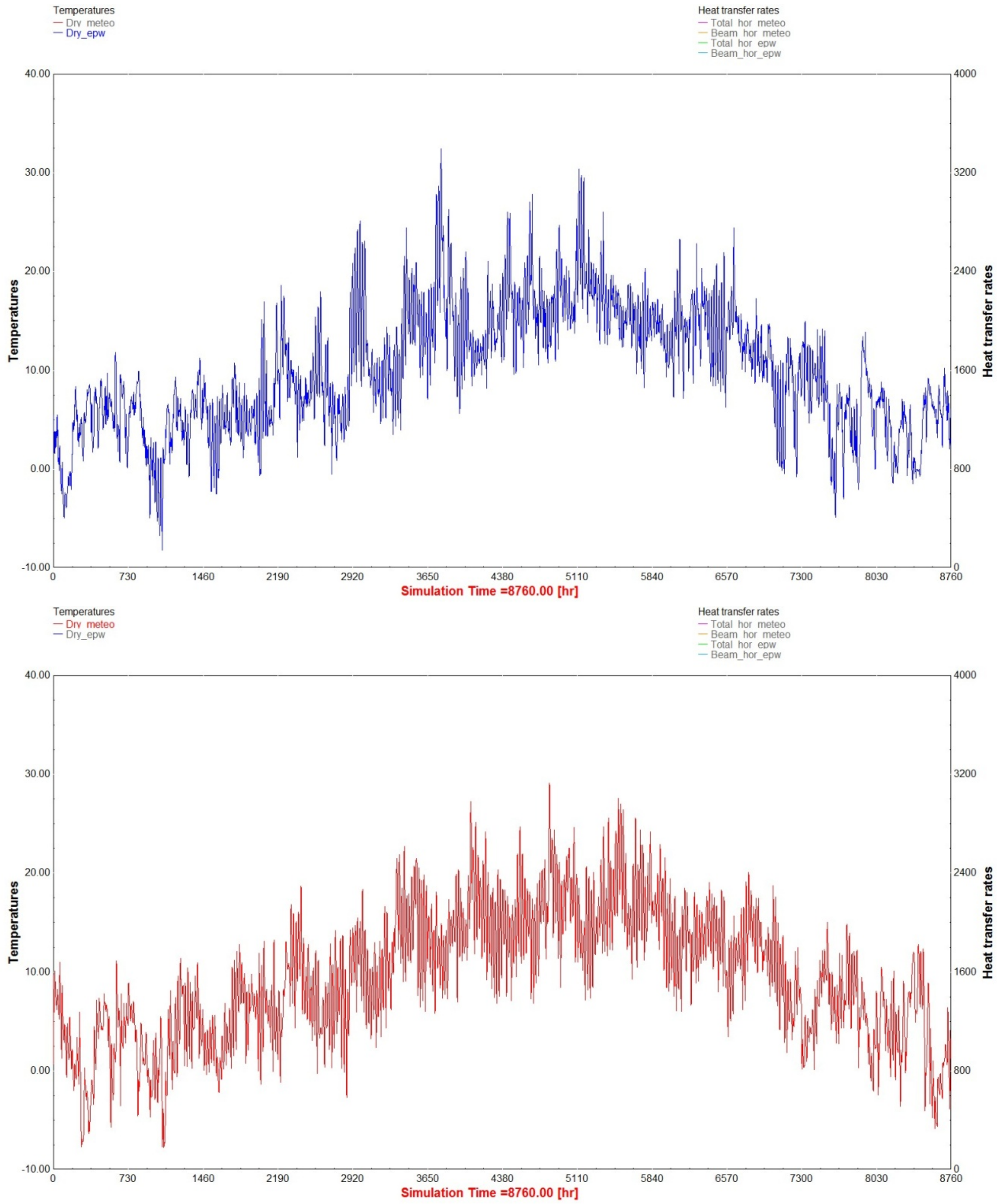


Figure 102: Outdoor annual air temperatures (dry bulb) according to the EPW datafile (top) and the Meteonormdatafile (bottom). The temperatures can be found on the left y-axis, which ranges from -10 to 40 degrees Celsius. In winter, the differences are not that big, but in summer, there are more extreme temperatures. In general, the temperature fluctuations are much larger in the EPW file (own image).

The chosen representation of the sky's brightness is the Perez model, which is commonly regarded to be the most suitable sky model for this kind of calculations (Kuhn et al., 2001). The alternative isotropic sky model would, in contrast to reality, assume a sky which at a clear day is less bright than it should be. The solar load values are more conservative than in the Perez model, because of which the heating loads are higher, the cooling loads lower and the effectiveness of shades lower (Bradley, 2007).

B.2 Radiation equation

The relevant data from the weather file are collected in the Radiation equation, which serves to avoid an unnecessarily large amount of connections between components. It combined the weather data with two other equations. The first one is the standard conversion of the integrated parameter TIME to the hour of the day, the other one calculates the fraction of diffuse radiation. To calculate the latter, the total diffuse radiation is divided by the total global radiation.

This file also contains a couple of equations related to time, which have the hour of the year or the day of the year as an output. These are used in most Excel lookup tables to determine the correct outside temperature or whether the coating should be reflective or transmissive.

The angle of incidence is not taken from the Weather data, but calculated manually and input as an equation. The azimuth (-90 = east, 0 = south, 90 = west) and zenith (vertical = 0, horizontal = 90) are taken from the weather file, and converted to the angle of incidence on a south facing surface, using the following formula:

$$Angle\ of\ incidence = \cos^{-1}(\sin(azimuth + 90) \cdot \cos(90 - zenith))$$

This results in the following output, showing an angle of incidence when the sun is behind the south facade (at these points the angle of incidence is not used) and apart from that a varying angle of incidence over the year based on the zenith and azimuth.

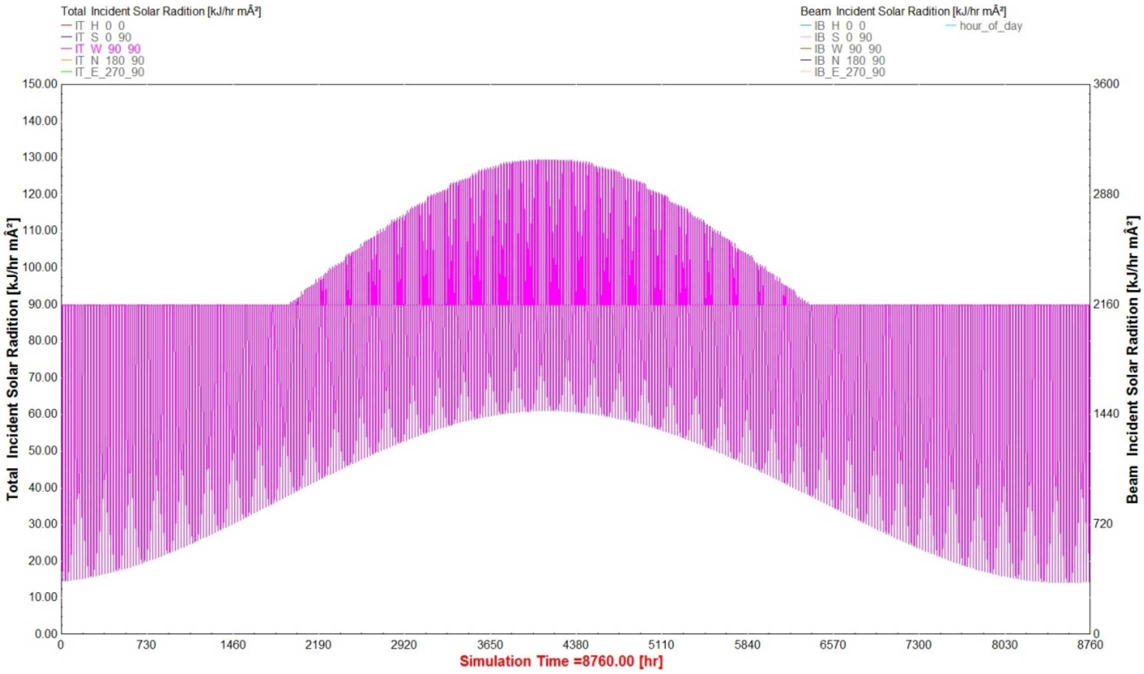


Figure 103: Annual representation of the angle of incidence as calculated by the formula given in this paragraph. It shows the angle of incidence increases in summer (see left y-axis for degrees), and also that in summer the sun rises behind the south facade, leading to an angle of incidence above 90 degrees (own image).

B.3 Excel lookup tables

Four Microsoft Excel lookup tables were used to calculate the transmission of direct and global radiation. For both the direct and the global radiation a combination was made of a lookup table with corresponding transmission data for the coating and one for the venetian blind. The coating transmission was used to correct the reflection of the opaque part of a regular venetian blind, but this will be discussed in more detail at the “Transmission equation” paragraph.

In general, the lookup tables handle up to 6 input variables, which influence the output by using the VLOOKUP function. The output is used again in the TRNSYS environment.

Venetian blind global

To calculate the angular dependent transmission values of a venetian blind, the WINDOW 7.1 software was used, in which matrix calculation was used to determine the transmission for a local coordinate system in a hemisphere around an axis perpendicular to the window surface. The rotation of the angle of incidence around this axis is called ϕ, the angle between the axis and the angle of incidence is called θ.

The ϕ and θ are not normal output values for TRNSYS, which is why the azimuth and zenith had to be used to convert the data using goniometric formulas. The outcome of this calculation was that

$$\varphi = \tan^{-1}\left(\frac{\tan(90 - zenith)}{\cos(azimuth + 90)}\right) + 180$$

if the azimuth ≤ 90, and

$$\varphi = \tan^{-1}(\frac{\tan(90 - zenith)}{\cos(azimuth + 90)}) + 360$$

if the azimuth > 90. Using the ϕ, the θ can be calculated using the following formula:

$$\theta = \sin^{-1}(\frac{\sin(90 - zenith)}{\sin(\varphi - 180)}$$

In this, the azimuth is corrected for south orientation by adding 90 to the input azimuth (normally -90 in the east, 0 in the south, 90 in the west). The zenith is corrected by subtracting it of 90, which converts it into the altitude. The addition of 180 is done because the data from window start counting below the horizon, so the first 180 degrees are not useful. Because mirroring the does not mean that the ϕ can be mirrored, the correct ϕ for an azimuth above 90 would be 180-ϕ'. However, since a cosine becomes negative with values above 90, this needs to be compensated, making the correct ϕ equal to 180+ϕ'. This explains the additional 180 to the formula for azimuths above 90.

In WINDOW 7.1 a glazing system is used in which the glass pane (which is obligatory) has a transmission of 100%, so it can be considered non-existing. A cavity of 100mm was used, in combination with slats of 300mm wide, with a 45 degree inclination towards the outside. The space between the slats was also kept to 300mm.

The lookup table uses the ϕ and the θ as an input to select the correct values from the transmission values, which are categorised for each θ and placed in order of ascending ϕ. First, the ϕ is used to select the correct transmission value for each θ. To find the correct ϕ, an approximation is made in which the value closest to the current ϕ is selected. For the correct θ, the lookup table finds the listed θ closest to the current θ.

Transmission values of venetian blind

Input 1 (solar azimuth)	-10	(-90 = east, 0 = south, 90 = west)	phi	258,3079
Corrected azimuth	80	(corrected for south facade: azimuth+90)	theta	41,02646
Input 2 (solar zenith)	50			
Solar altitude	40			

Theta	Transmission	
0	0,36162	0
10	0,248478	0
20	0,146616	0
30	0,093475	0
40	0,089398	40
50	0,086906	0
60	0,084494	0
70	0,082043	0
82,5	0,078724	0
		40

Output 1 (transmission value) 0,089398

Figure 104: Transmission values taken from the WINDOW 7.1 software. The column on the right shows the θ approximation based on Input 2. The influence of the ϕ is not shown (own image).

Coating transmission global

The global transmission lookup functions basically the same as the direct transmission lookup table, which is described below. The table still contains three columns in which respectively normal glass transmission, full reflective transmission and half reflective transmission are defined. In addition, the fraction of diffuse transmission is taken as an input from the Radiation equation. This is used to calculate the global transmission, since this is the combination of direct and diffuse transmission. As was mentioned before, the diffuse transmission is generally assumed to be approximately equal to the transmission at an angle of incidence of 60 degrees. Therefore, this value is taken from the table and multiplied by the fraction of diffuse radiation. Added to this is the direct transmission multiplied by the fraction of direct radiation (which is one minus the fraction of diffuse radiation).

To calculate the LTA value of the shading combined with the window, the LTA of the blinds is calculated in this component as well. In case of the glass or the half reflective coating, the glass transmission is taken as the LTA value, while when the fully reflective is used, this transmission value is taken. This selection method is necessary because of the spectral selectivity of the half reflective coating, due to which it is not representative for the visible light transmission anymore. The LTA of the slat is output to the transmission equation, in which the LTA of the whole louvre system is calculated in the same way the other total transmission values are calculated.

Transmission values of polyarch coating global

Input 1 (angle of incidence)	90 degrees		
Input 2 (Troom=<Tmin)	1 Celsius	--> use glass	2 Transparency control function
Input 3 (Troom=>Tmax)	0	--> use coating	
Input 4 (Troom=comfortable)	0	--> use vis transmission + NIR reflection (only from 1 June - day 152 - until and including 30 September - day 273)	
Input 5 (day of year)	122		
Input 6 (diffuse fraction)	0		
Inclination of louvres	45 degrees		

Transmission global					Transmission			
Angle	Glass	Coating	Half		Angle	Glass	Coating	Half
0	0,699	0,009121	0,518903	0	0	0,699	0,009121	0,518903
10	0,698	0,009142	0,505938	0	10	0,698	0,009142	0,505938
20	0,695	0,009258	0,492914	0	20	0,695	0,009258	0,492914
30	0,689	0,009531	0,480169	0	30	0,689	0,009531	0,480169
40	0,676	0,010023	0,467202	0	40	0,676	0,010023	0,467202
50	0,648	0,010893	0,453587	50	50	0,648	0,010893	0,453587
60	0,587	0,012172	0,439799	0	60	0,587	0,012172	0,439799
70	0,463	0,013831	0,427302	0	70	0,463	0,013831	0,427302
80	0,251	0,015635	0,41446	0	80	0,251	0,015635	0,41446
90	0	0	0	0	90	0	0	0
				50				

Output 1 (transmission value) 0,648

Figure 105: Global transmission values of the PolyArch coating. Input 1 determines the row in which the data is collected, Input 2, 3, 4 and 5 determine via the Transparency control function from what column the data should be collected. Input 6 is used to combine the direct transmission (on the right) with the diffuse transmission (approximately that at 60 degrees) and this combination is shown in the left table (own image).

Transmission values of polyarch coating global NORMAL BLINDS

Input 1 (angle of incidence)	40 degrees		
Input 2 (Troom=<Tmin)	0 Celsius	--> use glass	2 Transparency control function
Input 3 (Troom=>Tmax)	0	--> use coating	
Input 4 (Troom=comfortable)	1	--> use vis transmission + NIR reflection (only from 1 June - day 152 - until and including 30 September - day 273)	
Input 5 (day of year)	310		
Input 6 (diffuse fraction)	0,2		
Inclination of louvres	45 degrees		

Transmission global					Transmission direct			
Angle	Blind up	Blind down	Blind down		Angle	Blind up	Blind down	Blind down
0	1	0	0	0	0	1	0	0
10	1	0	0	10	10	1	0	0
20	1	0	0	0	20	1	0	0
30	1	0	0	0	30	1	0	0
40	1	0	0	0	40	1	0	0
50	1	0	0	0	50	1	0	0
60	1	0	0	0	60	1	0	0
70	1	0	0	0	70	1	0	0
80	1	0	0	0	80	1	0	0
90	1	0	0	0	90	1	0	0
				10				

Output 1 (transmission value) 1

Figure 106: Global transmission values of the coating to approach the performance of a normal venetian blind.Input 1 determines the row in which the data is collected, Input 2, 3, 4 and 5 determine via the Transparency control function from what column the data should be collected. Input 6 is used to combine the direct transmission (on the right) with the diffuse transmission (approximately that at 60 degrees) and this combination is shown in the left table (own image).

Venetian blind direct

Since the WINDOW 7.1 software that was used for the calculation of global transmission through a venetian blind does not include the same angular data for direct light transmission only, a small trick was used to find this transmission anyway. By reducing the reflectivity of the slat material to 0%, the transmission caused by reflections was eliminated, leaving only the transmission of direct light. The absorption remained equal to that of glass, meaning that the energy transmission did not drop to zero since direct light would be radiated into the room after being absorbed by the venetian blinds even when the angle of incidence would increase above the critical angle of 22.5 degrees, above which the window is entirely shaded. Apart from this, the calculation was identical to that of the global transmission.

Transmission values of venetian blind direct light

Input 1 (solar azimuth)	-10	(-90 = east, 0 = south, 90 = west)	phi	258,3079
Corrected azimuth	80	(corrected for south facade: azimuth+90)	theta	41,02646
Input 2 (solar zenith)	50			
Solar altitude	40			

Theta	Transmission	
0	0,351968	0
10	0,237089	0
20	0,133686	0
30	0,082098	0
40	0,082084	40
50	0,082077	0
60	0,08207	0
70	0,082063	0
82,5	0,082052	0
		40

Output 1 (transmission value) 0,082084

Figure 107: Transmission values taken from the WINDOW 7.1 software. The column on the right shows the θ approximation based on Input 2. The influence of the ϕ is not shown (own image).

Coating transmission direct

First of all, the transmission data in the lookup table are collected from the large calculation Excel file, in which the data provided by the TU Eindhoven is converted and modified according to the method described in chapter 3.3.2. The transparent state of the shade is taken from WINDOW 7.1, where the angular dependent transmission data for a combination of two layers of clear 6mm float glass were calculated. This represents the laminated glass that is used for the shade. The half reflective state represents the state that is used to prevent overheating in summer when the temperature inside is still comfortable: it transmits the visible light, but already blocks the NIR light.

This data offers transmission values for an angle of incidence varying between 0 and 90 degrees, with an increment of 10 degrees. The angle of incidence needs to be corrected with the inclination of the louvres to find the correct transmission value. With the controls from the ATG, the selection for either of the three columns is made. When it is too cold in the room, the clear glass is selected. When it is too warm inside, the fully reflective state is chosen. And finally, when the room temperature is comfortable and the day of year is between the 1st of May and the 30th of September (the period in which overheating is a larger risk than undercooling), the half reflective state is chosen. Outside this period, when the risk of overheating is small but instead the solar heat may be desired to keep the room temperature comfortable, the clear glass is selected again.

Transmission values of polyarch coating

Input 1 (angle of incidence)	90	degrees	
Input 2 (Troom=<Tmin)	0	Celsius	--> use glass — 2 Transparency control function
Input 3 (Troom=>Tmax)	0		--> use coating
Input 4 (Troom=comfortable)	1		--> use vis transmission + NIR reflection (only from 1 June - day 152 - until and including 30 September - day 273)
Input 5 (day of year)	122		
Inclination of louvres	45	degrees	

Angle	Transmission Glass	Transmission Coating	Transmission Half	
0	0,699	0,009121	0,518903	0
10	0,698	0,009142	0,505938	0
20	0,695	0,009258	0,492914	0
30	0,689	0,009531	0,480169	0
40	0,676	0,010023	0,467202	0
50	0,648	0,010893	0,453587	50
60	0,587	0,012172	0,439799	0
70	0,463	0,013831	0,427302	0
80	0,251	0,015635	0,41446	0
90	0	0	0	0
				50

Output 1 (transmission value) 0,648

Figure 108: Direct transmission values of the PolyArch coating. Input 1 determines the row in which the data is collected, Input 2, 3, 4 and 5 determine via the Transparency control function from what column the data should be collected (own image).

Transmission values of polyarch coating NORMAL BLINDS

Input 1 (angle of incidence)	40	degrees	
Input 2 (Troom=<Tmin)	1	Celsius	--> use glass — 2 Transparency control function
Input 3 (Troom=>Tmax)	0		--> use coating
Input 4 (Troom=comfortable)	0		--> use vis transmission + NIR reflection (only from 1 May - day 152 until and including 30 September - day 304)
Input 5 (day of year)	300		
Inclination of louvres	45	degrees	

Angle	Transmission Blind up	Transmission Blind down	Transmission Half	
0	1	0	0	0
10	1	0	0	10
20	1	0	0	0
30	1	0	0	0
40	1	0	0	0
50	1	0	0	0
60	1	0	0	0
70	1	0	0	0
80	1	0	0	0
90	1	0	0	0
				10

Output 1 (transmission value) 1

Figure 109: Direct transmission values of the coating to approach the performance of a normal venetian blind. Input 1 determines the row in which the data is collected, Input 2, 3, 4 and 5 determine via the Transparency control function from what column the data should be collected (own image).

Teref

To determine the desired maximum and minimum temperature in the office, the ATG method is used. ATG stands for “Adaptieve Temperatuur Grenswaarden”, which is Dutch for Adaptive Temperature Limits. This newly developed Dutch comfort assessment method takes the outside temperature weighted over a couple of days into account. It outputs a daily value that remains constant throughout the day, for both the upper and lower limit between which the indoor air temperature is considered comfortable.

Daynumber	Weighed temperature	Daynumber	Weighed temperature	Daynumber	Weighed temperature	Daynumber	Weighed temperature	Daynumber	Weighed temperature	Daynumber	Weighed temperature
1	4,58	62	7,43	123	14,39	184	16,19	245	15,19	306	10,61
2	3,88	63	6,59	124	16,11	185	18,38	246	15,11	307	10,63
3	2,44	64	5,35	125	17,12	186	20,01	247	14,81	308	9,25
4	0,50	65	3,85	126	16,88	187	19,12	248	14,55	309	8,72
5	-1,51	66	2,62	127	16,83	188	17,18	249	13,62	310	9,07
6	-2,49	67	2,09	128	14,91	189	15,76	250	12,75	311	9,32
7	-1,99	68	2,21	129	12,23	190	15,52	251	12,47	312	9,51
8	-0,72	69	3,67	130	10,81	191	15,34	252	12,34	313	9,67
9	2,27	70	4,51	131	9,41	192	15,88	253	12,73	314	9,35
10	4,36	71	4,99	132	8,80	193	16,84	254	14,28	315	8,44
11	4,38	72	4,92	133	8,64	194	18,62	255	15,81	316	6,07
12	4,14	73	5,38	134	8,28	195	20,17	256	15,56	317	3,22
13	3,89	74	6,90	135	8,86	196	18,86	257	14,17	318	0,70
14	4,86	75	6,77	136	9,61	197	16,94	258	13,80	319	1,33
15	6,41	76	6,30	137	9,90	198	16,40	259	13,57	320	3,73
16	6,07	77	5,55	138	9,33	199	16,46	260	14,75	321	4,62
17	5,64	78	5,02	139	8,93	200	15,94	261	14,73	322	3,74
18	5,91	79	5,02	140	9,34	201	15,35	262	15,48	323	4,62
19	5,31	80	4,84	141	9,27	202	14,97	263	15,30	324	5,45
20	6,36	81	4,90	142	9,91	203	15,14	264	15,27	325	4,73
21	6,31	82	5,09	143	12,39	204	15,70	265	15,99	326	3,92
22	6,39	83	4,88	144	14,82	205	16,48	266	16,10	327	3,32
23	6,58	84	4,34	145	15,77	206	17,98	267	15,55	328	1,85
24	6,44	85	5,31	146	16,23	207	18,62	268	14,47	329	4,76
25	5,85	86	7,29	147	16,25	208	18,09	269	14,04	330	8,41
26	6,66	87	7,37	148	16,67	209	17,71	270	14,02	331	9,93
27	5,34	88	6,43	149	16,32	210	17,22	271	13,78	332	9,71
28	6,25	89	5,70	150	15,14	211	16,32	272	13,53	333	8,29
29	7,21	90	5,66	151	14,26	212	15,85	273	13,98	334	6,03
30	5,69	91	8,46	152	13,70	213	17,80	274	13,03	335	4,90
31	4,56	92	9,30	153	13,31	214	20,69	275	13,69	336	5,54
32	5,02	93	10,98	154	13,79	215	22,75	276	15,04	337	6,53
33	5,68	94	12,88	155	14,58	216	23,08	277	16,74	338	7,01
34	6,54	95	12,88	156	17,21	217	21,40	278	16,75	339	5,92
35	7,86	96	11,84	157	20,26	218	20,06	279	15,59	340	4,97
36	7,38	97	10,47	158	22,96	219	19,25	280	14,52	341	3,97
37	5,74	98	9,69	159	22,90	220	18,76	281	13,22	342	2,28
38	3,83	99	8,84	160	19,33	221	18,37	282	12,66	343	1,31
39	2,24	100	7,58	161	18,50	222	17,86	283	12,92	344	1,35
40	0,74	101	7,08	162	18,67	223	17,87	284	12,40	345	2,69
41	0,33	102	6,53	163	17,25	224	18,48	285	12,10	346	4,32
42	-0,07	103	6,87	164	15,56	225	17,79	286	12,49	347	4,88
43	-1,19	104	7,13	165	13,65	226	16,71	287	12,22	348	3,57
44	-2,21	105	7,46	166	13,19	227	16,40	288	12,23	349	3,54
45	-2,36	106	8,45	167	13,88	228	16,78	289	11,31	350	2,10
46	-0,44	107	9,32	168	15,09	229	16,90	290	10,94	351	0,93
47	2,71	108	10,52	169	15,17	230	16,83	291	11,46	352	0,39
48	3,40	109	11,62	170	14,12	231	16,10	292	11,99	353	0,21
49	3,87	110	10,16	171	12,90	232	15,11	293	11,03	354	2,42
50	5,69	111	9,07	172	11,96	233	14,96	294	9,07	355	4,39
51	5,92	112	8,87	173	11,67	234	15,66	295	6,96	356	6,23
52	6,03	113	7,73	174	11,58	235	15,89	296	5,32	357	7,31
53	5,13	114	6,68	175	11,67	236	15,37	297	4,74	358	7,10
54	4,52	115	5,82	176	11,97	237	15,24	298	4,78	359	6,52
55	3,68	116	5,04	177	13,26	238	14,74	299	7,42	360	5,92
56	3,20	117	5,17	178	14,30	239	14,13	300	9,50	361	5,99
57	4,88	118	5,26	179	14,85	240	13,89	301	9,75	362	5,63
58	5,71	119	5,38	180	14,28	241	13,95	302	7,81	363	6,66
59	6,66	120	5,96	181	14,09	242	14,55	303	6,36	364	6,81
60	7,88	121	8,48	182	14,72	243	14,75	304	7,70	365	5,75
61	7,32	122	11,86	183	15,07	244	15,01	305	9,20		

Figure 110: Weighted outside reference temperature, based on today's, yesterday's, the day before yesterday's and two days before yesterday’s temperature (own image).

To calculate the ATG, a reference temperature is required. This reference temperature is calculated per day, and is based on the temperatures of the past four days (including today), in which the weighting factor decreases as the day is further in the past:

$$T_{e,ref} = \frac{T_n + 0.8 \cdot T_{n-1} + 0.4 \cdot T_{n-2} + 0.2 \cdot T_{n-3}}{2.4}$$

In which T stands for temperature and n represents today, n-1 represents yesterday, etc. The values for each day are calculated in Excel using output of the weather file and then placed into an Excel lookup table called Teref (Temperature, external, reference), with which the upper and lower limits are calculated in the Simulation Studio.

B.4 Transmission equation

The transmission factors of direct and global radiation are both calculated in the same way. First the transmission through the venetian blind is taken, on which the coating does not have any influence. Then the reflection of the venetian blind is multiplied by the transmission of the coating, because the light that is reflected from the blind is in reality not all reflected, but part of it is transmitted. The degree of transmission depends on the transmission of the coating. The transmitted energy of the venetian blind and the corrected transmission are added up to find the total transmission of either global or direct radiation.

B.5 Radiation resulting equation

The transmission values from the previous equation are multiplied by the direct incident radiation and the global radiation from the weather file, to find how much of the incident radiation is transmitted through the shade. This is used as an input to the multizone building component, which is used to calculate the indoor temperature. In a standard TRNSYS overhang simulation, these two inputs are also used to calculate the indoor temperature, which is why in this simulation the same two inputs were calculated using the project specific transmission data.

B.6 ATG equation

This equation was used to define the upper and lower limit for the ATG, as well as the comfort temperature. In addition, the controls for the ATG were calculated, which gave an output of either 1 or 0, by means of which could be determined whether the indoor temperature was below the ATG lower limit, in between the lower and upper limit (so in the comfortable zone) or above the upper limit.

This resulted in three temperatures (Tlow, Thigh, Tcomfort). The former two are used as an input for respectively the heating and the cooling setpoint temperature and also as an input to the ATG control components, while the latter is used as the setpoint temperature for the ventilation air.

B.7 ATG cold control and warm control

To avoid convergence errors, it was necessary to implement a dead band in the temperature control system. This means that for example the control for heating only turns on after a certain margin above the set temperature has been exceeded, and is turned off only after the temperature drops below a certain margin below this set temperature. The margins chosen were 0.5 degrees, and were controlled via two Type 2 controllers, one for the control_cold (T_{room}<lower ATG limit) and one for

control_warm (T_{room}>upper ATG limit). With an equation in the Schedules equation the control_comfort (lower ATG limit ≤T_{room}≤ upper ATG limit) is calculated, using a formula which outputs a 0 when one of the other controls is 1, and a 1 when both other controls are 0.

All three controls are used to determine the transmission state of the coating, and in addition the Control_comfort is used to determine the appropriate window from the Window Pool (see chapter 3.2.3 for more about the Variable window ID). The cold and warm control are also used to integrate a dead band in the temperatures at which the cooling and heating should turn on and off. More about this will be written in the paragraph about the Schedules equation. It is important however to mention already the difference in control between the heating/cooling system and the coating transmission in the weekends. During the weekends the heating/cooling system functions based on extended temperature limits (30 °C for cooling and 15 °C for heating), but the coating still tries to keep the indoor temperature within the normal ATG limits. Although the differences are not very large, the following two graphs show that higher extended limits for the coating lead to a higher energy consumption and larger temperature fluctuations.

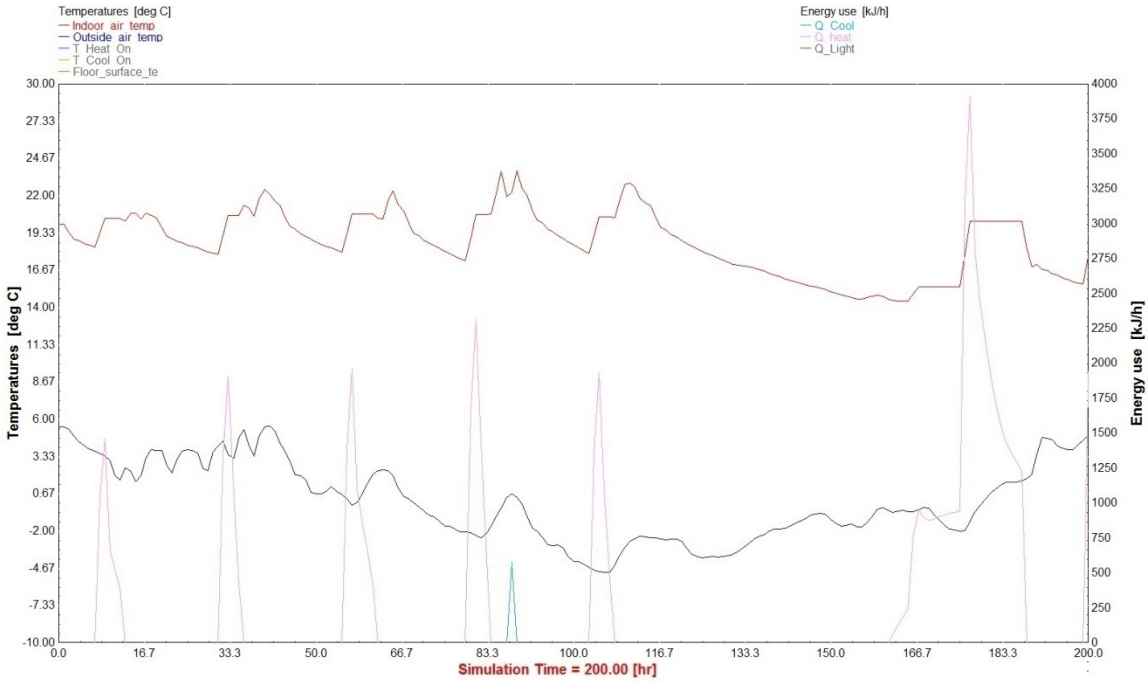


Figure 111: Indoor air temperature (red) and outdoor air temperature (blue), together with the energy consumption for heating (pink) and cooling (light blue), in a situation in which the coating is controlled by the same extended upper and lower limit in the weekend as the heating and cooling system (own image).

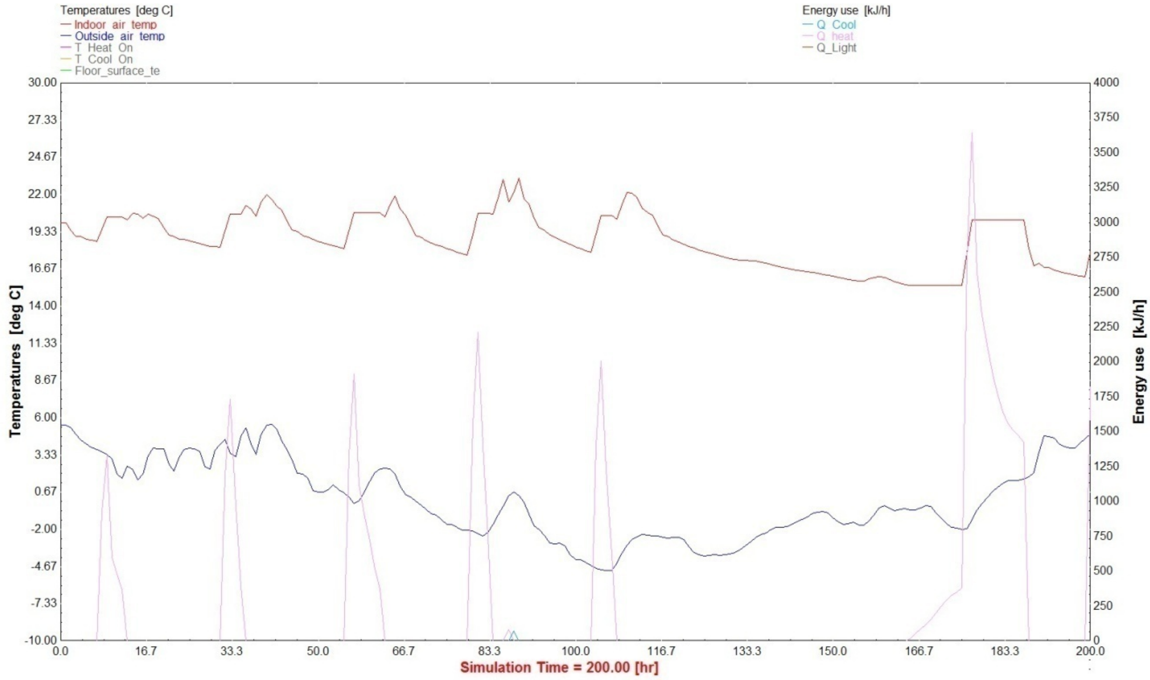


Figure 112: : Indoor air temperature (red) and outdoor air temperature (blue), together with the energy consumption for heating (pink) and cooling (light blue), in a situation in which the coating is controlled by the normal ATG limits at all times (own image).

B.8 Lights controller

Whether the lighting is turned on or off is determined by the radiation, because lux calculations are not enabled in the TRNSYS software. A higher limit and a lower limitare used to decide whether the light should be turned on or off. As soon as the irradiation exceeds the higher limit, the lights are turned off, and remain off until the irradiation drops below the lower limit. If that happens, the lights are turned on and remain turned on until the irradiation exceeds the higher limit. The output of this controller is either a 1 (on) or a 0 (off) and is connected to the Schedules equation.

The higher and lower limit are calculated based on a simple conversion equation presented in the digital ISSO guidelines (ISSO digitaal, 2010g):

$$q_{z,s} = \frac{E_{d,s}}{F_{v,h} \cdot LTA \cdot G_g}$$

In which $q_{z,s}$ is the solar radiation value at which the lighting should be turned on or off, $E_{d,s}$ is the desired interior light level, $F_{v,h}$ represents a conversion factor for light to radiation (window area = 36, middle area = 17 and isle area = 6), LTA is the light transmission of the facade and G_g the percentage of the facade which is glazed. The LTA is a combination of the light transmission of the coated louvres(taken from the Transmission equation) and the window (with an LTA of 0.746).To avoid quick switching of the light, there is a recommended dead band of ±50lux. This means that the higher and lower limit will be:

$$q_{z,s,higher} = \frac{550\ lux}{17 \cdot 0.746 \cdot LTA_{louvre} \cdot 0.5}$$

$$q_{z,s,lower} = \frac{450\ lux}{17 \cdot 0.746 \cdot LTA_{louvre} \cdot 0.5}$$

The formula that can be found in the input file in Appendix C shows an additional '+eql(LTA_louvre,0)', which means that 1 will be added to the denominator when the LTA of the louvres is equal to 0. This is done to avoid division by zero, and since the LTA of the louvres cannot be zero during the simulation, this is only relevant at the start of the simulation.

B.9 Internal loads/Ventilation/Heating and cooling

For the internal loads, this schedule is programmed to output a 1 when the building is occupied and a 0 when the building is vacant. This is based on the work hours described in the Standard office description (chapter 3.2.1), and takes into account the daily work hours and the weekends. There is a possibility to integrate holidays as well, but this was not done for these simulations. The same is done for the ventilation and the heating/cooling, which have different operating hours so they require a different schedule.

B.10 Schedules equation

This equation calculates for Internal loads, Lighting and Ventilation whether the system should be on or off. In addition, the ventilation schedule is used to calculate the air change rate and the Lighting schedule is used to calculate the lighting energy. Also for Heating and Cooling, the setpoint temperature for each time is calculated.

Heating and cooling

To calculate the heating and cooling setpoint temperatures, the heating and cooling schedule is multiplied with the ATG limit temperature. To avoid that the setpoint temperature drops to zero when the schedule is off, the formula is slightly adjusted, after which it reads as follows:

$$T_{heat} = Schedule \cdot (ATG_{low} - 15) + 15 + Control_{cold} - 0.5$$

$$T_{cool} = Schedule \cdot \left(ATG_{high} - 30\right) + 30 - Control_{warm} + 0.5$$

This means that the setpoint temperature for heating goes to 15 degrees when the schedule is off, and the cooling setpoint temperature goes to 30 degrees when the schedule is off.

The integration of the control makes sure that when the control is on, the set temperature is 0.5 degrees further towards $T_{comfort}$, while when the temperature is comfortable and the control is therefore off, the setpoint temperature is 0.5 further away from $T_{comfort}$.

Lighting

Whether the lights are on or off depends on two things, namely the building occupancy and the natural daylight entering the office. The former is represented by the Internal loads schedule, the latter by the output of the Lights controller.

In addition, the lighting energy is calculated here. Since the energy used when the light is on is constant, it can be calculated with a simple equation being the light control signal multiplied by the energy consumption of the light. The light control has been described in the previous paragraph, the light energy is 9W/m^2. This is 174.96 W or 630 kJ/h, which is why the formula for lighting energy is Light_on * 630.

Ventilation

The ventilation is controlled by an input value in the Schedules equation, which is used directly as an input in the Building component to determine the air change rate. The inflow air temperature is controlled by the Airflow equation. The air change rate is based on the ventilation schedule, combined with the relation between indoor and outdoor temperature. The essence of the scheme is to ventilate more when the building is occupied than when it is unoccupied, and to limit ventilation when the office does not need cooling at a moment when the outdoor air is cold (to avoid heat loss).

This is expressed in the following formula, which is also worked out in the corresponding table to provide more immediate insight in the effect of changing the parameters in the equation:

Vent*1.33+eql(Ccold_out*eql(C_warm,0),0)*(0.67+0.33*eql(Vent,0))

The 'eql(: , :)' part means that the output of this part is 1 when the first argument (an argument is here represented by a colon) is equal to the second argument, and otherwise returns 0.

Vent	Ccold_out	Control_warm	Air change rate
1	1	1	2
1	1	0	1,33
1	0	1	2
1	0	0	2
0	1	1	1
0	1	0	0
0	0	1	1
0	0	0	1

Figure 113: Schematic representation of the formula used to control the air change rate. It is controlled by the ventilation schedule (Vent = 1 means that the ventilation should be on since the building is occupied), the outdoor air temperature (Ccold_out = 1 means that the outdoor air is below 15 degrees) and the indoor surface temperature (Control_warm = 1 means that the indoor floor temperature is above the upper ATG limit). It shows that when the building is occupied (Vent = 1), the air change rate is 2 and when the building is unoccupied (Vent = 0) the air change rate is 1. The exception to this rule is the situation in which the indoor temperature is not too warm (Control_warm = 0) and the outdoor air is uncomfortably cold (Ccold_out = 1), because in that case the air change rate will be decreased for occupied and unoccupied situations to respectively 1.33 and 0. This measure is taken to avoid undesired energy loss through ventilation (own image).

B.11 Airflow equation

The airflow temperature is based on the outdoor air temperature, and depending on the conditions also influenced by the heat recovery system. Similar to the ATG dead band controllers, an upper deadband and a lower deadband have been defined for the upper limit and lower limit of the comfortable temperature, but this time to compare the outdoor air temperature with these limits. The upper limit is again the upper limit of the ATG, the lower limit is 15 degrees.

This is used to make sure that when both the outdoor air is comfortable and the indoor air temperature is too high (control with the abovementioned control warm), the heat recovery is bypassed. If so, the airflow temperature is the same as the outdoor air temperature. However, when the heat recovery is functioning, 70% of the temperature difference between the indoor air temperature (i.e. the outflow temperature) and the outdoor temperature (i.e. the inflow temperature) is added to the outdoor air temperature. This also means that when the temperature difference is negative (e.g. in summer, when it is warmer outside than inside) the inflow air is cooled with the outgoing air.

This means that the inflow air temperature that is used in the Building component is simply calculated with the formula:

$$Tair\_wtw = T_{out} + C\_bypass * 0.7 * (T_{air} - T_{out})$$

In which C_bypass is calculated with

$$C\_bypass = eql((C\_warm * CComf\_out),0)$$

Meaning that the bypass signal is only off when both the indoor floor temperature is uncomfortably high and the outdoor air has a comfortable temperature. Although the signal is off in that situation, this means that the bypass functions exactly and only then, since a C_bypass of 0 eliminates the heat recovery, as can be seen in the previous formula.

B.12Multizone building

This is a special TRNSYS type, which is too complex to describe entirely. For this reason, it has its own modelling environment. It represents the entire building, in which all the regimes for climate control come together, all room properties are specified and numerous outputs can be generated, among which the indoor air temperature and the required energy for heating, cooling and ventilation.

The room is characterised as a volume in which one wall is the exterior facade and the other walls have boundary conditions identical to those in the room. The specifications of the room, like the glazing percentage, insulation values etc. can be found in chapter 3.2.1. Heating and cooling equipment is not specified other than indicating their existence, and they have unlimited power to find the minimum amount of energy that is required to keep the indoor air temperature within the ATG limits.

Other inputs are the setpoint temperatures for heating, cooling and ventilation, which are calculated in the simulation studio. Also radiation and outside temperature data are input in this type. The internal gains are slightly different from what is presented in the standard office in chapter 3.2.1, because according to the table from which a certain degree of work intensity can be selected (from ISO 7730), a human being produces 150 W while performing light typing while seated. This is multiplied with the output of the internal gains schedule, the number of people in the room (2) and occupancy rate (0.8). Apart from that, two desktop computers have been selected and multiplied with a conversion factor because of the use of less energy consuming laptops (30W/140W = 0.21) and the number of people (2). Finally, lighting of 10W/m^2 has been selected with a convective part of 70%.

B.13Outputs

Three online plotters are used to graphically show the results from the simulation. One of them shows the transmission data of the shading system, in which the blinds and coating are combined. This is expressed in both the light transmission (a value between 0 and 1) and the transmitted global and beam radiation. The second one shows the outside temperature compared to the indoor temperature, including the upper and lower limit of the ATG and the floor surface temperature on which the control is based. The third and last one gives insight in the functionality of the comfort controls and the light control, because it shows when they are on and off, and additionally shows the ventilation air change ratio.

Furthermore, a data printer is used, which outputs the required power at that time for cooling, heating and lighting. This means that, since the time step is 0.2 hours, the total sum of this energy has to be divided by 5 to find the total required energy (for a constant power of 1000 kJ/h for example, the total sum after 1 hour would be 5*1000 kJ/h = 5000 kJ/h instead of 1000 kJ/h). It also outputs the indoor temperature and floor temperature, the former of which can be used to calculate the exceeding hours in Excel. To do that, also the Internal loads schedule is plotted, to determine which exceeding took place while the building was occupied and which while the building was empty.

C. Input simulation model

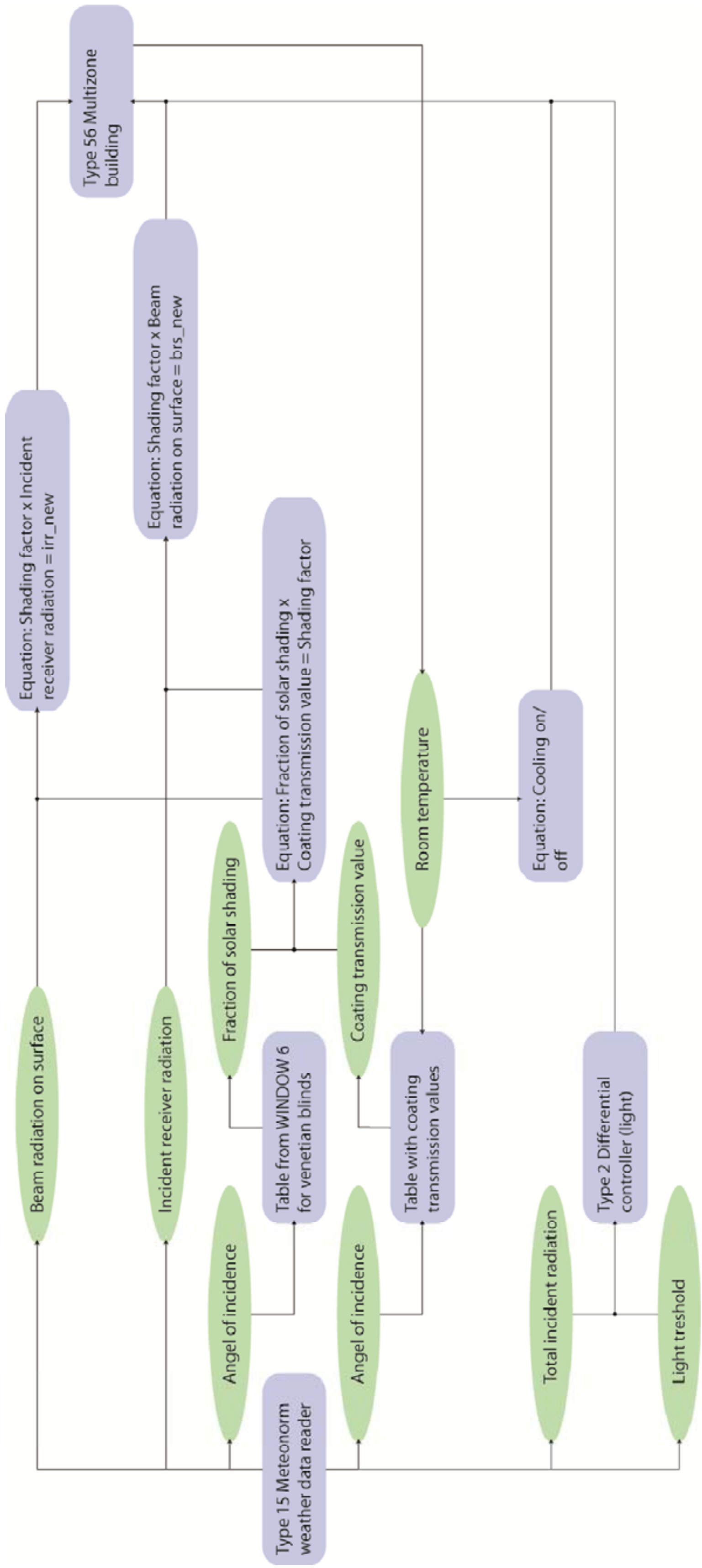
C.1 Input Multizone building

The input presented here was used for the Type 56 building component, in which the energy and indoor temperature calculations are made. It was created using the combination of the TRNSYS Simulation Studio and the special adjustment tool for Type 56 called TRNBuild. This input was identical for all simulations. The exact data of each simulation can be found in the digital appendix for further reference. It is presented as a text document in which the first part of the name indicates the performed simulation (e.g. "100hor" for the 100% case with horizontal louvres in winter) and the last part is "Input multizone building" to indicate that this is the information used by the Type 56 component.

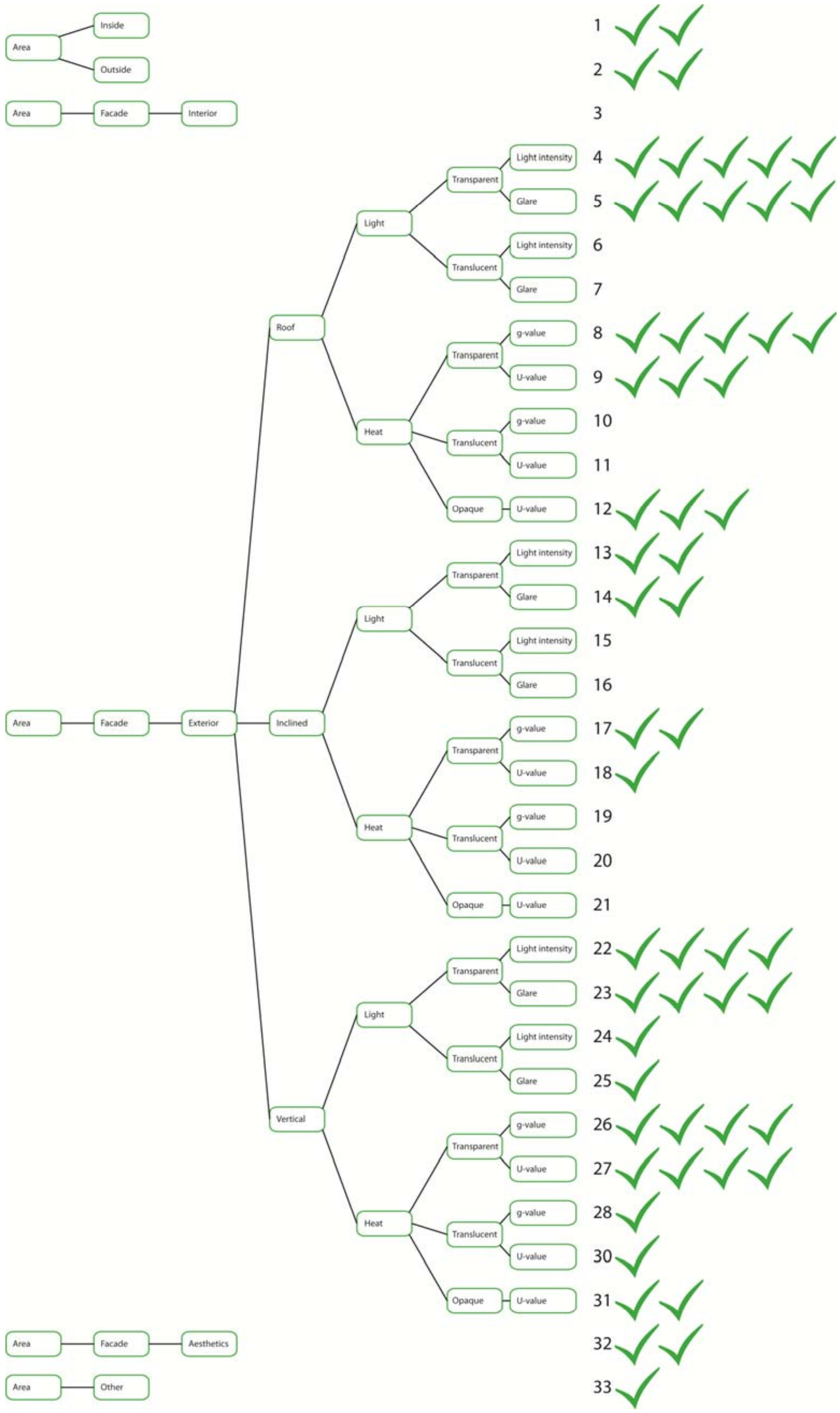
C.2 Input Simulation studio

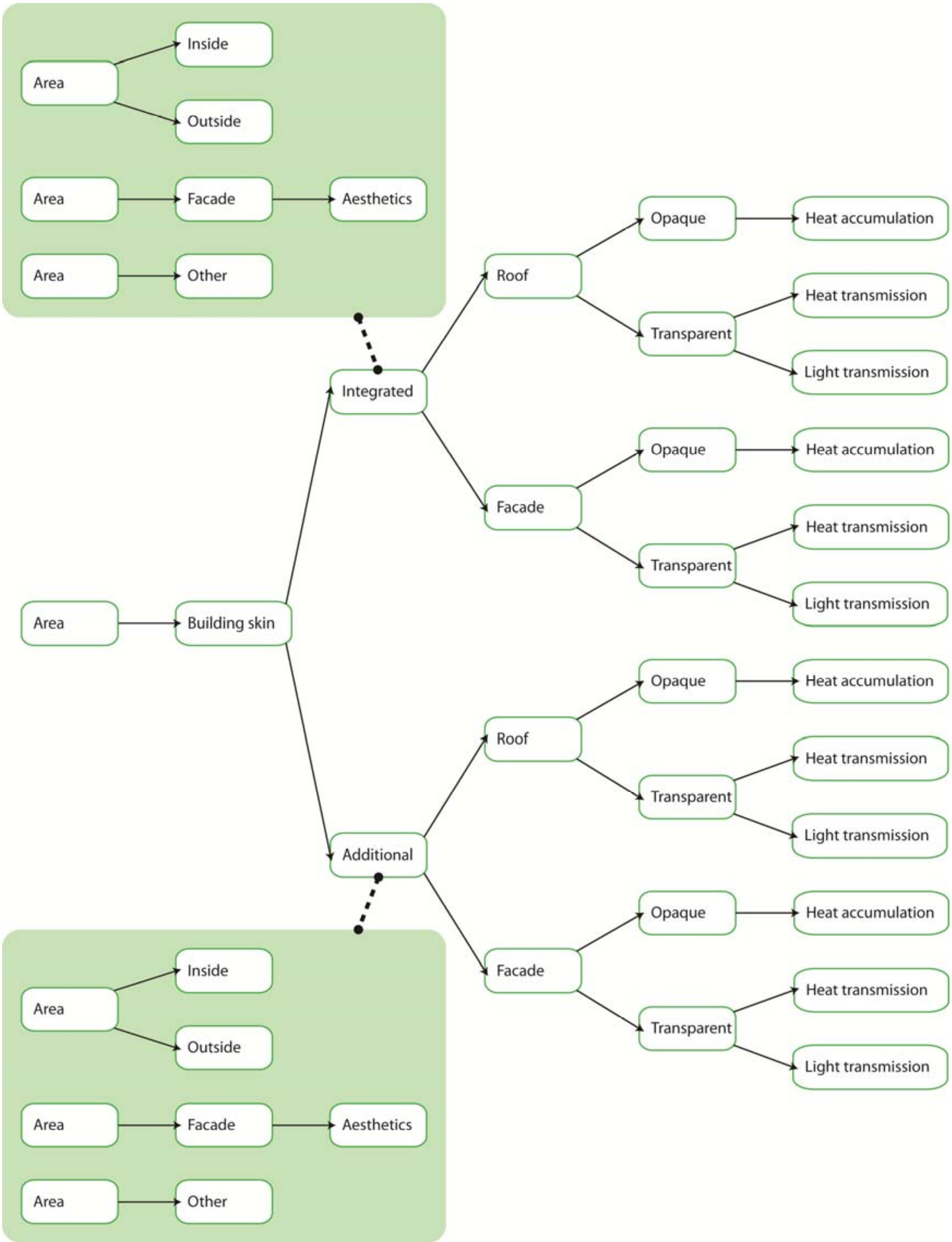
The input presented here is extracted from the List file which comes with every simulation. In this file, the components that were used in the simulation are displayed, the connections are presented in a scripted reference style and warnings are shown. The file also contains references to external files, in this case Excel lookup tables, which can be found in the digital appendix. This input is also included in the digital appendix for more detailed reference if specific questions about the performed simulation cannot be answered with the simulation description alone. It is presented as a text document in which the first part of the name indicates the performed simulation (e.g. "100hor" for the 100% case with horizontal louvres in winter) and the last part is "Input simulation studio" to indicate that this is the List file.

D. Flow diagram method of simulation



E. Possible coating applications




Area
Inside
Outside
Area
Facade
Aesthetics
Area
Other
Area
Building skin
Integrated
Additional
Roof
Facade
Opaque
Transparent
Heat accumulation
Heat transmission
Light transmission
Roof
Facade
Opaque
Transparent
Heat accumulation
Heat transmission
Light transmission
Area
Inside
Outside
Area
Facade
Aesthetics
Area
Other

F. Coating evaluation table

COMPARISON OF SUITABILITY OF VARIOUS COATING APPLICATIONS

Number	Application	Description	Selection criteria: Significant effect? Energy	Light	Aesthetics	Economically interesting? Easily applicable	One/more interesting market(s)?	Comment	Conclusion
1	ETFE Foil	Control of solar radiation in ETFE cushion without inflatable parts	++	+	+	++	+/++	ETFE foils now have problems with controlling solar heat. The advantage is that they are light weight, so a lightweight solar screen is a high potential.	LARGE
2	Darkening glass	Making parts of the glass opaque by applying the coating as a frit or window shape	++	+	+	++	++	Darkening may influence the light level badly, but it can be applied to virtually any glass facade (especially interesting for offices) and the level of opacity can vary.	LARGE
3	Controlling NIR transmission glass	Reflecting NIR and possibly also a little visible light to control heat transmission on windows, glass roofs and atria	++	++	+	++	++	Effects can be large, and invisible. Wide range of applications, especially offices.	LARGE
4	Compensate lack of heat accumulation	Prevent heating of the building by reducing the absorption of heat in visible light and NIR, or the other way around, on roofs and light weight constructions	++	0	-/+	+	++	Application on the roof may be difficult due to the commonly used roofing materials, but the effect on heat accumulation may be significant. Only heat application though.	LARGE
5	External shading	Fixed horizontal/vertical glass panes on the outside next to the window that can be darkened to provide shading. Can work with a cantilever or louvres, the latter also on the roof	++	++	+	++	+/++	Could work just like the darkening glass, but remains efficient when the window is opened and also allows view outside. External panels are not widely used though, but not difficult to implement either.	LARGE
6	Darkening window frame	Colouring the window frame when the glass is darkened	0	0	++	++	++	Every building has window frames, so wide application possibilities, but only aesthetical and only if the glass can darken too.	MODERATE
7	Absorb/reflect Vis+NIR on pavement	Prevent heating of the building by reducing the reflection of heat inwards, or the other way around	+?	0	0	++	+?	Easy application in many fields, but the effect remains uncertain, and probably not very high (because large coating areas are required compared to the glass surface area).	MODERATE
8	Public glass roof	Provide shade in large public glass roofs, like train or bus station canopies	0	++	+	++	+	There are not that many large glass public roofs, and the provided shade may not be worth the effort of applying the coating.	MODERATE
9	Double facade/ second skin	A glass skin placed in front of a facade, with function of adaptive solar control in the outside panel.	+	++	0	++	0/+	The second skin is used as a rain/ wind and solar screen. Solar control devices in the cavity are no longer needed. Can be used for high buildings.	MODERATE
10	Opaque louvres	For reflection or absorption of solar radiation	+	+	0	++	+	Not widely used, only in cavity systems.	MODERATE
11	Opaque cavity louvres	Opaque louvres in the cavity of a double facade that increase the thermal stack effect or provide sunshading	+	-	0	+	+	Adding a louvre system in a cavity should not be difficult, since it can take the space of the shading device that is already there. It compromises the light transmission though, and the effects on the thermal stack effect may not be very large.	MODERATE
12	Darkening parapet	Reflecting NIR and visible light on the parapet to avoid reflection on the balcony	+?	+	0	+	0	The effect may be small because the share of light that enters by reflection is not very large; moreover not many buildings have balconies or walkways next to glass facades.	SMALL
13	Control solar chimney	Control the heat absorption of the mass in a solar chimney, thus controlling the amount of ventilation	+?	0	0	++	0	Not widely used, and the effect is unlikely to be efficient compared to mechanical control.	SMALL
14	Control glass roof ventilation	Control the heating of air that is lead through a glass roof, in order to keep heat/cold storage balanced	+?	0	0	++	0	Not widely used, and uncertain effects.	SMALL
15	Solar panels	Prevent heating of solar panels, which leads to efficiency reduction	0?	0	0	++	++	Many application possibilities, but the effect is unlikely to be high.	SMALL
16	Extra heat storage	Coating on thermal mass, which can be 'activated' by letting the coating transmit, or 'deactivated' by letting the coating reflect IR light	0?	0	0	++	+	In potential it could work, but the wavelength bandwidth is too large to make it function efficiently.	SMALL
17	Light shelf	Adaptive control of the reflection and transmission of a lightshelf	0	+	0	++	0	Light shelfs have also a draw back that they reduce the total light transmittance, a glass plane used as light shelf can reflect light when needed.	SMALL
18	Media facade	The facade used as screen, every window/panel can be a pixel of the screen	0	0	++	0	0	Not easily (connecting all pixels) nor widely applicable, and only aesthetical.	SMALL
19	Internal walls reflection Vis + Nir	Control of the contrast levels or Daylightfactor inside the room	+	++	+?	0	++	The reflection of the walls determine how much the Daylightfactor is, so this can be controlled with the polyarch coating. Contrast levels are dependent of the point of view, so this is more difficult to control. Internal heat radiation can be controlled with the NIR coating.	SMALL
20	Trombe wall	Replacement of the shading system of a trombewand	+	0	0	++	0	The solar screen in the system is replace with the coating place at the glass layer in front of the massive wall. The trombewand is not widely used.	SMALL
21	Translucent Heat Insulation	Control the amount of light and heat transmitted trough insulation panel	+	++	0	++	0	Translucent heat insulation is not widely used. With application for control of solar radiation usefull for rooms with high demands for visual comfort.	SMALL

G. Reflection

In this reflection I will look back on the effectiveness of the method of research I chose to follow, and I will discuss what parts of the process went well or less well than expected. I will evaluate the possible causes that resulted into a larger or smaller degree of success for all aspects of the research process. If possible, I try to indicate what may prevent difficulties in the future.

G.1 Methodology

First of all, I think I should conclude that the method of research worked sufficiently, because not only could the research question be answered, there was also time in the process to create a fairly strong foundation for the continuation of research into the potential of the PolyArch coating. Many applications that have not been investigated thoroughly yet have been suggested, a method of approaching and categorising the applications and continuing the search for more applications has been designed, and not in the least a knowledge base about the PolyArch coating, based on literature and interviews, has been created.

In addition, research has been done both in width and depth, meaning that initially the ground for the coating applications has been explored and assessed, while further in the process more specific solutions were studied in greater detail. This has been the reason why the conclusions of this research can fuel further research as well as provide preliminary conclusions about the potential of the coating in architecture. However, not everything in the process of researching went as expected. The main two reasons for this were the cooperation between Guido and me, and the dependence on other people for certain data.

G.2 Cooperation with Guido

First about the cooperation, I think this has been both a benefit and a drawback. In cooperation, people help each other, which in an ideal situation means that the process is smoothened since the risk of getting stuck decreases. However, although being helped speeds up the research, helping slows it down. In addition, disagreements can help to provide a critical professional introspection, but may not always lead to satisfying conclusions, after which compromises may weaken the result. Finally, being part of the group brings along a certain responsibility towards the other person, which increases the motivation to work hard. In conclusion I can say that the benefits of working in a cooperation have outweighed the drawbacks, mainly because of the critical attitude I was forced to sustain during the process and the enlarged motivation to keep working hard continuously.

G.3 Data from Eindhoven

The second unexpected diversion from the proposed planning was less fortunate, since it did nothing but slow down the process and cause additional work. This was caused by three related issues which occurred. Firstly the provision of the coating’s transmission data was slower than anticipated. Secondly, it was less complete than what was hoped for, since the higher angles of incidence were missing from the data (due to reasons we found out ourselves during the measurements).Thirdly, and most disturbingly, the data turned out to be not adequately explained.

The first mentioned issue needs to be accounted for in the planning, since communication can always be subject to delays, which is why buffer time should be incorporated in the schedule. Although there was no directly specified buffering time, other activities could take place while waiting for the data, which is why this did not cause significant delays. The incompleteness of the data however was a problem because for a trustworthy simulation a complete dataset was required. This meant that we had to extend the data we were provided with, based on knowledge we did not have. Although reasonable assumptions were made in correspondence with communication with the developers in Eindhoven, these were rendered obsolete by later remarks by the same people. These remarks concerned the provided transmission data, of which the distortion of the graph turned out to be not valid for application on glass. Therefore extensive approximation methods we had developed to determine the performance of the coating, while a fairly easy approximation turned out to be more applicable.

This resulted in a waste of many day's work and could have been avoided by better communication. I cannot conclusively determine where the flaw in the communication lay, but I am sure that when the description of what was displayed in the data had been more detailed, these inconveniences could have been avoided. This mainly teaches that the desired transmission data need to be specified in detail and in a clear way by the people who are performing the simulation, after which the people with knowledge about the coating and the physical measurements should provide the data with again a detailed description of what can be observed, to avoid misunderstandings.

G.4 Personal deviations

Apart from these two unexpected diversions from the planning, the proposed methodology could be followed completely. There was however not a lot of attention for applying the coating in a design until P4. The reason for this was the fact that there were still many uncertainties about the coating until late in the process, to which finding a solution was esteemed more important. In addition, in the original planning, the designing period was scheduled in the period between P4 and P5, but since this turned out to be not possible, the planning until P4 had to be slightly condensed to include the design phase as well.

On the other hand, a weaker focus on design has resulted in a strong focus on research, which seems to be appropriate in a case where not much knowledge about the topic is readily available. In fact, the collection of existing theoretical knowledge and the generation of new theoretical knowledge has been one of the main focal points from the beginning on, and the chosen methodology has proven to work for this purpose. Although the focus in the Facade master for students may generally lie more on designing and less on researching, I do not feel that there has been a conflict between the Master track's orientation and the graduation research that I performed, because all research has been conducted essentially with an architectural product in mind and in that sense it fits in very well with the the Facade research conducted at the TU Delft, and although the conclusions are mostly theoretical, I feel that this is actually appropriate when approaching facades from a scientific point of view.

For scientific accuracy, validation of the results needs to be done and unfortunately this could not be performed within the scope of the graduation research, since the proposed measurements were insufficient for reliable evaluation of the coating's performance, and the budget, nor time, nor dynamic coating was available to create a full scale office test arrangement in which a dynamic coating could be tested on an annual basis.

Finally, defining an ideal coating turned out to be more difficult than expected. This was a result of the discrepancy between an ideal shading device and the expected ideal performance of the coating, because in the latter certain features that are inherent to the coating material were taken into account, such as the blue shift. In an ideal sun shading device, such blue shifts do not occur, and although it may be more ideal to look at the possibility that one day a coating will be invented which performs similarly to the PolyArch coating, but without this blue shift, this is not realistic when the PolyArch coating is concerned, which is why an ideal coating was defined in which the known inevitable aspects of the coating's performance were incorporated. Although a clause describing the intended action when such inevitable things would compromise the level of idealness might have prevented this, I strongly believe that such unexpected events cannot all be anticipated and are better solved once they occur than in advance.

G.5 Conclusion

Overall the process of this graduation has been satisfying, leading to the kind of results that was aimed for at the beginning, and in some cases even more. The process had to be adjusted a few times due to unexpected circumstances, but in case of the cooperation with Guido this had mostly positive effects and in case of the cooperation with the TU/e did not lead to insurmountable issues.

With hindsight I believe that it might have been good to redefine priorities after the real data from Eindhoven were obtained, since it turned out then that the angle of incidence was not as important as it had seemed before. This may have lead to a more simple, yet still trustworthy simulation. Perhaps this method would allow for a better combination of the transmission values of the coating and the glass louvres.

I can also state that creating a simulation model which gave reliable outputs turned out to be much more difficult than I anticipated, because of the many variables that influence the final outcome to a greater or lesser extent. This may be caused by the complexity of the model that I esteemed required to obtain useful results, but also by the lack of experience with indoor climate simulations in my previous education, which made it sometimes difficult to determine the reason of an unexpected result.

I would not change my methodology however, because I feel that a simulation process, much like a design process, is potentially endless process in which the results can always be improved. The given time limit made it inevitable to focus on the priorities of the simulation and eventually presented the results that were required in time. The same goes for the design process, which essentially could have been expanded for several months, but in the given time forced me to look at the most important things of the design, so the initial purpose of the design and its importance with regard to the entire graduation project were preserved.