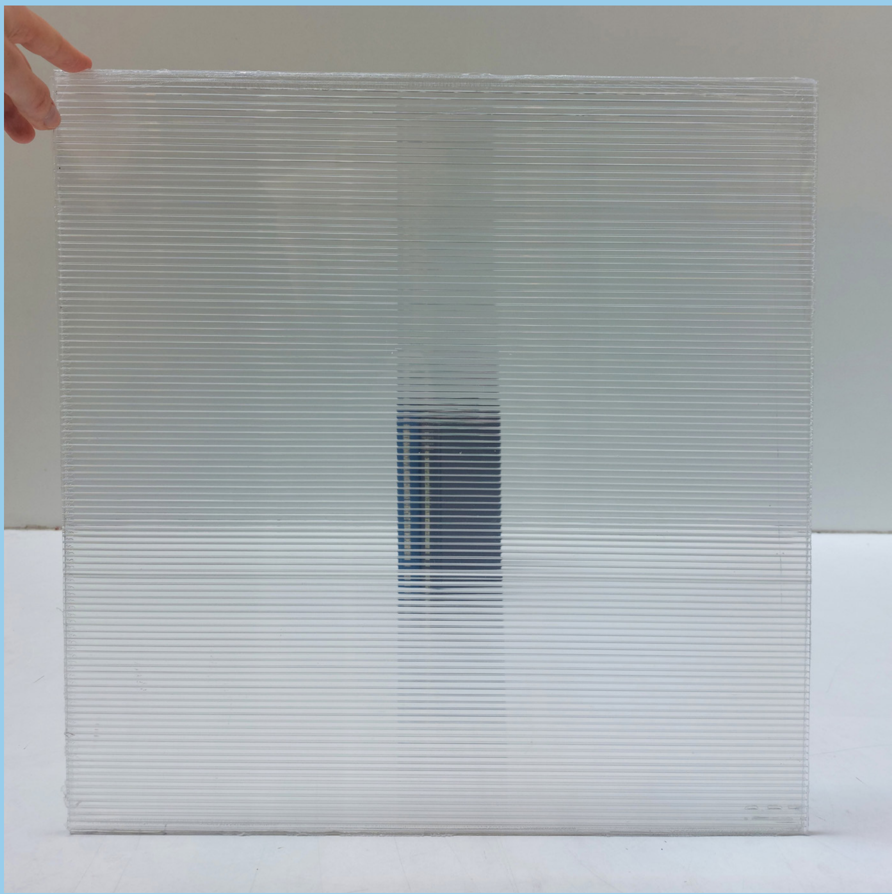

The use of thin glass in heritage window glazing; testing different design concepts

C.J. Backer
4552962
15-06-2022

TU Delft

ABSTRACT

To reduce the heat loss in heritage buildings, this graduation research aims to explore what alternative solutions arise when thin glass is used to design an insulating glass panel that replaces the single glazing? To do so, six different designs are proposed. The first two are an IGU with thin glass and laminated thin glass. The third design is made with a hollow twin-wall sheet of PC and laminated to thin glass. The fourth and fifth proposal are laser cut PMMA connected to thin glass. While design four uses a honeycomb pattern, the fifth proposal experiments with a more freely design of cavities. The last proposal uses glass balls in the cavity of the IGU.

Based on the computer analysis, design 5 and 6 fail on the thermal properties and design 1 and two cannot handle the wind load. For design 1, 2, 3 and 4 prototypes are made but design 4 did not succeed during this research. The others were then tested on the U-value and the maximum force before breakage. This concluded that design 3 performed thermally as expected but design 1 and 2 performed worse, due to a flaw in the computer modelling. Converting the force to the maximum distributed load showed that all designs could handle the wind load. The materials were also tested on ageing due to UV rays. Only the polycarbonate changed significantly over ten years, but with an extra UV-coating, this is avoidable.

The aesthetic of the design 3 and 4 and the opinion of the public are tested with a survey. It can be said that the division between design 3 and 4 was fifty-fifty. If the other design had a better U-value, they did not switch. Depending on the function of the space behind it, people chose design 3 for more private spaces and design 4 for more public spaces. To show the final appearance and precision of the designs, a rendering and details are given. After this, a table is made to compare the designs based on stars which concludes that design 2 is the best alternative solution to replace single glazing in heritage buildings.

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1. BACKGROUND

In recent decades, more and more attention has been paid to improving the carbon footprint and the climate change. Therefore, within the architecture it is important that existing and future buildings are decently insulated, so less heating and cooling energy is required to control the indoor climate. This is important because this energy is often provided by non-reusable resources that contain a lot of carbon. When looking into the insulation of a building in a heating demanding climate, the openings in the façade are the problem areas. The window frames and the glass have significant higher heat loss than the closed parts, which is mostly due to the higher U-value of the glass. To solve this issue, lots of research has been done to design new and better window glazing.

1.1 The glazing industry

The first use of glazing as windows dates to the Romans who used glass plates to cover small openings in the wall so light could enter a building while keeping the elements out. Within the Roman empire the know-how of making glass transferred to England and improved around the 17th century when the English came up with a way to make larger sheets of glass. However, due to a window tax, the development of the industry started after the 1850s. After 1900 laminated glass and the float process were introduced, making glass more available. Until then, the glass plates had a certain amount of distortion because of the thermal inhomogeneities in the process. In 1959 this issue was solved when Pilkington developed a method where glass floats along the surface of an enclosed bath of molten tin. This was the first time a distortion free plate is seen as used nowadays (Pilkington, 1969).

In the end of the 20th century people gained more awareness on improving the thermal performance of windows and double glazing was invented, also known as the insulated glass unit (IGU). With this arrival, the windows had a cavity with still air. The air has a particular low thermal conductivity compared to the glass (U-value = 2.8 W/m²*K). As a next step, researchers started to explore the possibilities within this cavity. Nowadays the cavity could also be filled with argon, krypton, and xenon. These gasses have an even lower thermal conductivity (U-value = 2.0 - 1.1 W/m²*K) but are more expensive. Besides the filling of the cavity, an extra glass panel could be added to create a second cavity. With triple glazing the insulation of this panel will improve (U-value = 0.9 - 0.5 W/m²*K), but the thickness will also be more (40 - 50 mm). A third possibility to decrease the heat loss is by adding a low emissivity coating on the inside of the external glass panel. This will reflect the warmth on the inside and prevents heat loss through the glass.

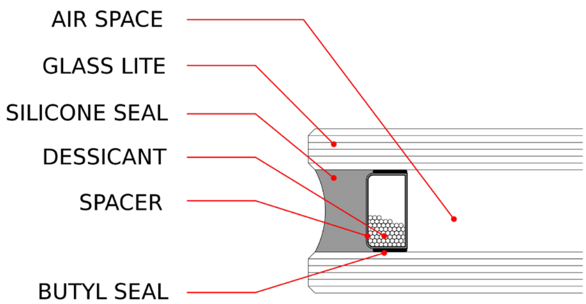


Figure 1: Typical section of a IGU (Sarega, 2007)

Looking more in detail into double glazing, the Insulated Glass Unit (IGU) consists of two glass sheet which are kept separate by a spacer. Inside in the spacer there is a desiccant to capture the moisture that might happen in the cavity. The spacer is connected to the glass with a butyl sealant which makes the IGU already gastight. During this step, the gas inside the cavity is added. The second sealant, most often a silicone seal, protects the spacer from moisture and makes the IGU even more gastight.

Spacers

Originally the spacers are made from aluminium or stainless steel. These spacers are stiff, easily to produce, inexpensive and available in any possible size. They give the glass panel a clean look with sharp sightlines. On the other hand, their material does not insulate very good and their stiffness cannot adopt to the small angle inflections that the glass sheets have. This can lead to a failure in the sealant, resulting in the loss of special gasses and more condensation inside the cavity. To solve these issues, new products have been introduced. These are so-called 'Warm Edge' spacers and are made from plastic composite materials. (Bayview Windows, 2020) Choosing these materials, there is less heat loss through the total panel.

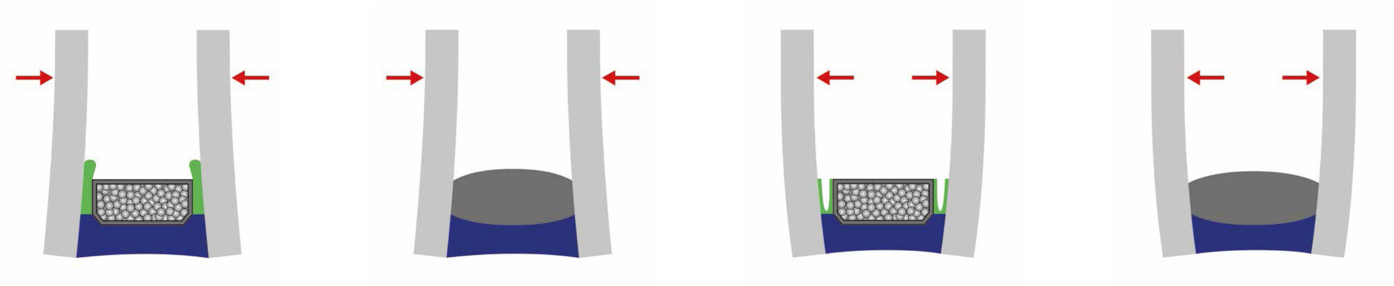


Figure 2: The working of the Kommerling® spacer (Kömmerling, n.d.)

Kommerling® has released a product on the market recently that deals with the angle inflections of the glass. This can be seen in figure 2. This reactive butyl can slightly deform as it stays connected to the glass surface with a special chemical bond. (Kömmerling, n.d.)

E-coatings

As written before, the addition of a low-emissivity coating can also help the thermal performance of the glass composition. The low E-coating can be divided into two types: the passive low E-coating for cold dominated climates and solar control low E-coating for mild to hot climates. The passive E-coating is letting through the sun's short-wave infrared energy but reflects long-wave heat energy. (Stanek Winodws, 2017) This coating is sprayed on the glass during the float glass process and forms a bond on the surface with the glass is still warm. It is therefore also called hard-coat. (Vitro Architectural Glass, n.d.) The solar control low E-coating block almost all the infra-red light and allows only the visible light to pass through. With this, also the thermal energy is reflected back into the interior and stays within the building. The solar control coating is applied after the glass sheets are already cut. The sheets go into a vacuum chamber at room temperature are the coating is sealed or laminated. This coating is therefore called the soft-coat. (Schlösser, 2018; Vitro Architectural Glass, n.d.)

Pricing

Depending on the composition of the product that is chosen, the prices also differ. The single glazing costs around €30-40/m2 and the simplest option of the IGU is €65/m2. Adding a coating to the IGU makes it a HR glazing which costs around €70/m2. In HR+ glazing argon, krypton or xenon is added to the cavity and the new price is €75/m2. HR++ glazing has an improved low E-coating and brings the value to €80/m2. This is the most commonly bought glass panel. HR+++ is also called triple glazing and exists of three glass sheets with two cavities. Those cavities could be filled with argon, krypton or xenon. The price of this product is around €100-120/m2. (040energie, 2021; Dubbelglas-Subsidie, n.d.)

1.2 Float glass process

Within the building industry, float glass is the most common type of glass. This production method is based on the design of Pelkington and only improved a little for a higher glass performance. First, the raw materials are added, crushed, and mixed. The mixture mainly consists of silica sand ($SiO2$), soda ($Na2O$), lime (CaO), magnesia (MgO) and sometimes waste from previous sheets (Schlösser, 2018). The materials are melted to 1550 °C and

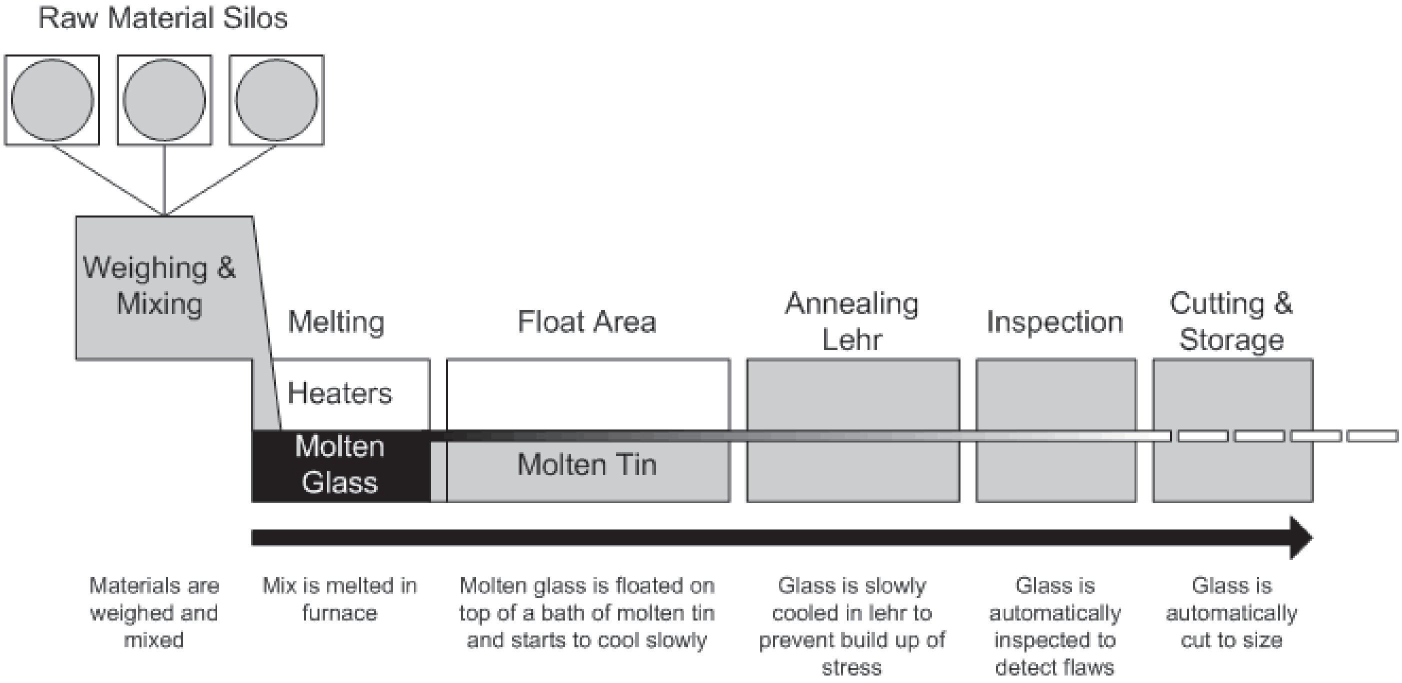


Figure 3: The float glass production line (Tangram Technology Ltd, 2010)

continue over a tin bath where they start cooling down. The second tin bath is enclosed and denser. This is where the thickness of the sheet is determined by the speed of conveyor rollers. This ranges between 2 and 25 mm (Schlösser, 2018). Next, the glass goes into the lehr where the permanent stress is fixed and the glass is cooled more. After this, the glass is checked, cut, and stacked. A schematic production line is given in figure 3.

The glass that is produced with the float glass line is called annealed glass, since the glass only goes through the annealing lehr. This glass has a maximum design stress of 15 N/mm². If this glass breaks, the pieces will be large and long.

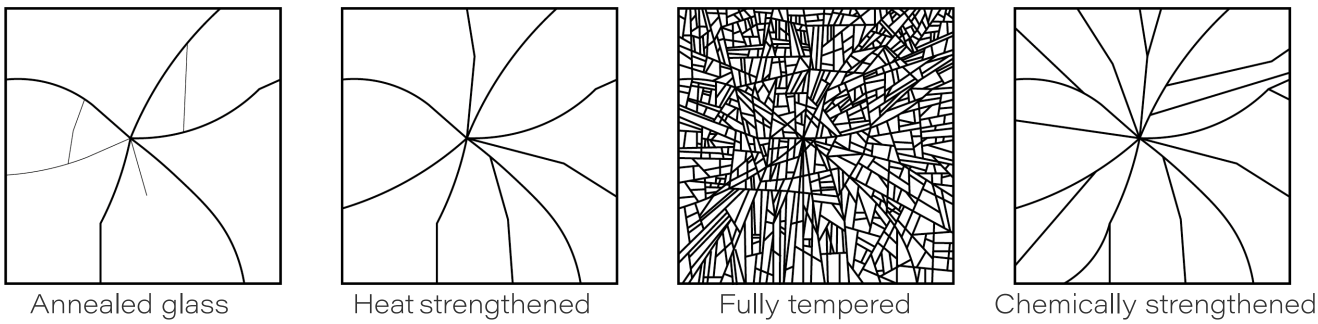


Figure 4: Different breakage patterns (Author)

At the end of the float glass line, extra steps can be done to optimize the strength of the glass sheets. For these glass types, the annealed glass is placed on ceramic rolls and conveyed to an oven that heats up the glass again to 650-700 °C. The glass is then more quickly cooled which results in internal stresses. Depending on the speed of the conveyor belt, the glass can either become heat strengthened glass or fully tempered glass. The heat strengthened glass has a maximum design stress of 30 N/mm² but has a higher price because the glass needs to be heated up again. It has the same breakage pattern as annealed glass but the pieces will be slightly smaller. The fully tempered glass has four times the strength of annealed glass (60 N/mm²) but costs even more than the heat strengthened glass and scatters completely in small pieces when it breaks. When designing with glass, it is therefore important to consider which glass type would suit the project.

The last option to improve the glass strength is with the chemical tempering process where the annealed glass is placed into a hot salt bath. The glass will exchange the sodium ions with the salt ions; resulting in a compression layer on the surface and a tensile core. The maximum design stress of this process is 90 N/mm². The breakage pattern of this glass is similar to the heat strengthened glass but with slightly smaller pieces. (Rammig, 2022)

Lamination layers

Beside the different types of glass, the glass sheets can also be combined to the best performance. This is done using a lamination layer which will hold the glass sheets together in case of breakage. Polyvinyl butyral (PVB) is the most used but other options are ethylene-vinyl acetate (EVA), thermoplastic polyurethane (TPU) and ionoplast polymers such as SentryGlass Plus (SGP). PVB has good transparency and sound insulation but does not perform well with moisture and in a humid environment. The EVA has a lower melting temperature than the other interlayers and a better fluidity but changes colour over time due to UV rays. TPU layers have the same disadvantage but the TPU has a very high tensile strength and does not degrade as quick as the others. SGP is designed to be used in structurally challenging projects but has a higher pricing than PVB. However, while the PVB layer 'falls over' after breakage, the SGP layer still stands, see figure 5. (MORN, n.d.; Schlösser, 2018)

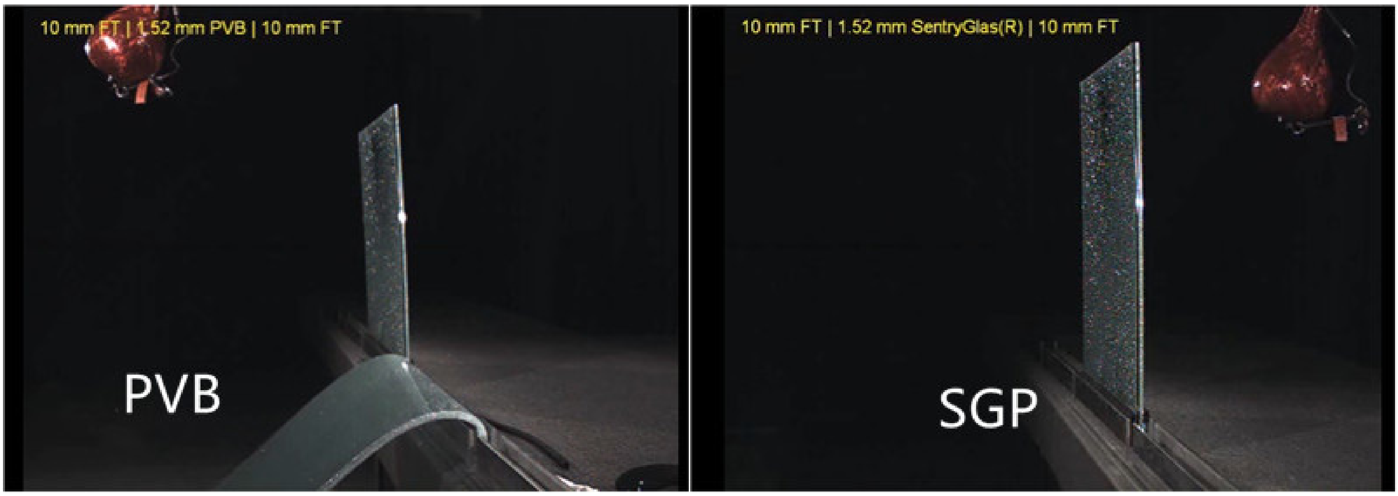


Figure 5: Difference between PVB and SGP post breakage (Su, 2017)

1.3 Thin glass

Besides the innovation in double and triple glazing, glass is also made in a thinner panel. This is so-called thin glass and varies between 0.4 and 2.0 mm. This was originally discovered by Corning Glass and is famous for the flexibility of the material, the high strength, and the scratch resistance (Rohrig, 2015). Currently, this product is mainly used in the automotive and the electronics industry, such as phone screens.

There are three ways to produce thin glass. The first method is the float glass described above. As mentioned, the minimum thickness of float glass is 2 mm and therefore it is part of the thin glass group. The second method is the overflow-fusion process. The raw materials are melted and poured into a bath. Once this reaches its limit, the glass flows evenly over the two sides of the bath and joins at the bottom. Depending on the pouring speed, the

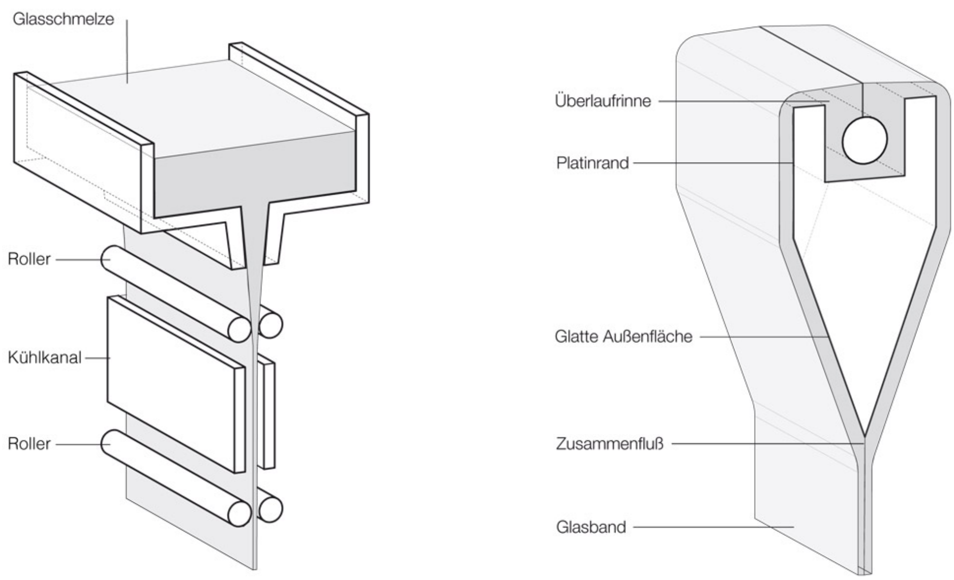


Figure 6: a) down drawn process, b) overflow-fusion process (Albus, 2014)

fusion will be between 0.4 and 2.0 mm thick. This forms a sheet that has not been in contact with any other surfaces while cooling. After this, the flow is cut and stacked for shipping. The last possible production method is the down-drawn process, which is similar to the overflow-fusion process. The difference is that the melted materials leave the bath through a gap on the bottom of the bath instead of flowing over the top.

The thin glass that is used in this graduation research is made by Corning who uses the overflow-fusion process. This glass has a slightly higher design stress than the anneal glass. However, for this research, the same design stress of 15 N/mm² is taken.

1.4 Heritage buildings

The solutions that are currently on the market are broadly used in the new designs of the build environment. However, since the goals is to be climate neutral in 2050, it is also critical to investigate the existing buildings. According to CBS (2022) only 0.9% of the building stock is added per year. That means that most of the buildings in 2050 are already built. Within this building stock, the most problem causing properties are the heritage buildings that are not yet renovated. Almost all of them were designed with single glazing and therefore likely to have a high U-value (5.8 W/m²*K) and a (slight) distortion within the glass panel. Besides the energy saving aspect, the important heritage buildings should be preserved. However, since the aesthetics of the building are protected, the window frames cannot always be replaced or adjusted. This means that the better insulating glass panel should try to fit within the existing window frame.

The current building industry currently offers three solutions. The first one is single heritage glazing with a coating. With this option, it is possible to use a sheet of 4 mm and even create the same distortion to match the original aesthetics. The U-value does improve a little to 3.8 W/m²*K, but that is still worse than a simple double glazing panel (2.8 W/m²*K) (Allwin, 2006). The price of this solution is around €80/m².

The second solution is a thin insulating glass unit where glass sheets of 2 mm are used instead of the regular 4 mm sheets. This reduces the thickness of the total a little and still leaves space for a cavity. For instance, the Dutch company Stolker Glas has this product called Monuglas® which is available from 7 mm with 2 mm glass sheets and 3 mm cavity, see figure 7. Depending on the cavity infill and the addition of a coating, the U-value ranges between 3.6 and 2.0 W/m²*K (Stolker Glas, n.d.). The outer 2 mm glass is also available with a light distortion for buildings built between 1920-1960. The company also offers Monuglas® of 8 mm of which the outer sheet is made of 3 mm glass with a distortion. This is mainly for building built before 1920. Depending on the composition of the requested panel, this solution costs between €200 and €250/m².

The third solution is the placement of vacuum glass. This is a relatively new technique where the cavity is a vacuum space of 0.3mm between 3mm annealed glass sheets. This results in a thickness of just up to 6mm and an excellent U-value around 0.6 W/m²*K (Collins, 2019). The vacuum glass seems to be the best solution looking at the thickness and the thermal performance. However, since the product is new and complex, the price still too high for most renovation projects, starting from €300/m².

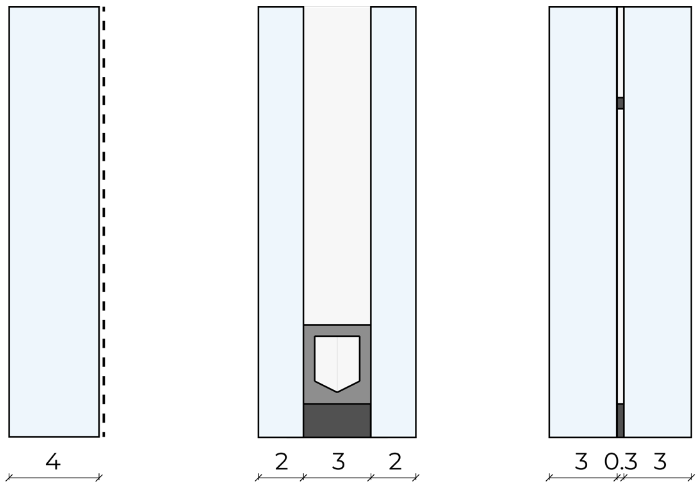


Figure 7: a) float glass with coating, b) Monuglas®, c) vacuum glass (Author)

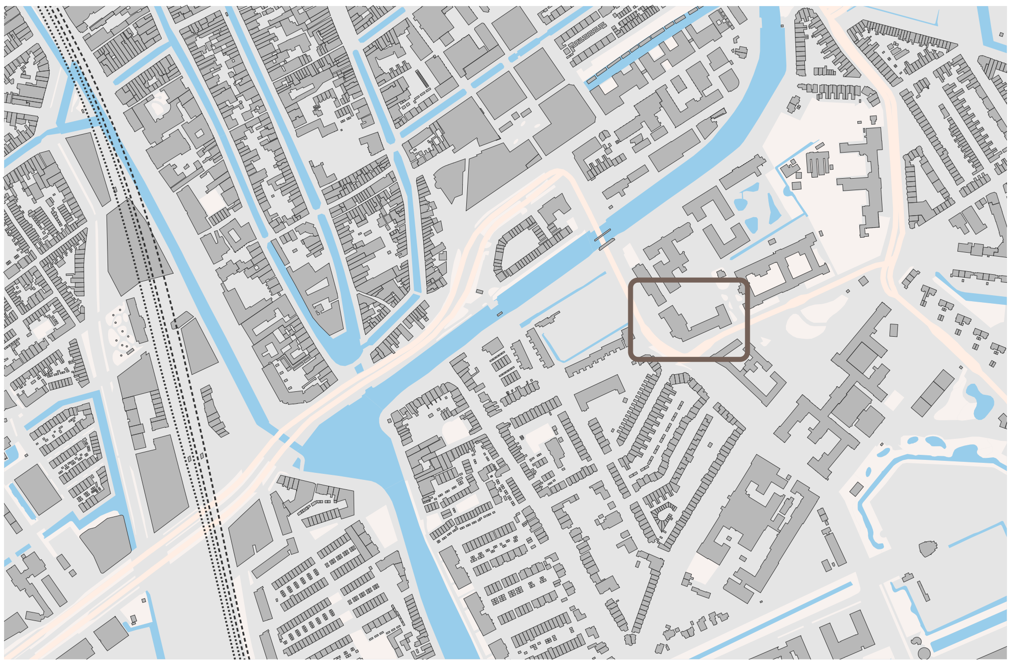


Figure 8: Map of the case study location (Author)

To illustrate the current situation in heritage buildings, a case study is done. The chosen building is the former TU Delft faculty of Applied Physics at Mijnbouwplein 11 in Delft, the Netherlands. The building was built in 1930 by architect Gerard van Drecht (1879-1963). In 1966 the new faculty for Applied Physics was done on the Lorentzweg 1 and the building became available for general business of the TU. In 1975 DUWO took over the ownership and transformed it to student houses. Nowadays this is still its function and in 2008 the building was renovated.

During the renovation, DUWO placed new glass and chose to redesign some window frames. During a meeting with Arjo Boerstra from DUWO, it became clear that the most common solution was to replace the single glazing parts with a single glass sheet with a coating, see figure 13. This was chosen because the appearance had to match the original distortion in the glass. An additional advantage of this choice was that it was not necessary to adjust the frame and that the costs remained low. On other locations of the façade, a new glass sheet was placed of 8.5 mm thick. This had to be done to make the façade more soundproof on the side of the roads. (Crone, 2011) In these situations, the new glass sheets precisely fit the existing window frames and the maximum thickness is reached as figure 13 illustrates.

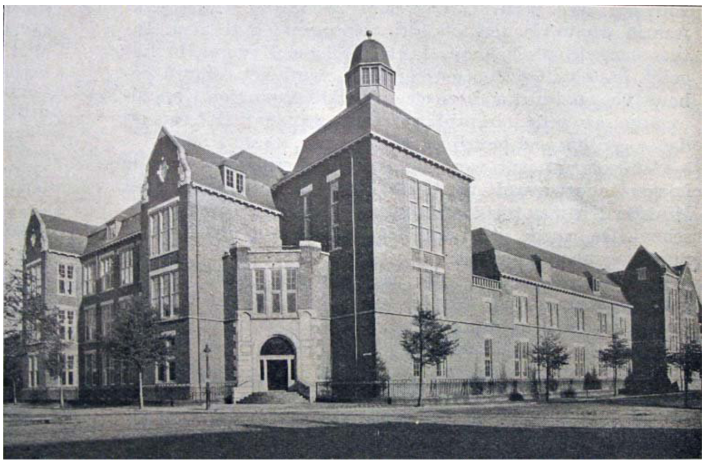


Figure 9: Black and white photo of the case study (Herbestemming.nu, n.d.)

Figure 10: Photo of current building (Herbestemming.nu, n.d.)

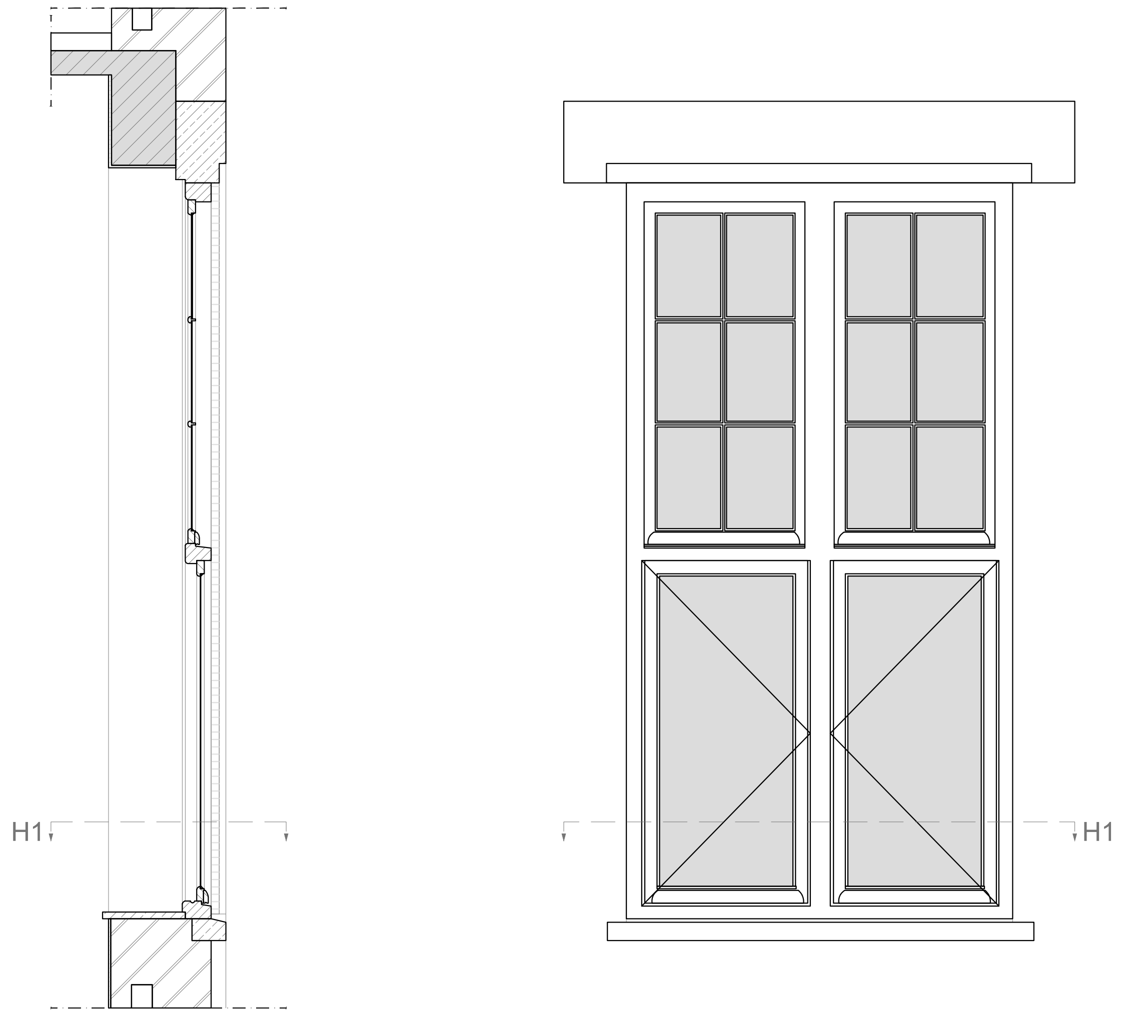


Figure 11: Old situation of typical window frame 1:40 (Author)

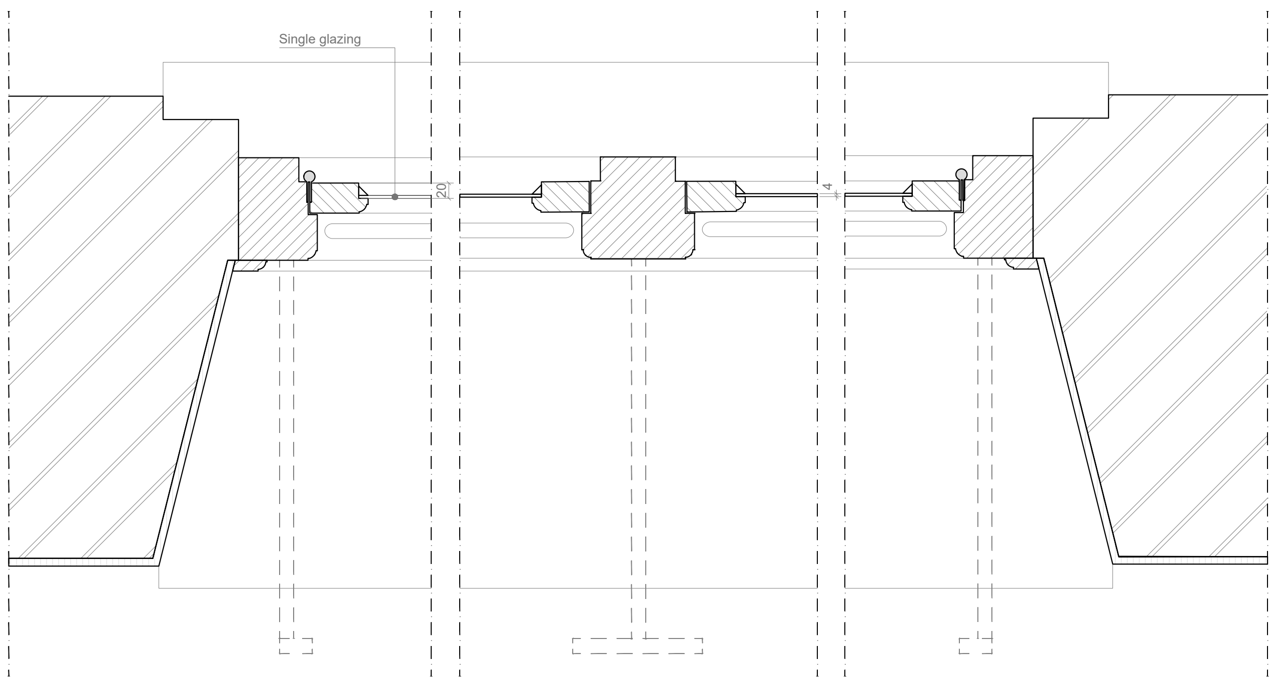


Figure 12: Old situation of typical window frame 1:10 (Author)

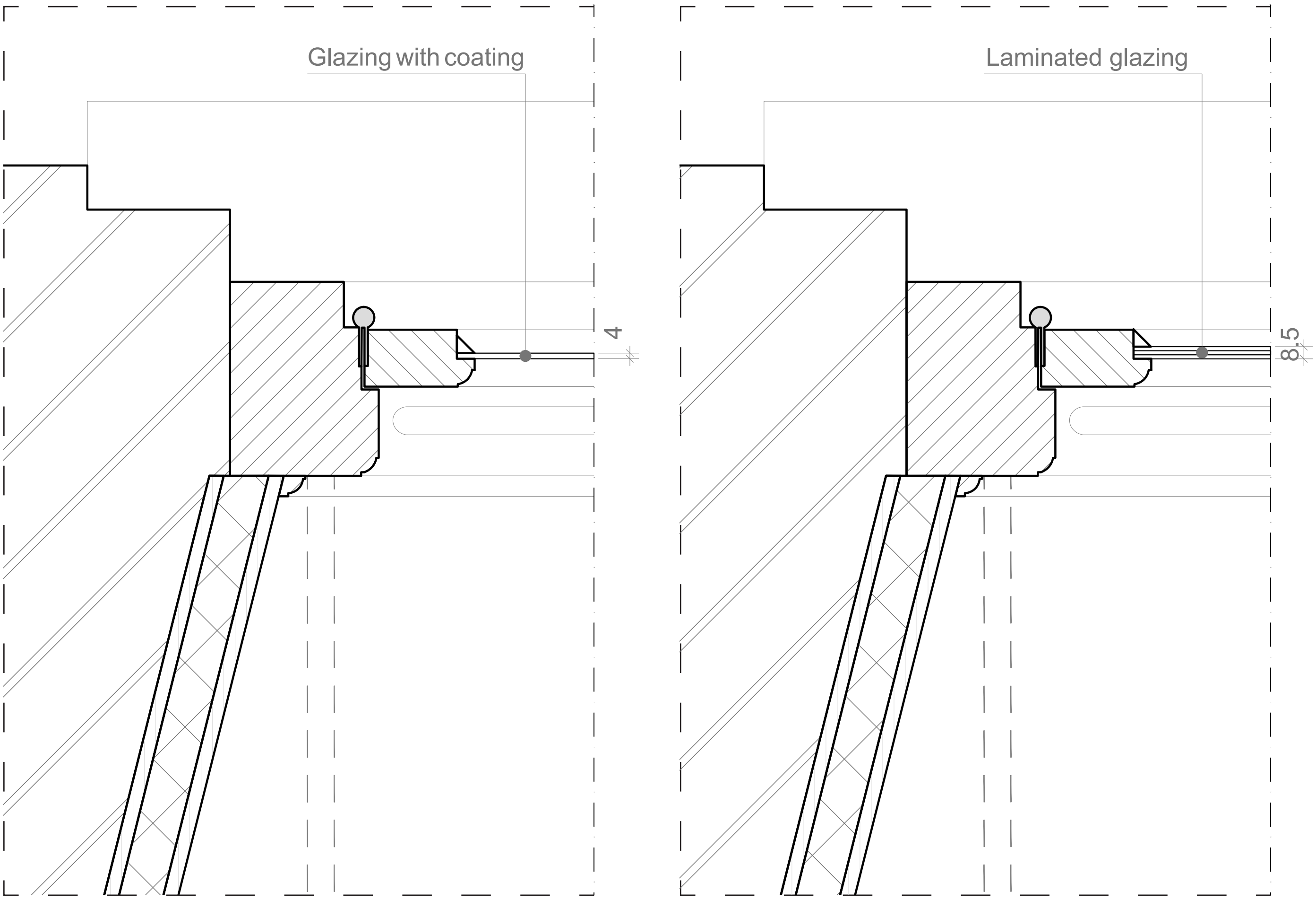


Figure 13: Details after renovation 1:5; a) Merk 04, type 1, b) Merk 04, type 2 (Author)

3. PROBLEM STATEMENT

Reading the introduction in the previous chapter, it can be concluded that there is a need for a reduction in the use of heating energy. More in detail, there is a need to improve the current solutions for replacing heritage window glazing. This leads to the main problem statement: **To reduce the heating energy in heritage buildings, modern solutions that replace the single glazing are not as good as solutions for non-heritage buildings.**

After establishing this main problem statement, certain other sub-problem statements can be determined.

- First of all, the window frame of heritage buildings may be protected from being adjusted to make space for the new glass panel. This means that the new glass panel cannot be thicker than the original 4 mm glass or only slightly thicker if the window frame allows.
- Moreover, in current solutions, the glass that is used is float glass. As described above, the thickness of this glass starts from 2 mm. Adding these sheets together will already give the thickness of 4 mm and will not leave space for an air gap.
- In addition to this, the glass production techniques before the 1960s gave a distortion on the glass sheets. Therefore, most glazing in heritage buildings should be replaced with a product that resembles that aesthetics. The difficulty is that this glass is only available from 2 mm and up.

Besides the product related problem statement, I would like to add some personal difficulties which I want to tackle during my graduation. In the previous years I became aware of the fact that I am satisfied too quickly during the design process. This resulted in not having the most optimal compositions or ideas. Furthermore, I have never worked on an architectural product as if it would become available on the actual market. I feel like this could be a disadvantage when I would start to work in a product making company.

4. OBJECTIVE

Reading the problem statement, it becomes clear that there is a need for a new product that suits the demands of heritage windows to reduce the heat loss through the glass. Therefore, the general objective during this graduation will be **to design a thin glass panel that could replace single glazing in heritage buildings, aiming for similar U-values as solutions for non-heritage buildings.**

In addition to the general objective, sub-objectives can be formed to help directing the outcomes.

- In case the new glass product can only be 4 mm it just has to be better than the U-value of single glazing with a coating. This will therefore directly be an improvement on the modern solutions. In case the heritage window frame allows a glass panel of more than 4 mm, the objective is to design as low as possible U-value within the possible range of thickness.
- The use of thin glass seems to be an excellent outcome in designing a new product for heritage window glazing. Reducing the required space for the glass sheets leaves more space for an insulating material.
- Within the limited time frame of this graduation project, the use of distorted glass might fall outside the scope of this research. However, in the end a suggestion on further research should be given on how to continue this topic.

Reflecting on my personal difficulties written in the problem statement, I would like to add personal objectives to this section. Therefore, I shall try not to be easily satisfied and listen carefully to my mentors. In other courses, they have proven to always question the proposed designs and I should learn from their critical thinking. To improve my current knowledge on the product making process, I aim to make prototypes and test them on applicable safety regulations.

4.1 Final products

To set up a guideline during this graduation project, the following final products are proposed.

- A well written report should be made with a detailed literature review on the previous and current products available on the market. The report should also include a section that explains the manufacturing of the glass and ongoing research in the field.
- In the end of this study, multiple designs proposals should be considered. These designs are first designed on paper, but later also build as prototypes and tested on thermal performance and mechanical properties. Taking all the test results into account, this should give the best design.
- During the process, the designs will be placed in a case study to show the applicability in an average heritage building.
- A consideration whether the product can be made for the market. Otherwise, some advice for improvements shall be given.

4.2 Hypotheses about the direction of solutions

The final product will consist of thin glass sheets. These sheets are separated with an in between layer which should have a certain insulating gas to provide a good U-value. In case of a polymer in between layer, the product will be made by either laminating, casting or UV gluing the parts together.

4.3 Boundary conditions

During the graduation research the following boundary conditions were taken into account.

- The design product will be made for a heating demanded environment.
- The final sizes of the panel should be able to fit in a window frame, at least 1m x 1m.
- The final product needs to be less than 12 mm in thickness, preferably between 4-8 mm.
- The final product cannot crack (between the layers) due to thermal expansion.
- The final product aims to suit the NEN on (safety) glass for windows.
- The final product needs to have a lower U-value than single glazing with a coating (3.8 W/m^2*K).
- The final product needs to be at least translucent, however transparency is preferred.
- It would be nice if the product does not change significantly in colour or transparency over time.
- It would be nice if the product is made from recycled material or is recyclable.

5. RESEARCH QUESTION

The main research question in the graduation research will be: **What alternative solutions arise when thin glass is used to design an insulating glass panel that replaces single glazing in heritage buildings?**

After establishing this main research question, the sub-questions can be determined.

- What are the possibilities in designing a 4 mm glass panel that insulates better than single glazing with a coating?
- Which materials are suitable to become the layer in between the thin glass sheets to enhance the insulating values?
- How is the connection between the layers established?
- How well do the prototypes test based on thermal and structural performance?
- How well does the final design suit in the case study?

Besides the sub-questions, background questions are needed to establish a good start on the graduation project.

- What makes the current products on the market good insulators?
- Looking at the connection, how are similar products made?
- What are the properties of the case study?
- Which materials fit in the boundary conditions?
- How can we test the (structural and) thermal performance of the prototypes?

6. APPROACH AND METHODOLOGY

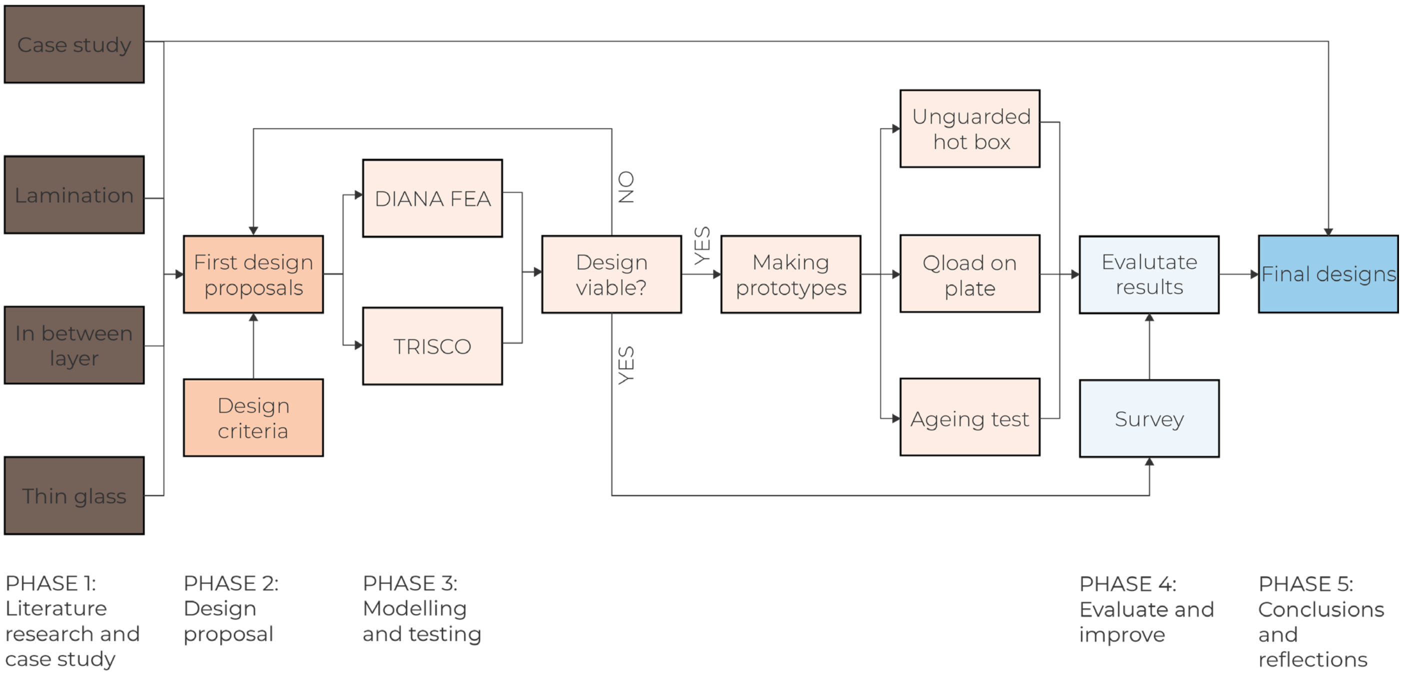


Figure 14: Flowchart of the graduation process (Author)

During the graduation research, the research through design approach is applied. This means that multiple designs are examined in detail on various aspects to see which proves to be the most interesting. It is therefore important that these designs are conceived at an early stage. In figure 14, a flowchart is given of the step-by-step approach of the graduation project. A larger figure of this is added in the Appendix. The next paragraphs will describe each phase.

6.1 Literature research and case study

In phase one literature research is done on the topic. This starts with gaining background information on the history of architectural glass, the manufacturing method of (thin) glass, the current products on the market and the detailing and manufacturing of those products. Then, recent papers are searched in order to gain perspective on the current situation and ongoing studies. This will guide the research in a more detailed direction and prevent repeating conclusions. Moreover, it might help to set up an academic research method by using the methods that are described in the research papers. Finally, a case study is done on a heritage building to prove that the research is useful in practice.

6.2 Design proposals

After gathering information sources and knowledge, drafts can be made for the first design proposals (phase two). These should be in line with the design criteria that have emerged from the literature reviews. Even though the first draft should be logical, they can be very out of the box. It should be the phase where sketches are made and anything is still possible. At the end of this phase, a list of more realistic design proposals is given so they can be examined following the research through design approach.

6.3 Modelling and testing

In the third phase 'Modelling and testing' the proposals will be studied with a computer analysis, made as prototypes and tested on thermal and structural performance. The paragraphs below describe the stages step by step. They will only touch upon the theory. The next chapter goes more into the specific detailing of the phases.

Thermal performance

Since the project is mainly focused on the thermal performance, the program SOLIDO by Physibel is used to see what the expected U-value will be. Within this program, the composite can be imported from a Rhinoceros model and analysed in a set environment. After running the simulation, the heat flow (Q) of the sample is given and can be used to calculate the U-value with the following equations.

$$R_{SOLIDO} = \frac{Q}{A * \Delta T}$$ *Equation 1*

$$U_{SOLIDO} = \frac{1}{R_{SOLIDO}}$$ *Equation 2*

Structural performance

After analysing the thermal performance, the structural performance of the designs will be checked. If the composite glass panel is placed on a building, it must deal with wind forces. In this case all sides of the glass panel are clamped in the window frame. Therefore, the element should be tested as a plate with an equally distributed load where all sides are clamped. When the wind force is applied, it is important that the glass does not break or bend too much. This should be in line with the NEN-norms.

Since the designs have non-uniform layers, the models will be more complex to analyse. Therefore, the designs are first simplified to a clamped beam with a q-load. In case the design is a composite, the width of the glass is multiplied by a factor to make is act like a complete polymer section, see equation 3. A weak section of the sheet is taken to calculate the moment of inertia for that specific section which is then assumed for the complete width of the plate. Using equation 4, the deflection of the clamped beam can be calculated. Next, the maximum stress in the materials is also calculated with equation 5 and equation 6. Note that the maximum moment is located at the clamped edges.

$$Width_{(g,new)} = width_{glass} * \frac{E_{glass}}{E_{polymer}}$$ *Equation 3*

$$\delta_{max} = \frac{1}{384} * \frac{ql^4}{EI}$$ *Equation 4*

$$M_{max} = \frac{1}{12} * ql^2$$ *Equation 5*

$$\sigma_{max} = \frac{M * y}{I}$$ *Equation 6*

Using DIANA FEA, the moment of inertia that is found with the hand calculations is used in a model of a clamped beam set up. This will check the deflections and stresses found with the hand calculations. Moreover, a simplified 3D model is made in Rhino with 2D sheets to analyse the workings of the inhomogenous designs. In DIANA these sheets can be given a certain thickness to represent the real life situation. After the first analyses are done, the design proposals can be optimized and possibly be reconsidered.

Making prototypes

When the computational modelling is done and a selection of the designs seem to be sufficient, the making of the prototypes can begin. To save large expenses it is important to start the search for materials and suppliers in an early stage. A list of required materials and products should be made and close attention should be paid to the safety measures that are needed.

Testing

Once the prototypes are made, they will be tested. The goal for this is to do a quality check on the material properties and the design accuracy. The computational models gave a good indication of the values but are based on the most optimal properties. Since the prototypes are composites and complex in shape, the testing will result in more precise values for the thermal performance and the strength. The final U-value of the product is essential within this research. It is therefore important to test the actual U-value of the prototypes. If a prototype fails to reach the threshold value, it can be said that the design is not viable.

The unguarded hot box method is a box made of Styrofoam with a hole cut out in the exact shape of the prototype. The temperature is measured on four locations: inside and the outside of the box and on the inner and the outer side of prototype. The heat flux is also measured with a Hukseflux gauge on the inner and outer side of the prototype. Inside the box, a lightbulb goes on and heats up the indoor temperature. Once the temperature on the inside of the hot box has reached a constant, the measurements are taken for at least one hour, every 30 seconds. The average of the collect values is then used to calculate the thermal conductivity in the following equation. (Van der Velden, 2020)

$$R_c = \frac{(T_{inner\ air} - T_{outer\ air})}{q}$$ *Equation 7*

$$R_{total} = R_{si} + R_c + R_{se}$$ *Equation 8*

$$U_{total} = \frac{1}{R_{total}}$$ *Equation 9*

As stated in the DIANA FEA modelling, the prototype should be tested with an equally distributed load where all sides are clamped for the most realistic results. For the testing in real life, the prototypes will be placed in a wooden frame that can be seen as a simple support on all sides. Then, a so-called elephant foot in the Z100 machine will press on a set of wooden blocks that distribute the force over a certain area of the prototype. The machine measures the displacement (δ) and the force (F) and continues until the samples break. The gained values can be made into a graph. However, since the test is done on simple supported edges, an extra calculation must be done to see the deflection and the stresses in a clamped situation. Equation 10 gives the maximum stress in the centre of a simple supported plate with a concentrated load at the centre. Equation 11 gives the maximum stress at the centre of the edge of a clamped plate under an equally distributed load. Assuming the thickness a constant, the maximum stress the same and the plate a square (k_2 = 0,564), the equations can be combined to find the distributed load (w).

$$\sigma_{max} = \frac{1.5 * F}{\pi * t^2} * [\ (1 + v)\ \ln \frac{2 * b}{\pi * r} + 1 - k_2\ ]$$ *Equation 10*

$$\sigma_{max} = \frac{w * a^2}{2 * t^2 * (0.623 * (a / b)^6 + 1)}$$ *Equation 11*

$$w_{max} = \frac{1.5 * F * 3.246}{a^2 * \pi} * [(1 + v) \ \ln \frac{2 * b}{\pi * r} + 0.436]$$ *Equation 12*

Since the composite panel will be used as a window, the translucency and colour are important for aesthetics. Polymers tend to change colour over time due to UV rays and the designs should therefore be tested on ageing. The UV ageing test can be done in a UV accelerated weathering test machine with an UV source light. The panels can be placed below the lamp for a period of time. One week in the machine represents one year in real life. Saleh (2020) placed similar glass polymer composite prototypes in the machine for two weeks.

6.4 Evaluate and improve

Finally, research should be done on the aesthetics of the design proposals. To see how the chosen designs will look, the options will be placed in a case study. The case study that is used for this graduation is the building on Mijnbouwplein 11. This will show how the product would work in the detailing of the window frames and moreover it can give 3D visuals on the aesthetics. To get a more scientific argumentation of the quality of the aesthetics, a survey is sent out. Once all the test data is collected, a table should be made to measure the quality of the designs. Each design will be evaluated on all the aspects compared to the other designs. Within this table, there is a possibility to add a weight factor for the more important aspects. This table will be the critical part of the final decision making on choosing the best design.

6.5 Conclusions and reflections

The results are then all considered and the most promising design is chosen. However, since the graduation research is limited to 30 weeks, not all the possibilities and optimalisations could be analysed. Therefore, recommendations and further research will be added so more detailed exploration on the product can be done. Besides this, a reflection is written to deliberate the choices that were made in the graduation research and to discuss to what extent the process went well.

7. ELABORATION OF THE RESULTS

First, existing papers and product were search in the field of glass panels for windows. The products that are already available are described in the background chapter of this report. Therefore, this paragraph will only discuss the papers that were found and their most interesting ongoing research.

As the initial design idea was to laminate a polymer with thin glass sheets, the paper written by Hänig and Weller (2021) showed up quickly. In this paper Hänig uses a PMMA interlayer to connect two thin glass sheets. The design is 8 mm thick and uses either 1 mm or 2 mm thin glass. The acrylic is cast so the product becomes a solid element that is much lighter than 8 mm glass. Continuing the previous paper by Hänig and Weller (2020), the composite panels are in dept tested on the material properties, specifically on the load bearing behaviour.

When looking into the thermal performance of the product by Hänig and Weller (2021), a simple hand calculation shows that the U-values would be around 4.8-5.0 W/m²*K.

$$R_c = \Sigma \frac{d}{\lambda} = 2 * \frac{0.001}{0.8} + \frac{0.006}{0.17} = 0.040 \text{ m}^2\text{*K/W}$$

$$R_{total} = R_{si} + R_c + R_{se} = 0.13 + 0.040 + 0.04 = 0.21 \text{ m}^2\text{*K/W}$$

$$U_{total} = \frac{1}{R_{total}} = \frac{1}{0.21} = 4.8 \text{ W/m}^2\text{*K}$$

Even though this is a small improvement from single glazing with a U-value of 5.8 W/m²*K, this cannot compete with the current solutions on the market starting from 3.8 W/m²*K. It became obvious that a simple bulk polymer would not be sufficient for the thermal performance. It was therefore necessary to look for other intermediate layers.

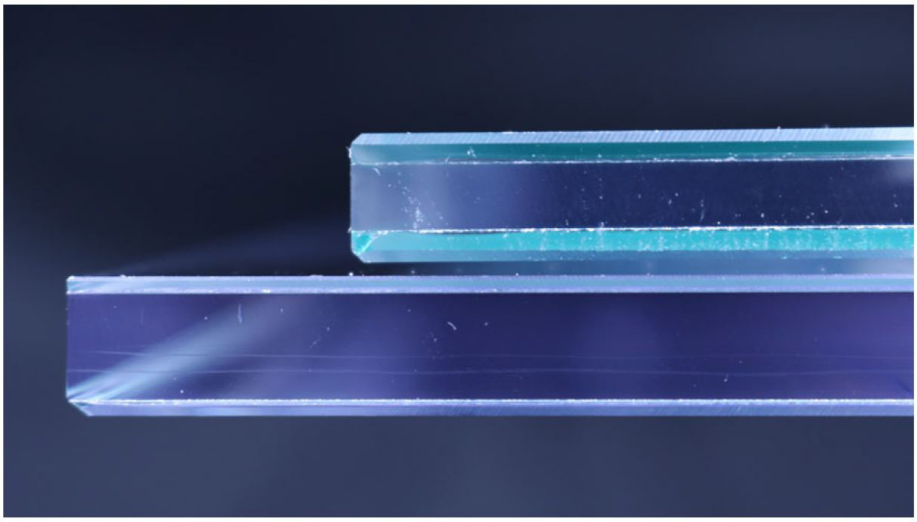


Figure 15: Two composite glass panels of 8mm (Hänig & Weller, 2020)

Looking back at the current products for window glazing, all double or triple glazing use a cavity to improve the U-value. This can be explained by the low thermal conductivity (λ). The λ of air is 0.024 W/m*K while the λ of glass and PMMA is only 0.8 and 0.17 W/m*K. For that reason, a search for new materials began with the focus on material that are hollow or could provide another way of creating an air layer.

7.1 Recent papers

At the TU Delft, more research has been done on using a polymer in between two glass sheets. For instance, the paper by Saleh (2020) discusses the structural strength of a 3D printed recycled PET design inside glued to thin glass with UV curing glue. Moreover, the product is placed in a UV accelerated weathering machine to see how much the PET yellows over times as that is one of the common issues. The paper does not tackle the aesthetics of the product and the thermal performance which leaves possible improvements for this graduation study.

The paper by Van der Weijde (2017) researches the possibility of using aramid paper with a honeycomb structure to design a thin and lightweight façade panel. Besides the structural performance and the insulating properties of this lightweight and hollow material, it discusses the methods of laminating the layers together. The paper experiments with an acrylic adhesive bond and SG laminated bond and concludes that the laminated bond works the best. However, the so-called lens effect appeared and is described as a negative effect on the transparency. This opens an opportunity for this graduation research to come up with another technique to prevent this from happening.

The graduation research that is done by Van der Velden (2020) does not involve thin glass but has a very structured method on validating designs of a cast glass block on thermal properties. It also includes a step-by-step approach on hand calculations and a way to test the samples with a thermal performance software. To analyze the prototypes, the paper gives well explained description of the unguarded hot box which is available at the Architecture faculty in Delft. These methods can be very useful during this graduation research.

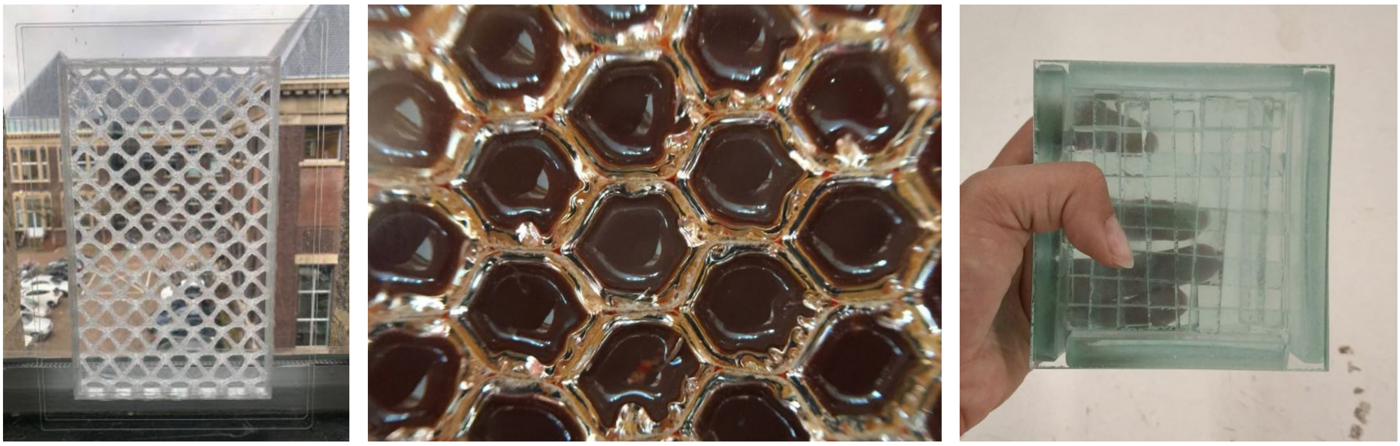


Figure 16: Different photos from reference papers: a) Saleh (2020), b) Van der Weijde (2017), c) Van der Velden (2020)

7.2 First design proposals

To help the research project, Corning Glass will send thin glass sheets of 0.7 mm. Therefore, the first design proposals are made with glass sheets of this thickness. This paragraph will discuss the six design proposals that were chosen to start the modelling and testing phase with. To compare the properties of the ideas, the interlayer has a thickness of 4 mm in all the designs. This is chosen since the hollow multi wall sheets start from this size. However, as the other ideas have more flexibility and they could be adjusted to a preferable thickness. At the end of this paragraph, other proposals are discussed and reasons are given why they were not included in the selection.

Insulating thin glass units

Thinking of the glass panels in buildings, the insulated glass unit (IGU) is commonly used. Based on this concept, the simplest design proposal is to do the same. Now using 0.7 mm thick glass sheets instead of 3 or 4 mm and creating an insulating thin glass unit, the thickness of the panel will be decreased by 4.6 or 6.6 mm. Depending on the size of the spacer, this might just be the reduction that is needed in heritage buildings. A disadvantage of this design might be that the glass is too flexible and that the displacement in the centre is too much for a market product due to the wind forces. To solve this, a second design proposal is made where two sheets of thin glass are laminated, resulting in thin glass of 1.4 mm. The sections in figure 17 and 18 show the possible thickness of 6.4 mm and 7.8 mm.

Composite glass with multi wall sheets

Besides using a spacer in between the thin glass sheets, other materials can be thought of which might also solve the possible stiffness issue. After drawing the conclusion from the papers by Hänig (see background literature), existing materials were searched that are thin, stiff, and transparent or translucent. The first result were hollow polymer sheets; so-called hollow multi wall sheets. These sheets will provide stiffness to the thin glass and are available in a wide range of colours, thicknesses, and structures. Even though the twin wall already has an even outer layer, the addition of thin glass is essential since this makes the panel much more scratch resistant.

For this project the clearest and thinnest sheet is chosen for the thirst design proposal, which is the twin wall of 4 mm. To combine the glass and the polycarbonate, a lamination layer should be chosen. Since most of the lamination layers have a thickness of 0.76 mm and the thickness decreases a bit while laminating, a thickness of 0.7 mm is assumed for the final lamination layer. Together with the two thin glass sheets and the twin wall sheet, the total thickness will be 6.8 mm, see figure 19.

Composite glass with acrylic and air cavities

The next design is based on the use of PMMA as an in between layer like Hänig and Weller (2021) tested. Since the lack of still air in this concept gave a high U-value, the fourth idea proposes to laser cut hexagonal shapes out of an acrylic sheet and to laminate that to thin glass, see figure 20. In this situation the PMMA sheet will give support to the composite panel and the hexagonal spaces are enclosed by the glass, resulting in small rooms with still air. This concept has been tested in a similar way by Van der Weijde (2017), but in this research an aramid (paper) sheet is used instead of the proposed acrylic.

Since the PMMA will be laser cut, the size of the air cavities and the honeycomb 'wall' can be adjusted to a preferable dimension. Therefore, design four will experiment with different radii and give more variations on one design concept. Design 4a will have a radius of 10 mm, design 4b a radius of 20 mm and design 4c a radius of 30 mm.

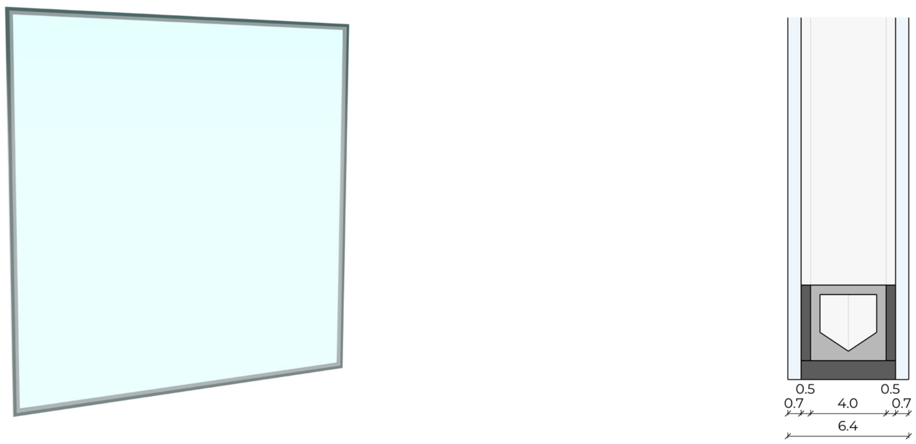


Figure 17: Design proposals 1 (Author)

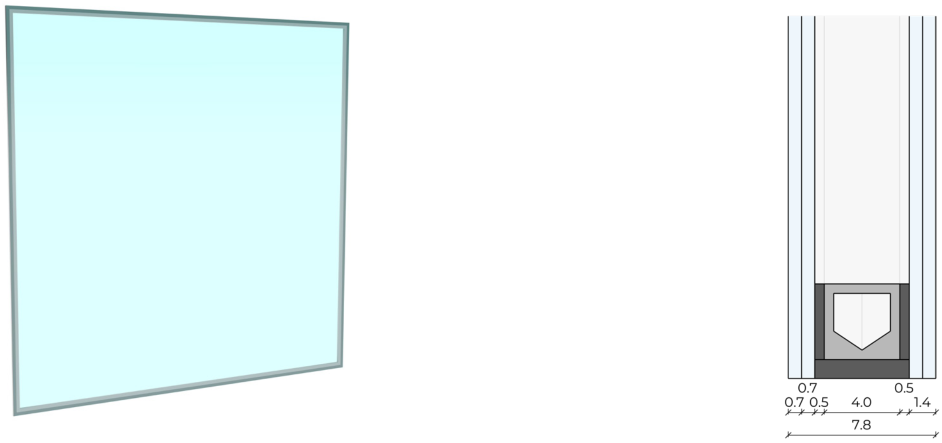


Figure 18: Design proposals 2 (Author)

Figure 19: Design proposals 3 (Author)

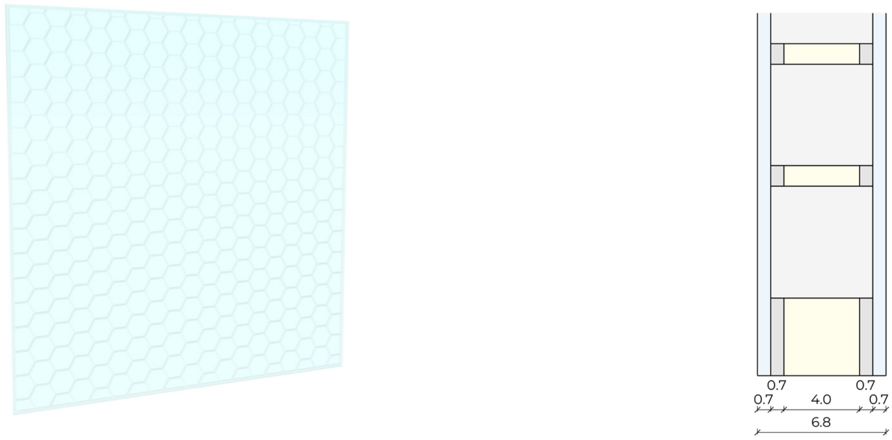


Figure 20: Design proposals 4b (Author)

Figure 21: Design proposals 5 (Author)

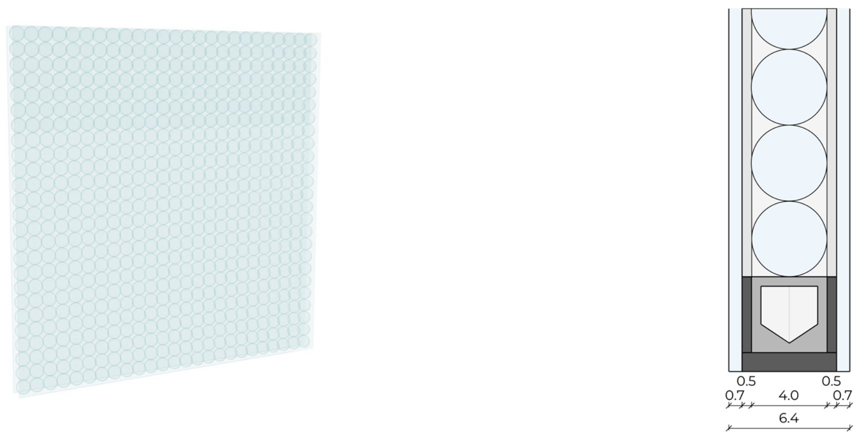


Figure 22: Design proposals 6 (Author)

This can be taken an extra step further and giving the client the opportunity to import their own design into the laser cutter. To test this possibility, a fifth design proposal is made where three different sizes of circles are randomly placed on the PMMA surface. This design proposal can be seen in figure 21.

Composite glass with balls

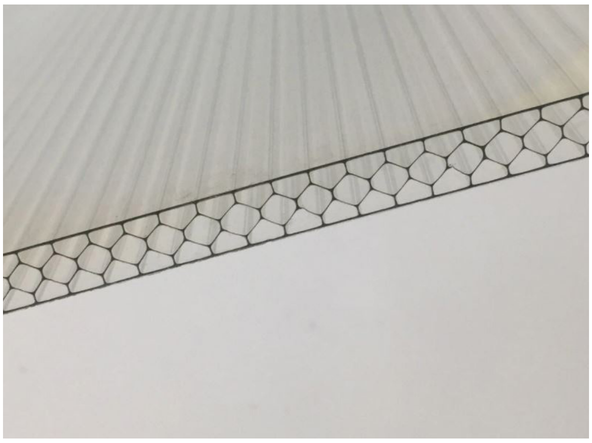
The most out of the box concept is a design where glass balls are placed in between two thin glass sheets. To create a stiff interlayer, the balls are attached to the glass sheets with a glue. Ideally the glass balls are transparent, and the glue can be set perfectly without getting in between the glass balls, resulting in an optimal volume of still air. Currently for this concept, reflective beats have been used with a size of 4 mm so the design options can be compared easily.

Non-suitable ideas

During the design phase, more ideas have been reviewed and did not meet the requirements. For instance, besides the twin wall sheet that is chosen now in proposal three, more prefabricated products were considered. Instead of the rectangular walls in the multi walls sheets, some manufacturers also offer sheets with a honeycomb structure in the centre, see figure 23. This improves the stiffness of the sheet but also results in less transparency due to the extra wall connections. In the end the material was not chosen since the thickness start from 16 mm and up and would exceed the maximum thickness of 12 mm of the final product.

Another product was found by the company Bencore® where two transparent polycarbonate sheets are attached to different polycarbonate compositions with adhesive. The design with various white circles is transparent bur starting from a 30° angle, the material is no longer see-trough. The other design in figure 23 has a good structural core but is only translucent. The products are mostly used for indoors and starts with a thickness of 19 mm. This is also the reason why the research did not continue with this possibility. (Bencore, n.d.)

Before design six with the glass balls was finalized, the first proposal was making use of hollow plastic balls. These would be casted in between the glass sheets with PMMA. In that case, the air captured inside the balls would work as insulating material. However, hollow plastic balls with a size of 4 mm in diameter do not seem to be an existing product on the market. Since glass balls/beats do, the research was continued with this more common product.



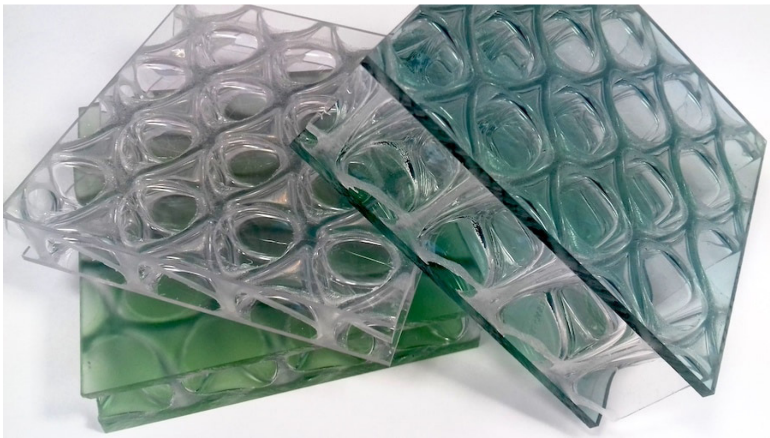


Figure 23: Different photos from reference papers (Saleh 2020; Van der Velden, 2020; Van der Weijde, 2017)

7.3 Modelling

The main goal of this section is to analyse if the design proposals will pass the boundary conditions. If sufficient, the prototypes can be made. The ideas will first be checked on thermal performance and then on deflection and stresses due to the wind load.

Thermal performance

To measure the thermal performance, a student license of SOLIDO by Physibel is used. The proposals are first modelled in Rhinoceros in which each layer represents a different material. The next step is to download each layer as a separate .stl file and to import those in SOLIDO. Each different layer needs to be addressed to a material from the material list. Then, two extra blocks should be added to represent the interior and the exterior properties. Moreover, an area needs to be determined to measure the Q and the U-value. After this, the grid can be made and the software can run the analysis. Unfortunately, the grid could not handle the 500x500 mm panel of design proposal six. This is therefore done with a 100x100 mm panel.

Figure 24 shows the analysis of design proposal 4c where the radius of 30mm is chosen. It can be seen that the centre of the hexagon has the best thermal performance. This is also the reason why the other sizes of the honeycomb patterns have a higher U-value, which are summed up in table 1. Since the thin insulated glass units have the most still air with the largest continues area, it is no surprise that they result in the best thermal performance. It can also be seen that design proposals five and six perform much worse than the maximum U-value of 3.8 W/m²*K. The lower percentage of still air is the cause of this. Therefore, these options are no longer explored in this graduation research.

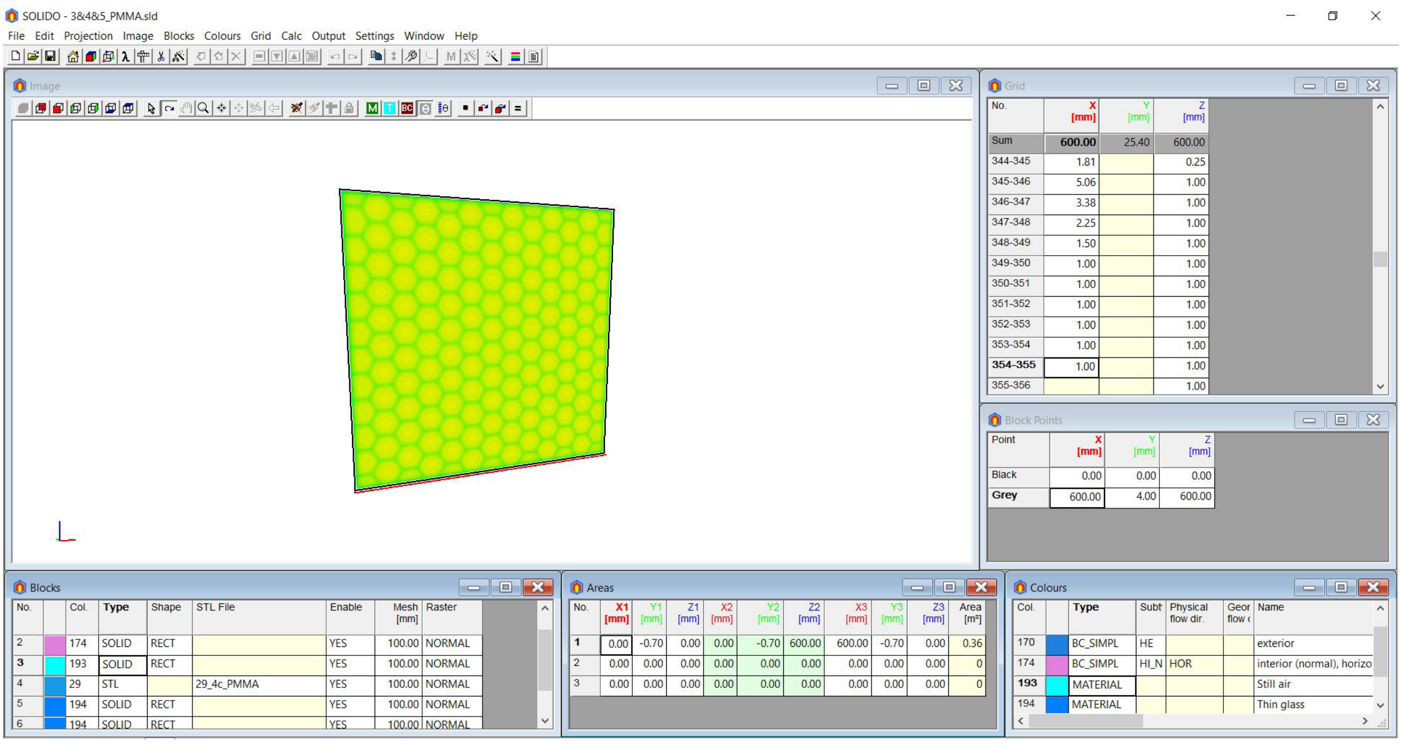
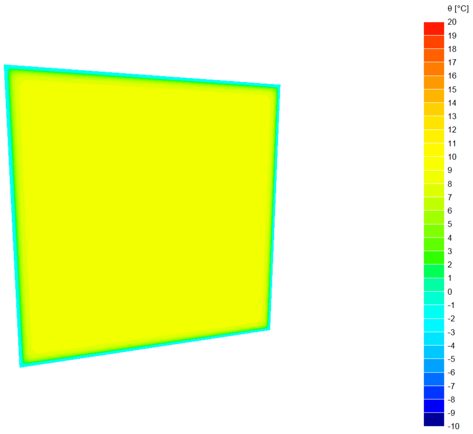
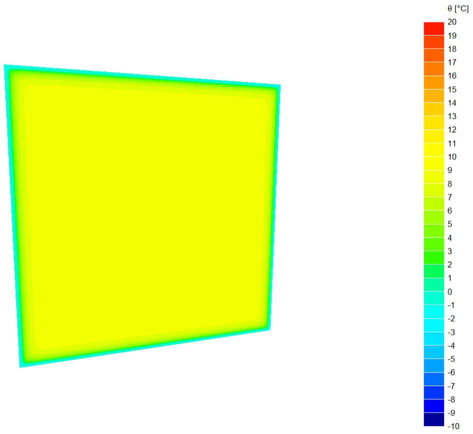


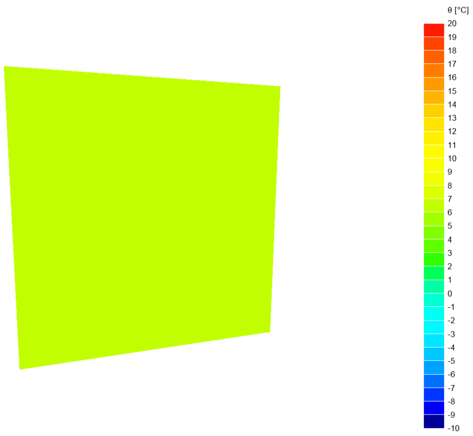
Figure 24: Screenshot of the SOLIDO software (Author)



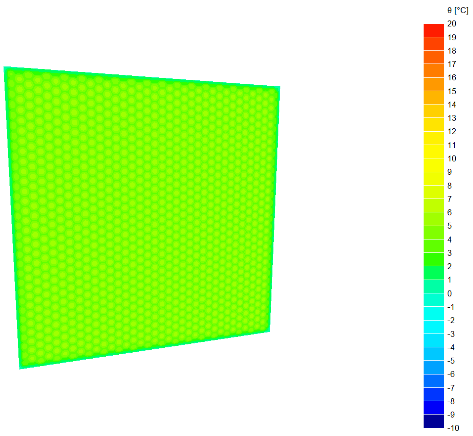
U-value 1 = 3.182 W/m²*K



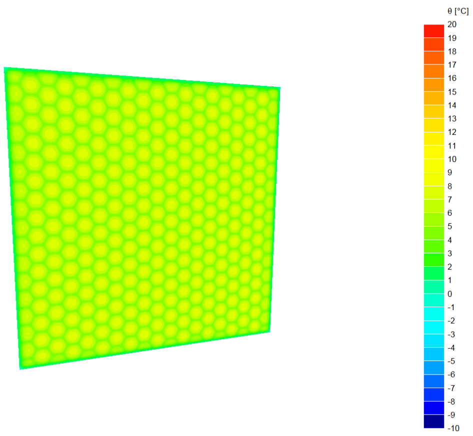
U-value 2 = 3.203 W/m²*K



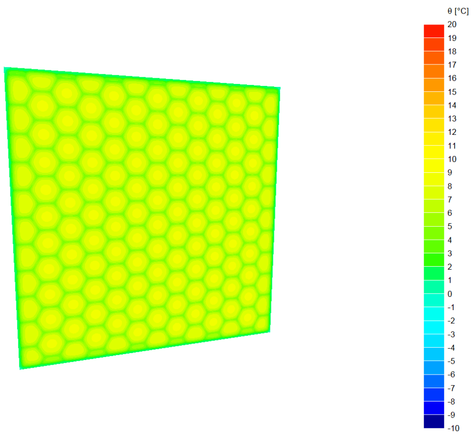
U-value 3 = 3.466 W/m²*K



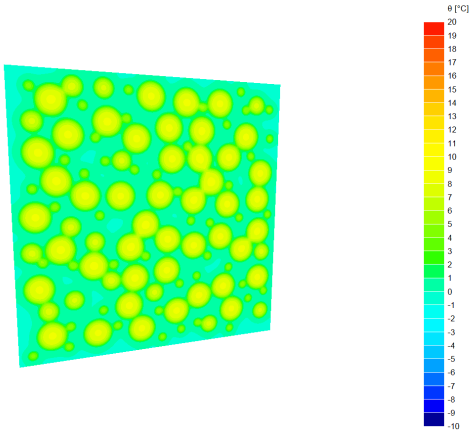
U-value 4a = 3.962 W/m²*K



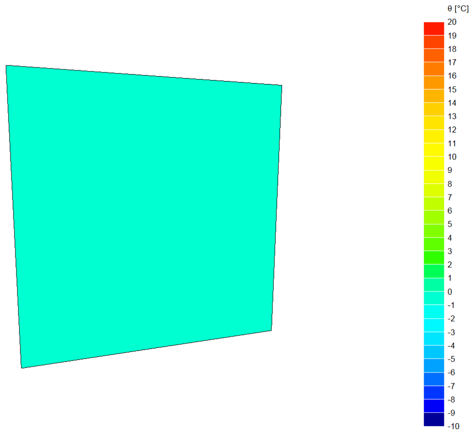
U-value 4b = 3.596 W/m²*K



U-value 4c = 3.471 W/m²*K



U-value 5 = 4.393 W/m²*K



U-value 6 = 5.224 W/m²*K

#	% still air	Q	A	U-value	>3,8
1	97%	23,87	0,25	3,18	:)
2	97%	24,02	0,25	3,20	:)
3	93%	26,00	0,25	3,47	:)
4a	76%	29,72	0,25	3,96	:(
4b	86%	26,97	0,25	3,60	:)
4c	89%	26,03	0,25	3,47	:)
5	44%	32,95	0,25	4,39	:(
6	48%	1,57	0,01	5,22	:(

Table 1: Output of the SOLIDO software (Author)

Structural performance

As described in the approach and methodology chapter, first the moment of inertia of the designs is calculated on a weak section. Since the sheet is seen as a beam, the wind load needs to be rewritten from a distributed load on a plate to a distributed load on a beam. With the Q = 1000 kPa and a width of the plate of 500 mm, the q = 0.5 N/mm. In case of design options one and two, the q is half since the short-term load is divided on both of the glass sheets of the IGU. Together with the young's modulus and the length of the beam, the deflection can be calculated using equation 4.

The next step is to calculate the stresses that occur in the beam. Since multiple designs are a composite, there is a difference in the materials and the maximum stress needs to be calculated at the most out of plane locations of the material. The stress of the glass needs to be multiplied by the factor of the young's modulus as the whole composite is now only seen as the polymer. The full calculations can be found in the Appendix. The final values are given in table 2 and compared to the maximum allowable deflection and stresses. According to the NEN norms, the maximum deflection is given in equation 10. (Nederlands Normalisatie-instituut, 2014) For the 500x500 mm prototypes, this is 10.88 mm. The table is also added to the Appendix.

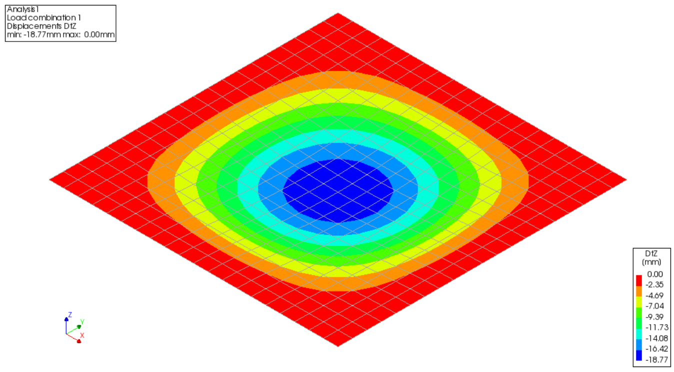
$$u_{dia,max} \leq \frac{l_{dia}}{65} \leq 50mm \qquad \textit{Equation 10}$$

#	Material	Deflection	Allowed deflection	Check deflection	Max stress	Allowed stress	Check stress
1	Glass	40,673	10,88	:(	127,55	15	:(
2	Glass	5,084	10,88	:)	31,89	15	:(
3	Glass	0,29748	10,88	:)	7,20	15	:)
	PC				0,17	70	:)
4a	Glass	0,29753	10,88	:)	7,21	15	:)
	PMMA				0,22	70	:)
4b	Glass	0,29793	10,88	:)	7,21	15	:)
	PMMA				0,22	70	:)
4c	Glass	0,29806	10,88	:)	7,20	15	:)
	PMMA				0,22	70	:)

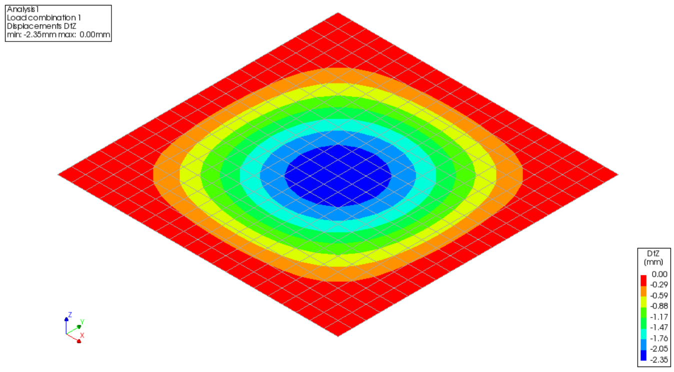
Table 2: Outputs of the hand calcualtions (Author)

In the DIANA software a beam with clamped supports is modelled using the found moment of inertia in the hand calculations and the height of the beam, which is related to the analysed design. Then, the same q load and the young's modulus of the polymer are used to find the deflections and the stresses. However, DIANA only gives the maximum stresses of the cross sections, so the stresses that are given in table 2 are the stresses on the most outer part of the cross section seen as a complete polymer. When these are multiplied by the factor of the young's modulus they can be seen as the maximum stress in the glass sheets.

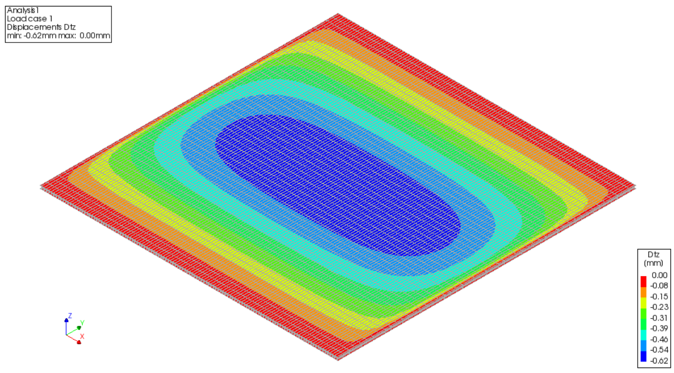
The method above is relatively simple method to verify the hand calculations. To analyse the more complex compositions as a whole, the models are made into 3D shapes. Design proposal three will be made with two sheets to represent the glass plates and small, long sheets to represent the walls of the PC twin wall sheet. Within this design, the PC sheet parallel to the glass is neglected since the glass will take most of the forces because it is almost 25 times as strong. Within DIANA the sheets can be assigned a certain thickness, representing the properties in real life. For design proposal four, the honeycomb sheet and the glass are also simplified to sheets. The outcomes are given in the next pages.



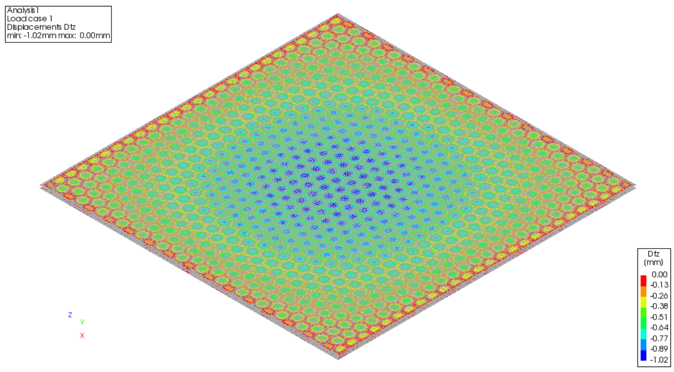
Deflection 1 = -18.77 mm



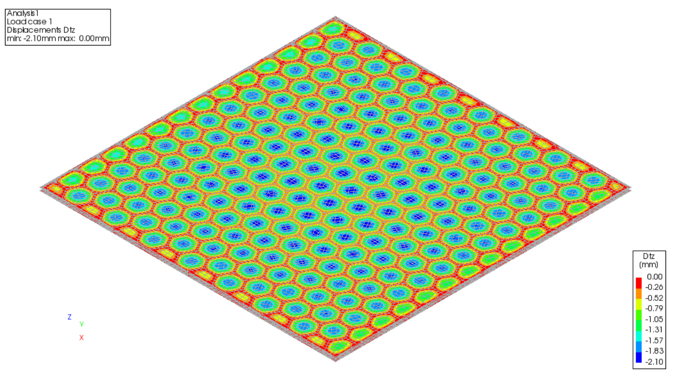
Deflection 2 = -2.35 mm



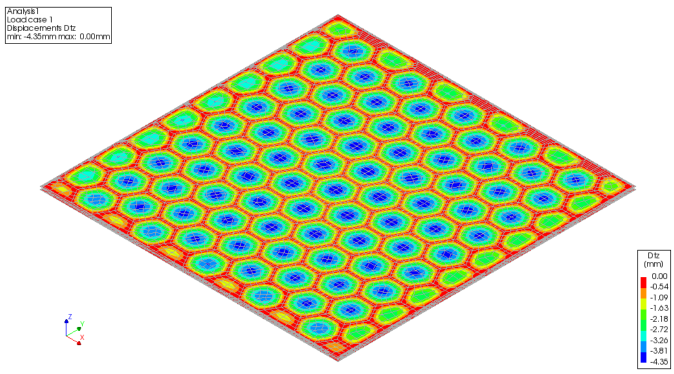
Deflection 3 = -0.62 mm



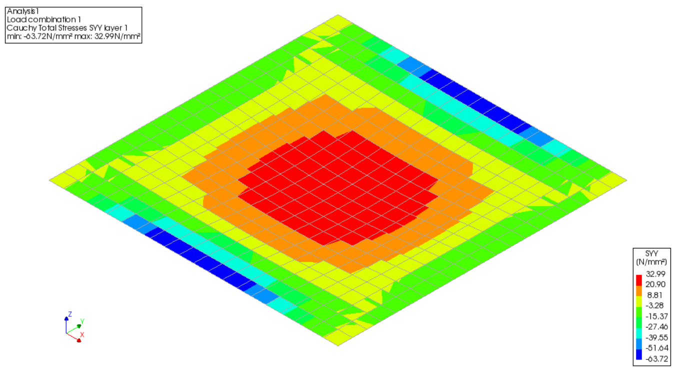
Deflection 4a = -1.02 mm



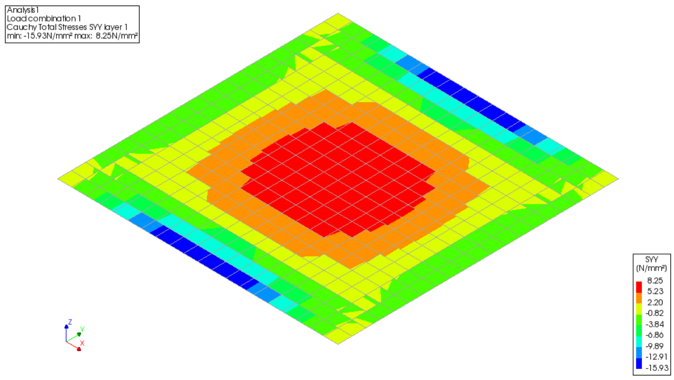
Deflection 4b = -2.10 mm



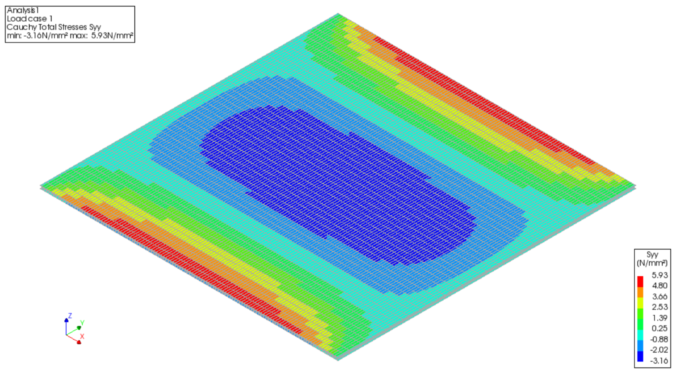
Deflection 4c = -4.35 mm



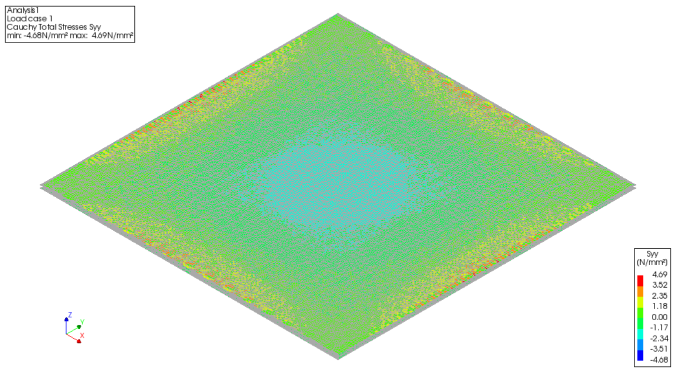
Maximum stress 1 = -63.72 N/mm²



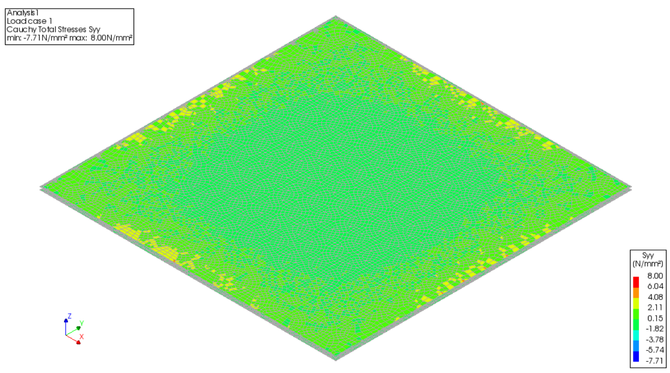
Maximum stress 2 = -15.93 N/mm²



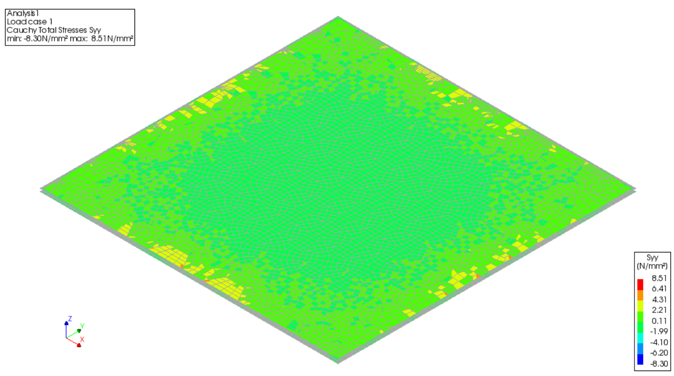
Maximum stress 3 = 5.93 N/mm²



Maximum stress 4a = 4.69 N/mm²



Maximum stress 4b = 8.00 N/mm²



Maximum stress 4c = 8.51 N/mm²

#	Material	Deflection	Diana deflection	Check deflection	Max stress	Diana stress	Allowed stress	Check stress
1	Glass	40,673	18,77	:(	127,55	63,72	15	:(
2	Glass	5,084	2,35	:)	31,89	15,93	15	:(
	Glass				7,20		15	:)
3	PC	0,29748	0,62	:)	0,17	5,93	70	:)
	Glass				7,21		15	:)
4a	PMMA	0,29753	1,02	:)	0,22	4,69	70	:)
	Glass				7,21		15	:)
4b	PMMA	0,29793	2,10	:)	0,22	8,00	70	:)
	Glass				7,20		15	:)
4c	PMMA	0,29806	4,35	:)	0,22	8,51	70	:)

Table 3: Outputs of the DIANA calcualtions (Author)

Looking at the new DIANA values, they have the same order of magnitude as the hand calculations. However, they do show the importance of the clamped edges and the complete working of the 3D structure. Because the design is now supported on four sides of the model, the deflection of design one and two is half of the value from the hand calculations. This is the same for the stress in these designs. Unfortunately, this is still not enough to make design one and two pass the limits.

The deflection values that are given by DIANA for design three and four are more in line with the expected behaviour of the design options. For design 4, the larger the cavities, the greater the deflection. Even though this is already slightly showing at the hand calculations, the values from DIANA make this more visible. This is because the larger cavities have relatively less PMMA and more air. This is an advantage for the thermal performance which was stated before, but also works as disadvantage for the structural performance. A next step for this research could be to find the most optimal ratio between the air and the PMMA.

When looking at the different stress figures on the previous page, a few notes can be made. First, design three has a relative broad 'blue' area compared to the two figures above. This is because it has an inhomogeneous design and is stronger in one direction, just like wood. In the figure, the 'walls' go from the bottom left to the top right. When using this product in a window frame, the preferred way to do this, is to place the walls in the longest direction. Moreover, in design 4a the colour pattern of design one and two can be seen, but in design 4b and 4c this fades away more. In these designs the 'blue' areas are getting bigger as they are closer to the centre. Finally, it can be said that the highest stresses appear near the edges. This can be explained by the fact that the highest stresses in a clamped plate are near the supports. If this would be a simple support, the maximum stress would be in the centre of the plate. The figure for design 3 should also display the red colour on all edges. The turquoise, green, yellow, orange, and red should all follow the blue circles for the stresses. This flaw is due to the iaccuracy and generalizing of the design in DIANA.

7.4 Prototypes

When the modelling is done and the designs seem to be sufficient, the making of the prototypes can begin. For this step, lots of materials are needed. Since all the material has to be bought by the student, multiple companies and suppliers were contacted to ask if they were able to send some samples or products. A list of these products is given in table 4, including their supplier or store that they were bought in and their size. The glass sheets of 500x500 mm that were received from Corning are annealed. The 600x600 mm sheets are chemically strengthened.

Material	Supplier/store	Gift vs. bought	Size
Thin glass sheet	Corning	Gift	20x 500*500*0.7 mm and 15x 600*600*0.7 mm
Spacer	Stolker Glas	Gift	6x 2 m
Butyl sealant	Stolker Glas	Gift	On location, as much as needed
Multiwall sheet	Witteburg B.V.	Gift	2x 900*900*4 mm
EVA	PV Lab	Gift	On location, as much as needed
PMMA 4mm	CAMLab	Bought	1x 300*300*4 mm and 2x 800*450*4 mm
Reflective beads	Marcel Bilow	Gift	Small bag with beads of 1000-1300 μm

Table 4: Material list for prototyping (Author)

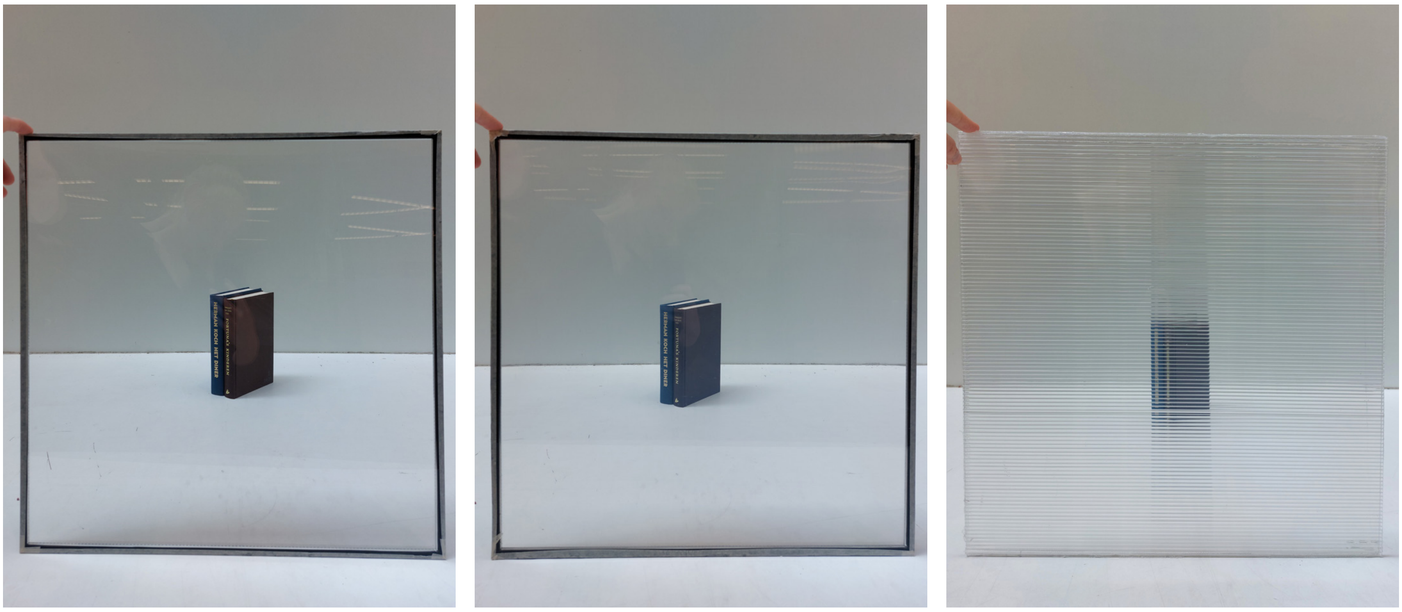


Figure 25: The final prototypes f.l.t.r. design 1, design 2 and design 3 (Author)

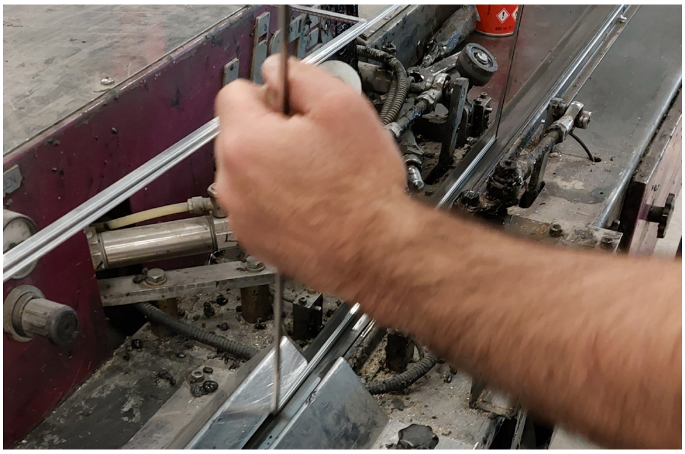
The final three 500x500 mm prototypes were measured and weighted 8 times and then averaged. The thickness of design 1 is 1 mm thicker than expected value of 5.4 mm. This is probably due to the roughness of applying the butyl to the edges where leftover material stuck to the outside of the prototype. To prevent the butyl from sticking to all other materials, tape was used around the edges. All this could become the extra 1 mm. Design 2 is only 0.2 mm thicker than the expected thickness and design 3 is 0.7 mm smaller. This is probably because the EVA melted more than predicted. The weight of design 2 is doubled because the glass volume is doubled. Compared to the glass, the weight of the spacer and EVA can be neglected. The twin wall is 0,8 kg/m² so the weight of design 3 falls within the expected range. (Exolon Group, 2021)

#	Thickness (mm)	Weight (g)
1	6,5	910
2	8,4	1955
3	6,1	1221

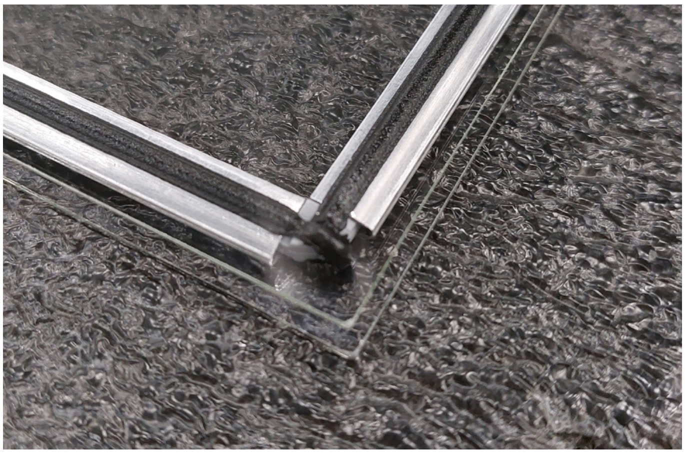
Table 5: Measurements of the final prototypes (Author)

First, the spacer should be cut to the right size with a small band saw. The edges can be made smooth with a file.

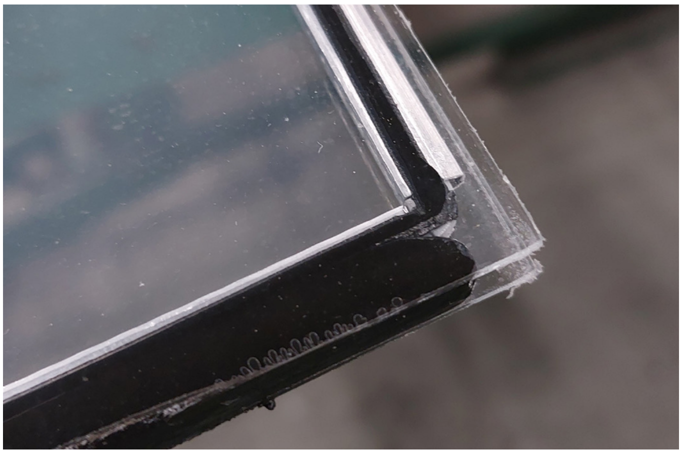
Next, plastic elements with a 90-degree angle are used to connect all the spacers together. In this step, also small absorbing balls can be added to prevent moisture inside the IGU.



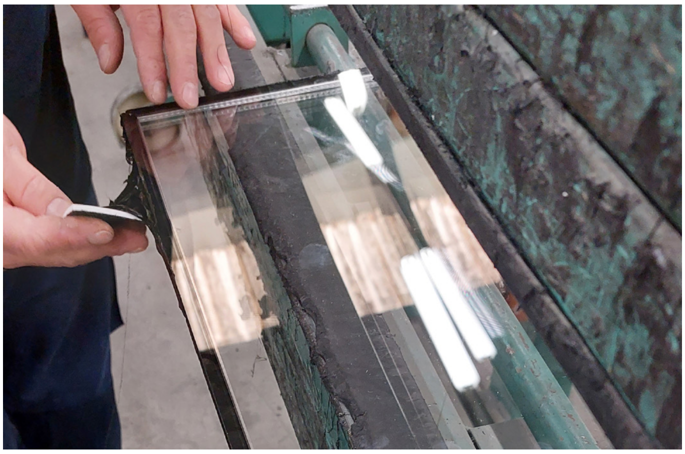
The spacer then goes to a small machine where the first sealant (butyl) is applied.



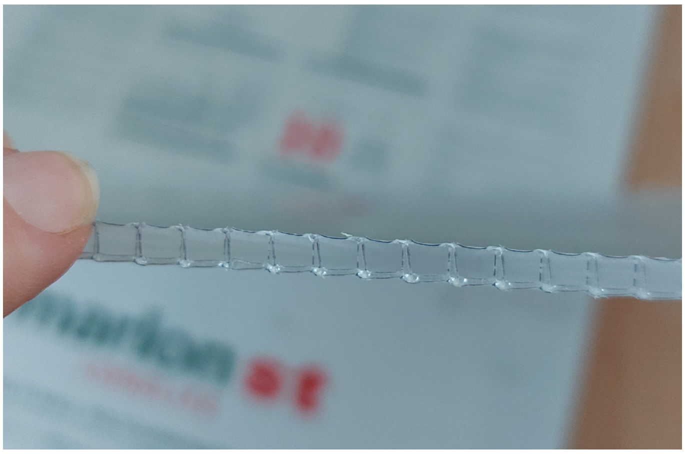
Using small pressure, the glass can now be added on each side of the spacers. For design one, a single sheet of glass is used. For the second design, a laminated sheet is used, made with an EVA interlayer.



With a hot melt butyl gun the second sealant is then applied. This fills up the distance from the spacer to the edge of the glass.



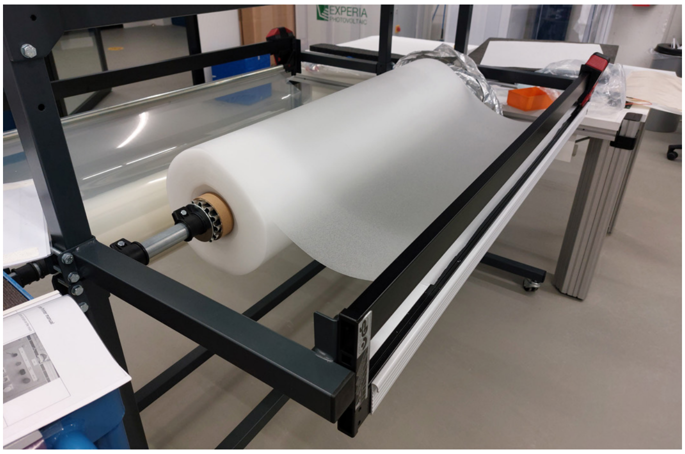
Finally, the excess of the butyl can be scraped off when the butyl is still warm. This is done with a special piece of material that is not sticking to the butyl.



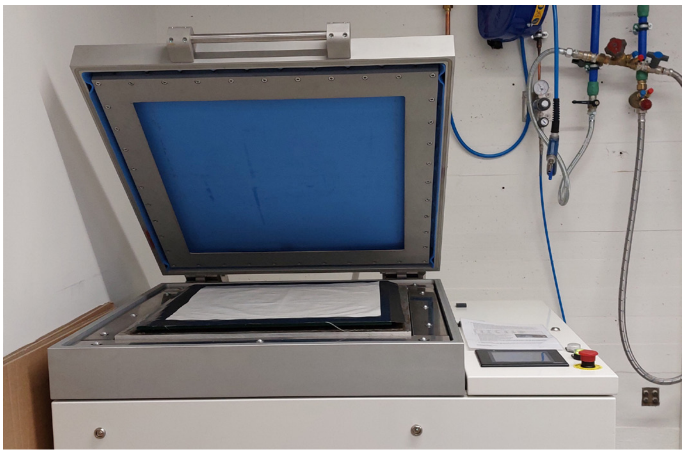
Two sheets of 900x900x4 mm have arrived for the company Witteburg B.V.

The sheet needs to be cut to the right size. This is done with a circle saw at the BK faculty.

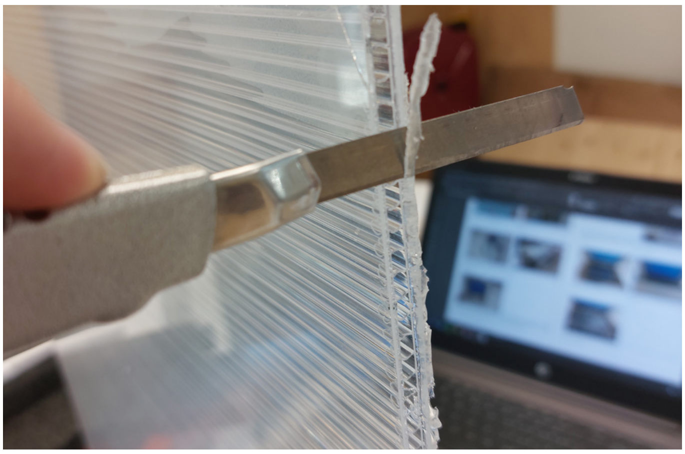
Dust is created during the cutting and gets caught in the small cavities of the sheet. This is blown out with an air pressure machine at the PVLab.



The EVA interlayer is shipped in large rolls. At the PVLab, the sheet is cut to the right size.

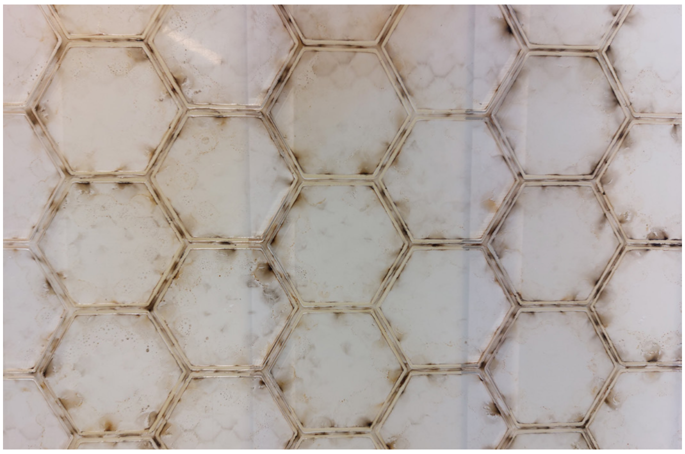


The materials are then placed in the correct order and placed in the lamination machine. This process takes about 30-45 minutes.

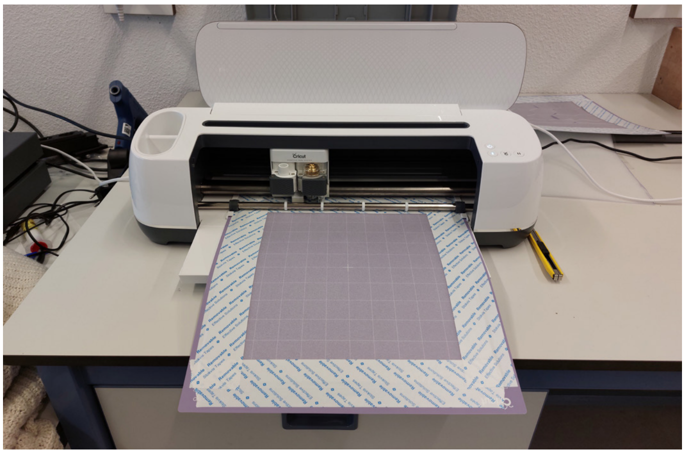


After the lamination is done and it is cooled down, the excess of the EVA can be cut off with a sharp Stanley knife.

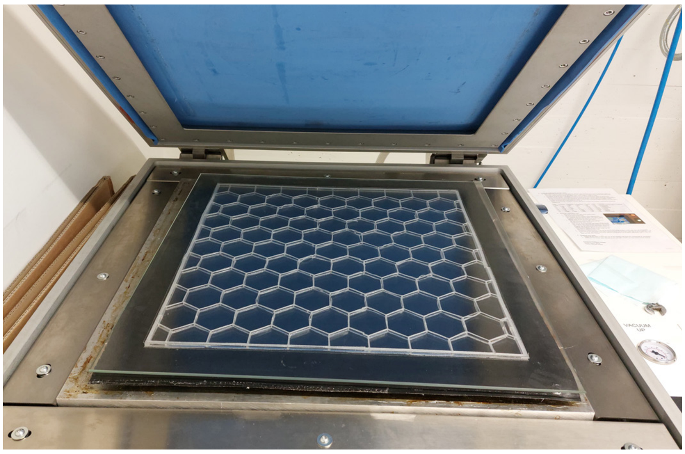
Build order design 4



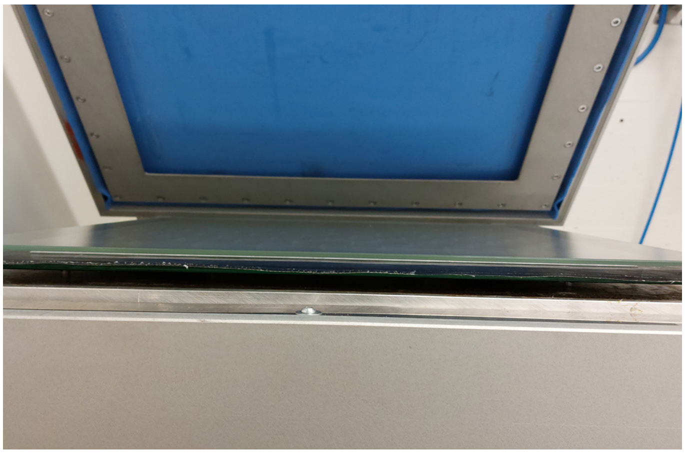
First, the honeycomb pattern is laser cut into the PMMA by the CAMLab at the BK faculty.



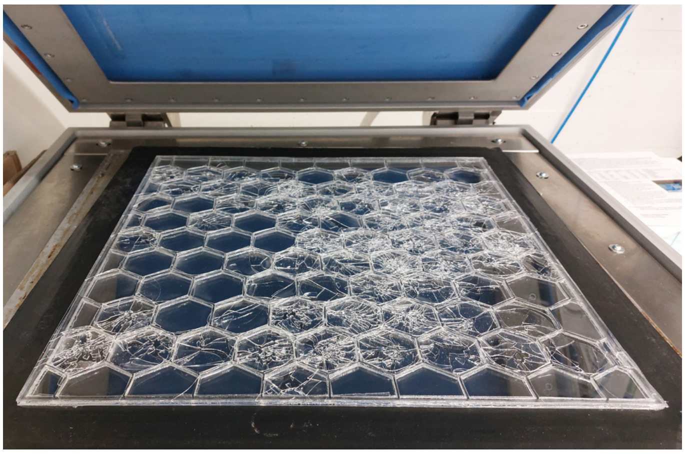
The EVA layers also has to be cut with a Cricut Maker® so the EVA does not fill the air cavities.



Next, the different layers are place correctly in the lamination machine.

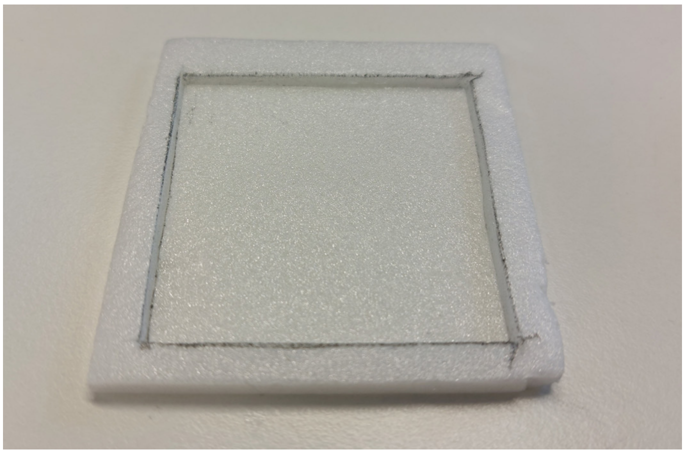


To distribute the compressive force on the prototype, a thicker glass panel is placed on top.



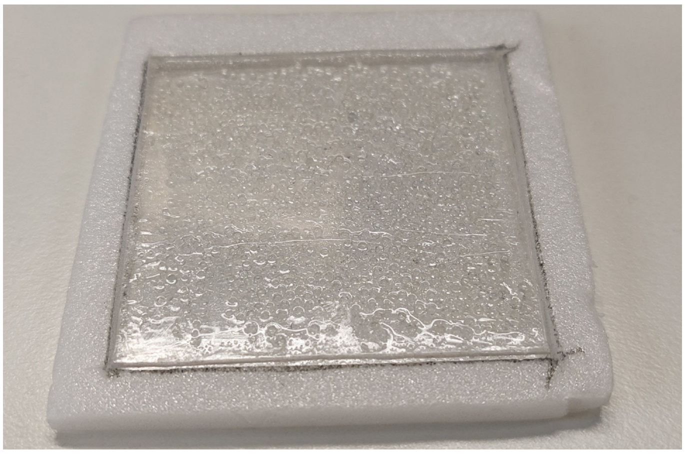
Sadly, the glass still broke during the process. This is discussed more in dept in the next paragraph.

The sixth design proposal with the glass balls did not pass the thermal performance analysis, but a sample was made to see the transparency / translucency. For this, reflective glass beads were used (1300μm).

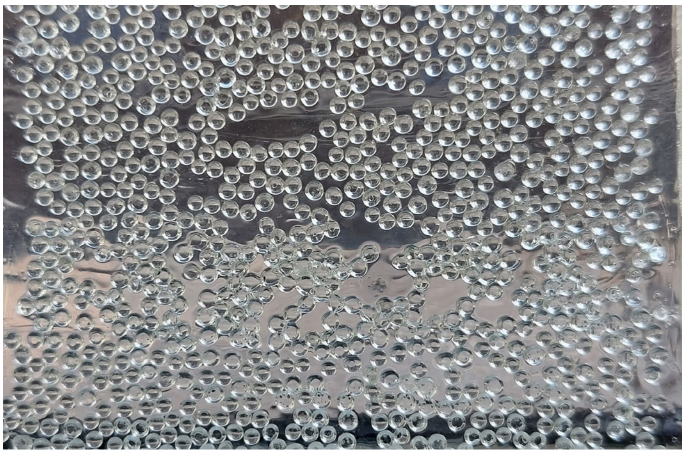


A small cast for the glass was created and COLLALL® all-purpose glue was poured on top of the glass sheet.

Then the reflective beads were poured on top, so they would stick to the glass. However, since they are round, they did not bond well and lots fell off.



A new glass sheet was placed in the cast and glue was again poured. Then, the previous sheet with the bead was placed on top of it.



Once the glue was completely dried, it became clear that the test piece was not transparent but only translucent. This is mainly because the beads give the rays of sunlight a curve.

Issues during the process

Make the prototypes has come with multiple difficulties. Glass does not bend, but it breaks if the maximum stresses are reached. This makes it more difficult to estimate when the glass will break if you are working on it on site.

For making the prototype for design one and two, the IGU was made in the manufactory of Stolker Glas. For this trip to Ede, the Netherlands, I brought two sheets of 500x500 mm thin glass, two sheets of 500x500 mm laminated thin glass and two sheets of 600x600 mm thin glass The production of the IGU was done very carefully and worked. However, when we cleaned the 500x500 IGU with non-laminated glass, we pushed a bit too hard on the glass and it broke. Figure 26 shows the crack on the top layer and confirms that the glass was indeed non-strengthened glass, because the glass pieces are big and long.

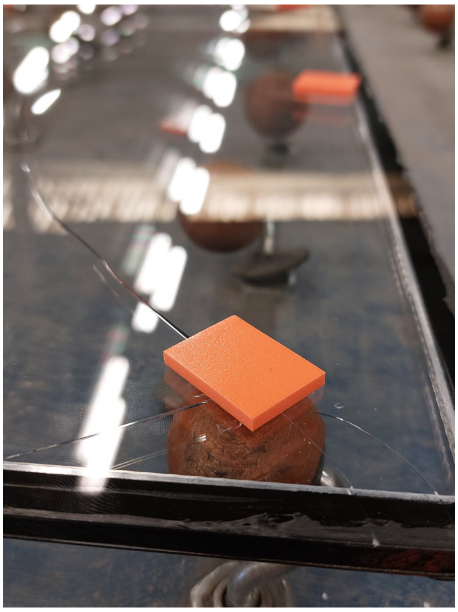


Figure 26: Crack on glass due to point load (Author)

To transport the glass to the manufactory in Ede, a larger construction of a cardboard plate and foam elements was made. Using straps, the foam could be set in place and secure the glass in between. However, using public transport to make the trip, made me accidentally bump into a train seat which caused a point load on the edge of the IGU and the glass. This damaged the 600x600 IGU and both of the glass sheets broke. Figure 27 shows that the location of the load is scattered and how the crack lines have formed from there.

For design three and four, the lamination machine was used at the PVLab. To use this machine, the different steps must be set in advance. These settings determine, among other things, the temperature and the duration of the process. The temperature needs to be higher than the melting temperature of the EVA lamination sheet, but lower than the softening and melting temperatures of the other layers. This makes the duration of the process besides the thickness of the product also dependent on the temperature. Since the people at the PVLab had no experience in my polymer products, multiple test samples were made.

For design three, a small test sample of 100x100 mm was made. The outcome of this sample was good, but still a few notes were taken. First, the interlayer was cut a bit larger around the edges. This was done so hopefully the EVA would fill the gaps of the twin wall to create closed cavities. Sadly, it did not completely cover the holes and the air could still flow through the sample. Moreover, after some time, the sample showed small inequalities near the edges. In these areas the EVA had disconnected to the parallel elements of the twin wall sheet. The assumption is made that this had to do with the thermal expansion of the

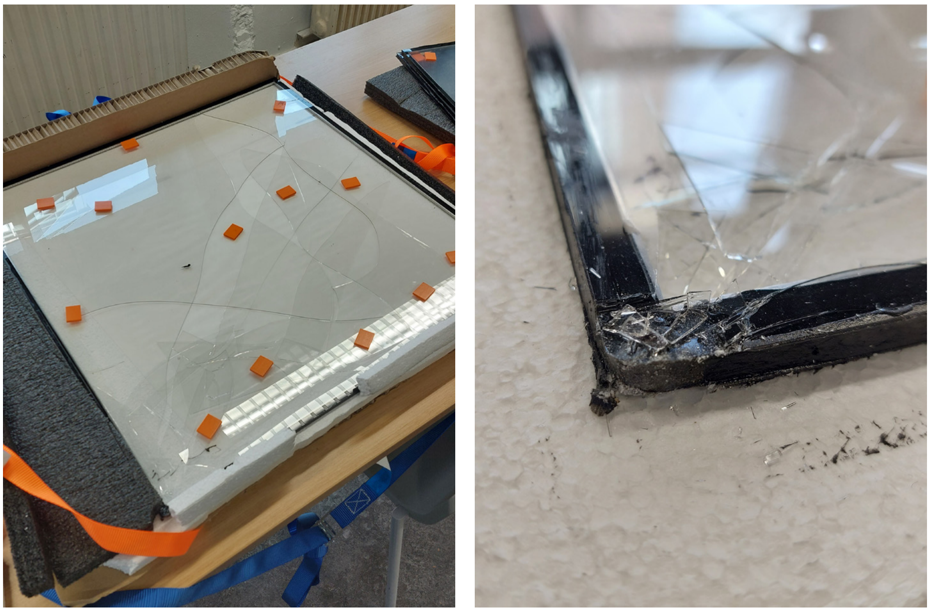


Figure 27: Cracks on IGU of 600x600mm (Author)

twin wall compared to the glass and EVA, but later the issue also showed at PV cells, made by the PVLab team. To solve this issue, the next prototype was placed in the machine for a longer period so the EVA could attach better.

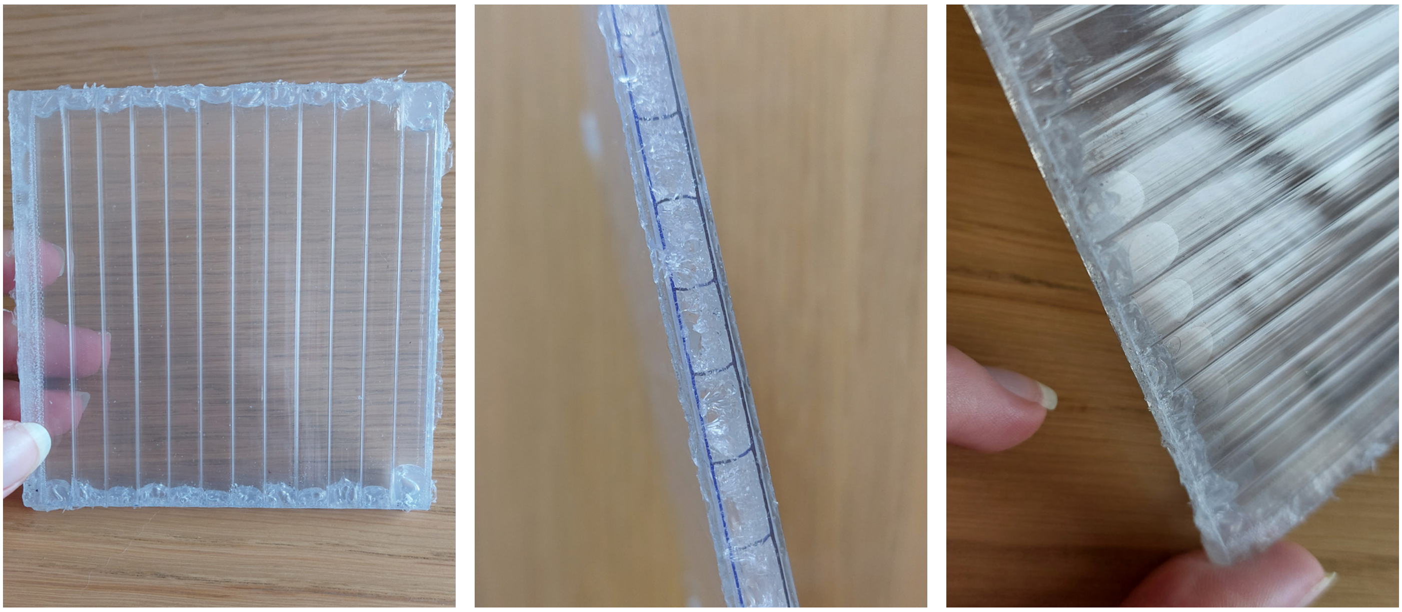


Figure 28: Sample of 100x100mm of design three (Author)

Making the larger size of design 3 came with a small issue. The twin wall had gotten a slight curvature after the cutting it. When the prototype was placed in the lamination machine, the machine pressed the sheet flat but probably also broke the thin glass on the edges with this movement. Generally speaking, this breakage is not a large issue for this graduation research but should be resolved if the product would become available to the public. Another complication was that the twin wall sheet had bent a bit before the lamination. This gave a small dent in between the walls and gathered more EVA than the rest of the sheet. In this line, the panel is less transparent.

Two samples for design 4a and design 4b were made. This was done so a variation between the 'walls' of the honeycomb pattern was created. For design 4a the walls had a thickness of 1 mm and 2 mm. The walls of design 4b were 2 mm and 3 mm. This difference was made to experiment with the running of the EVA, which was cut to 1 mm in all cases. In figure 30, the EVA has run a lot compared to the others and this gave bubbles that disturb

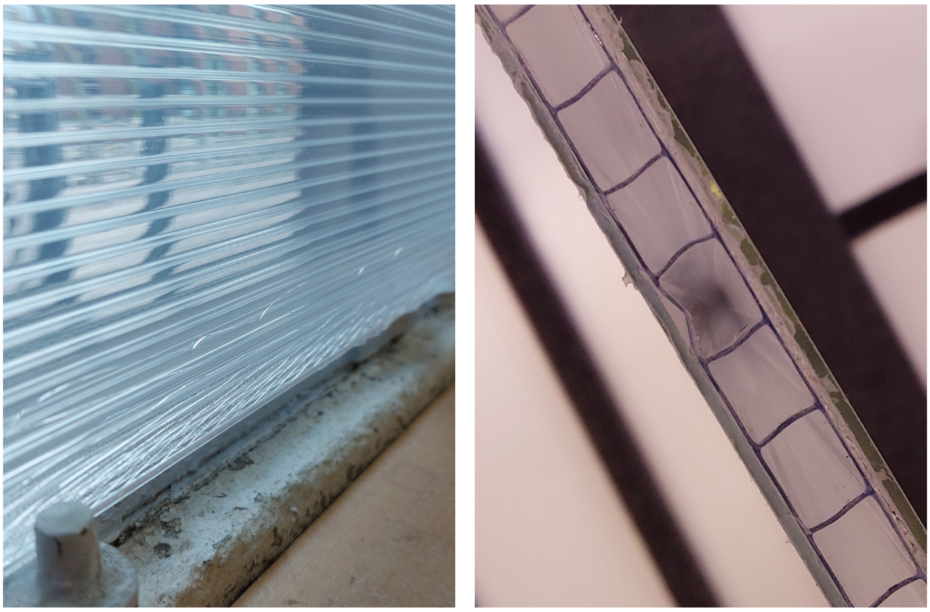


Figure 29: Issues in the prototype of design three (Author)

the transparency. Moreover, one of the walls in the 1 mm sample broke even before the lamination started. Between the excess of the EVA in 2 mm and 3 mm there is not so much difference. The final prototypes were therefore designed with a wall of 2 mm in thickness.

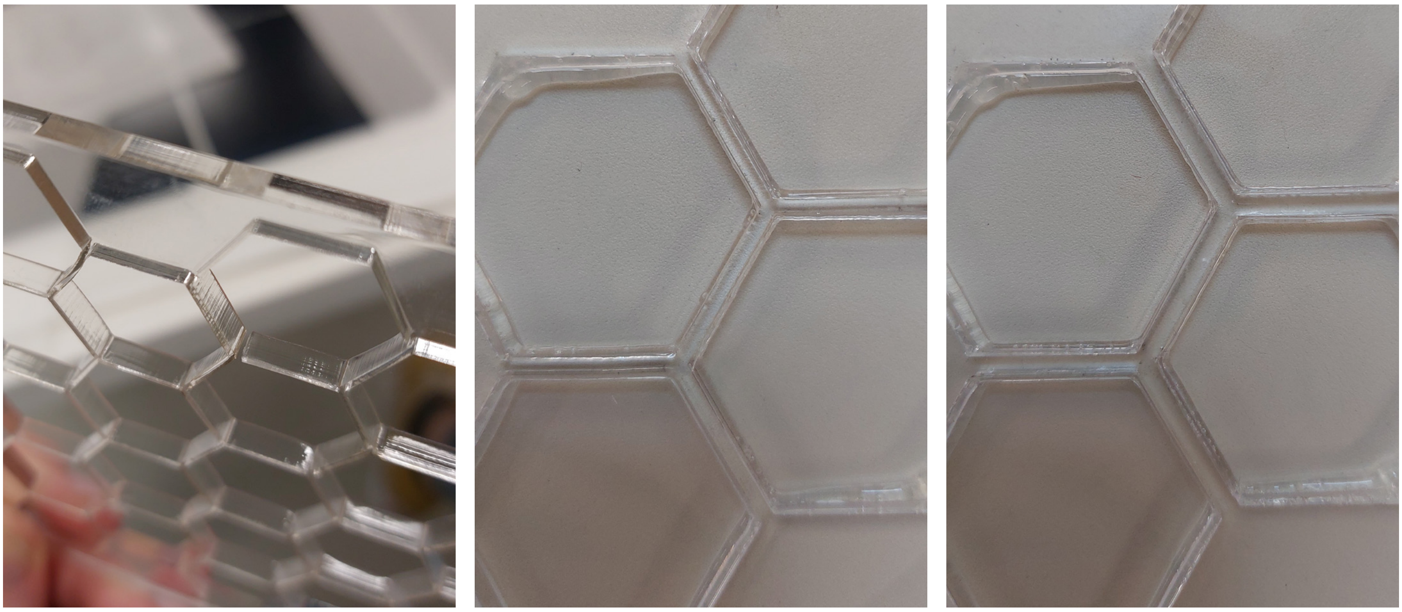


Figure 30: Test samples of design four (Author)

Once the larger sized materials were ready to be laminated, design 4c was placed in the lamination machine first. Even though no cracking noise was heard during the lamination process, the upper glass sheet was completely scattered when the machine was opened at the end. The bottom glass sheet was still intact. When looking at the breakage patterns, two types of figures are common. One is seen in figure 31 where almost a 'circle' is made with a small distance from the PMMA walls. The second one is more some sort of broom breakage with a certain point where all the lines start from. Both are due to the pressure that is applied by the lamination machine, but the first one can be explained by looking at the theoretical principle. In a plate that is clamped on all edges, the stresses due to a uniform load are the highest near the supports. The second one is more due to a peak stress that starts at one point and splits into different directions (the broom). This is an unexpected situation, so to distribute the force of the lamination more across the prototype, the idea was suggested to place a thicker glass sheet on top.

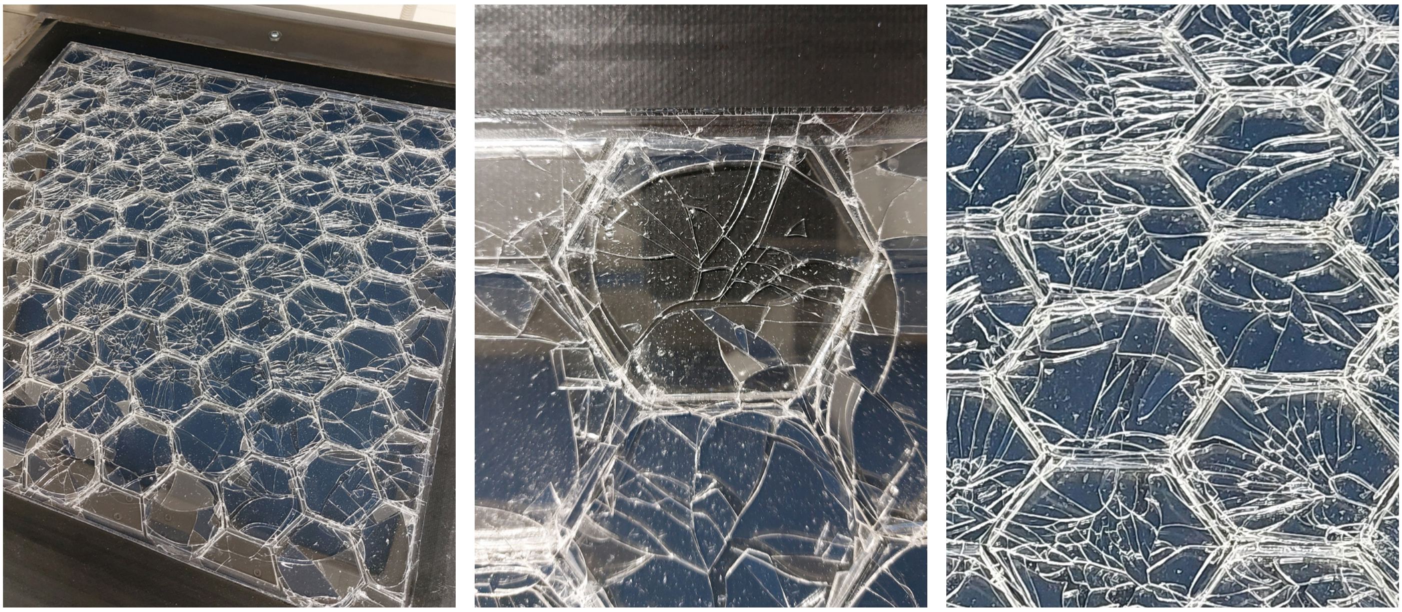


Figure 31: Breakage on the larger prototype of design 4c (Author)

For the prototype of design 4c, the EVA was cut with a Stanley knife by hand. This process took 6 hours to cut one sheet, so a total of ± 12 hours for only one prototype. Since this is such a time-consuming job, other ways were searched. Using the laser cutter for this is not an option because the EVA gets very sticky in its melted state and would reconnect to the split part. Then, a cutting machine was found at the Reactor Instituut Delft (RID) via Ernst van der Wal. This machine is from the brand Cricut Maker® and has a sharp rolling blade that can cut out any design by 30x30 cm or less. The machine is mostly used in the sticker branch and cutting out the two EVA sheets took now ± 3 hours.

Sadly, as already described in the build order, the addition of an extra glass sheet on top of the prototype did not prevent the glass from breaking. However, another pattern in damage can be seen. Or perhaps the lack of pattern is what is most interesting. Of all the cavities, none of them have remained intact. About 60% of them are completely shattered, just as the previous trial, but the others have only the crack near the wall of the PMMA. This means that the force is more distributed but not as much as hoped. Looking at those less damaged cavities, no clear pattern can be seen in the location of those cells. It can be said that they do appear more near the top and bottom edges of figure 32b, but those cells are

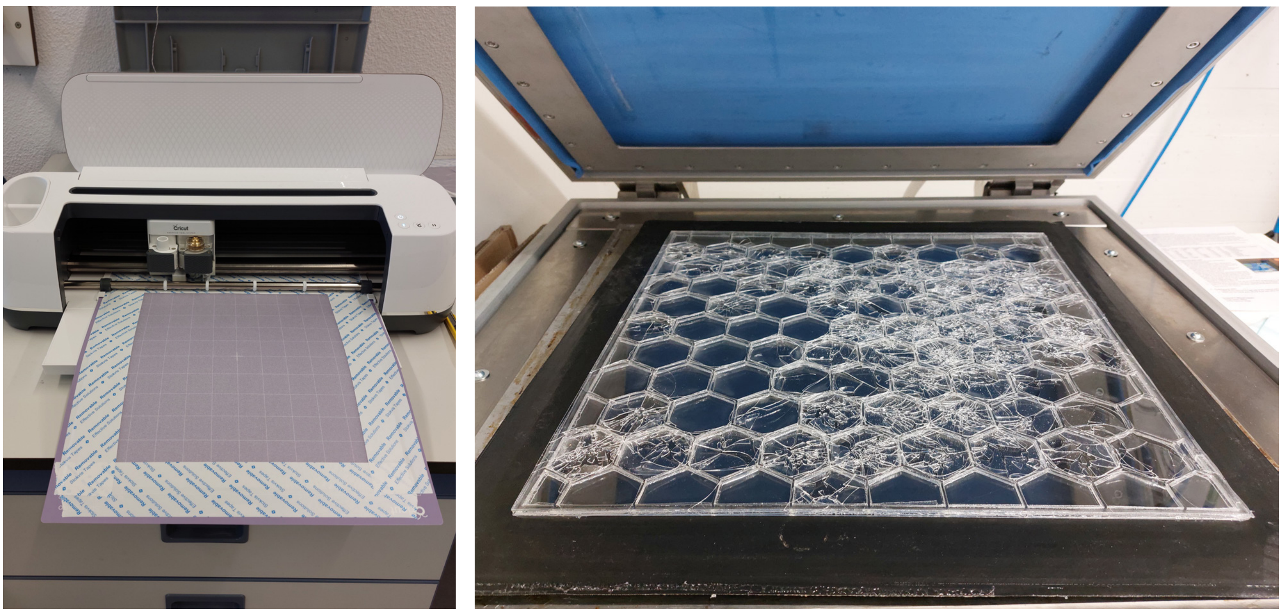


Figure 32: a)The Cricut Maker® cutter, b) Breakage of the second prototype of design 4c (Author)

also smaller. And even that is not completely true, since there is also a larger area in the centre with this damage type. It is therefore assumed that the lamination machine has a non-uniform load distribution, which is already a known fact by the PVLab staff.

Another small issue was the transparency of the EVA sheets. After the lamination they did become transparent but had a 'milky' haze of them, which is not ideal. A comparison can be seen in figure 33. However, in this graduation research it was the only material that was available, but for further research other types of lamination layers could be tested. Multiple options for this are given in the background literature of this graduation report.

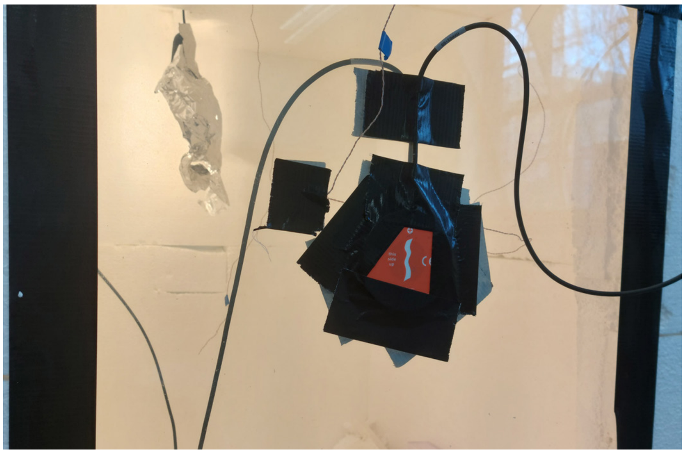
Figure 33: 'Milky' haze on the laminated IGU (Author)

Most of the issues that were seen are small and due to human mistakes or clumsiness. If the final products are made in a professional firm and perfect circumstances, those simple complications are solved or unlikely to happen. For instance, the glass of design 3 would not crack on the edges, giving a higher strength, the twin wall would not bend before it is laminated to the glass and the 'milky' view would be much less.

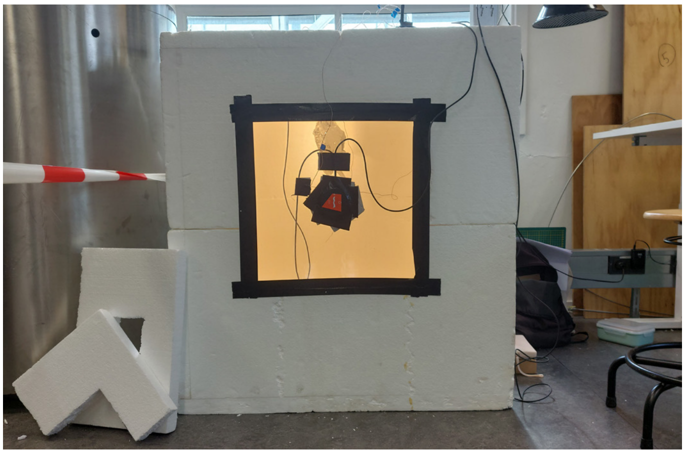
7.5 Testing the thermal performance

To test the prototypes in the unguarded hot box, the hole had to be cut to 500x500 mm for the first series. This was done with a Stanley knife.

Next, the Hukseflux sensor and a temperature sensor are taped to the inner side of the prototype. The second Hukseflux sensor and temperature sensor are attached on the outer side of the sample on the same spot.



The test sample can then be placed in the gap and be extra secured by adding more tape. This also prevents air leakage around the prototype.

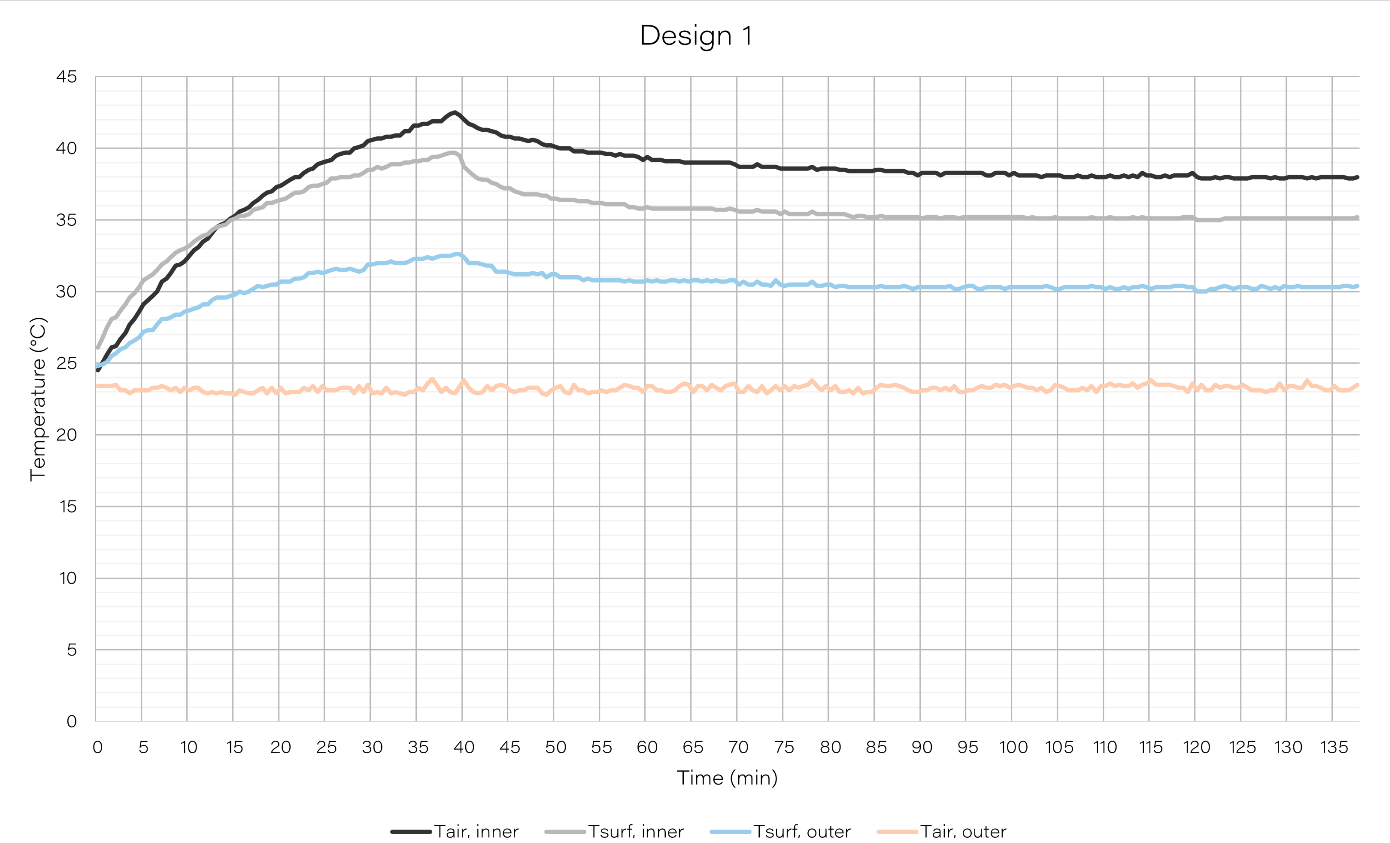


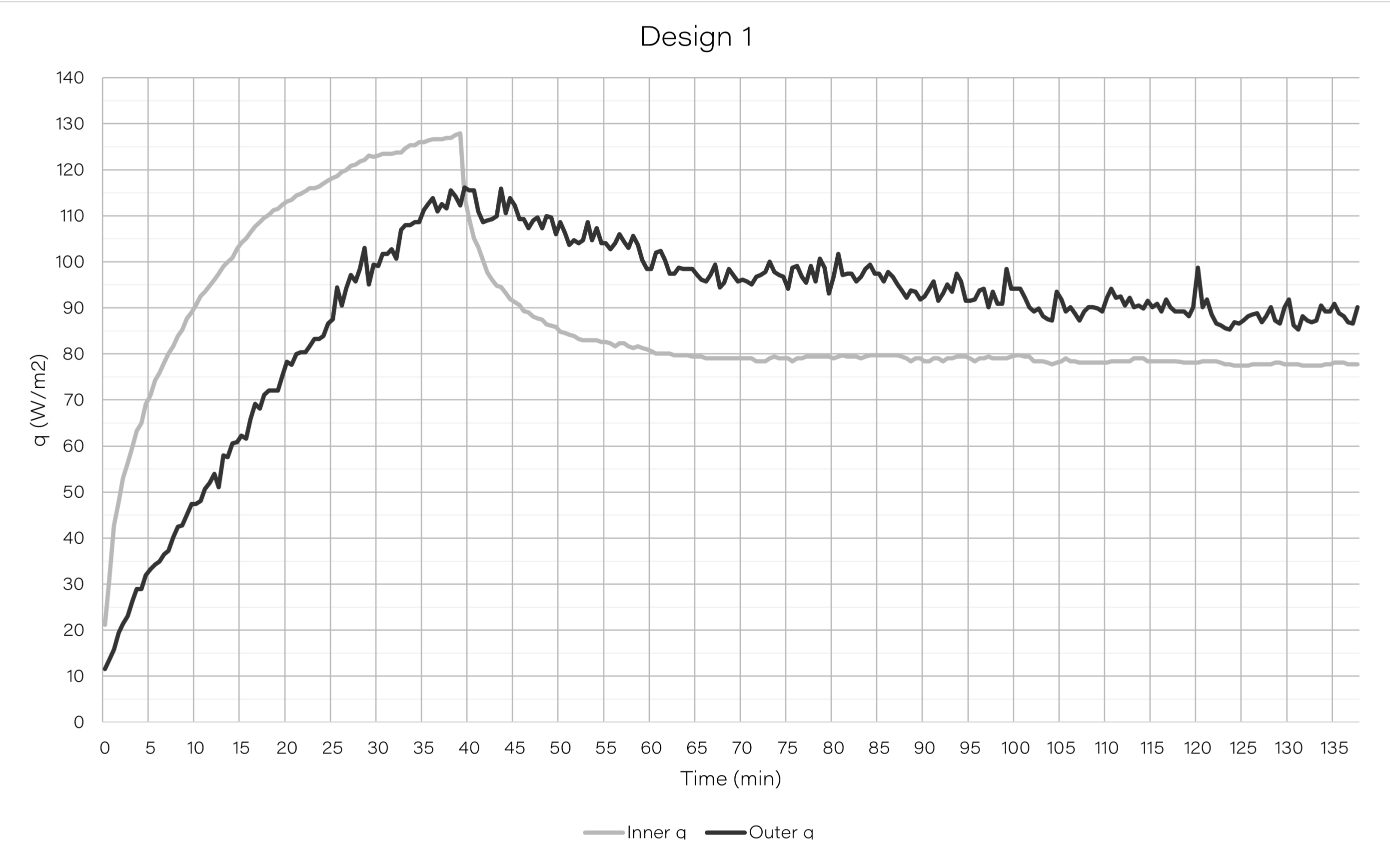
Once all the sensors are on place and the data can be read by the computer software, the test can begin.

For each of the designs a graph is made with the temperatures and the time. At the location in the graph where the temperatures start to become horizontal lines, that is where the measurement of one hour starts. Over this time period, the two surface temperatures and the two heat flux sensors are used for the average temperature difference and the average q-values.

In the computer software, the heat flux sensors give a value in mV. At the cable of the sensor a value is given to rewrite μV to W/m^2. For the Hukseflux on the inside, this value is 62.23 μV/(W/m^2) and for the Hukseflux on the outside, this value is 60.76 μV/(W/m^2).

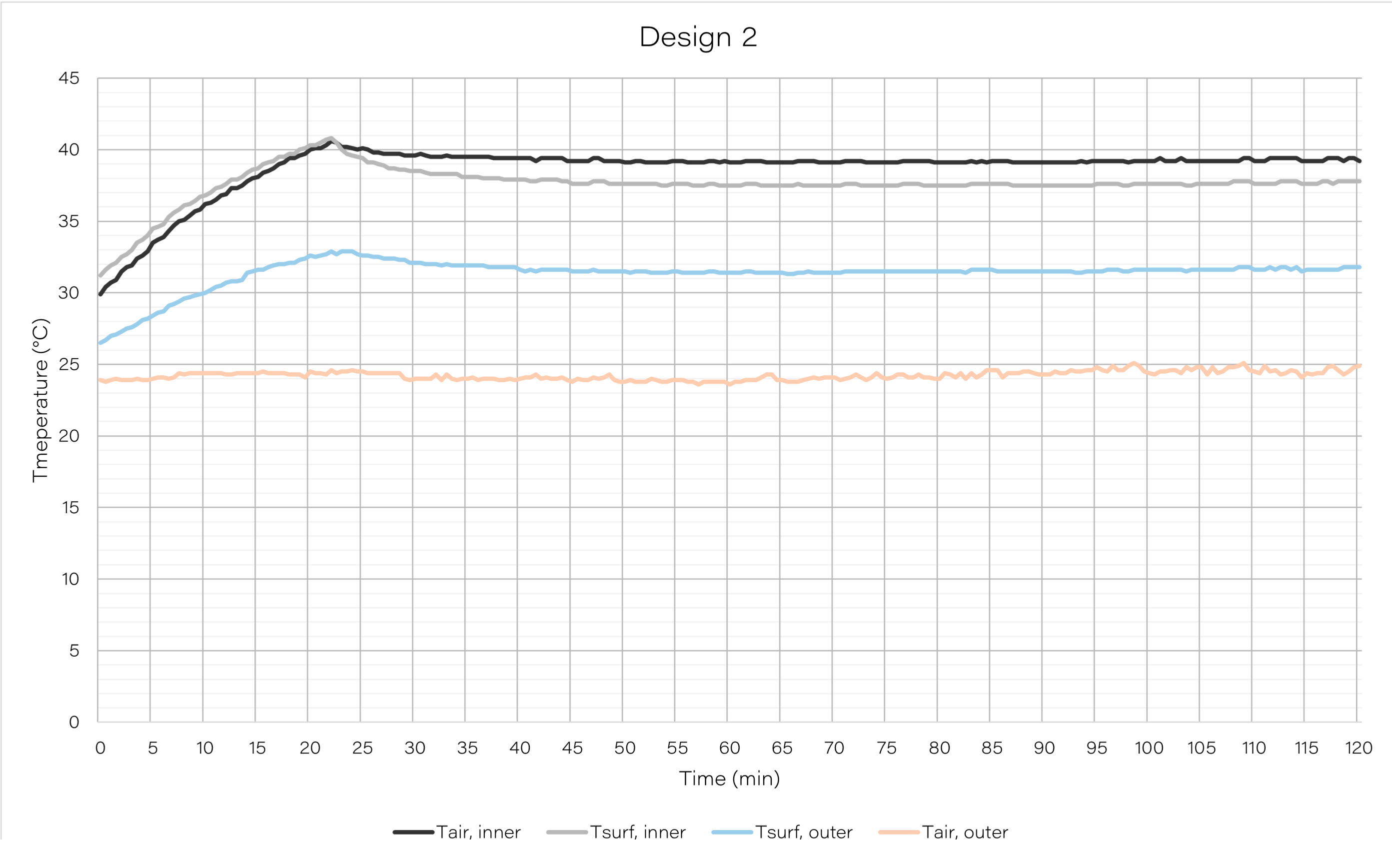
Design 1

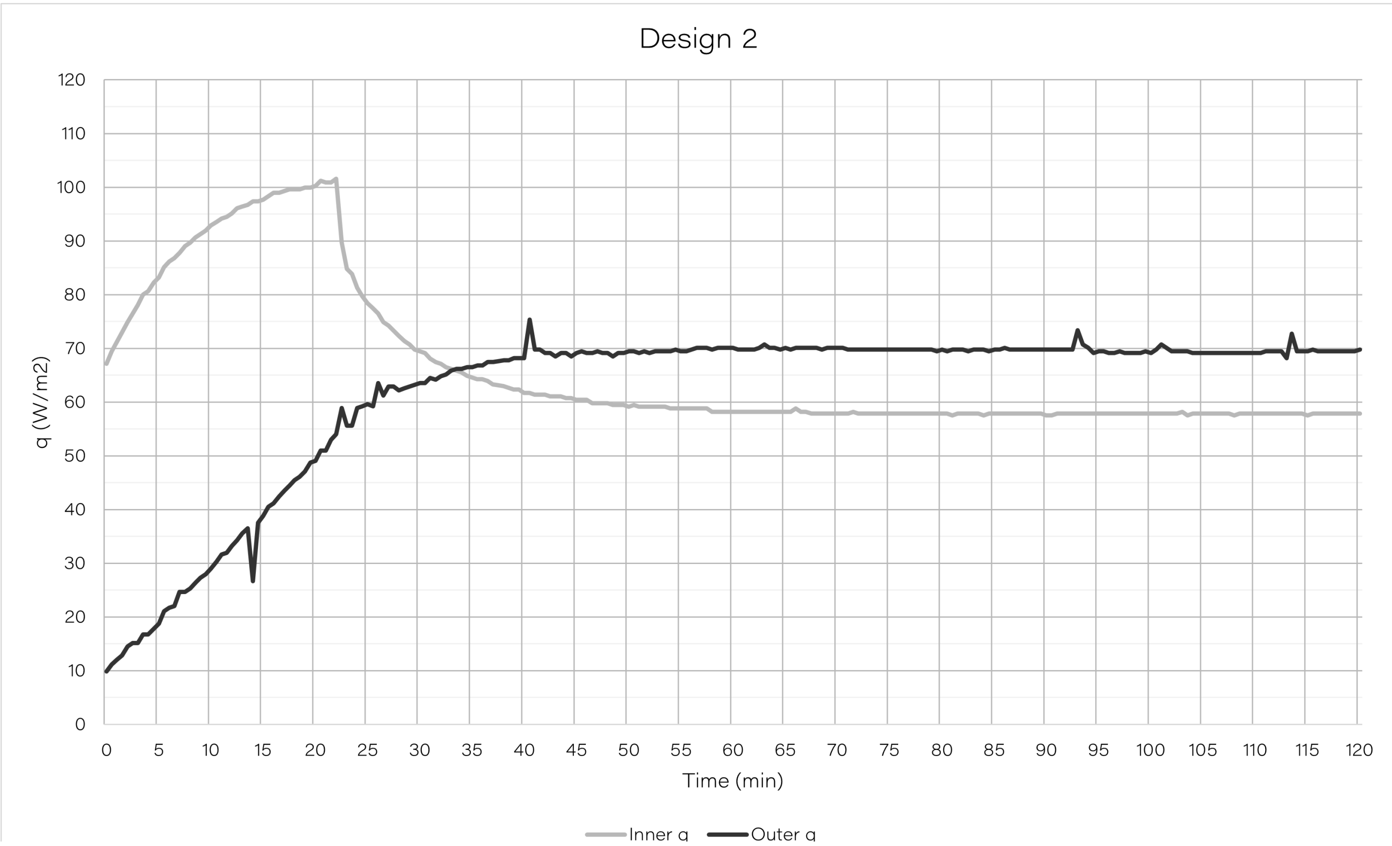




Time laps:	77 minutes to 137 minutes
Average temperature difference:	35.2 °C - 30.3 °C = 4.9 °C
Inside heat flux:	78.57 W/m^2
Outside heat flux:	91.63 W/m^2

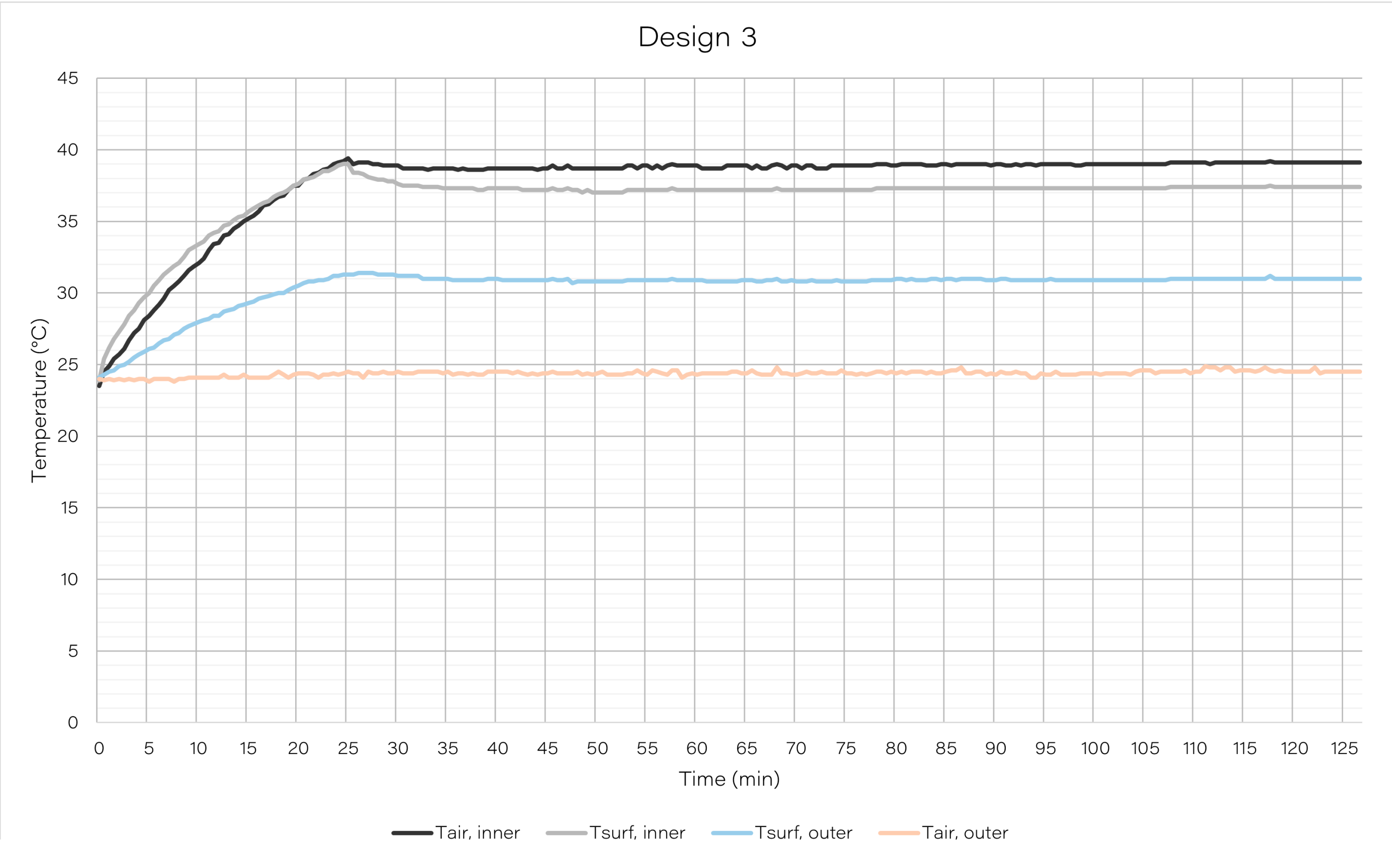
Design 2

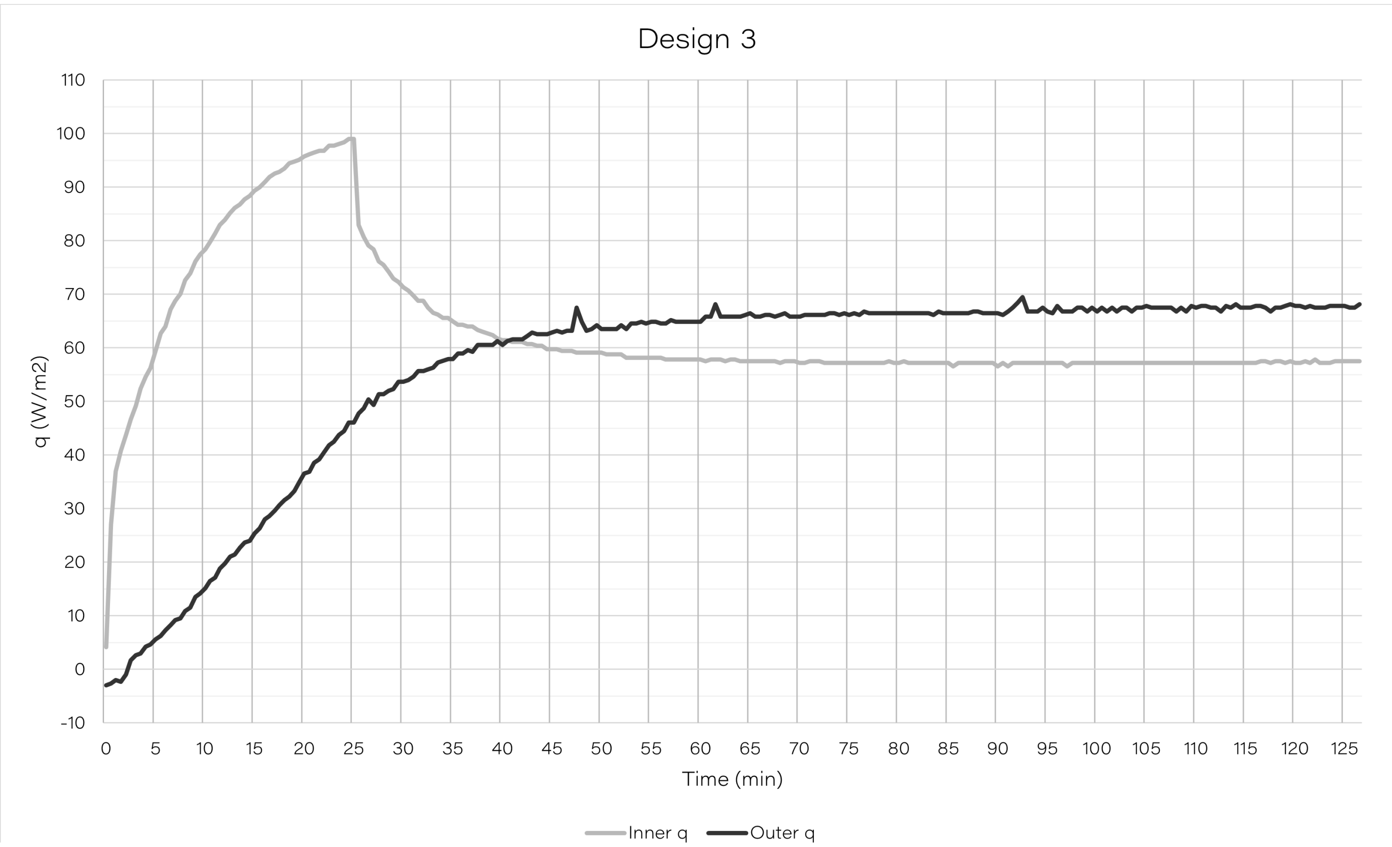




Time laps:	47 minutes to 107 minutes
Average temperature difference:	37.6 °C - 31.5 °C = 6.1 °C
Inside heat flux:	58.12 W/m^2
Outside heat flux:	69.71 W/m^2

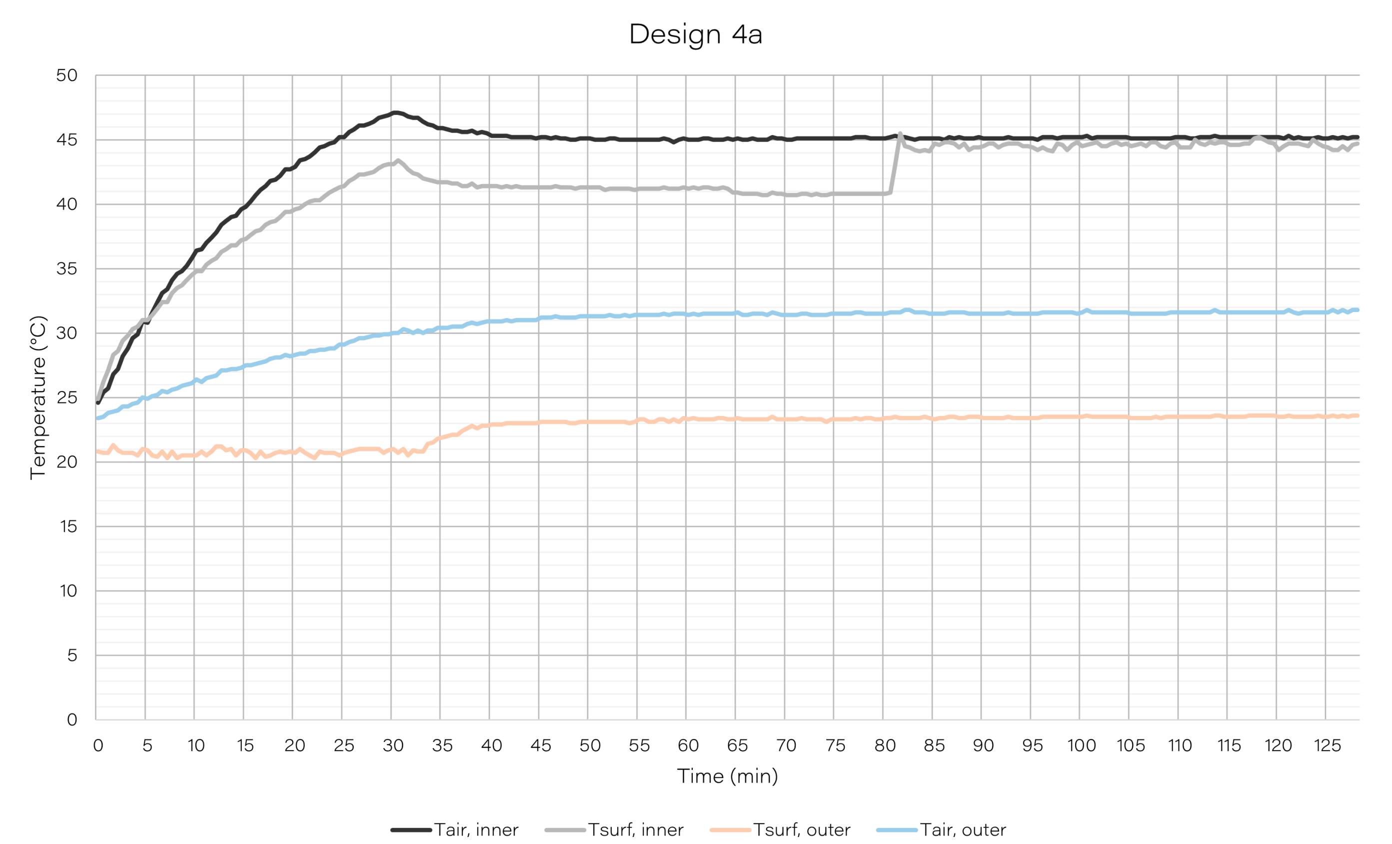
Design 3

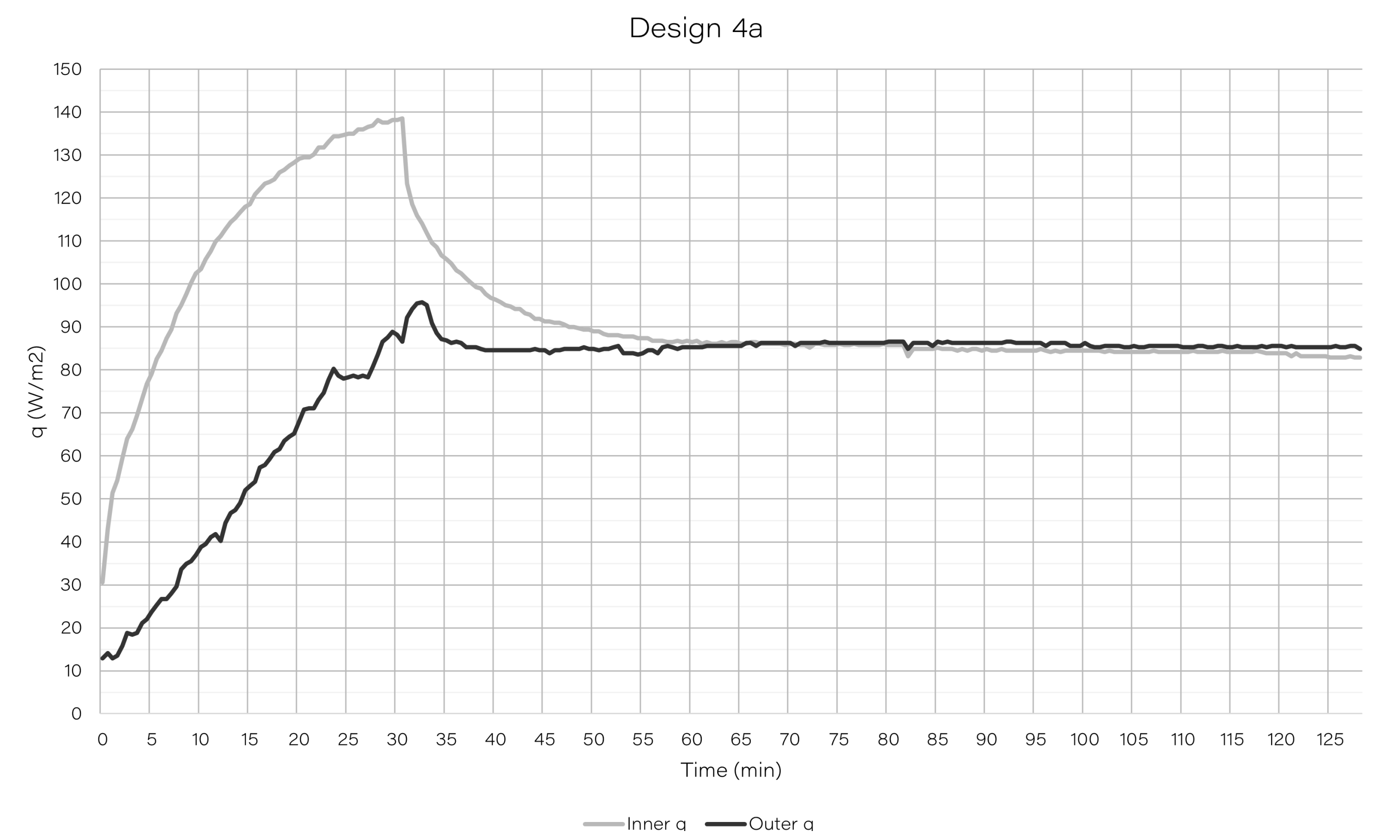




Time laps:	48 minutes to 108 minutes
Average temperature difference:	37.3 °C - 30.9 °C = 6.4 °C
Inside heat flux:	57.50 W/m^2
Outside heat flux:	66.20 W/m^2

Design 4a





Time laps:	60 minutes to 80 minutes
Average temperature difference:	40.9 °C - 31.5 °C = 9.4 °C
Inside heat flux:	84.96 W/m²
Outside heat flux:	85.88 W/m²

Evaluation of the results

Looking at the graphs of the different designs a few things can be seen. First, the temperature of the prototypes in for instance design 2 is higher than the inner air temperature. This is the case until the second lamp is turned off. This lamp was much closer to the prototype temperature sensor and therefore given that sensor more heat than the other sensor inside the hot box. Moreover, the prototype temperature sensor was covered with black tape. Since black absorbs more of the visible light than the red and white wire, it heats up more. This explains why the first lamp is covered with an aluminium foil: to minimize the effect of radiation. Looking in more detail to the heat flux graph of design 4, the inner air temperature becomes much higher than the other prototypes. This sample has a much smaller area than the previous ones, which leaves the unguarded hot box with more Styrofoam to insulate the box.

#	Delta T	Inner q-value	Inner U-value	Outer q-value	Outer U-value	Delta U-value	SOLIDO
1	4,9	78,57	4,30	91,63	4,47	**4,39**	**3,18**
2	6,1	58,14	3,64	69,71	3,88	**3,76**	**3,20**
3	6,4	57,50	3,55	66,20	3,75	**3,65**	**3,47**
4a	9,4	84,96	3,56	85,88	3,58	**3,57**	**3,96**

Table 6: Measure values of the unguarded hot box

Table 6 shows the results of the different tests. The values of design 1 and 2 seem to be much worse than the values from SOLIDO. This is because the SOLIDO model works with a lambda value of 0.024 W/m*K, but this value does not take the emissivity into account which will give a higher λ. The real life test does measure this, so therefore the U-value of the hot box are more likely to be correct. The result of design 3 comes closer to the expected value, slightly worse due to small inaccuracies of the prototype.

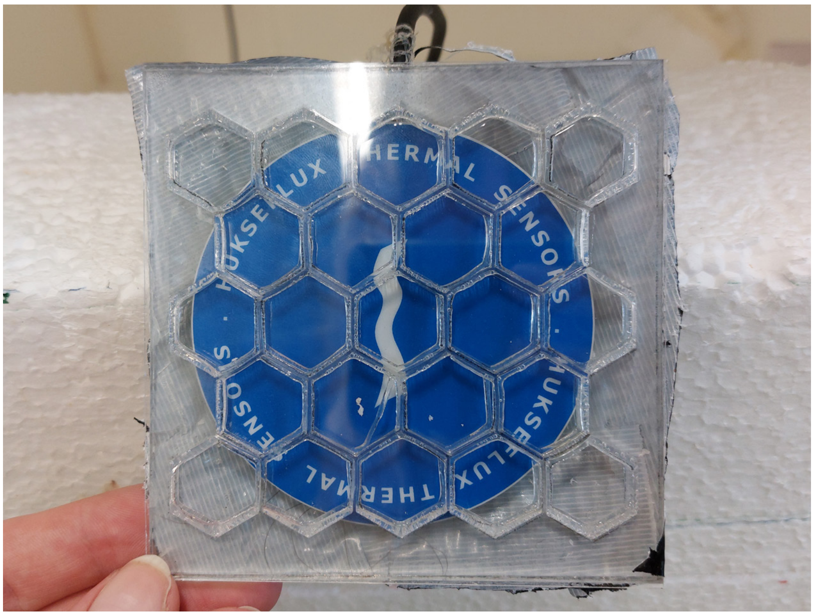


Figure 34: Hukseflux sensor on sample 4a (Author)

To test design proposal 4, a smaller sample of 100x100 mm is used, since the larger prototypes broke. However, this size does come with a few flaws in the testing process. Figure 34 shows that the diameter of the Hukseflux sensor is almost as big as the sample. Placing the tape and sensor on the correct place was hard. Some air might have been captured between the sensor and the glass, resulting in a better U-value. During the measurements, the sensor might also measure side effects that are coming from the edge.

The graph of the temperature measurements of design 4a shows that the inner surface sensor fell off during the experiment. This is why in the end, the temperature is more or less the same as the inner air temperature. This is why for the calculations only the number from 60 minutes to 80 minutes are taken. At the time the second lamp was turned off, the windows were also closed. This why the outer air temperature rises slightly from that moment on.

Moreover, in this case design 4a with a hexagon radius of 10 mm was used. The Hukseflux sensor does cover multiple air cavities and could give a relative reliable value of the overall composite. But for design 4c with a radius of 30 mm the sensor would mostly cover only one cavity cell, which will not be a good representative for the complete composite. This could be improved by moving the sensor around, taking multiple runs and using the average of the outcomes.

The hot box has been used by others who have had different prototype sizes. This results in existing cuts and small openings in the unguarded hot box that become thermal bridges. Due to this, the temperature inside the box is lower than in the most optimal newest state. This is also one of the reasons why the inner air temperature needs to be constant first. Additionally, the sensors have a certain inaccuracy in their values. The temperature sensors have either an accuracy of +/- 1.0 °C or +/- .75%. This depends on which one is the greatest. (REOTEMP Instrument Corporation, 2011) The Hukseflux sensor has an uncertainty of calibration of ± 3% (k = 2). (Hukseflux, n.d.)

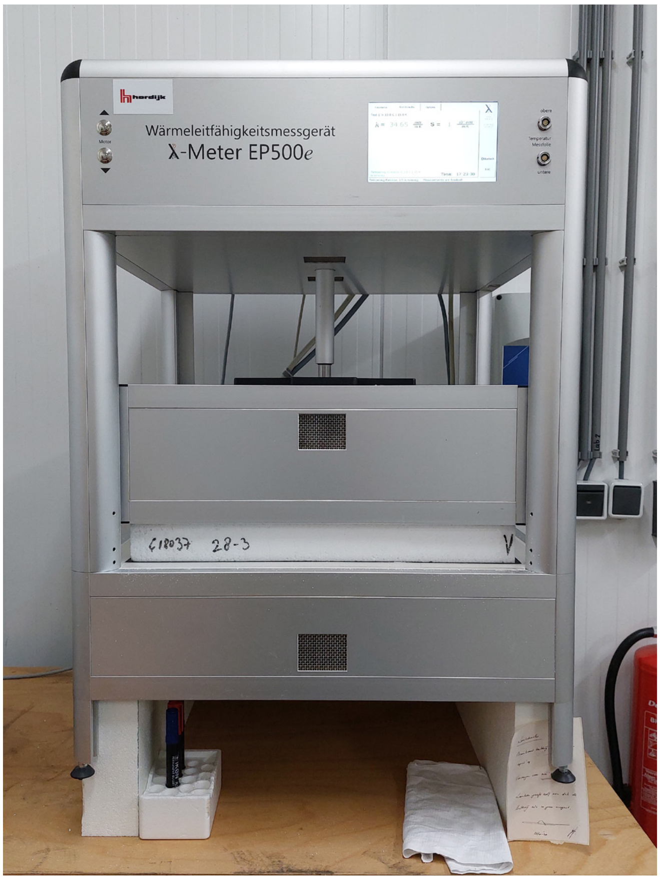


Figure 35: Guarded hot plate machine (Author)

Since the unguarded hot box has some flaws, the guarded hot plate was found at the company Hordijk in Delft. This machine can test a sample with the maximum size of 500x500 mm and gives a much more precise lambda-value since the measurement area of the sensor is 150x150 mm and can measure inhomogeneous materials. Moreover, the high-performance Peltier modules make sure that the temperature is constant during the testing. (Lambda-Messtechnik, n.d.) Hordijk was contacted and willing to test the samples for this research. However, later on it was found that the guarded hot plate could only measure samples from 9-10 mm in thickness and above, so therefore it could not be done.

7.6 Testing the structural performance

For the testing of the structural performance, the Z100 at 3ME is used. This machine measures the force (F) of the 'elephant foot' and the deflection (δ) of the prototypes. A wooded frame with the size of the prototypes is needed to hold the models with simple supported edges. This frame is made in the model hall at BK. Moreover, to distribute the force of the 'elephant foot' an extra wooden layer is added in between the load and the models. This should be three wooded plates of 10 mm thick with the sizes 125x125, 80x80 and 60x60 mm. The plates will be glued together to make sure they work as one element. The test setup can be seen in figure 36.

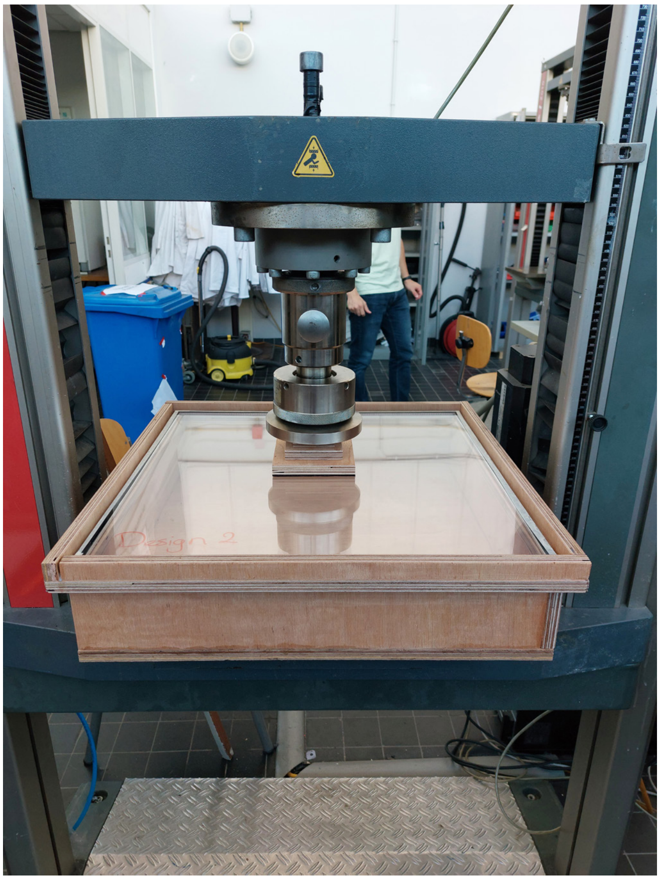
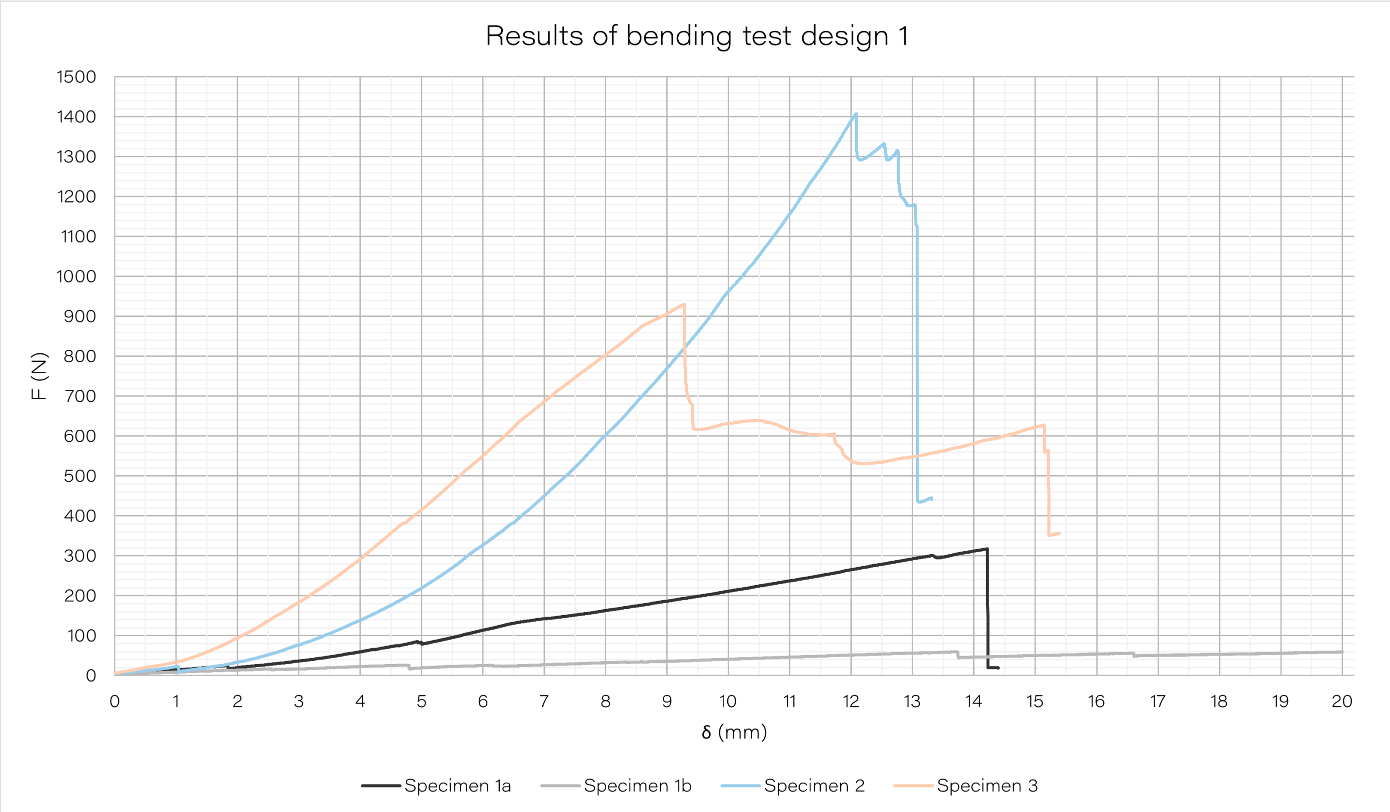


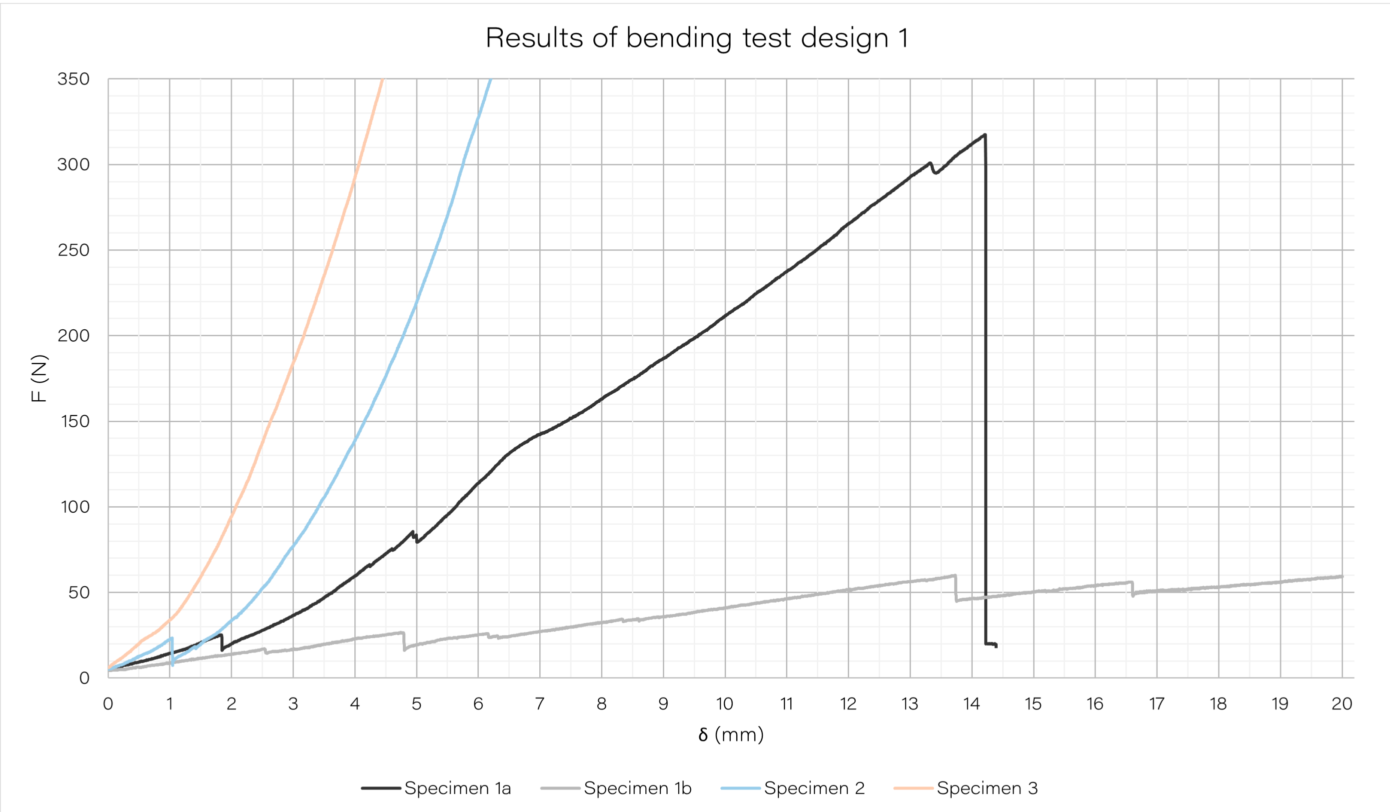
Figure 36: Test setup of the Z100 (Author)

Four different samples are measured with this method: two prototypes of design 1 (a&b), one of design 2 and one of design 3. In the graphs on the next page, those samples are expressed in force per deflection. This is because the machine was programmed to lower 2.5 mm per minute. So, the deflection was at a constant speed, with a maximum deflection of 20 mm. Overall, the curves are a linear line and after reaching its peak, it goes down immediately. This is a typical characteristic of glass because it is very brittle.

Before the test began, specimen 1a had already a couple of cracks on the top glass sheet. This explains why there where several small bumps in the curve. At those moments, the top glass layer shifted a bit of made an extra small crack. Looking at figure 37a, the edges started to fold upwards. The folding is a second order effect and also takes stresses. This is exactly the reason why simple calculations of the first order are not giving all aspects of the behaviour. The bottom glass sheet broke at 317.5 N with a deflection of 14.2 mm. After this, the test was stopped manually.

The second prototype of design 1 had a crack on the top and bottom sheet. However, these were slightly different than design 1a because they were connected to two edges





Design 1a:	14.2 mm	317.5 N
Design 1b:	13.7 mm	60.0 N
Design 2:	12.1 mm	1407.4 N
Design 3:	9.3 mm	930.9 N

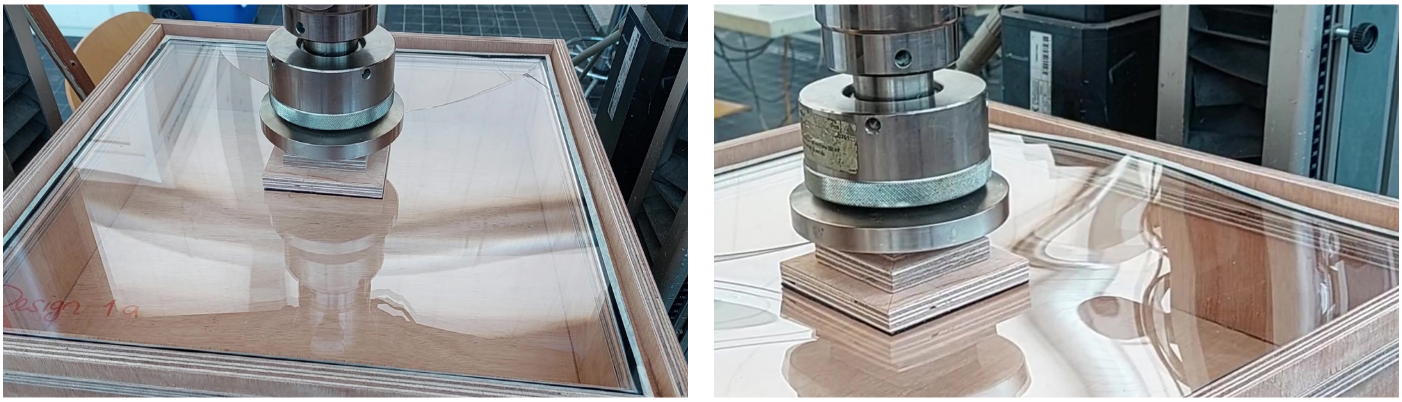


Figure 37: Specimen 1a; a) the begin state, b) deformation on the centre of the edge (Author)

of the prototype. Therefore, the testing gave other results and the corner of the prototype was lifted instead of the centre of the edge. Moreover, figure 38b shows that the wood loses contact with the glass on one side since that side deforms more near the crack. This is because the crack can be seen as an edge with no supports. Looking at the graph of this sample, the maximum force reaches only 60 N within 20 mm deflection. After this, the machine was programmed to stop the test. Even though the glass did not break at once but step by step, it can still be assumed that the maximum force of this prototype lays around 60N as the glass just shifts once this value is reached.

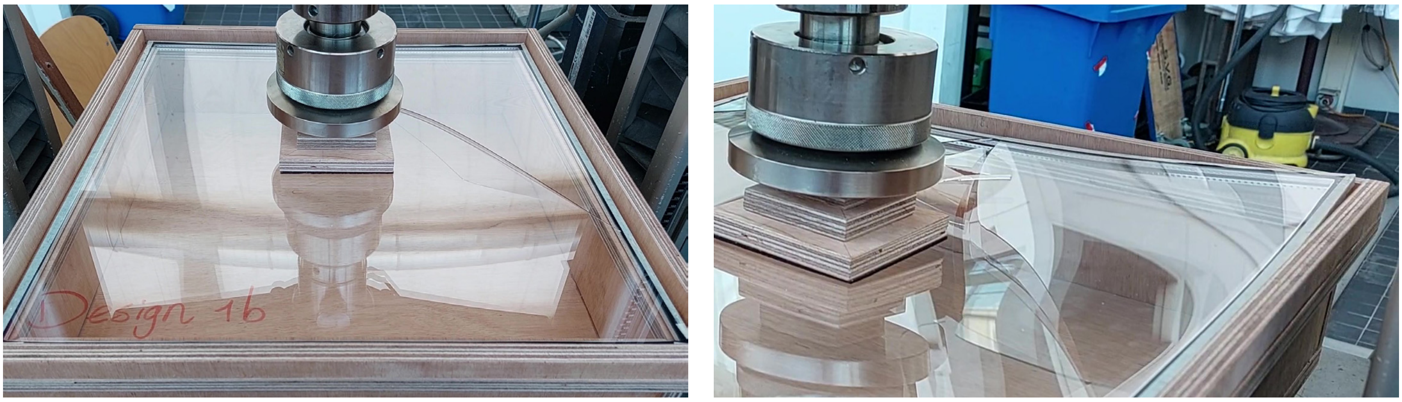


Figure 38: Specimen 1b; a) the begin state, b) deformation on the corner (Author)

Test specimen 2 was completely intact when the testing began. Around 1400 N the edge starts to deform which resulted in circular cracks around the centre point of that edge, perfectly following the second order effects of mechanics, figure 39b. Just moments after that, the glass reaches its peak stress on the same location on the edge and cracks completely. This is also when the machine is stopped. Figure 40 shows those crack lines beautifully, but besides that, more damage is shows around the edges and mostly around the corners of the wooded block. This would have been less significant if the block would

Figure 39: Specimen 2; a) the begin state, b) deformation on the centre of the edge and cracks (Author)

Figure 40: Cracks on specimen 3 after the test (Author)

have been round. Reviewing the graph of specimen 2, a new thing is seen. The curve does not show a linear but a more quadratic line. This has to do with the fact that the plate is thin but also has a relatively large deflection. These types of plates start to show a non-linear behaviour in the force-deflection graph.

The two of the edges of specimen 3 had cracks on the top layer. On one side there was one large burst parallel to the edge. One the other edge there were smaller cracks. However, the lamination layer was keeping them together. Like the previous specimen, the centre of one of the edges wanted to bend upwards. To do this, the glass detached from the EVA and bended, while the PC and the bottom glass sheet stayed the same, because the EVA was not able to carry the stresses. This action is the first dip in the graph. After this, the side with the longitudinal crack moved upwards, but while the first edge showed detachment, this side moved as composite. This is because the PC is an inhomogeneous material. However, the upper glass piece on this edge also broke, which is the small dip in the end of the graph. One second later the bottom sheet broke and the test was stopped manually. The bottom glass pieces did stay attached to the EVA and the cracks seem to begin near the corner of the wooden block.

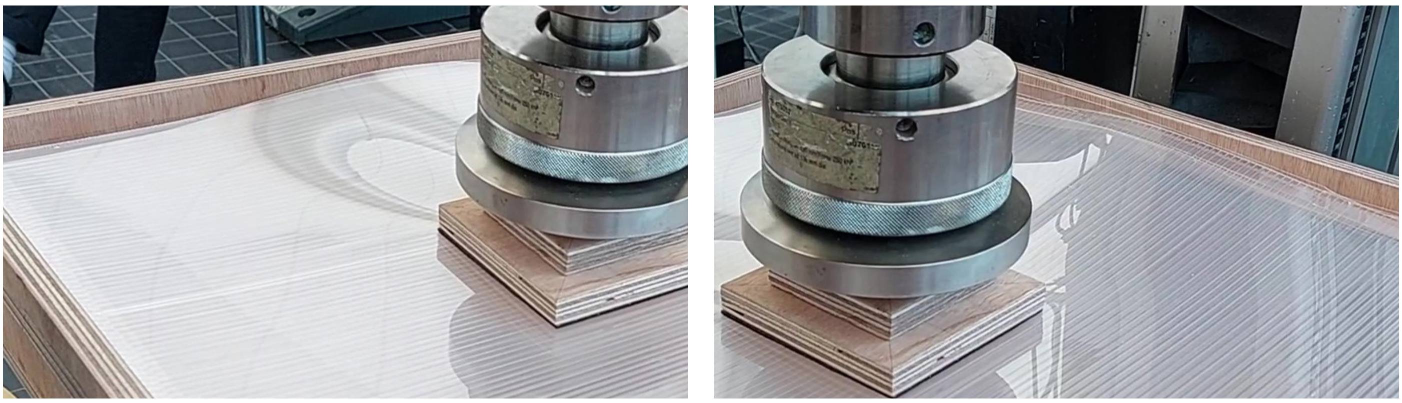


Figure 41: Specimen 3; a) delamination of glass, b) deformation on the centre of the edge (Author)

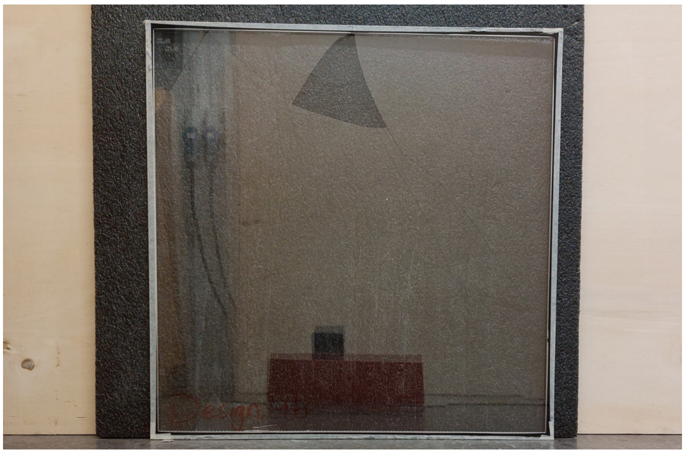
Next, equation 12 can be used to calculate the maximum distributed load (w) when the maximum stress is reached. The output per specimen is specified in table 8, using a radius of 0.0705 m and Poisson's ratio of 0.2. Besides the w in N/m², the number of times the wind load of 1000 N/m² that could be applied on the specimen is given. If the value is higher

	F_{max} (N)	w_{max} (N/m^2)	<1
Specimen 1a	318	4800	4,8
Specimen 1b	60	908	0,9
Specimen 2	1407	21276	21,3
Specimen 3	931	14071	14,1

Table 7: Maximum distributed force per specimen (Author)

than 1, the wind load will should not damage the specimen. This means that in this case only specimen 1b was not able to pass the boundary condition. In contrary to the analytical calculations of the structural strength, the tests on the specimen suggest that design 1, 2 and 3 could manage the wind force. Moreover, the wind load can be seen as a temporary force, while the Z100 applies a more permanent force. Since the glass sheets of the IGU work together in a temporary force, the designs are even more likely to pass the boundary conditions. However, to make sure this is the case, more research should be done!

Specimen 1a: Failure of the bottom sheet with large crack lines. Centre pieces fell through.



Specimen 1b: Large crack lines, but not much more than the starting point. Small piece fell out.

Specimen 2: Smaller crack lines due to lamination layer. The bottom layer was still intact. No pieces fell out.

Specimen 3: Permanent deformation of the PC sheet and detachement of the upper glass. Large crack lines on the top glass sheet, smaller ones on the bottom sheet which is still laminated to the PC.

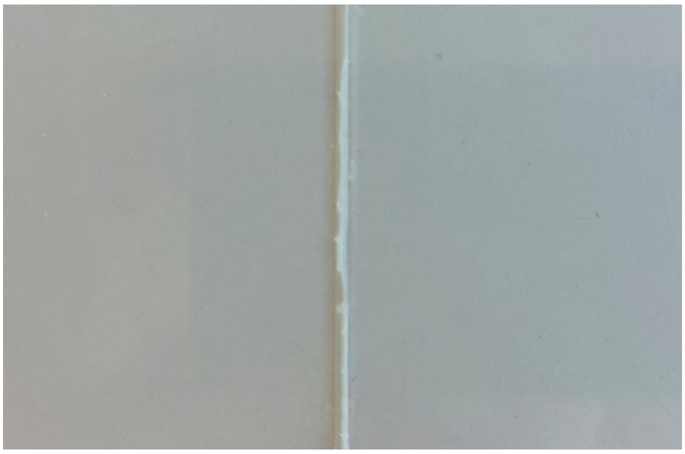
7.7 Testing the ageing

Four different prototypes of 100x100 mm were placed in a UV accelerated weathering test machine: a simple laminated glass piece with EVA, the laminated PC sheet to thin glass, and the PMMA honeycomb pattern design with a radius of 10 and 20 mm. The UV machine takes one week to represent one year. On the 28th of March, the samples were placed inside the machine and they were taken out on the 3rd of June. So, the samples were in the machine for roughly 10 weeks, representing about 10 years of UV ageing.

Figure 42: UV accelerated weathering test machine (Author)

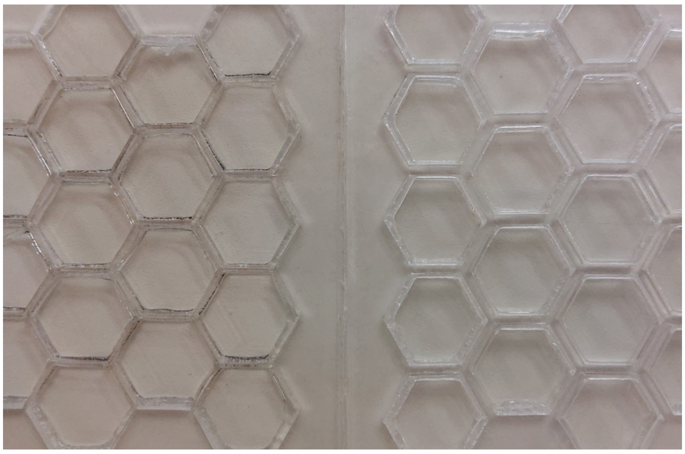
The research team at the PVLab suspects that the EVA interlayer will start to change colour after 8 to 10 years. Besides the EVA, the PC and the PMMA might also change colour overtime. This does depend on the properties of those materials and if the manufacturer has added a special anti-ageing coating. Figure 43 shows that the manufacturer of the PMMA claims that the material will be good for at least 10 years. The PC twin wall sheet is protected against UV on only one side according to the brochure (Exolon Group, 2021). This side should be placed towards the outside or upwards. The inside of the UV machine has reflective material on all sides and will reflect to all sides of the test samples. It is likely that the other side of PC sheet will change due to this. The left photo is the non-threatened sample, the right one has been in the UV machine.

Figure 43: Brand and guarantee of the PMMA (Author)

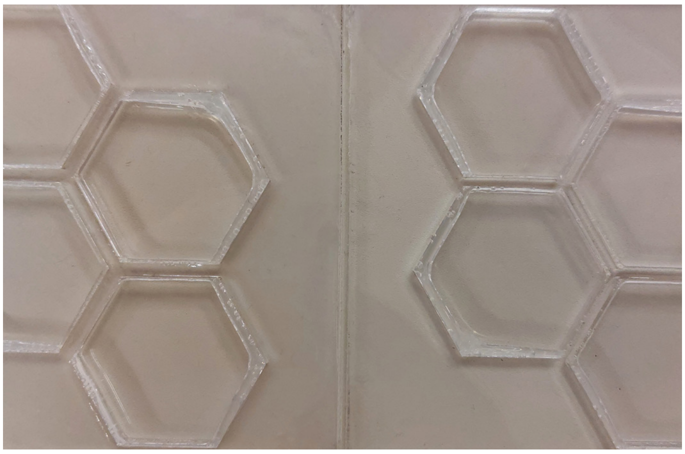


The simple laminated glass sheets did not show a visible change in colour. This suggests that the EVA and therefore design 2 would not significantly change in colour over the lifespan of 10 years.

The sample of design 3 did yellow over time. As expected this has to do with the test set up. Figure 44 shows that the side with the UV layer is less yellow than the other side where the PC has aged.



Design 4a has not changed in colour. The darker lines on the non-threatened sample (left) are leftover marker strips from drawing the honeycomb.



The sample of design 4b has a larger area of PMMA, so if it would change, it would show on this sample. However that is not the case, concluding that the PMMA will not change in colour over the lifespan of 10 years.

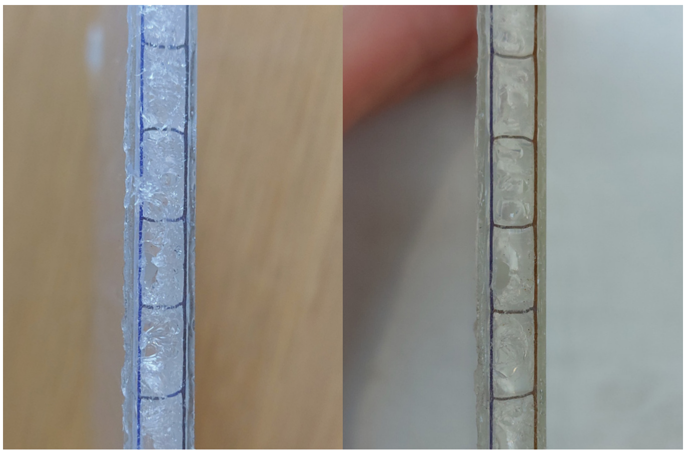


Figure 44: Side view of design 3 before and after the UV machine (Author)

The yellowing of the PC seems to be problematic but that is not true. The final product will be used in a window and therefore only face the outdoors on one side. If the side with the UV layer is placed on the outer side of the window, the PC is protected from ageing.

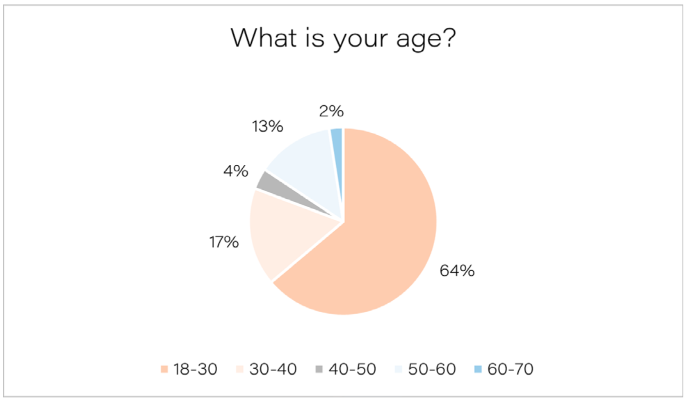
7.8 Survey results

To collect a broader view on the aesthetics of the designs, a survey was sent out. It received 83 responses which are analyzed in this part. Design options one and two will presumably have the first choice, judging on the aesthetics, so therefore the survey only takes the more visually present designs. Design five and six have a poor thermal performance, so the questionnaire focuses on design three and four. The full survey can be found in the Appendix. To illustrate the looks of the two options, two types of renders were made. The first one can be seen in figure 45. This window is taken from the case study and figure 45b and 45c show how the designs would look from ± 3 meters away. Figure 46 gives a more detailed render of how transparent the designs are. Please note that design three is called Design 1 and design four is called Design 2 for this survey.

Figure 45: a) Current situation, b) Design 1: Horizontal lines, c) Design 2: A honeycomb pattern (Author)

Figure 46: a) Current situation, b) Design 1: Horizontal lines, c) Design 2: A honeycomb pattern (Author)

Looking at figure 47a, more than 60% of the participants were between the age of 18 and 30 years old. If this age group has a strong contradictory opinion with the other age groups, this might influence the outcome of the survey results. Figure 41b tries to analyze the



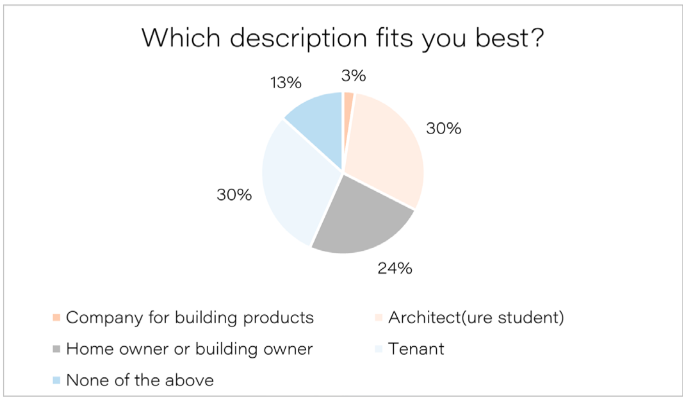
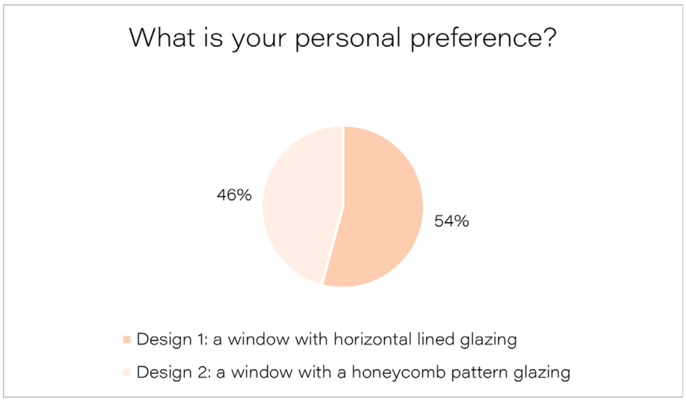


Figure 47: a) Age of the participants, b) Profession of the participants (Author)

knowledge of the participant. It is likely that the participants that work for a company for building products, architects and architecture students have more background knowledge and can make a more considered choice.

The participants were asked to choose their most preferred design option without any background knowledge, so they would base their opinion only on the aesthetics of the renders. Figure 48a shows that the participants are evenly divided on their likings, with a slight preference to the horizontal lined glazing. This gives the conclusion that both designs can be favored and that there is no popular option. To verify if perhaps the architects and the architecture students would have a certain preference, having their background knowledge in their mind, figure 48b is made. However, this figure also shows that the opinion is split about fifty-fifty.



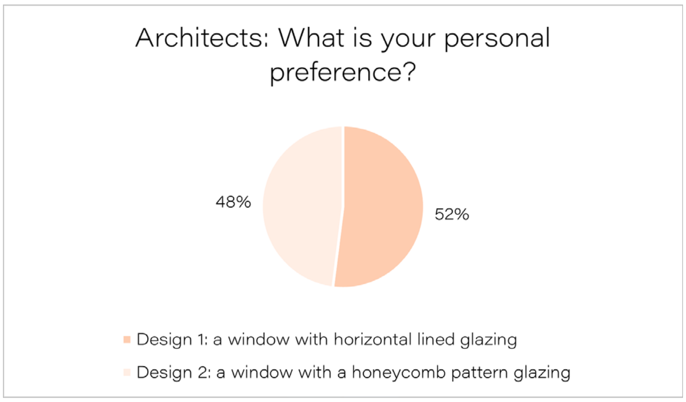


Figure 48: a) Personal preference of the participants, b) Personal preference of the architects (Author)

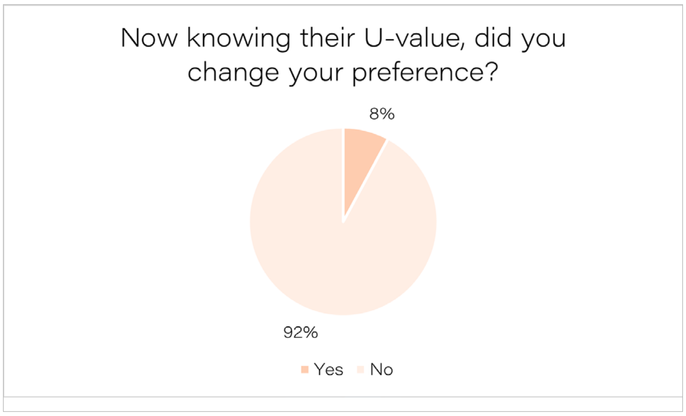
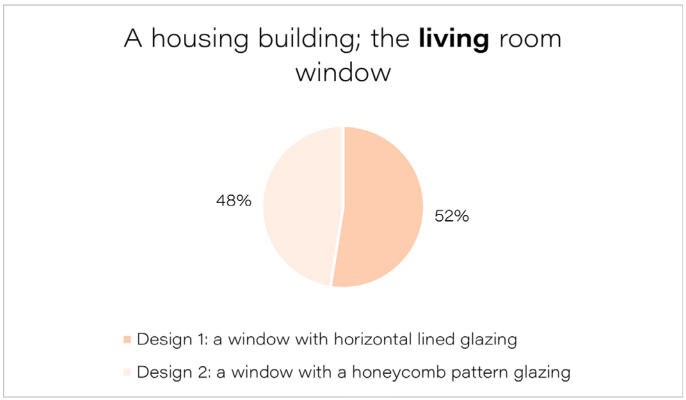


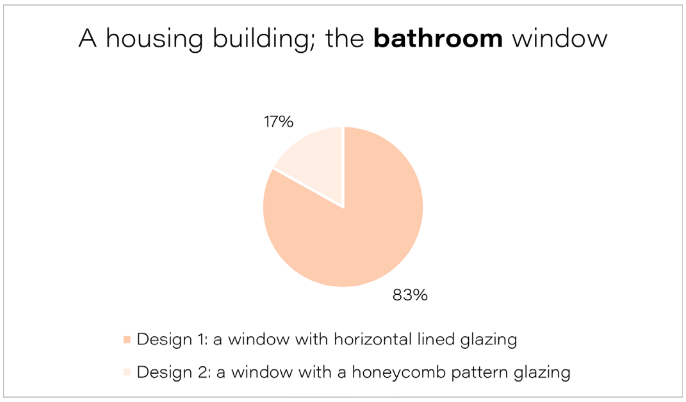
Figure 49: The change in preference after knowing the U-value (Author)

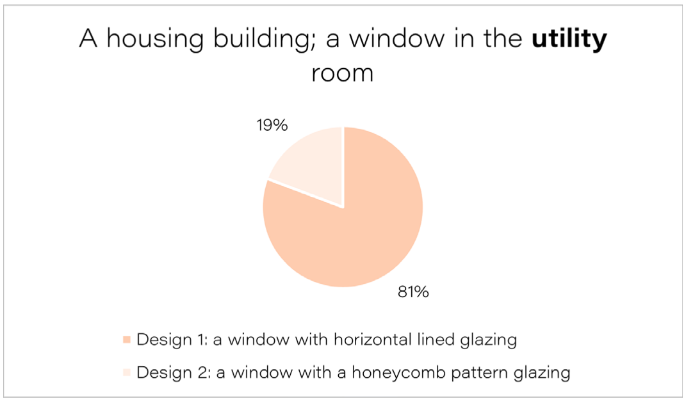
For this survey, design 1 was given a U-value of 3.4 W/m²*K and design 2 a U-value of 3.6 W/m²*K. After explaining the difference in U-value to the participants, they were asked to reconsider their opinion. For participants that already choose design 1, they all choose design 1 again. However, if they choose design 2 previously, they now had to rethink their preference. Figure 49 shows that out of this group, only 8% decided to switch from design and therefore prioritize the insulating properties over the aesthetics. Looking at the comments that were given on this question, most remarks were that they found the difference too little and that it would only have a larger impact on a larger building. This can conclude that the feeling towards their preference is strong and cannot be changed with (small) environmental aspects.

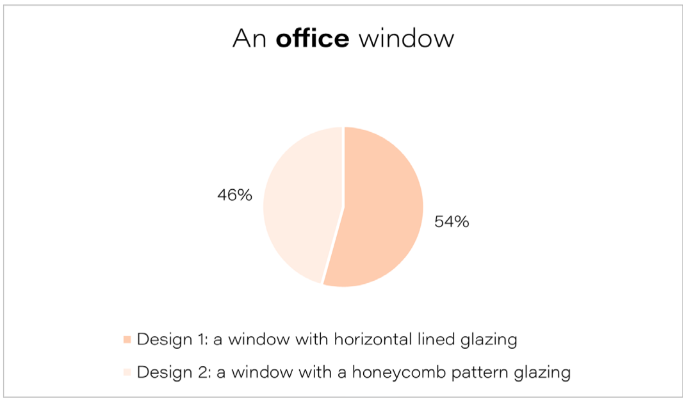
On the next part of the survey, the participants were asked how they felt on different functions of the glazing. The outcome of those options is represented in the graphs on the next page. A few things can be noticed. First, in the general functions, the living room, the office and the corridor, people tent to stay with their preference, which is the almost 50/50 division. However, looking at the more private functions as the bathroom, the utility room and the toilet, a much larger percentage chooses design 1 with the horizontal lines. This can be appointed to the less transparent vision of that design, which is also given as main comment. People that prefer the honeycomb design in these situations suggest that the design can make the 'boring' room more interesting and fun. Moreover, it can be noticed that the more public places as the church, the library, the museum, and the shop have a higher percentage of design 2. The comments suggest that these functions can have a more outstanding design and the transparency is more important.

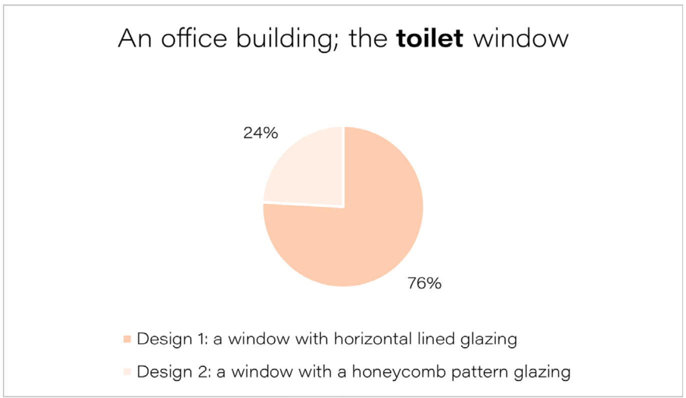
Placing the outcomes of this survey in a broader perspective, it can be said that the general opinion on the aesthetics is equally divided and that the homeowner or building owner must make the final decision of their product choice. If the U-value of those products is relatively similar, the customer will only focus on the visuals. However, focusing on the function of the room or building, their preference might vary between the rooms within in the same building. Both the design with the horizontal lines and the design with the honeycomb pattern could become actual products on the market for heritage glazing. This is however with the sidenote that it should have one large advantage compared to the existing glazing product, since both lack transparency in some way. This advantage could be for instance the insulating value, preserving the window frame or the costs. In the end, the buyer has to choose this product over other existing products for a good reason.

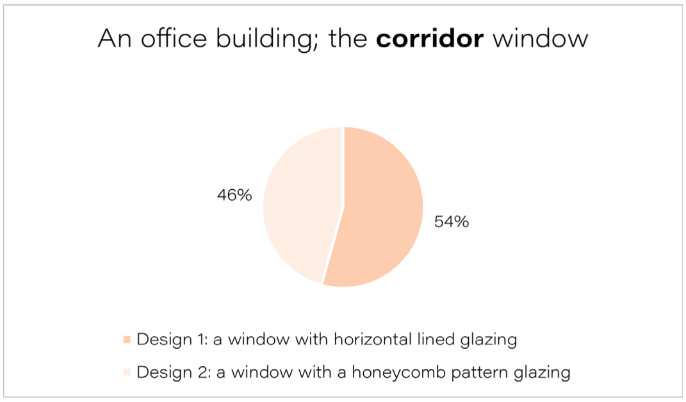

A housing building; the living room window
48%
52%
Design 1: a window with horizontal lined glazing
Design 2: a window with a honeycomb pattern glazing

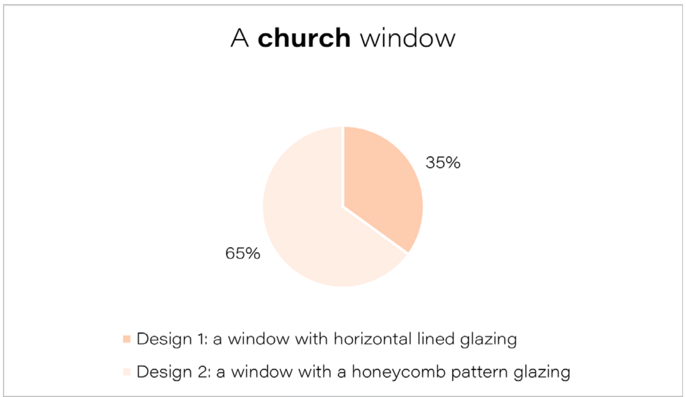

A housing building; the bathroom window
17%
83%
Design 1: a window with horizontal lined glazing
Design 2: a window with a honeycomb pattern glazing

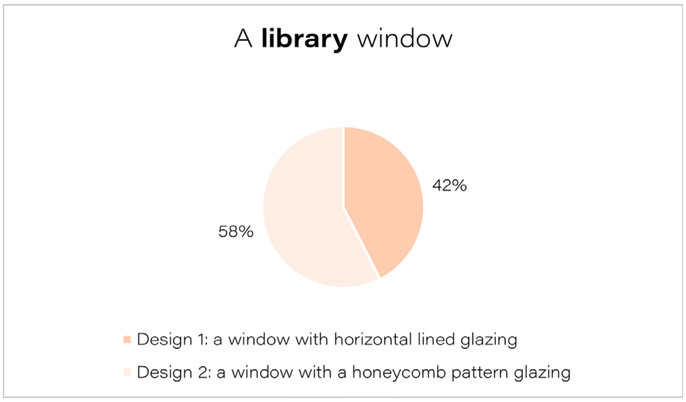

A housing building; a window in the utility room
19%
81%
Design 1: a window with horizontal lined glazing
Design 2: a window with a honeycomb pattern glazing

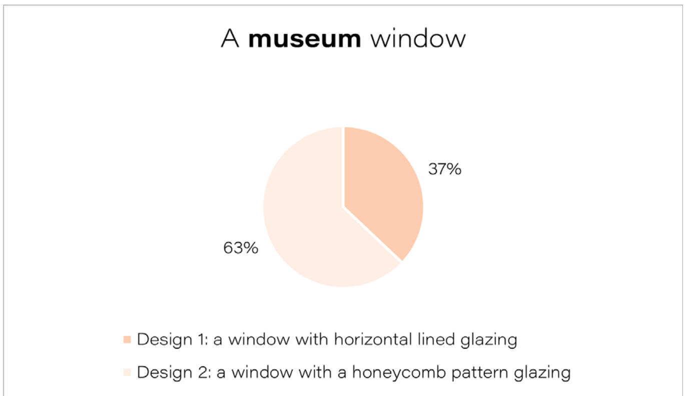

An office window
46%
54%
Design 1: a window with horizontal lined glazing
Design 2: a window with a honeycomb pattern glazing


An office building; the toilet window
24%
76%
Design 1: a window with horizontal lined glazing
Design 2: a window with a honeycomb pattern glazing


An office building; the corridor window
46%
54%
Design 1: a window with horizontal lined glazing
Design 2: a window with a honeycomb pattern glazing


A church window
35%
65%
Design 1: a window with horizontal lined glazing
Design 2: a window with a honeycomb pattern glazing


A library window
42%
58%
Design 1: a window with horizontal lined glazing
Design 2: a window with a honeycomb pattern glazing


A museum window
37%
63%
Design 1: a window with horizontal lined glazing
Design 2: a window with a honeycomb pattern glazing


A shop window
37%
63%
Design 1: a window with horizontal lined glazing
Design 2: a window with a honeycomb pattern glazing

7.9 Application in case study

To test if the four most promising designs, the case study is analyzed again to see how an architect or property owner could work with the products. Assuming that the buyer would always prefer design 1 or 2 over design 3 and 4, the floor plans are only making a choice between design 3 and 4. This is done based on the function of the room and their privacy level. The floorplans show the functions of the different rooms. The living rooms, the bathrooms, the toilets, and the storage rooms will use design 3 if that room has a window. The corridors, office areas and public rooms will use design 4c. First, a rendering is given to illustrate the different glass panels applied in the building. Then, the details of the window frames are given. These also show how design 1 and 2 could be used.

The rendering suggests that the new designs would not hinder the view from the outside. Design 3 is less transparent than the single glazing, but not an eye-catcher. The honeycomb pattern is more visible, but still not intrusive. Because Mijnbouwplein has mostly living rooms on the façade side, most windows would receive design 3. Looking at the detailing, the largest design of 8.2 mm still fits the current window frame. However, the measurements of the prototype suggests that this thickness will be 8.4 mm, but that is still less than the 8.5 mm of the laminated glass solution shown in chapter 2.

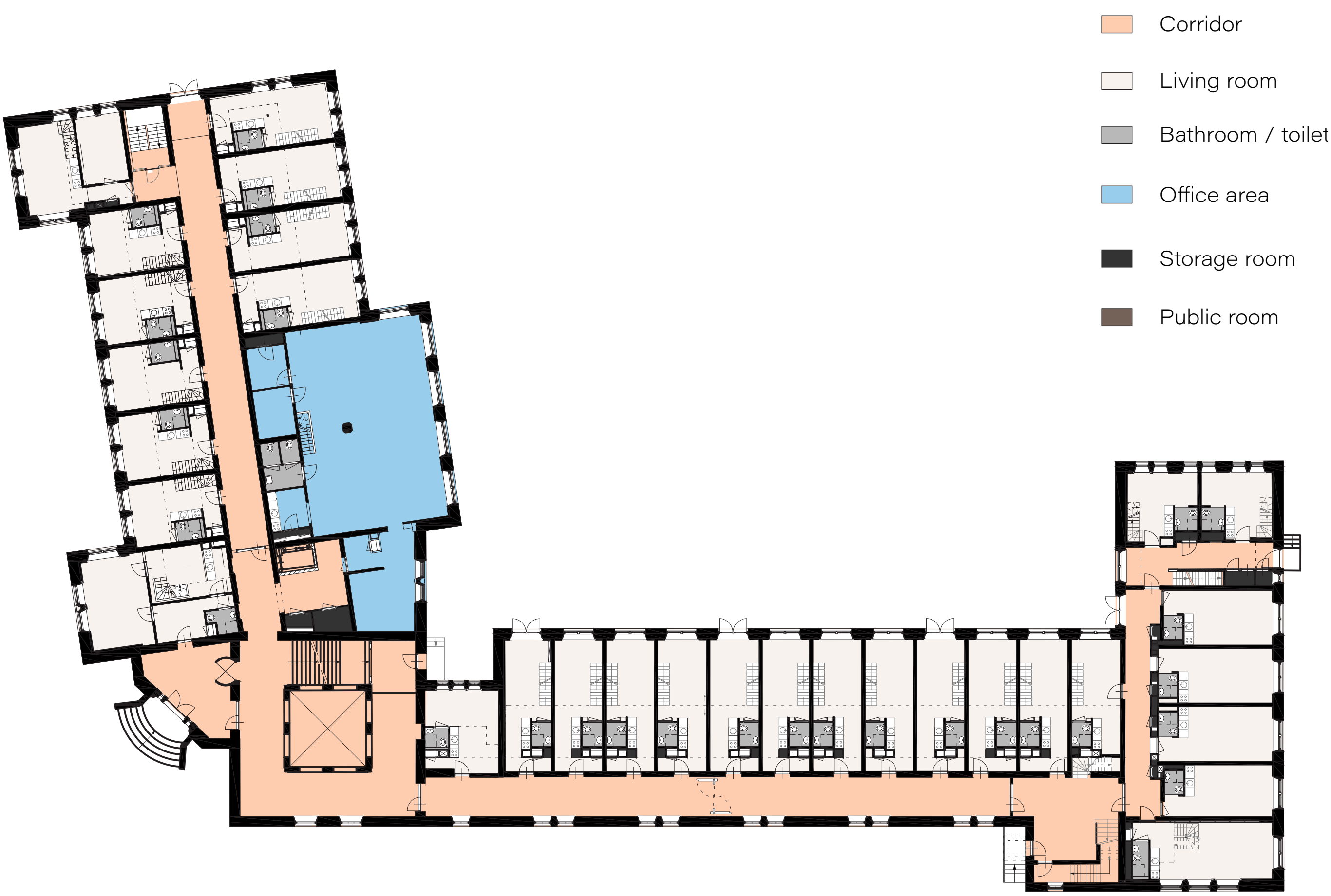


Figure 50: Ground floor of Mijnbouwplein (Author)

Figure 51: First floor of Mijnbouwplein (Author)

Figure 52: Second floor of Mijnbouwplein (Author)

Figure 53: Rendering of product use; based on the function of the rooms (Author)

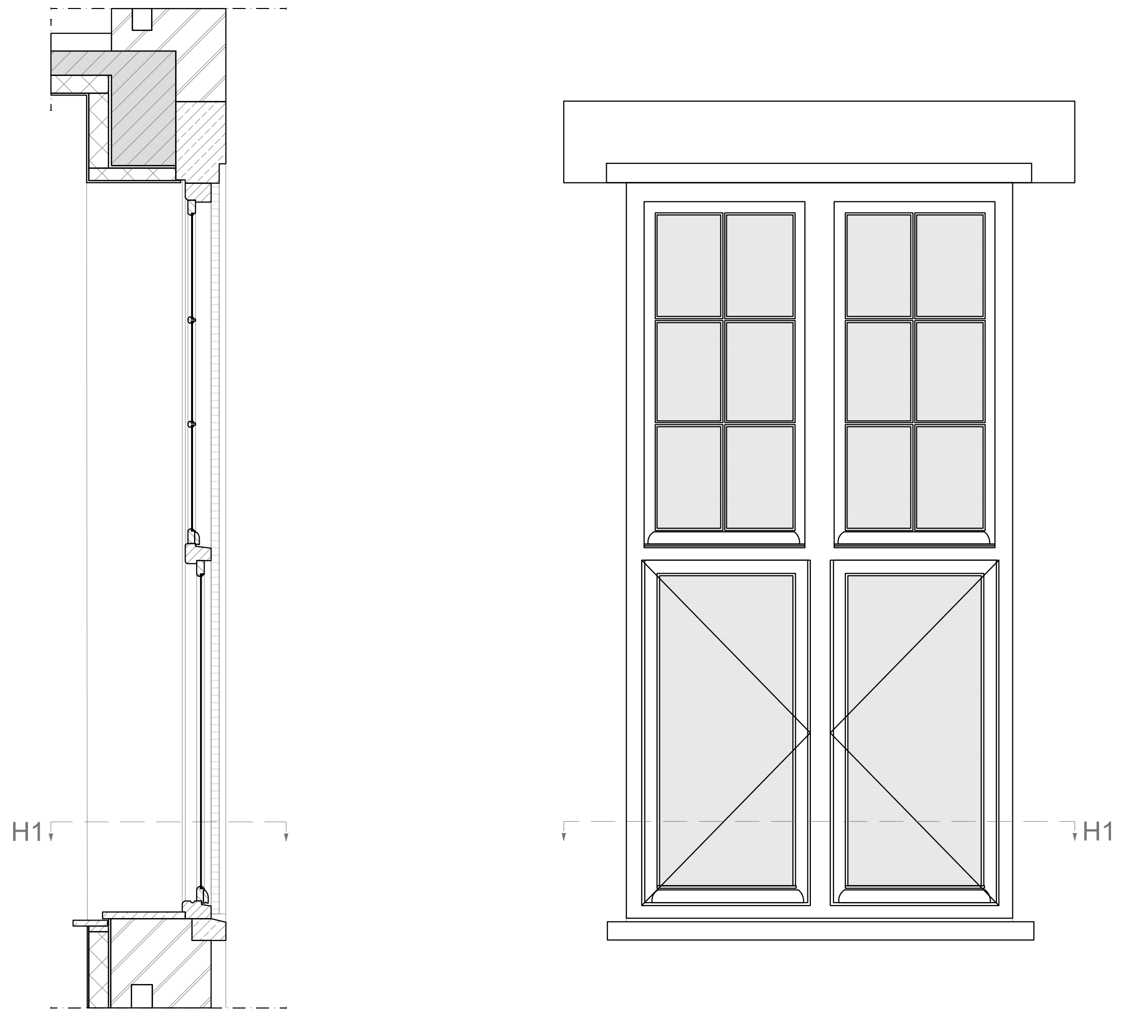


Figure 54: Design 3 in typical window frame 1:40 (Author)

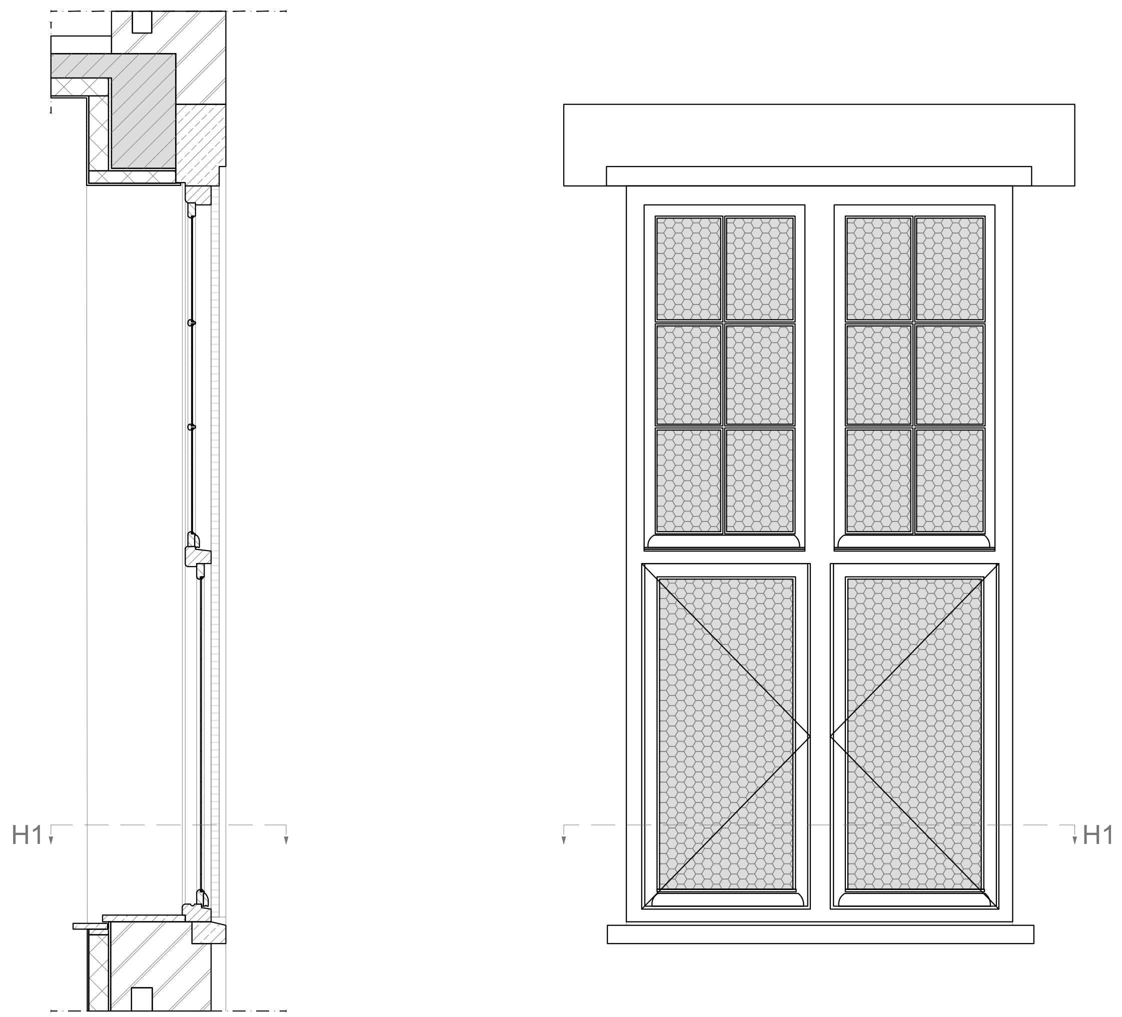


Figure 55: Design 4c in typical window frame 1:40 (Author)

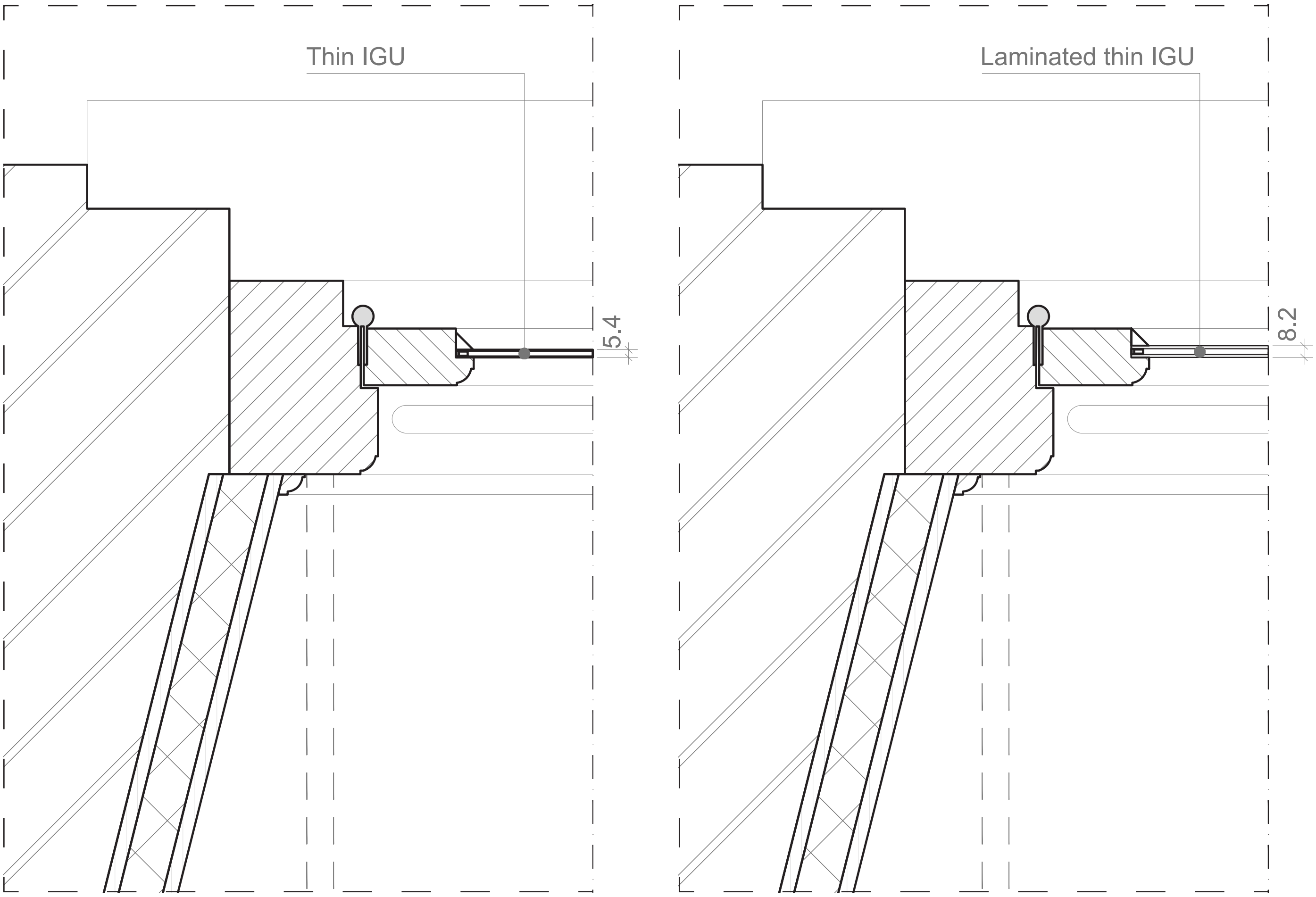


Figure 56: Detailing in case study 1:5; a) Design 1, b) Design 2 (Author)

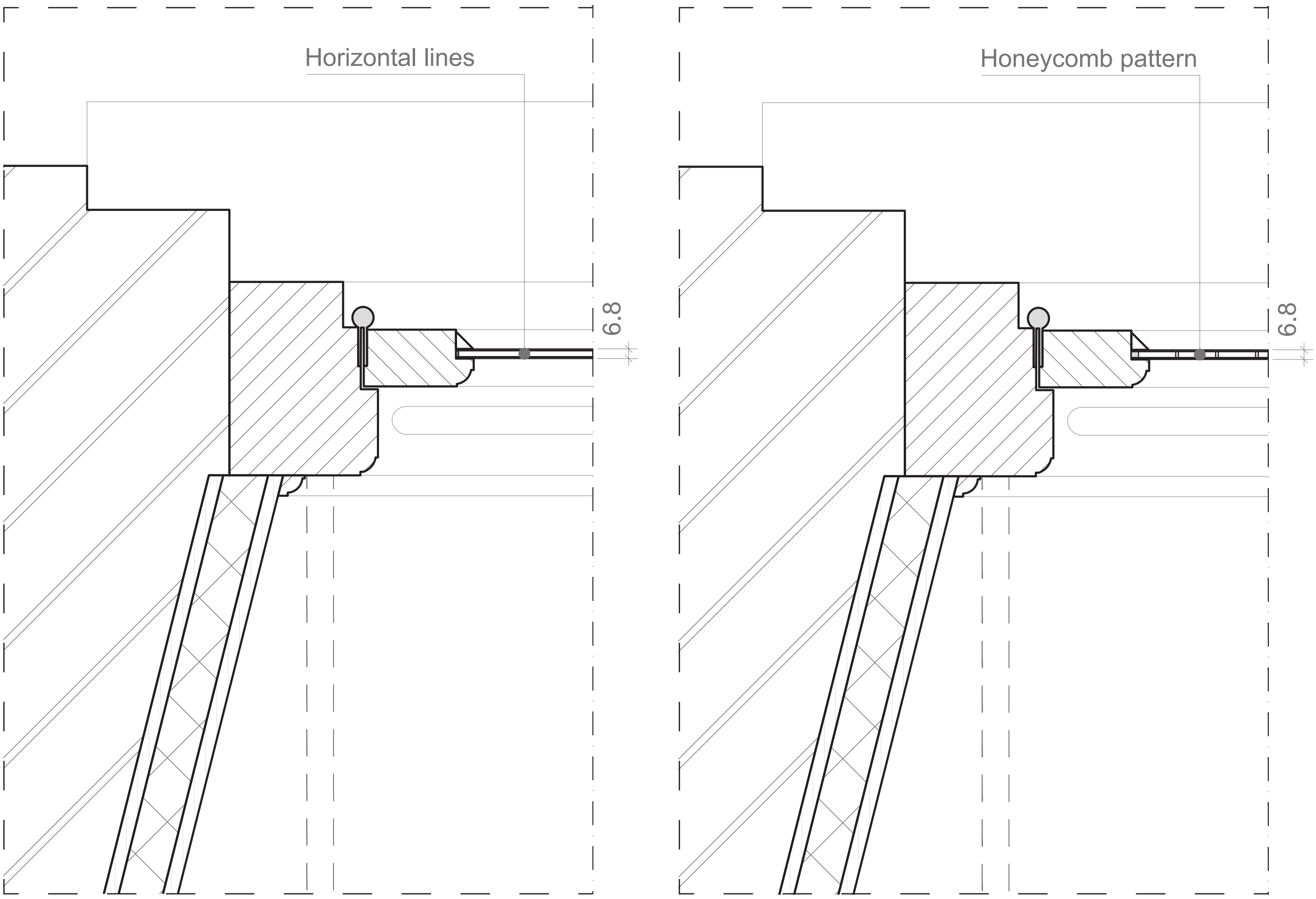


Figure 57: Detailing in case study 1:5; a) Design 3, b) Design 4c (Author)

8. CONCLUSIONS AND REFLECTIONS

Nowadays, most energy is still provided by non-reusable resources that contain a lot of carbon. To reduce the need for heating energy for indoor climates, it becomes more and more important to decently insulate buildings. More in detail, the window frames and the glass have significant higher heat loss than the closed parts and will therefore have the focus in this research.

In the end of the 20th century, the first designs for an Insulated Glass Unit (IGU) were made. Over the years, the IGU has improved with the use of argon, krypton, or xenon in the cavity, the improvement of the spacer or the addition of a low E-coating. Depending on the composition of the IGU the prices can differ from €65/m² to €80/m² with a U-value that starts from 2.8 W/m²*K, but the better versions have a U-value between 2.0 and 1.1 W/m²*K. For the option of so-called triple glazing, the prices range from €100/m² to €120/m² which U-value could range from 0.9 to 0.5 W/m²*K. In these cases, the thickness starts from 40 mm.

The standard IGU is made with float glass which can vary between 2 and 25 mm. The most basic form is annealed glass but to make the glass stiffer, it can either become heat strengthened glass or fully tempered glass by going through an extra oven. The glass can also be chemically strengthened for a better stress performance. Each type of glass has different pros and cons, so it could be wise to combine different sheets for the best performance. This can be done with a lamination layer, such as PVB, SGP or EVA. Besides float glass, new techniques are developed to create thin glass. This can be made with the overflow-fusion process or the down-drawn process. This glass can be between 0.4 and 2.0 mm thick.

Looking at heritage buildings, the 'normal' IGUs would not suit the existing window frames because the original frames are designed for 4 mm single glazing. The first solution to this issue is single glazing with a coating. The U-value of this is 3.8 W/m²*K. The second product is an IGU made with 2 or 3 mm float glass and a spacer of 3 mm. This results in product of 7 or 8 mm with a U-value of 3.6 W/m²*K. Even though, these products can fit the window frames, it is likely that the frame needs to be adjusted. The third product is vacuum glazing which is relatively new on the market. This makes the price still high for most renovation projects, but the U-value is excellent.

The case study at the Mijnbouwplein 11 in Delft showed that a new glass panel of 8.5 mm does fit the existing window frame However, the window putty reaches its maximum so the glass panel cannot be larger than 8.5 mm in this case. In general, the windows are replaced with single glazing with a coating. The windows with 8.5 mm laminated glass are situated on the two busier roads and are chosen to block the traffic noise.

After all the background knowledge written above, the following problem statement can be given: To reduce the heating energy in heritage buildings, modern solutions that replace the single glazing are not as good as solutions for non-heritage buildings. Trying to solve the problem statement, the research question will be: **What alternative solutions arise when thin glass is used to design an insulating glass panel that replaces single glazing in heritage buildings?**

To get started with this graduation research, recent papers and graduation reports were searched on the topic of architectural glass. A few sources were analyzed in more detail. Hänig and Weller (2021) discuss the use of acrylic in between thin glass sheets, which would be the starting point of this research. However, this paper does not reflect on the thermal performance of their product. With a quick calculation, it can be said that the product needs certain (air) cavities to achieve a better U-value. Other papers were found where the (glazing) products were composed with an extra interlayer. This layer would consist of hollow elements where the air could work as an insulator. This is where the idea started to look at existing, translucent materials to combine with thin glass.

After searching and evaluating different existing materials, multiple products did not pass since they were too thick or the overall design was inconvenient. At the end of the design proposal phase, six different designs were given. The first two are an IGU with thin glass and laminated thin glass. The third design is made with a hollow twin-wall sheet of PC and laminated to thin glass. The fourth and fifth proposal are laser cut PMMA connected to thin glass. While design four uses a honeycomb pattern, the fifth proposal experiments with a more freely design of cavities. The last proposal uses glass balls in the cavity of the IGU.

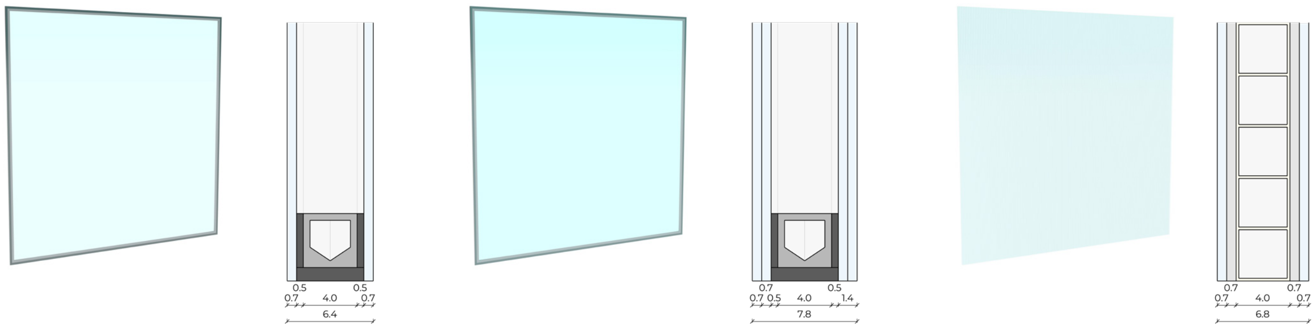


Figure 58: F.l.t.r. design 1, design 2 and design 3 (Author)

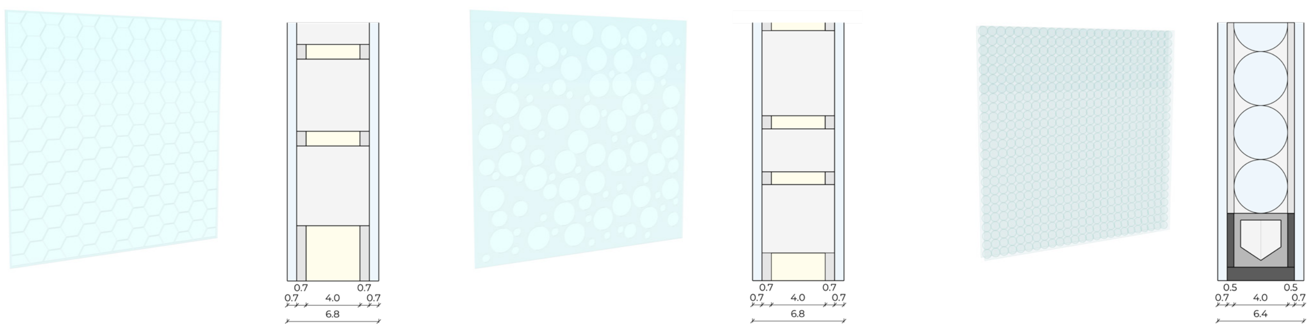


Figure 59: F.l.t.r. design 4, design 5 and design 6 (Author)

In the next step, the designs are compared to each other based on the thermal and structural analysis. For the thermal performance it can be said that the higher percentage of air, has a better insulating value. Besides this, it also matters how large the area of the cavities is since larger areas have fewer thermal bridges. At the end of the analysis, design 1, 2, 3, 4b and 4c seem to be sufficient and better than the single glazing with a coating. In the analysis of the deflection and the stresses due to the wind load, designs 1, 2, 3 and 4 are compared. Table 7 shows that design 1 and 2 could not handle the wind load even though design 2 came close. This leaves design 3, 4b and 4c to pass the theoretical tests.

#	Deflection	Max. deflection	Check deflection	Stress	Max. stress	Check stress
1	18,77	10,88	:(	63,72	15	:(
2	2,35	10,88	:)	15,93	15	:(
3	0,62	10,88	:)	5,93	15	:)
4a	1,02	10,88	:)	4,69	15	:)
4b	2,10	10,88	:)	8,00	15	:)
4c	4,35	10,88	:)	8,51	15	:)

Table 8: Outputs of the DIANA calcualtions (Author)

For the prototyping designs 1, 2, 3 and 4c are made. During the process, design 1 cracked due to two point loads. The broken pieces of the 500x500 mm prototype were long and large, which confirmed that the design was made with anneal glass. The 600x600 mm IGU cracked into much more and smaller pieces. This confirmed that it was made with chemically strengthened glazing. Comparing design 1 with design 2, the laminated glass has a certain 'milky' haze which makes the design slightly less transparent. Design 3 was the easiest to produce and came only with a small flaw where an edge broke during lamination. However, the EVA kept the glass pieces together. If the products were made in a professional firm, these small issues would not happen.

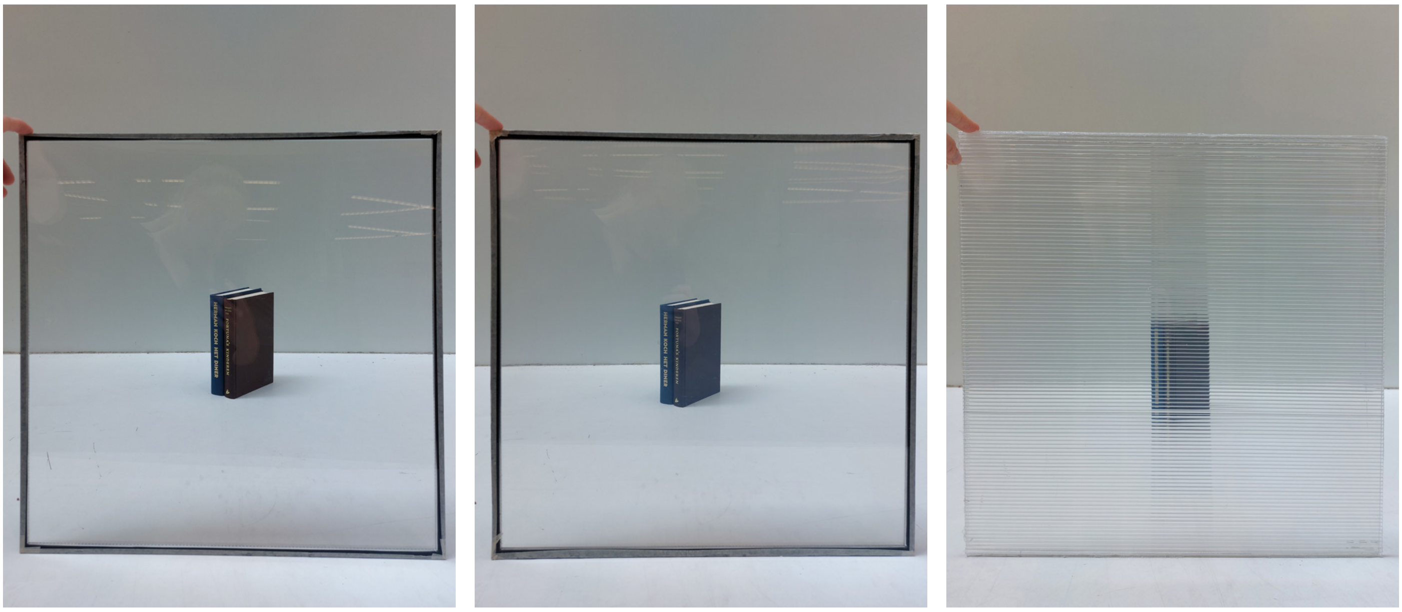


Figure 60: The final prototypes f.l.t.r. design 1, design 2 and design 3 (Author)

The making of design 4c was the most difficult and failed in the time of this graduation research. Two different types of cracks of the glass can be analyzed, both due to the pressure of the machine. The first one is a more circular crack that can be explained because of the clamped construction and the maximal stress near the supports. The second one is more random and is due to odd peak stresses. This concludes that the lamination machine did not distribute the force equally over the glass panel and even with a thicker sheet on top of the design, it still cracked. Assuming that the air pressure in the cavities was the problem is incorrect since the bottom glass layer was still intact and would have been broken if this was the issue.

After measuring the samples in the unguarded hot box, the gained U-values seem consistent with the expected values from SOLIDO. Design 1 and 2 are performing a bit worse than anticipated, but design 2 still passes the boundary condition. Design 3 comes close to the SOLIDO value. The sample for design 4a was much smaller, so more flaws show during the measurements. Moreover, the sensor fell off halfway and the numbers became less reliable.

The testing of the different specimen gave new insights into the structural performance of the designs. The samples show the second order effect which were not considered before. Almost all the samples pass the boundary condition, but it must be noted that the prototypes of design 1 were already broken before the tests started. This means that the results are not completely reliable, but moreover that the designs are too fragile to use or to transport. In design 3, the EVA is the weakest link, since it detached before the glass broke.

To see if the materials would age over 10 years, small samples were placed in a UV accelerated weathering test machine. Comparing those to the non-treated samples, the EVA and the PMMA did not change colour over time. However, the polycarbonate did significantly yellow. To prevent this the manufacturer already uses an UV coating on one side of the twin wall product. In the machine, the rays are distributed to all sides of the sample and therefore the side without a coating has yellowed.

The survey showed that design 3 and 4 are both chosen to be the most aesthetically pleasing. The division between the two was almost even. Also, the participants that have more background knowledge, such as architects, were split equally. The participants were so sure that they would not switch if the U-value of the other was better. However, focusing on the function of the room or building, their preference will vary between the rooms within in the same building. In more private and less used areas, a larger group of people choose design 3 because of the lower transparency. In more public and larger areas, the group choose design 4 more often because it is more prominent and eye-catching.

When the designs are placed into the case study, all designs fit the existing window frames without the need to adjust the wood. Depending on the function of the rooms, the glazing type is chosen, which is mostly design 3. The case study confirms that the designs pass the boundary conditions.

	Thermal performance	Structural performance	Aesthetics	Makeability	Ageing	Total
Design 1	★★★	★★	★★★★★	★★★★	★★★★★	3,8 ★
Design 2	★★★★	★★★★★	★★★★	★★★★	★★★★	4,2 ★
Design 3	★★★★★	★★★★	★★★	★★★★★	★★	3,8 ★
Design 4	★★★★	★★★★	★★★	★★	★★★★	3,4 ★
Design 5	★★	★★★★	★★★	★★	★★★★	3,0 ★
Design 6	★	★★★	★	★★	★★★	2,0 ★

Table 9: Ranking the six different design proposals (Author)

Table 9 ranks each design on a scale from one to five stars based on different aspects of the design process. **It can be said that design 2 is the best alternative solution to replace single glazing in heritage buildings.** Design 1 and 2 have the most asthetically pleasing view and design 2 scores also good on the structural performance. Since design 3 has better insulating properties, it is ranked second. However, before the solutions are presentable on the market, more in dept research should be done; mostly on the correct thermal and structural properties.

Looking back at the products that currently exist on the market, I would say that design 2, 3 and 4c are better than the single glazing with a coating. Mostly because they have a lower U-value. Comparing design 2 with the products of Monuglas®, the weight and thickness of the panel have become less, but the thermal and structural performance stayed more or less the same. Moreover, the product was already made in the Stolker manufactory, so they could easily add this to their product line. Comparing design 3 and 4, the consideration must be made whether it is preferred to use glazing with a pattern (design 3 or 4) or to adjust the window frame a bit more. To relate the design proposals to vacuum glazing, most research should be done towards the pricing and costs of the designs. Vacuum glazing is already a good insulator and thin enough to suit all window frames. However, it cost a probably more, because the design proposals are simpler to produce which saves on expenses.

8.1 Further research

Design 5 and 6 were the first ones to not pass the tests. The focus of this research is the thermal performance of the products and while I personally see no future for design 6, I think that design 5 can be optimized to a shape where there is a much higher percentage of air cavities and the cavities have a larger area. In this graduation research a simple Grasshopper script was written to randomize the three different sized circles to illustrate the idea, but this can become a much more in dept research topic.

ollowing on the parametric design method; the larger the area of the air cavities in design 4, the lower the U-value. However, the larger those areas, the higher the deflection and stresses become. This means that there would be an optimal size of the cavities, where the design would not reach the limits. To research this, more computational design could be used.

Because the hot box measurements were not in line with the expected values from SOLIDO, a flaw in SOLIDO was discovered. To reanalyse the gained values, it would be needed to do more thorough research on the correct U-value of design 1 and 2. To do so, a new software or multiple excel sheets by Martin Tenpierik for simple calculations could be used.

In the structural analysis, the maximum design stress in the glass can be 15 N/mm2. The glass that arrived from Corning in the size 500x500 mm had this property, but the 600x600 mm was made with chemically tempered glass which has a maximum design stress of 90 N/mm². If this type of glass was taken for the calculation, design 2 would have passed the maximum stress and with that pass all the tests. This new design possibility suddenly makes it achievable to product a completely transparent option. Besides this, with the use of chemically tempered glass the needed thickness might be even less. For instance 0.5 mm thin glass could be used, resulting in an even lower total thicknesses.
The analytical testing of the structural properties of the designs is now done in DIANA. For this program the 3D designs were made as simple 2D sheets with a thickness. This is also the reason why the stress figure of design 3 did not show the correct stresses everywhere. Moreover, the lamination layer is not considered within these designs which will give slightly different values. To analyse the designs in more detail, another program such as SCIA could be used.

As already mentioned in chapter 7, the EVA gave a 'milky' haze. To optimize the transparency, other lamination layers could be researched. After trying to laminate design 4c two times in the lamination machine, it was concluded that this would not work. Because the cracks of the prototype were around the edges of the PMMA walls, it could help to round off the edges as seen in figure 61. However, other ther methods to 'laminate' the PMMA to the glass should be researched. Saleh (2020) used an UV adhesive to glue the PET to the glass. However, this Delo Photobond 4494 might be too liquid and become messy to work with. Another alternative might be the use of 3M VHB adhesive tapes which are thin tapes that also have a structural function.

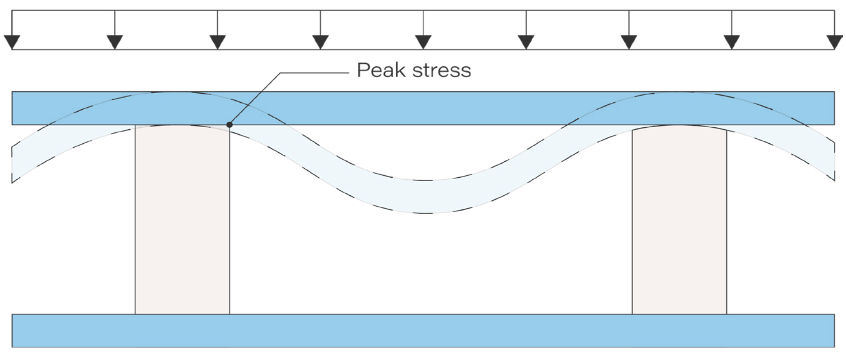


Figure 61: Lowering the peak stress with rounded edges (Author)

To test the structural strength of the prototypes, a wooded construction was made as a support frame during the test. The point load was applied through multiple squared stacked blocks where the corners give higher peak stresses then the edges. It would have been better if the blocks were round, so all the stress is evenly distributed. Moreover, the equations that were used to calculate the situation for a clamped plate were an only a first order approach working with and standard values. With further research on the structural area, the second order effects should also be considered with a finite element method.

Due to the limited time of this graduation research, the small samples have been in the UV accelerated weathering test machine for only 10 weeks. The new glazing of the heritage window frame would probably be in the window for 50 or more years. It would be interesting to see how much change the materials would show after 50 or more weeks in the machine and moreover, how they would behave with an extra UV coating.

Evaluating the results of the survey, it is unfortunate that the age group of 18-30 has more participants than 30-70 altogether. Even though this is no surprise, it would have been better if the other group was more represented. Moreover, I am curious to see if the U-value would have had more impact on the results if the difference was higher, for instance with a difference of 0.5-1.0 W/m2*K. This result could have been predicted and done differently before the survey was sent out.

For this specific graduation research, the simplest version of an IGU is taken to compare the results. The thin IGU is filled with air and the cavities in design 3 and 4 too. However, nowadays more gasses and coating can be used to optimize the thermal performance. A next step could be to apply these on the different design. Thinking about the manufactory process, it would be needed that in design 3 and 4 the cavities are connected to easily add the gas. Further research could be done on how to achieve this, for instance creating small gaps in the walls of design 3 and 4.

The case study showed the importance of sound insulation. This is not analysed in this research and should be done. Moreover, Arjo Boerstra explained that for the case study the use of distortion glass was important. This glass starts from 3 mm and up. Using that for instance in design 1, it would perhaps not suit in the existing window frame. However, it would still be thinner than the product by Monuglas® of 8 mm. Further research could be done about the use of this specific distortion glass.

The goal of this research was to make the new panel as transparent as possible. A certain transparency is achieved in every design, but not measured in SI values. To explore this in a more scientific way, multiple tests could be done. Opposed to this, the use of colour is not explored during this research. Either the glass or the polymers are available in a broad range of colours, which could be requested for more extraordinary projects. In fact, one of the participants of the survey was reminded of stained glass by the honeycomb pattern.

The products that are designed and researched with this graduation project are innovative and improve the current solutions for heritage buildings. By renovating existing buildings, their use becomes more sustainable. However, the method for making these products is not necessarily sustainable. The prototypes have used adhesives that are not reversable, making the samples not recyclable. This is mostly because the EVA and butyl are very sticky once they are heated and cannot be taken apart later. Further research could improve on this scope of the product design. Even though this might be hard for a gastight glass panel.

9. PLANNING AND ORGANISATION

The timeline below is also added in the Appendix and shows a global planning of the graduation research. Roughly speaking, it is split into five phases. The first phase is the literature and case study phase. This phase focuses mainly on gaining (background) knowledge and getting grip on the size of the research scope. Somewhat together with this, the second phase, the design proposal starts. During this phase the first drafts are made, and a criteria list is concluded. Halfway through this phase the designs should become more concrete, and the manufacturing of the designs should be thought of. The design proposals of this phase will be finalized just after the P2.

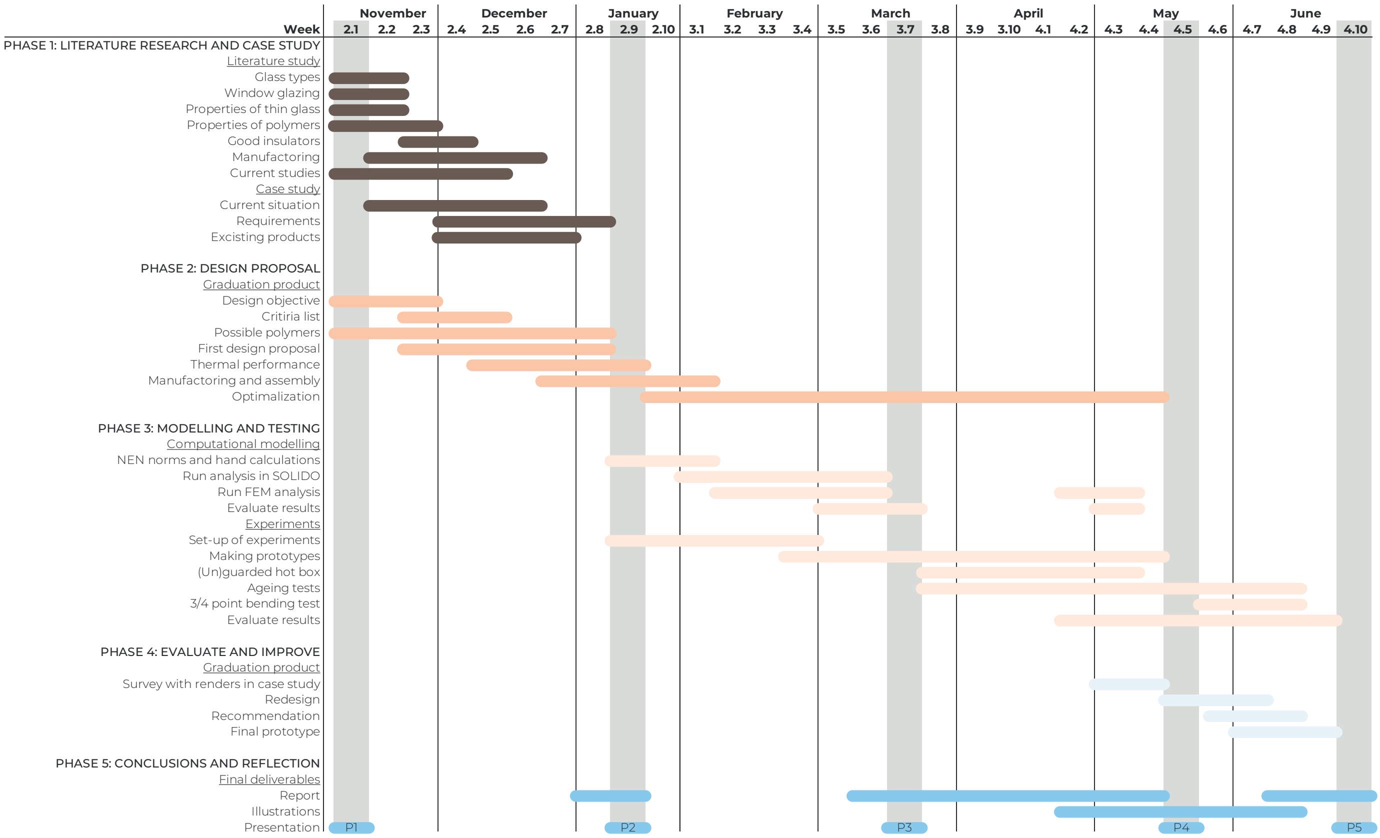


Figure 62: Timeline of the graduation project (Author)

With the final design proposals ready, the next phase begins. During the modelling and testing phase the ideas are analysed in SOLIDO and DIANA FEM. For each program about four weeks are given to import all the data. However, while using SOLIDO, small adjustments were made in the designs, so the overall timespan took a bit longer. At the end, the outputs are compared and evaluated. For the use of DIANA, first the designs were analysed with hand calculations. To see if those were correct, they were imported in DIANA and a 2D shell was also imported. Nonetheless, these were still not completely reaching the expectations. To work those out in detail, multiple meetings were helt which resulted in some delay. This is why the DIANA analysis is final just before the P4.

Parallel to this, the preparation for the prototypes needed to start. This came down to gathering the materials and reserving the machines. In the beginning the timespan of six weeks was taken to make sure all the prototypes could be done in time. However, this was completely incorrect. The main issue for the delay was that most of the prototyping had to be done during an appointment. These were sometimes hard to schedule. Moreover, some of the prototypes broke during the assembly and had to be done again, on a new time and date.

Once the final three prototypes were done half way during April the physical experimenting could begin. The preparing of the unguarded hot box did start a bit earlier so those tests were done relatively quick. The samples of the design had to be in the UV accelerated weathering test machine for 10 weeks, so this had to be done early. Due to the delay in the making of the prototypes the structural test had to be done after the P4.

Once a rough conclusion can be drawn from the testing, the evaluate and improve phase can begin. In this phase all the results are evaluated and some final adjustments can be done. Around that time, the survey is sent out and the results can be gathered, just before the P4. This leads to the final phase, the conclusions and reflection phase. In this phase the final deliverables are made for the P5 and an overall conclusion of the graduation study and a recommendation for further research are given.

9.1 Research team

Working on a graduation project with thin glass, you immediately think of James O'Callaghan as mentor. He has a broad knowledge in the field and is known for many architectural highlights, such as the Steve Jobs Theater. His wisdom could help this research in gaining interesting insights and taking directions that were not seen before. Moreover, he has connections with thin glass suppliers who could help in offering materials for the prototypes.

Marcel Bilow is asked to be the second mentor. His hands-on approach is much appreciated while planning to make prototypes and performing multiple tests on them. Additionally, he is familiar with the product making process which is useful in this design though research process. Furthermore, on a personal note, Marcel challenges me to keep looking for better solutions instead of going with the first option that crosses my mind. This has been a flaw of mine and a point of improvement during this graduation study.

Besides the chosen mentors, the TU Delft asks for an external examiner. This is assigned by the TU Delft and therefore this graduation project is also presented to Susanne Pietsch. Since she is not from the track of Building Technology but the Architecture studio Interiors Buildings Cities, she will have a broader view. Hopefully, this will create an interesting addition to the graduation research.

Moreover, there are several people who have helped in specific parts of the study. First, Juan Camilo Ortiz Lizcano, who is doing his PhD at the PV Lab at EWI, explained the lamination machine they use for the lamination of solar cells. After each prototype, he always gave advice on how to continue. Furthermore, Martin Tenpierik and Fred Veer helped to physically test the prototypes on thermal and structural performance. They had access to the needed test setup and the specific knowledge. Rik Rozendaal has helped me with the structural analysis in DIANA.

10. REFLECTION

A reflection on the relevance, the connection to the master Architecture, Urbanism and Building Sciences and the process of this graduation research is given. It considers the impact of the study and the method that has been used. It is also the moment for the author to give a personal view upon the final graduation work and deliverables.

10.1 Social and scientific relevance

In recent years, the climate crisis, the carbon footprint, and fossil fuels have become part of our daily life and vocabulary. When this is applied to the build environment, it results in a need for a more sustainable and durable structure. Moreover, there is a rise in the need to renovate and repurpose existing buildings instead of demolishing them. This brings along the question on how to make these buildings more sustainable and in line with the building regulations, while leaving the essence intact. Within the graduation work the focus will be on improving façades and in more detail, the glass within the window frame. This is mainly because windows are generally the largest factor in heat loss and in older buildings this difference is even greater. Improving these glass panels will contribute to the increase of the insulation values, the lifespan of buildings, the ease of renovating existing buildings and the preservation of cultural heritage.

The current possibilities to replace the glass panel are thin glass (2 mm) panels with a cavity (3 mm) in between, single glazing with an extra coating, or vacuum glazing. However, these options might be too thick to fit into the original window frame, show only a small improvement on the thermal performance, or are quite expensive. The graduation project will research a design with thin glass (0.7 mm) and a polymer (2-6 mm) in between. Preliminary, research has been done on how to design a composite like this, but the graduation research will focus on the thermal performance of the product for the first time. Resulting in transforming the current studies towards a product that could be ready for the market.

10.2 Relation between graduation topic and MSc AUBS

When making a new glass panel to place in monumental buildings, the designer needs to take a close look into multiple aspects that are relevant within the master track Building Technology. First of all, it is important to consider the climatic influences of the glass in the overall façade and the thermal performance it will have, touching upon the climate design chair. Moreover, the product needs to be tested on all sorts of mechanical tests to fit within the NEN norms. This is essential since glass is known for its brittleness and unexpected breakage. Hence, the graduation topic has a close relation with the structural design track. Additionally, to test the design on structural properties, prototypes should be made. The process and the making of these prototypes are an important part of the (façade/) product design chair. Furthermore, the designer should check what typical façade elements and window frames are used in a monumental building to confirm whether the design suits the case.

Even though, the final product will mainly be focusing on the building sciences, the outcome should still be applicable for the general building industry. Once the product is maximally optimized, it could become a real product on the market. This could mean that architects who are involved in the renovation and restoration of monuments can order the product and use it in future designs. Since the design and the looks are important to the architect, the product should be aesthetically pleasing.

10.3 Graduation process

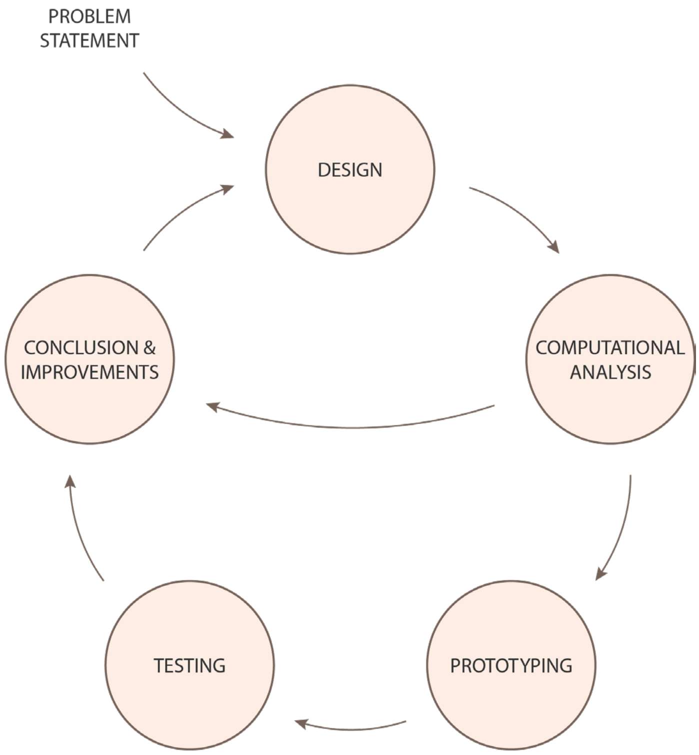


Figure 63: Loop of the design process (Author)

The research approach is displayed in figure 63. The graduation started with gaining knowledge on the research topic and to come up with a clear problem statement. Even though formulating the exact problem statement took a bit longer than expected, the main issue was clear in the very beginning. Since I generally am satisfied with my design too quickly, it was good to spend some more time on the design phase to really try to come up with the most ideas. This is also why the computational analysis starts with six different ideas and already eliminates two of them, based on thermal performance. I feel that in this way, I was able design with an open mindset and not always think if the design would work in the next step. It also shows the research through design method, which I think suited this graduation research. Beginning with the making of the prototypes, it needed some more research which I did not expect. This was mainly because I was still missing some materials and other solutions had to be found. However, the way the prototypes are made, is directly a good method to see if they could be made on a larger scale. The setup for the thermal testing was prepared during the extra time of making the prototypes, so the tests could be done right away. After one test run, the samples could be measured quickly and the conclusions could be drawn. Moreover, a survey was send out and received 80 responces in five days. Currently I have five weeks left to analyse the survey data, test the three final prototypes in structural performance and draw the conclusions. I feel confident that this will succeed.

Looking at the method that is described above, its strength is that it gave the opportunity to examine all the possible designs that could be thought of and to get a touch of the full building product design process. However, a small weakness can be found in the search for the correct materials and the suppliers. It could have gone better if I started with approaching more contacts at the same time instead of waiting for a reply from each one of them. This also is related to the so-called threat of the method since it is depended on the willingness of the suppliers to send the materials. On the other hand, these contacts gave the opportunity to discuss the graduation research and showed the relevance of the study. Most suppliers though it was an interesting project with possibly some good outcomes.

Research vs. design

The thesis explores the possibilities of developing a new (composite) glass panel by examining its thermal and structural performance. These aspects can be seen as strict values that the product needs to achieve. To do so, research plays a large part in selecting the best designs. This means that the research can prove that a design is not reaching the threshold value and should be reconsidered or redesigned. On the other hand, if the properties are sufficient, that does not directly mean that the design is suiting the aesthetics and purpose of the product, since the aim to replace the single glazing which is transparent. Moreover, some of the design proposals even can be adjusted to match the preferred appearance of the buyer or architect. This relationship can be seen clearly in the design with the honeycomb structure. The size of the honeycombs has an impact on the transparency, the thermal performance and the stiffness of the panel.

Moral issues

In general, the graduation research did not tackle much ethical dilemmas. However, there were some moments which come to mind. During the meeting with Julian Hänig and Christian Louter, I was asking about the method they used to cast the PMMA in between the thin glass. Unfortunately, they were not able to tell me this in detail since they were still working on their patent. This was something I did not foresee and I felt foolish for asking. Another thing I experienced is that companies are willing to send materials for a graduation study but sometimes ask you to do something in return. For instance, Witteburg B.V. send two twin wall sheets, but asked to write a Google review. Of course, I was happy to do so but this could have been a more extreme request.

The graduation research was done in times of the Covid-19 epidemic. This made the contact with the mentors a bit more complicated, because in an online meeting it is harder to quickly sketch an idea or explanation. Besides the pandemic, I have been sick for a couple days, which were in the prototyping stage. Due to this, I had to cancel a few meetings and the next meeting moment was more than a week later. Of course you cannot really blame an illness for the delay, but it was a superior force which I did not forsee.

Moreover, I experienced some inconvenience between my mentors. Not in an alarming way but sometimes one mentor told me to go one way and the other one disagreed with that. In that case, it was up to me to find a solution that would take in both of the opinions. Besides getting help from my mentors, I needed some extra help from professors or employees at the TU Delft. Even though they were friendly and willing to help me voluntary, it was hard to estimate how much you could ask them since they are not getting paid and their time is valuable.

11. REFERENCES

The following persons and institutions are consulted:

- **Corning Glass**: contact via James O'Callaghan, they have sent 15 thin glass sheets of 600x600x0.7 mm and 20 thin glass sheets of 500x500x0.7 mm.
- **Witteman B.V.:** contact via mail and they have two twin wall sheets of 900x900x4 mm.
- **Bart Vroegh** from Stolker Glas: contact via mail and telephone. He delivered six spacers of 2 m and **Mustafa Akbulut** helped me with constructing the IGU with thin glass in their workspace.
- **Julian Hänig** and **Christian Louter** from Technische Universität Dresden: had a meeting on the papers from Hänig.
- **Mariska van der Velden** and **Charbel Saleh**: contact via LinkedIn and explained more detailed about their research papers.
- **Arjo Boerstra** from DUWO: had a meeting about the case study and lend out detailed drawings from the renovation of Mijnbouwplein 11.
- **Rik Rozendaal**: gave advice on how to model the 3D elements in DIANA FEA
- **Ernst van der Wal** from Reactor Instituut Delft: gave access to the Cricut Maker® cutter and explained how it worked.
- **Juan Camilo Ortiz Lizcano** and **Manuel Dakessian** from the PVLab: helped me to use the lamination machine at EWI.
- **CamLab**: laser cutting polymer with a honeycomb pattern.
- **Hans van Ginhoven** and **Bas Valz**: helped me with small modelling questions and the use of the machines in the model hall of BK.
- **Martin Tenpierik**: availability and explanation of unguarded hot box at the faculty.
- **Fred Veer**: testing method for the wind load and the UV accelerated weathering test machine.
- **Eloi van Keep** from Hordijk: contact via mail and small tour around the manufactory, showed the guarded hot plate on location.

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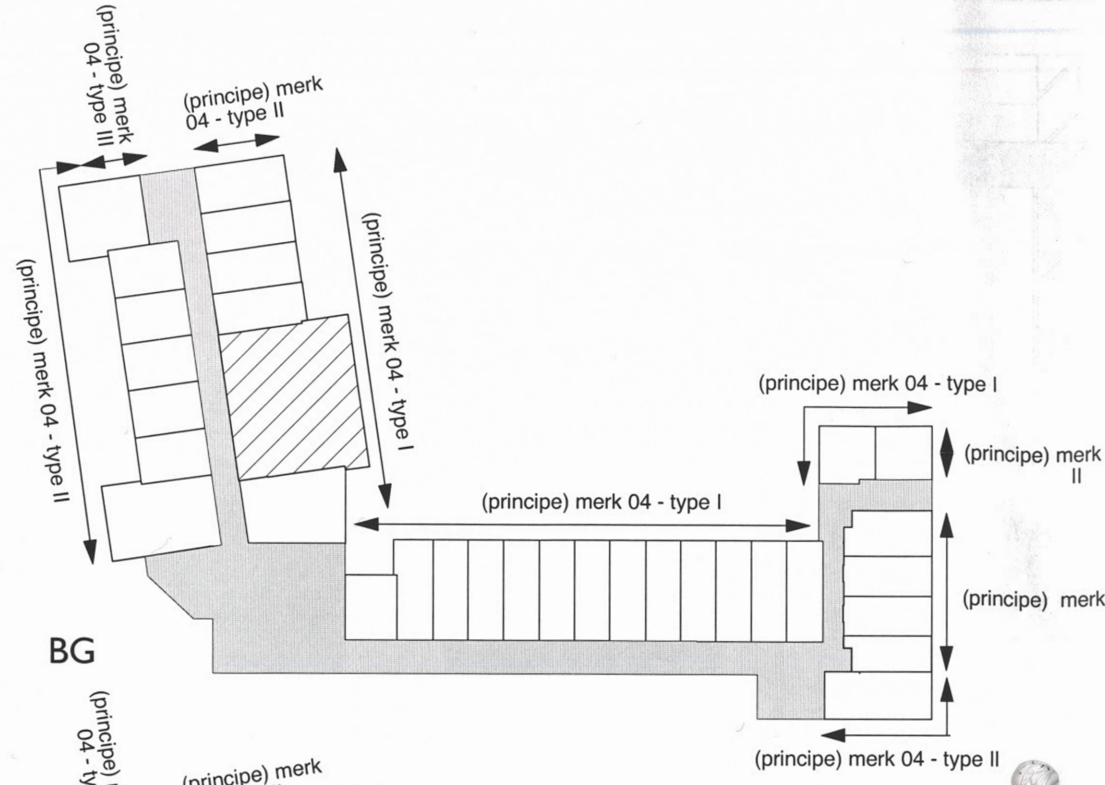
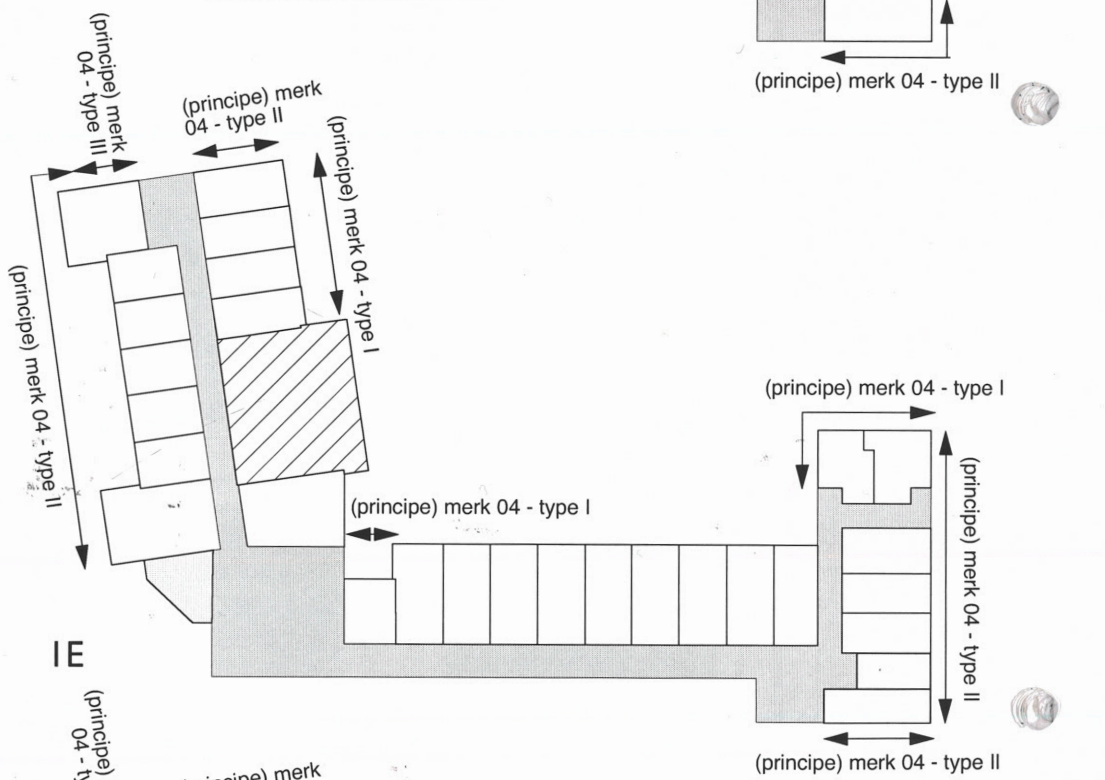
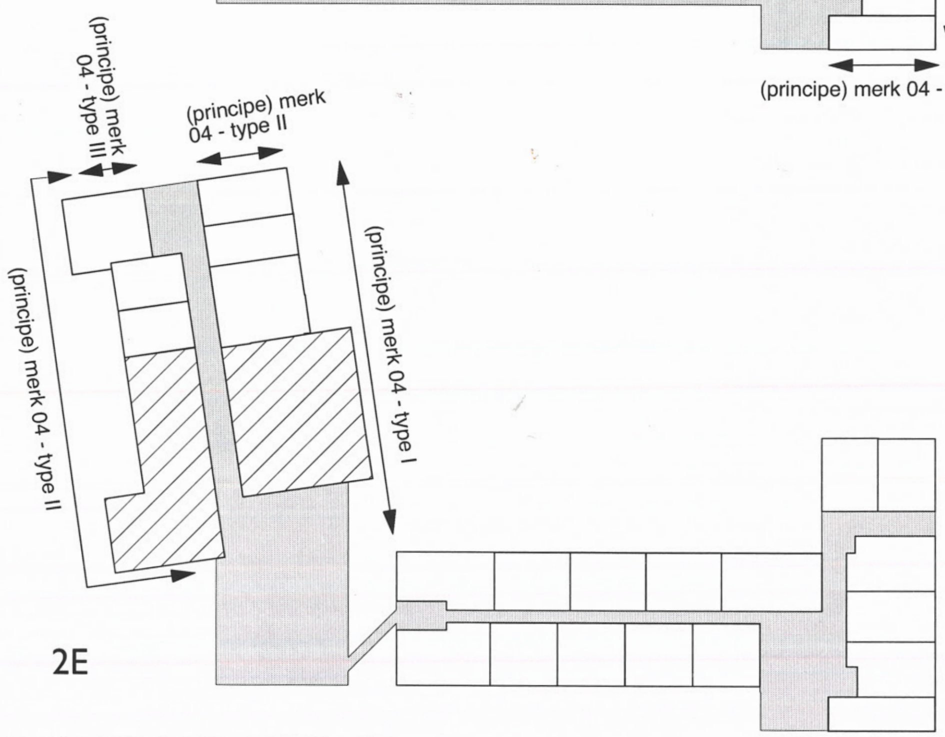
Appendix A







PLAATSAANDUIDING KOZIJNTYPES

04 - type

04 - type III

DETAILVERWIJZINGEN

Woningen BG 1e 2e 3e

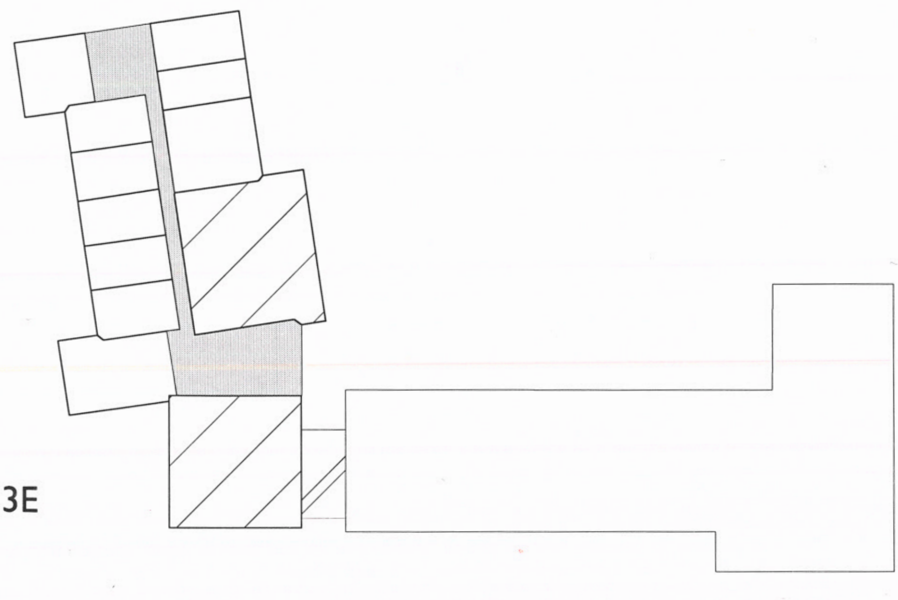
Bedrijfsruimtes

Algemene verkeersruimte (gang, trap, hal)

Algemene gebruiksruimte (wasruimte)

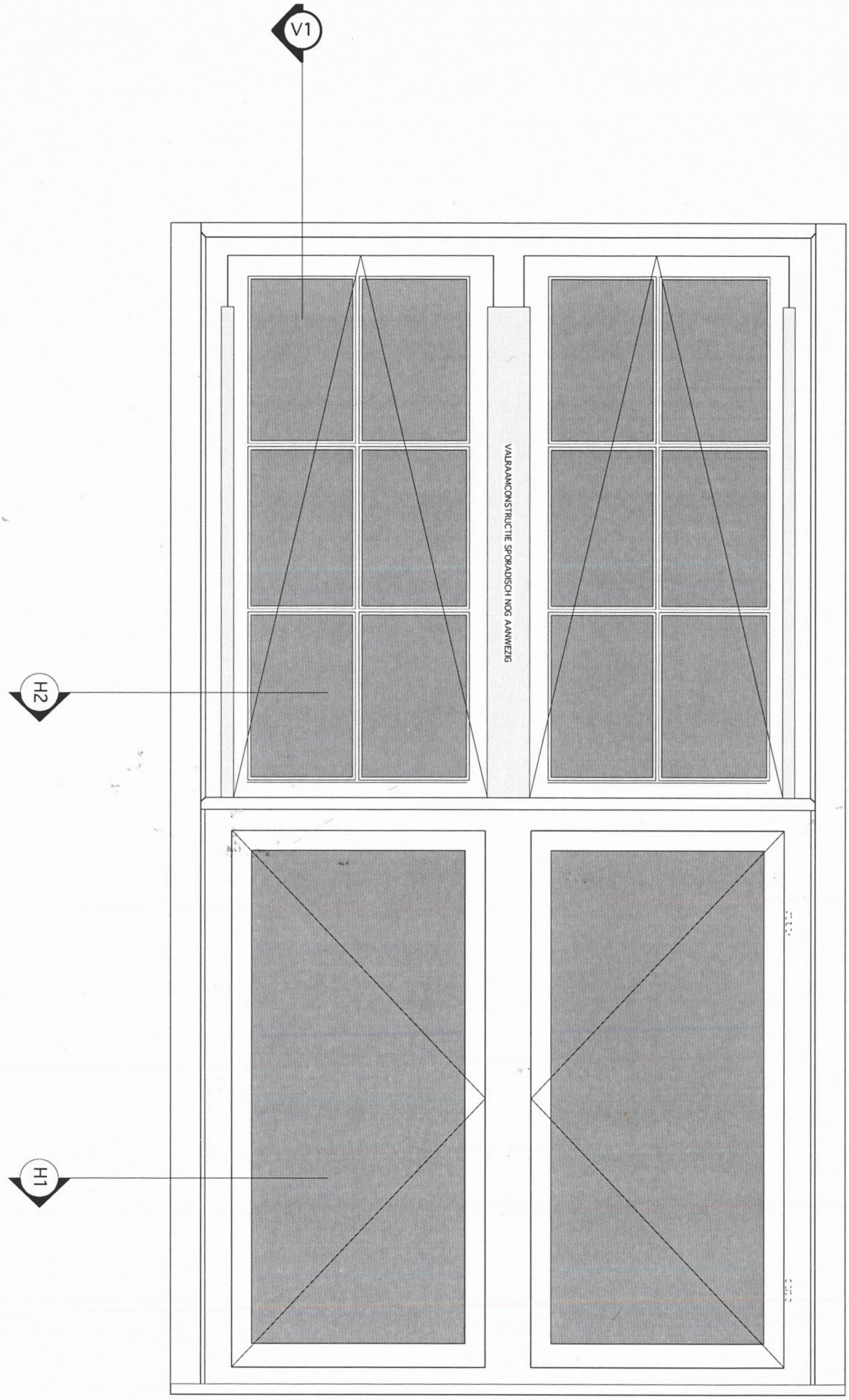
Restruimtes

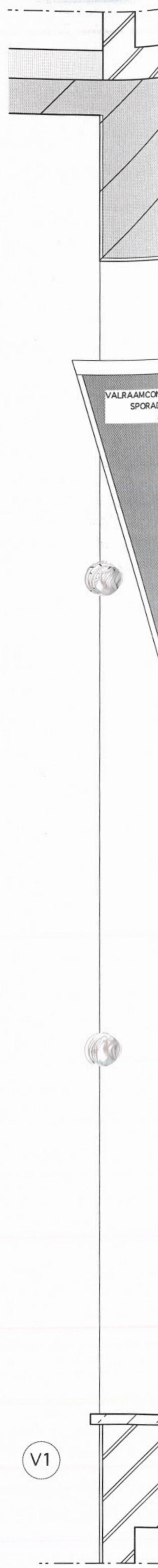
Alle kozijnen in betreffend gevelvlak
worden gelijkwaardig opgelost i.o.m. architect



3E

BINNENAANZICHT





KOZIJNDETAILLERING MERK 04

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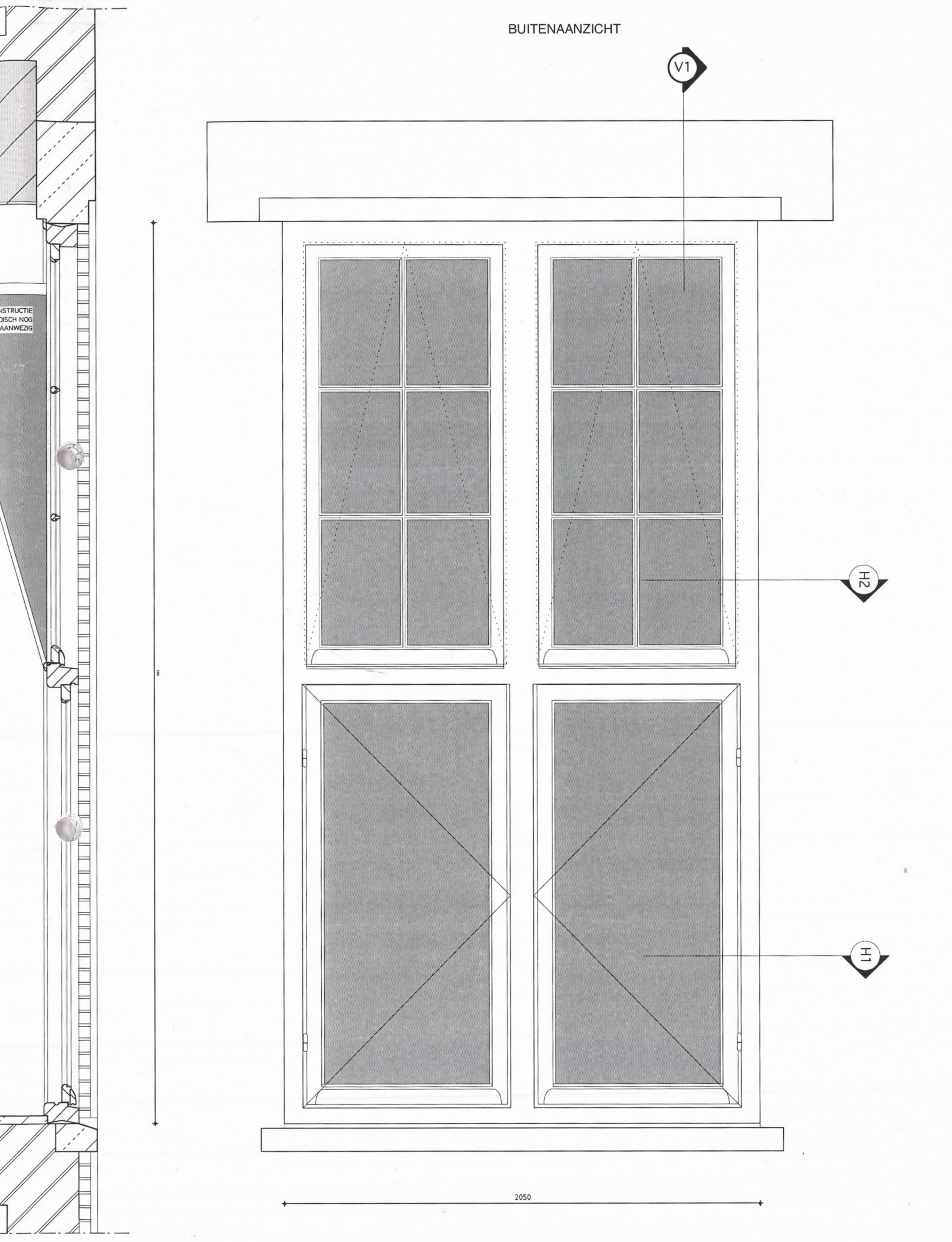
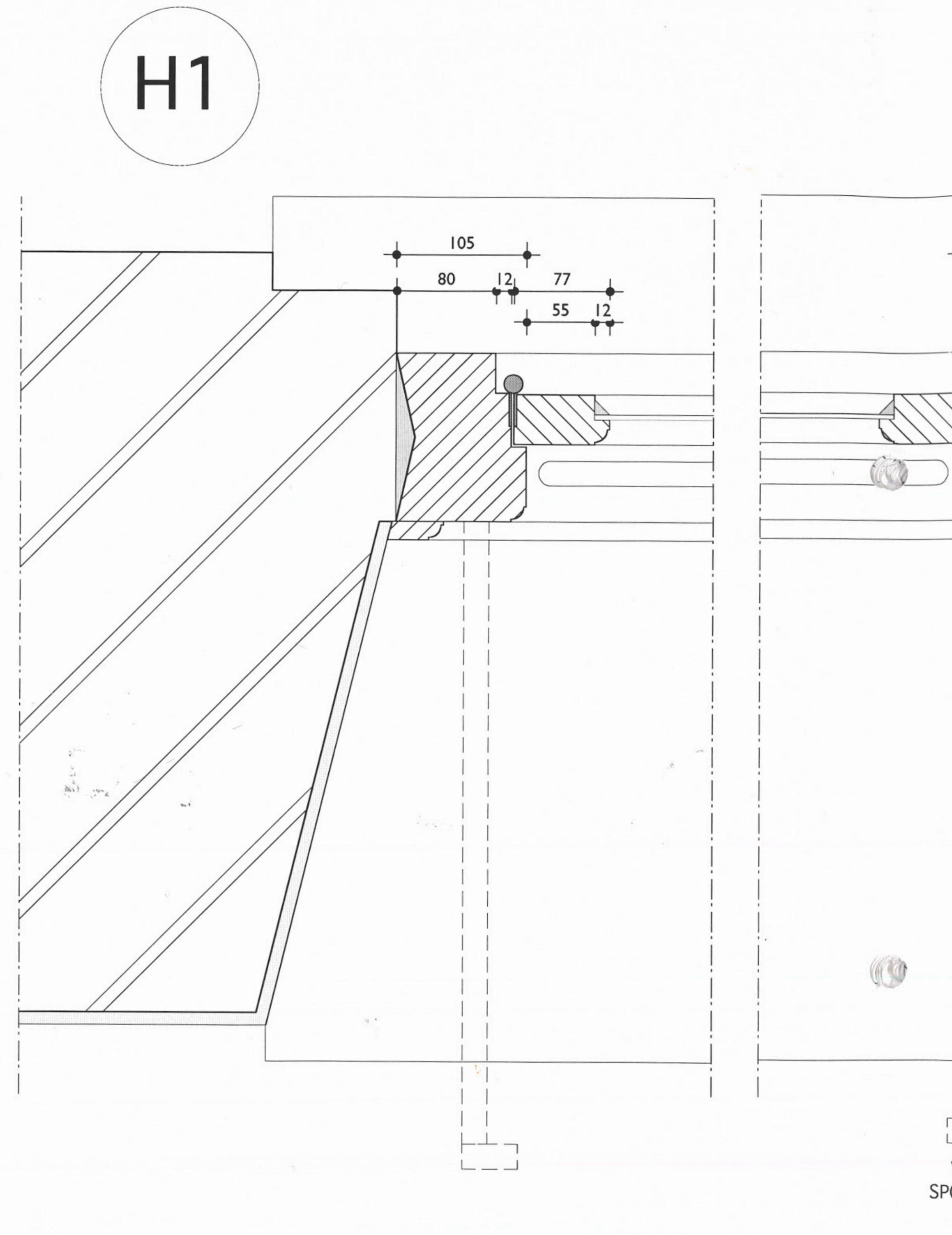

BUITENAANZICHT
V1
H2
H1
NSTRUCTIE
DISCH NOG
AANWEZIG
2050



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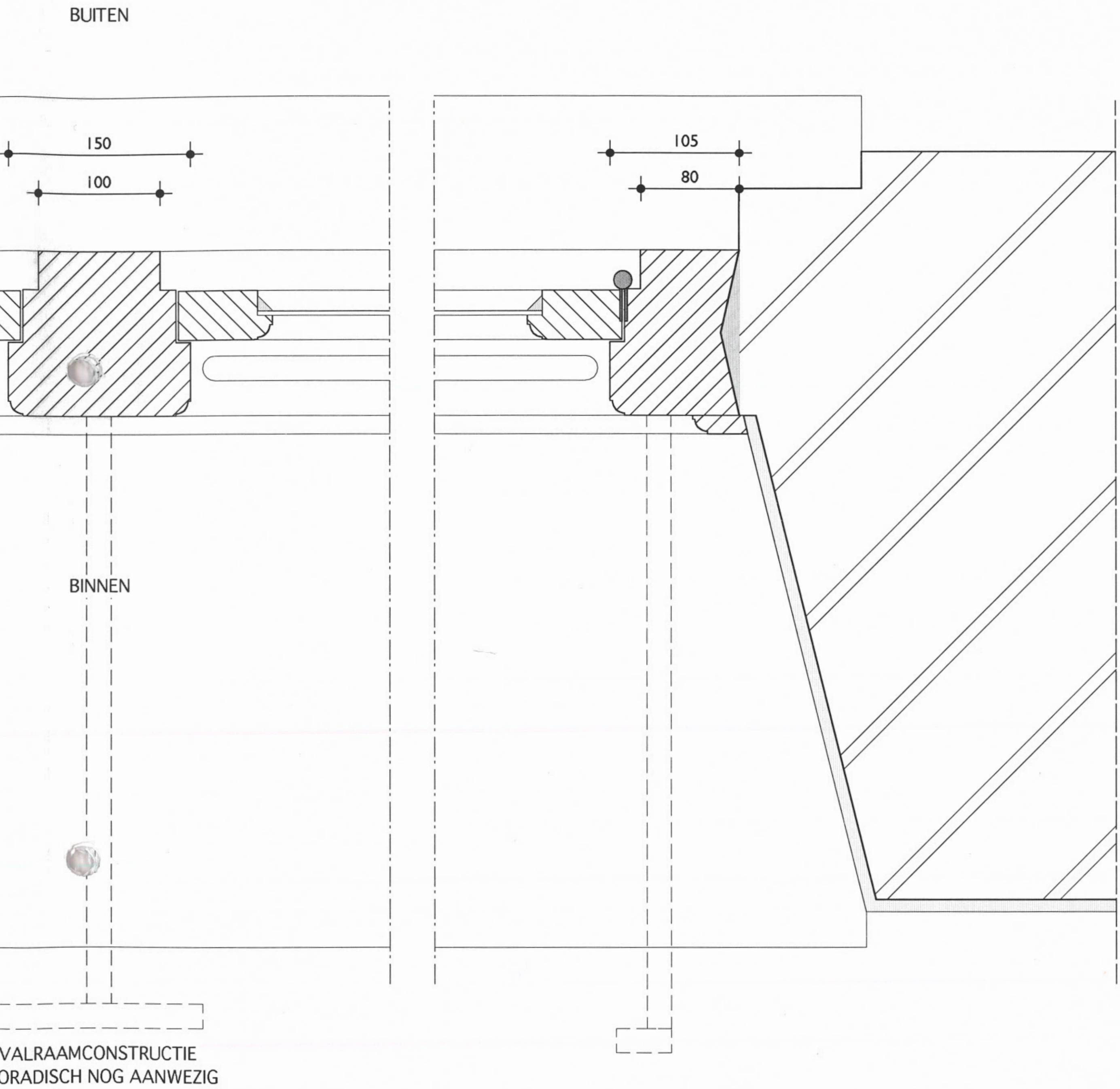
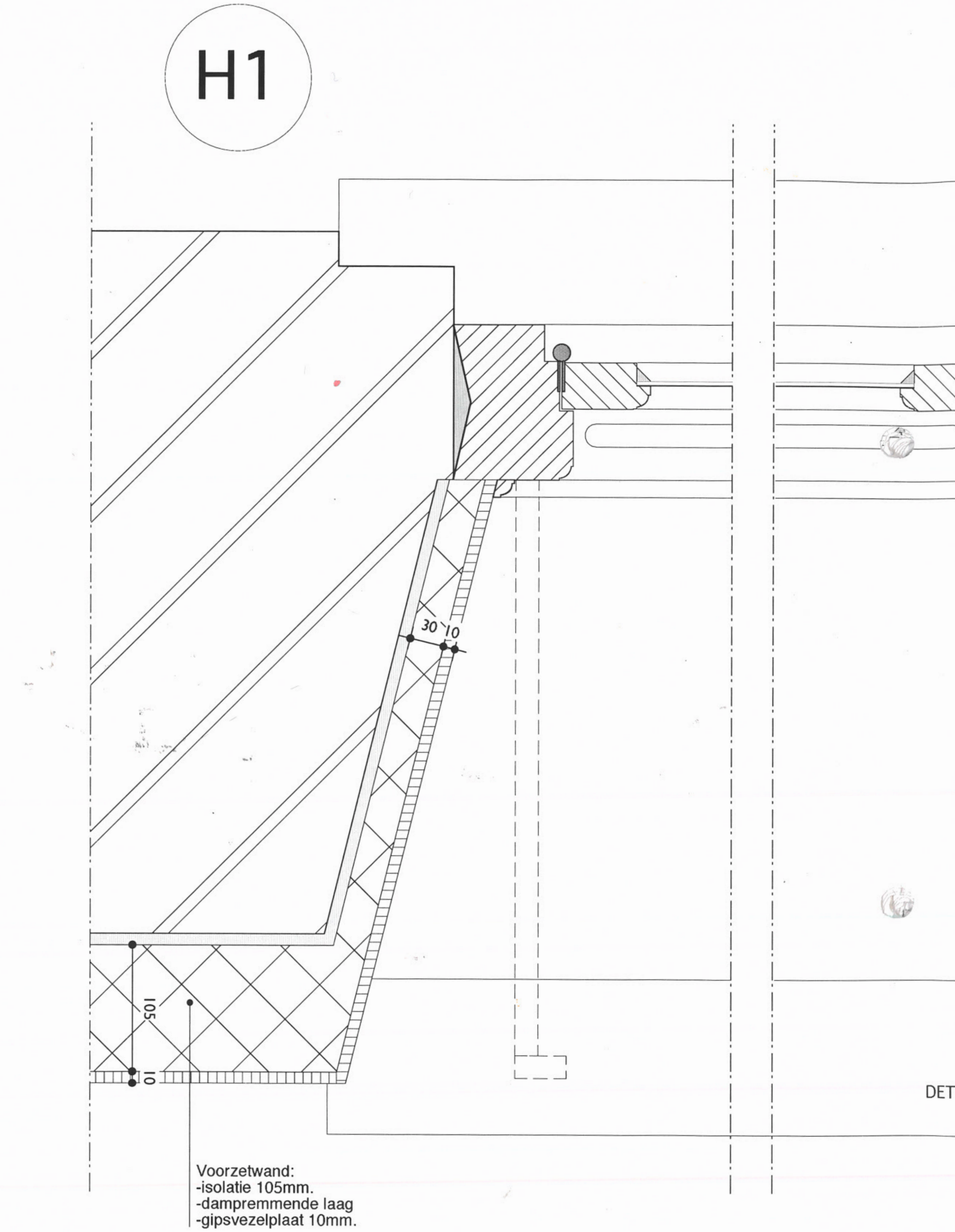


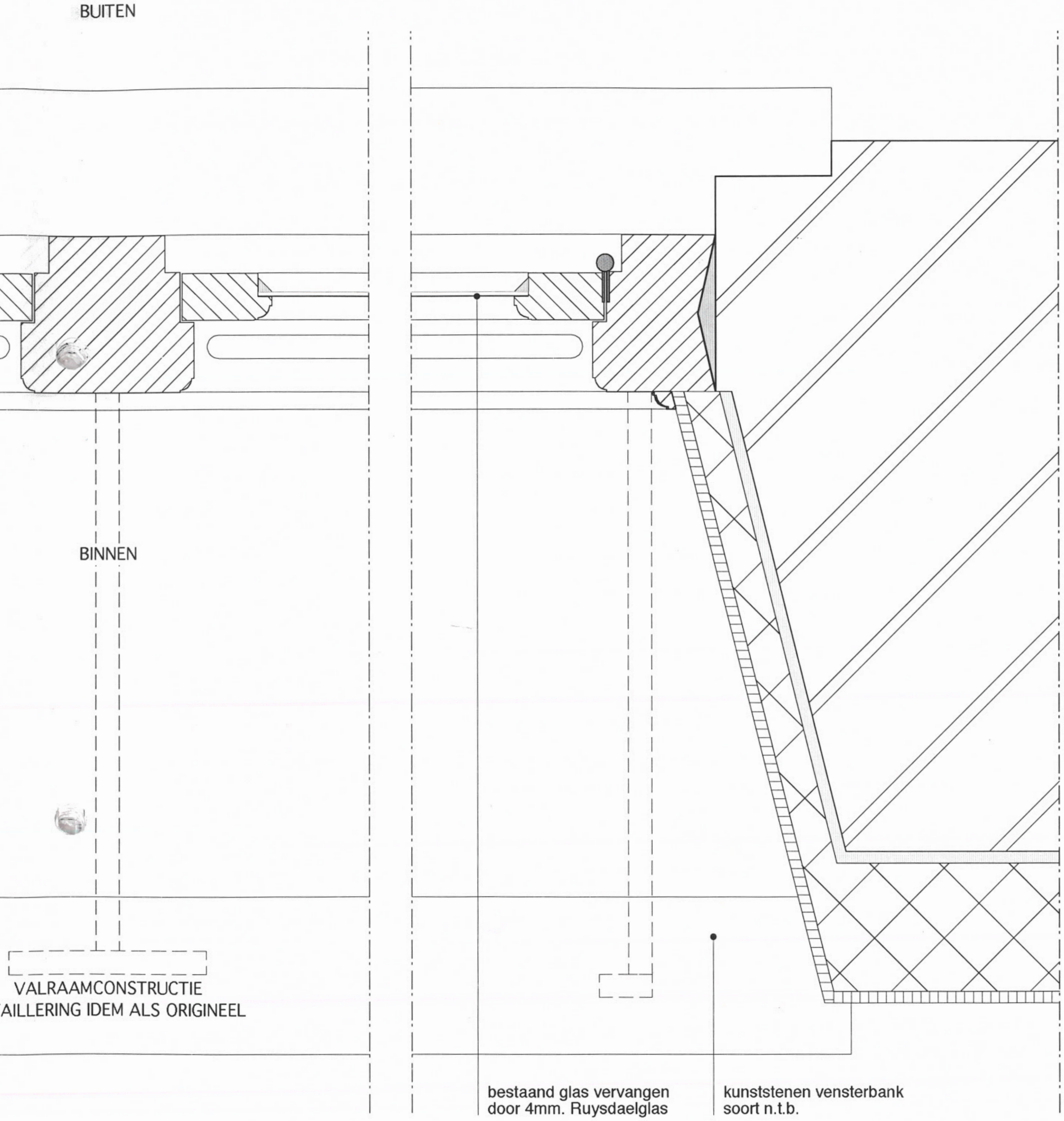
AND (horizontale doorsnede onder)

MB-BT-402 (1:5) Blad:4

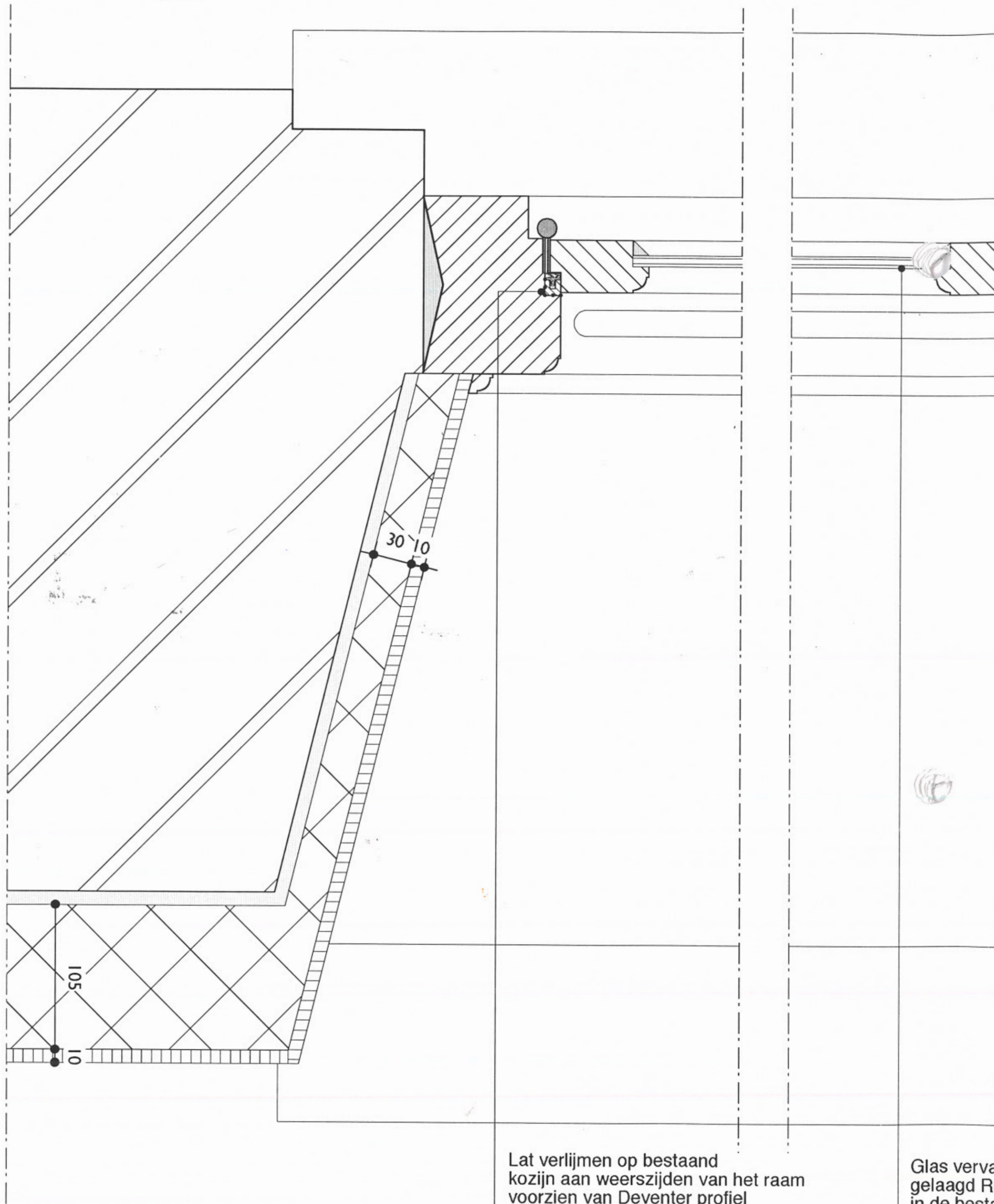


KOZIJNDETAILLERING MERK 04

TYPE


BUITEN
BINNEN
VALRAAMCONSTRUCTIE
AILLERING IDEM ALS ORIGINEEL
bestaand glas vervangen
door 4mm. Ruysdaelglas
kunststenen vensterbank
soort n.t.b.

H1



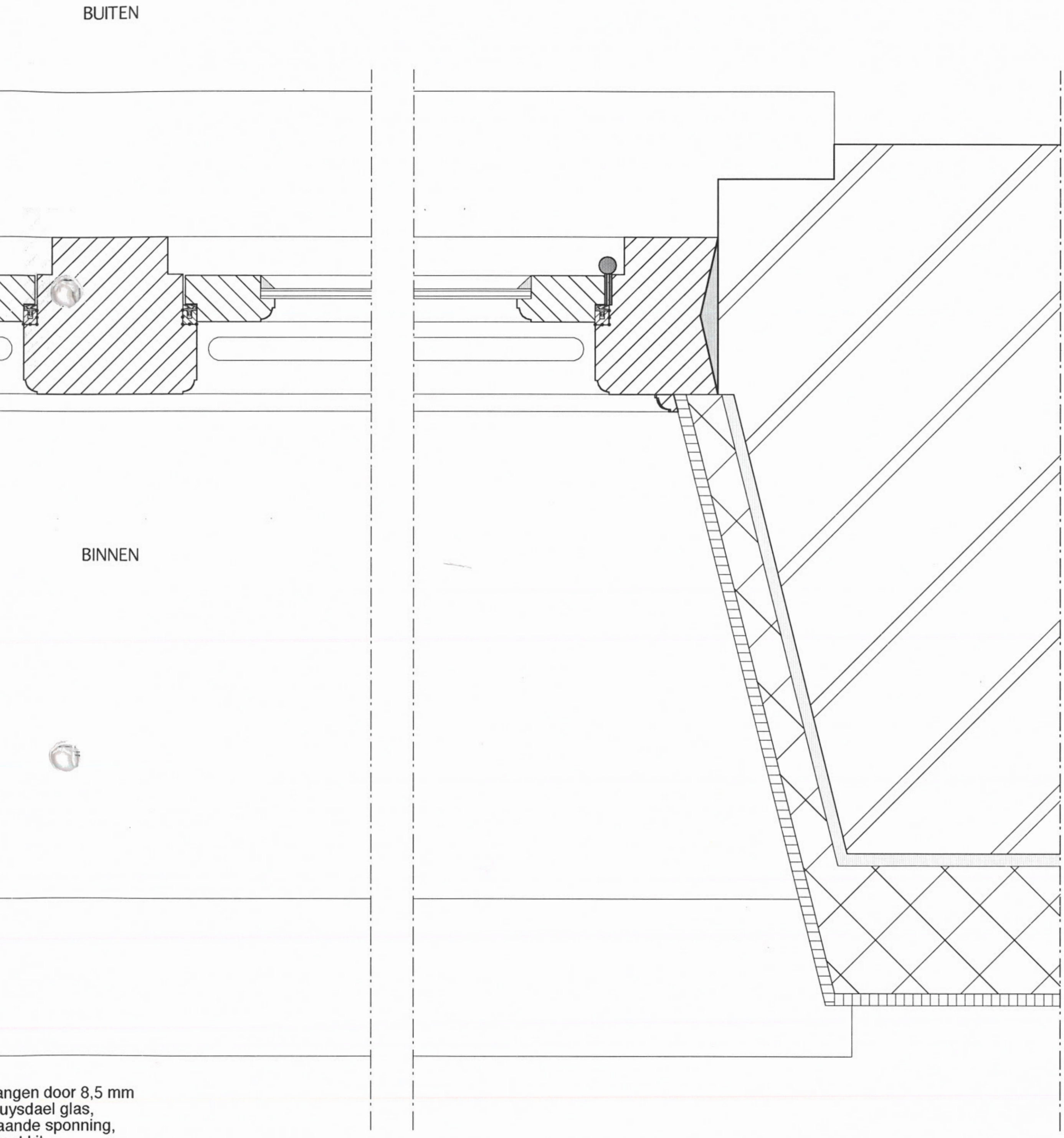
Lat verlijmen op bestaand
kozijn aan weerszijden van het raam
voorzien van Deventer profiel
S 6577, indrukking 3 mm
geluidwering: 35 db(A)

Sparing frezen in bestaand raamhout
tbv het creeren van een aanslag

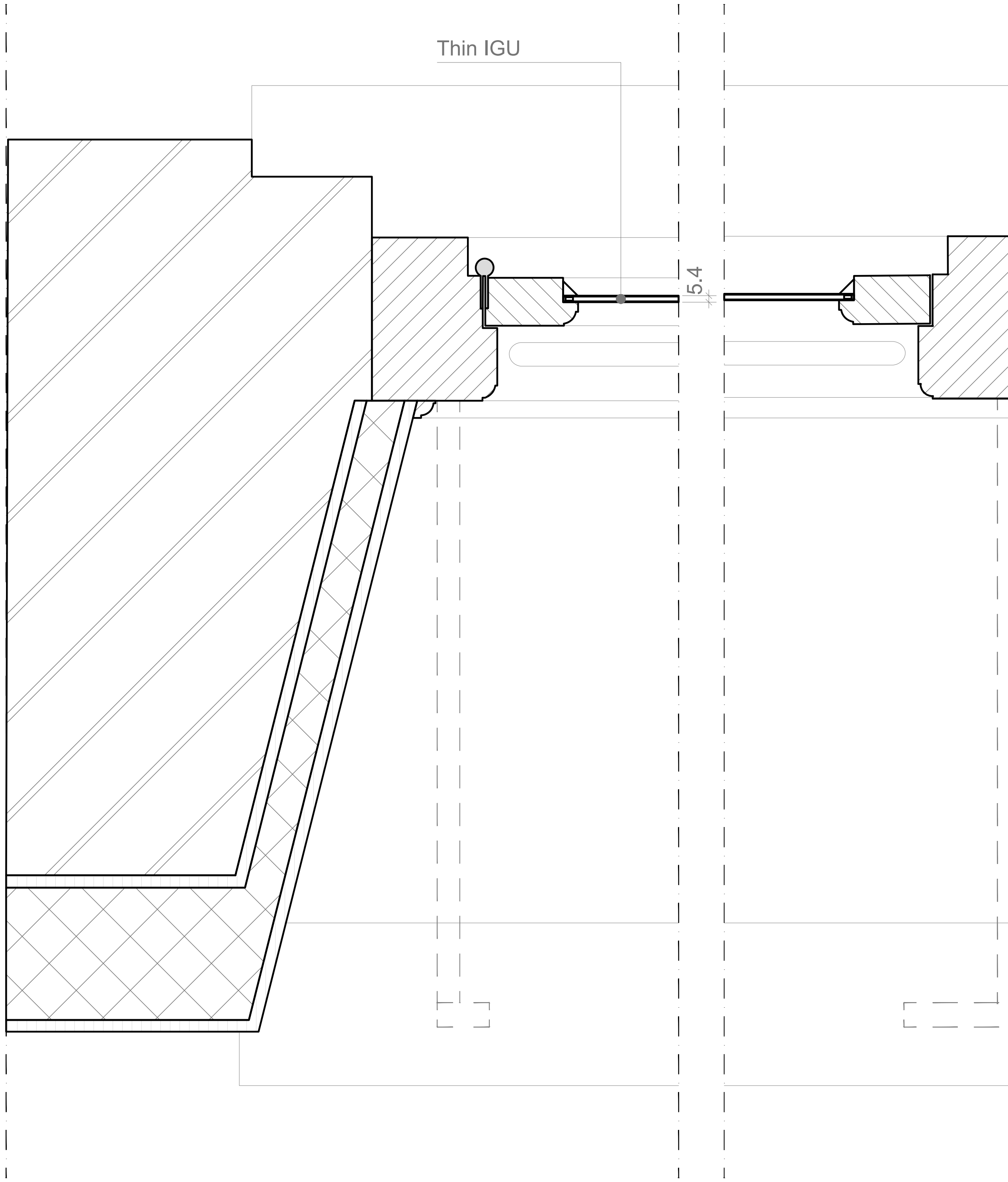
Glas verva
gelaagd R
in de besta
afwerken r
Geluidweri

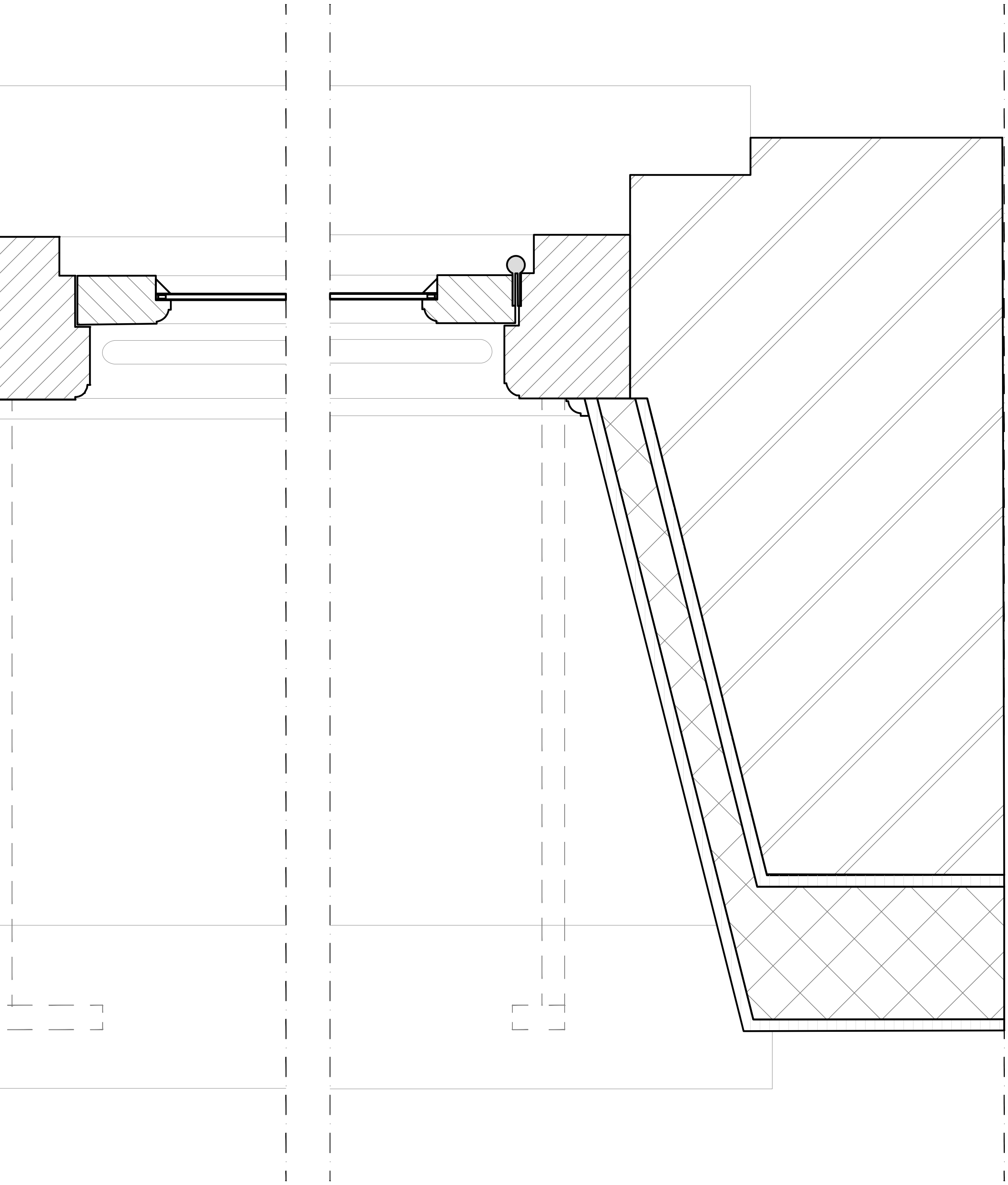
KOZIJNDETAILLERING MERK 04

TYPE

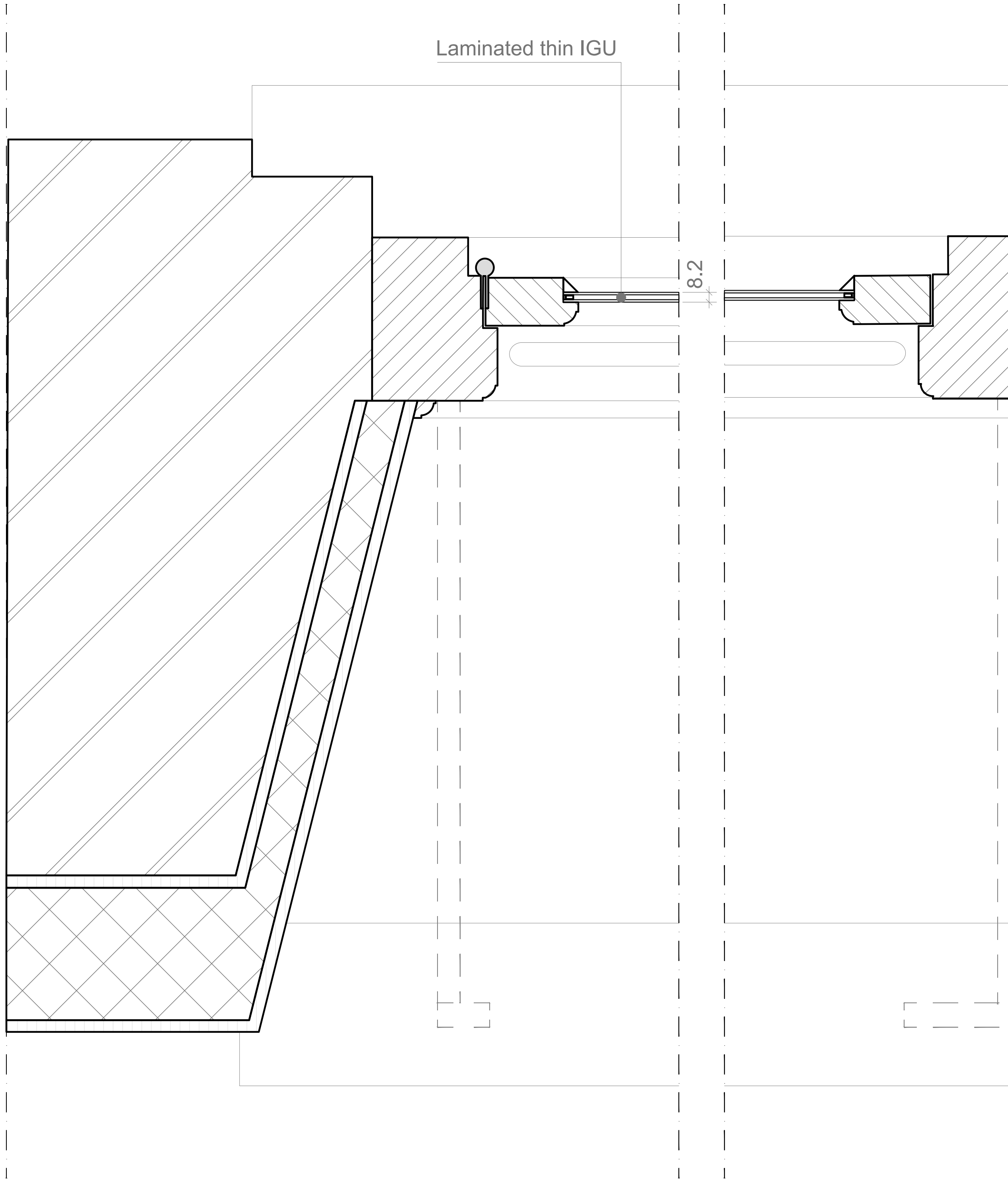


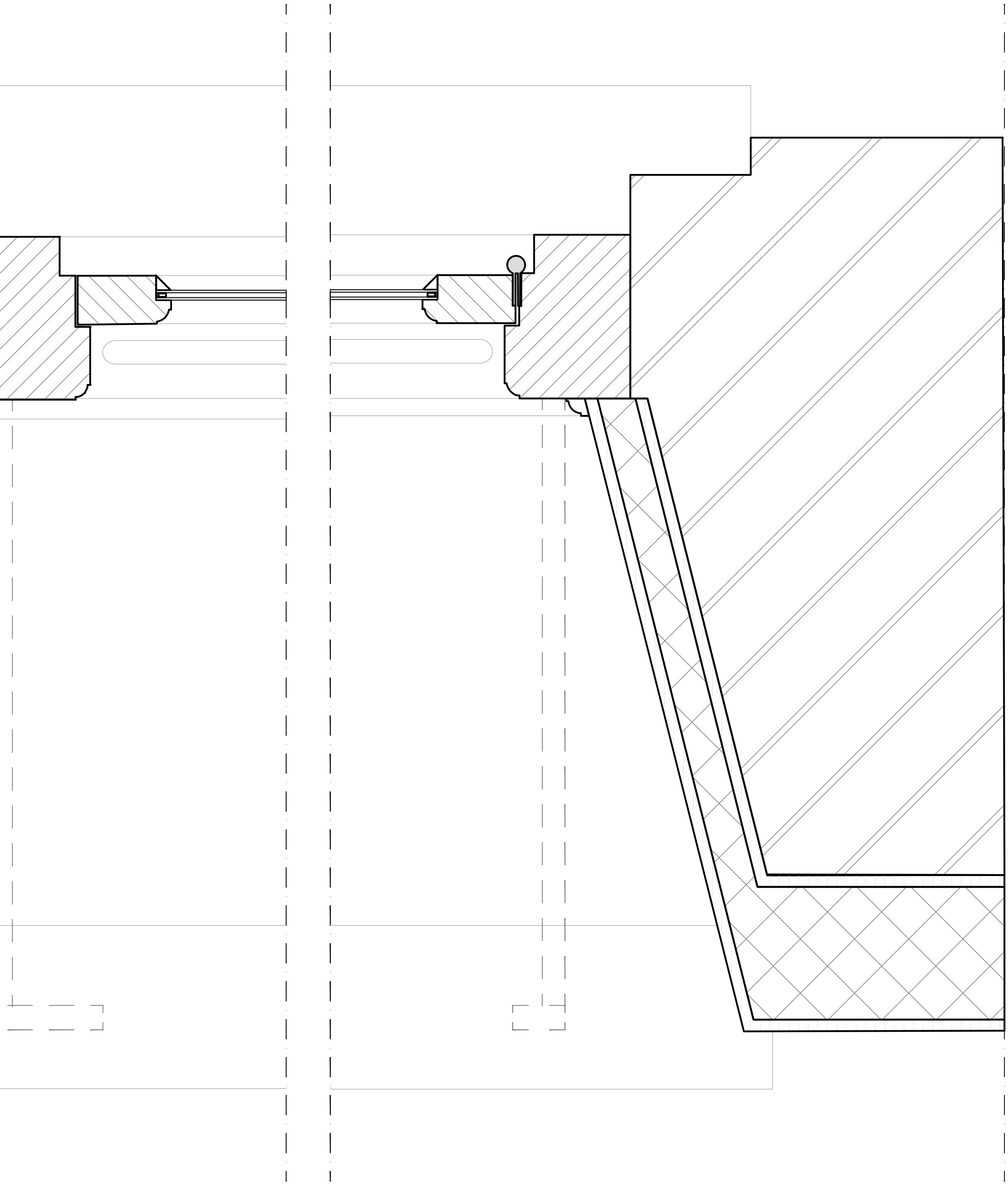
angen door 8,5 mm
uysdael glas,
aande sponning,
met kit
ing 32 db(A)


Thin IGU
5.4



Scale (1:5)


Laminated thin IGU
8.2



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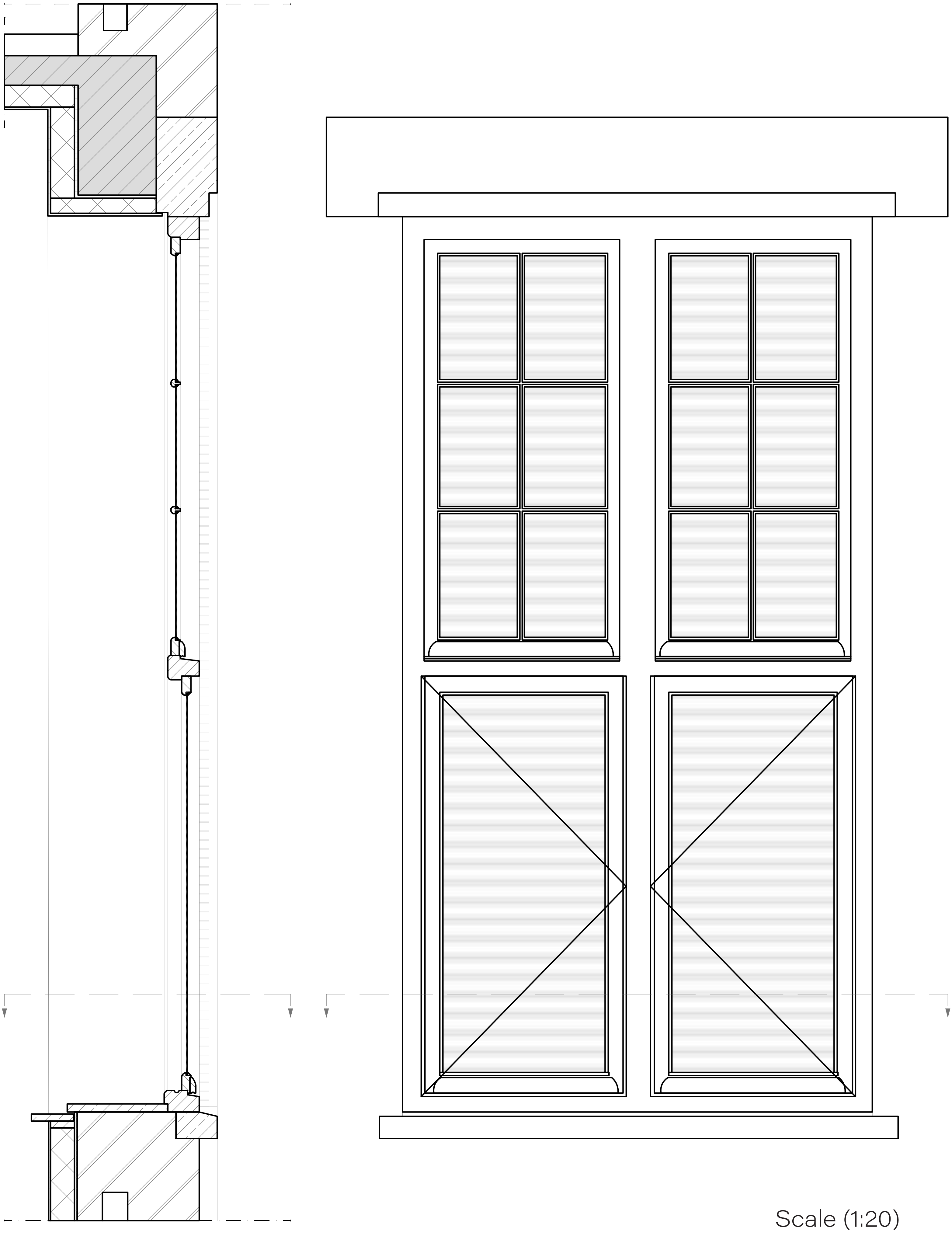
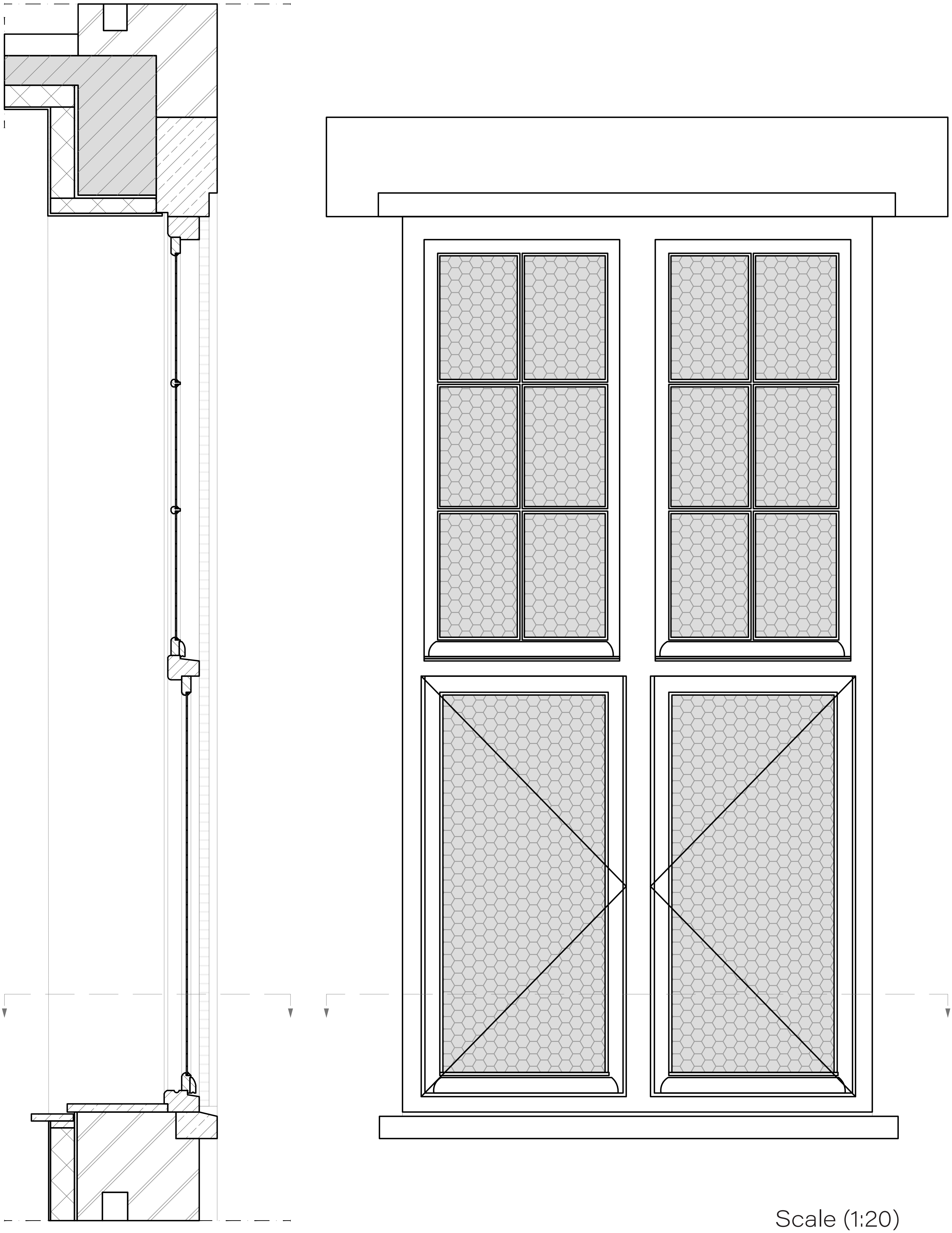
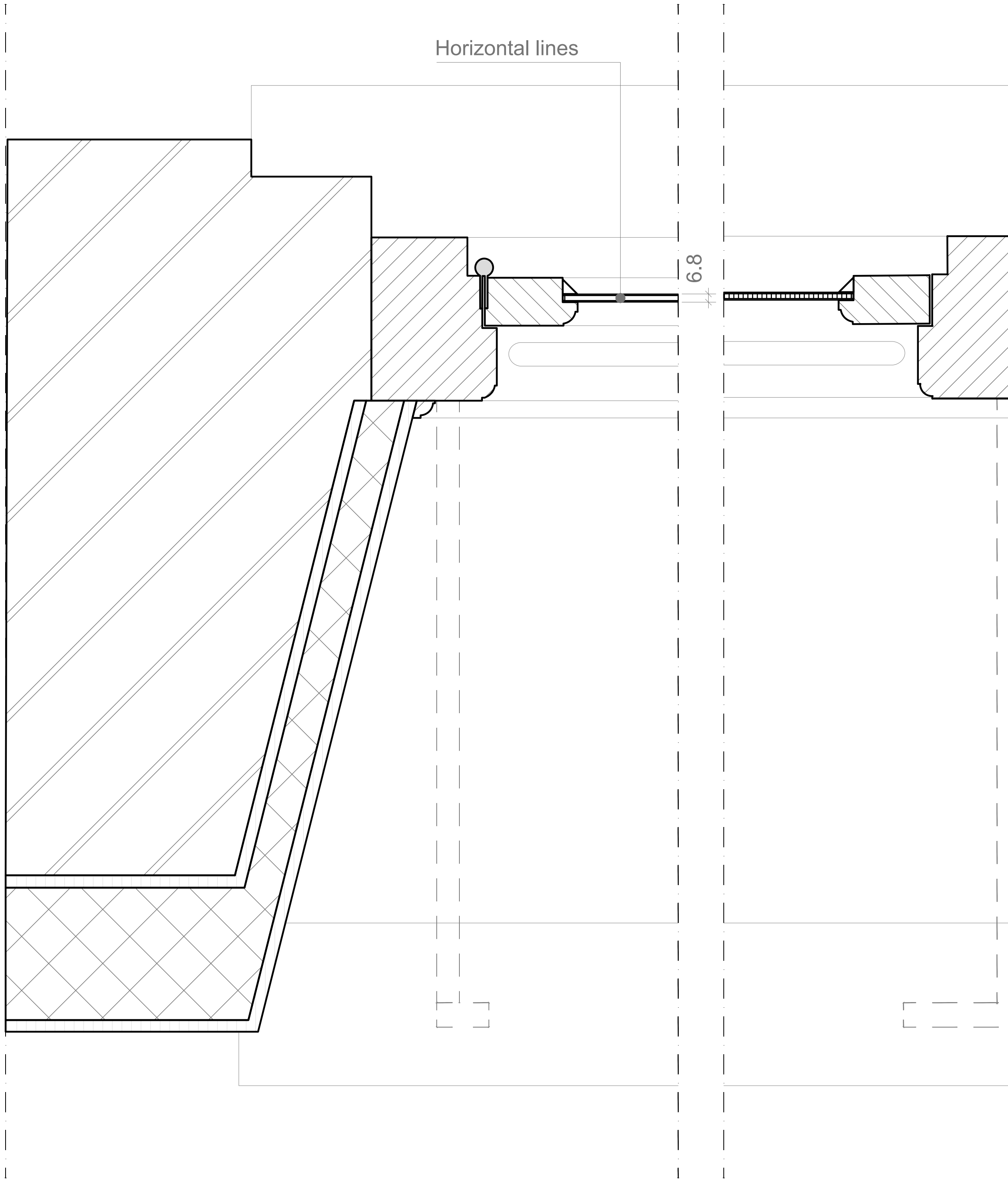
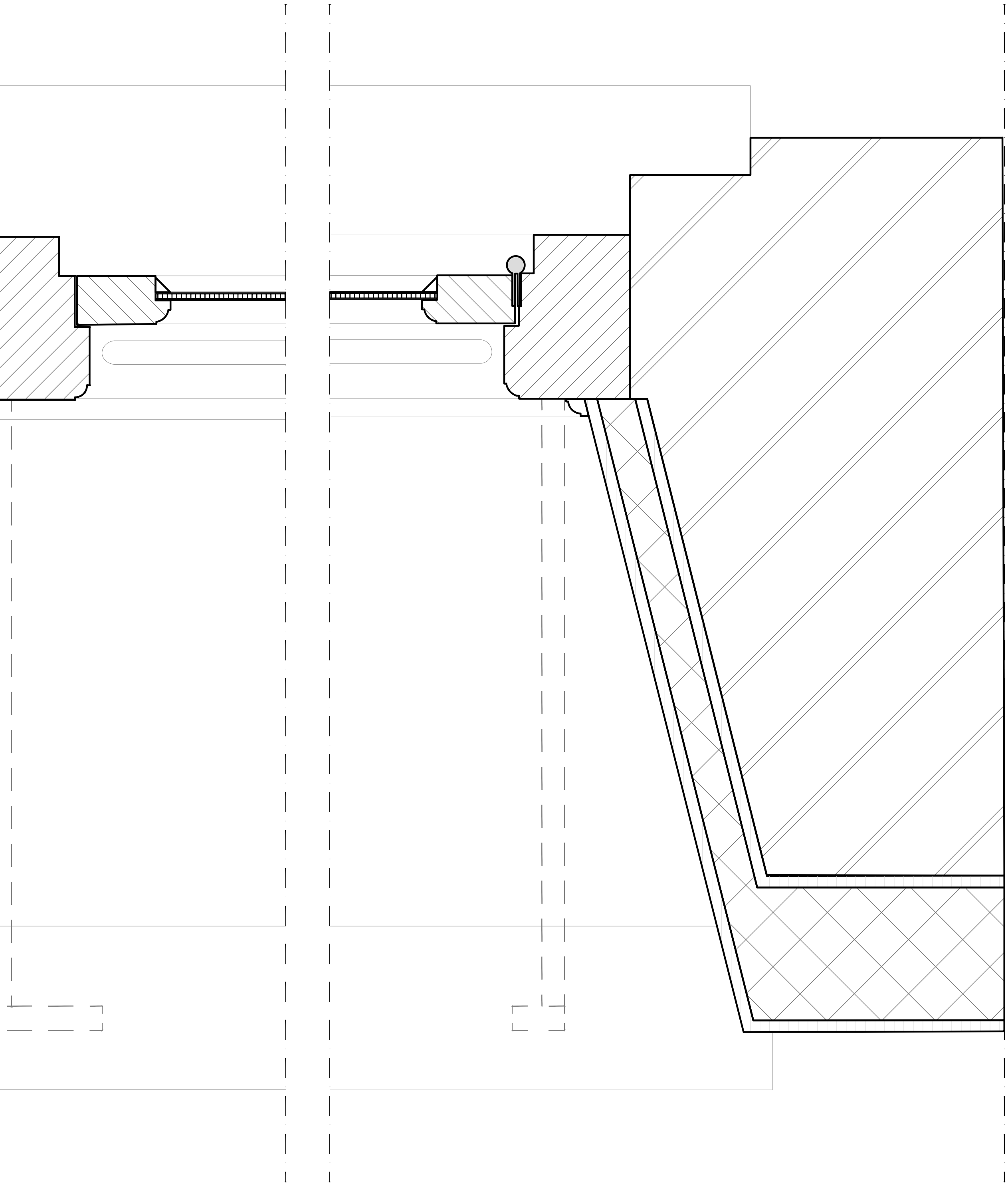


Scale (1:20)

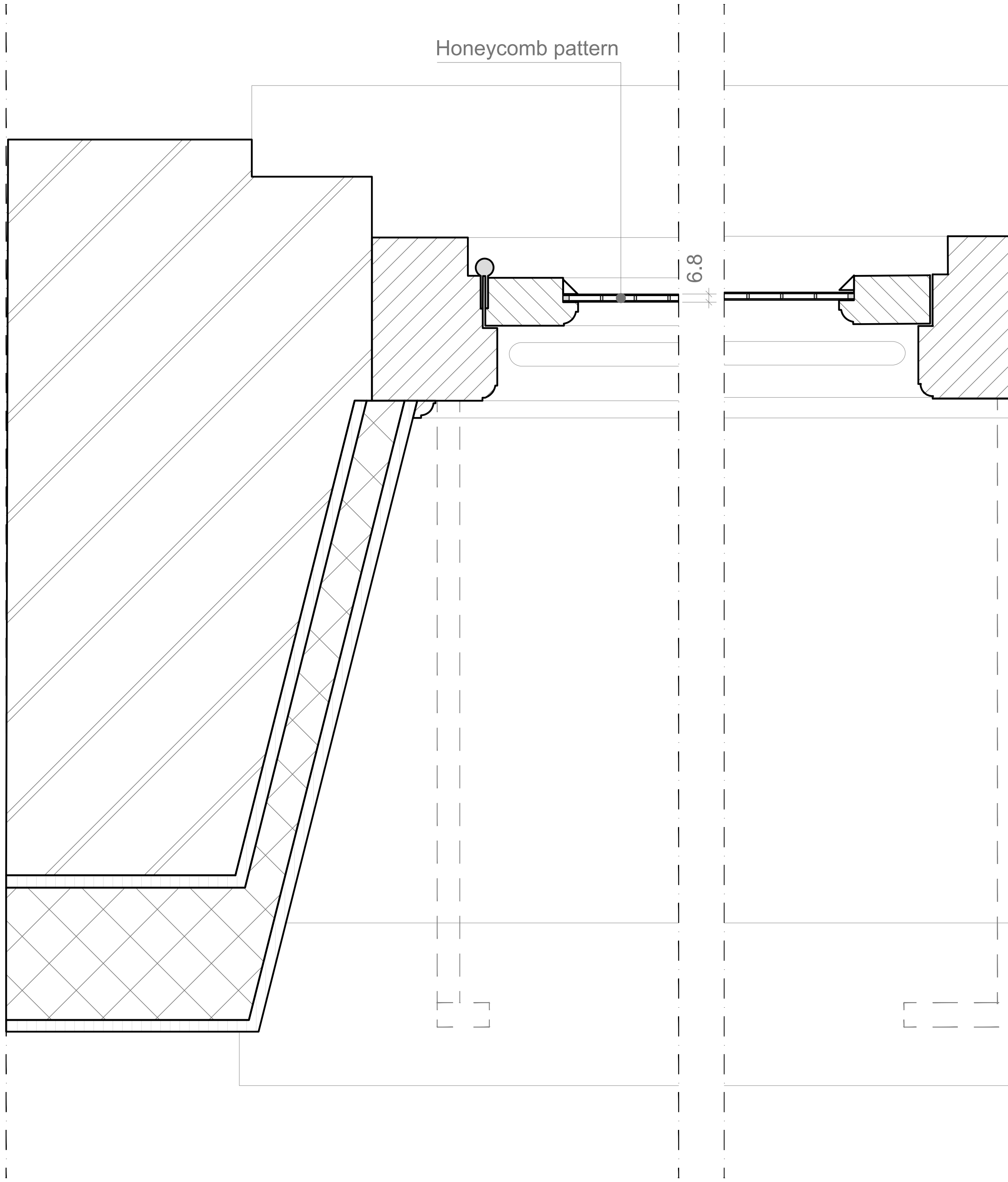


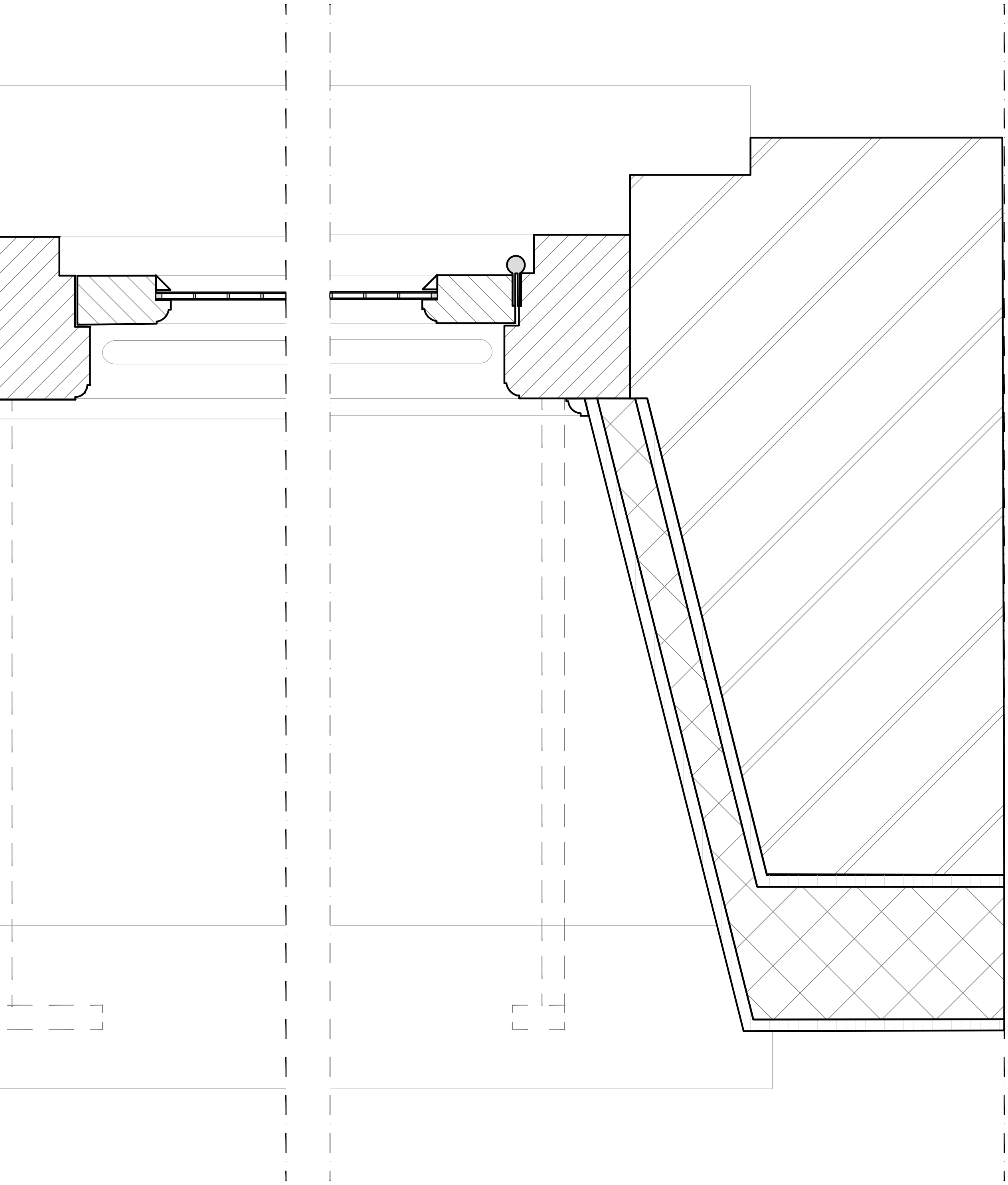
Scale (1:20)


Horizontal lines
6.8



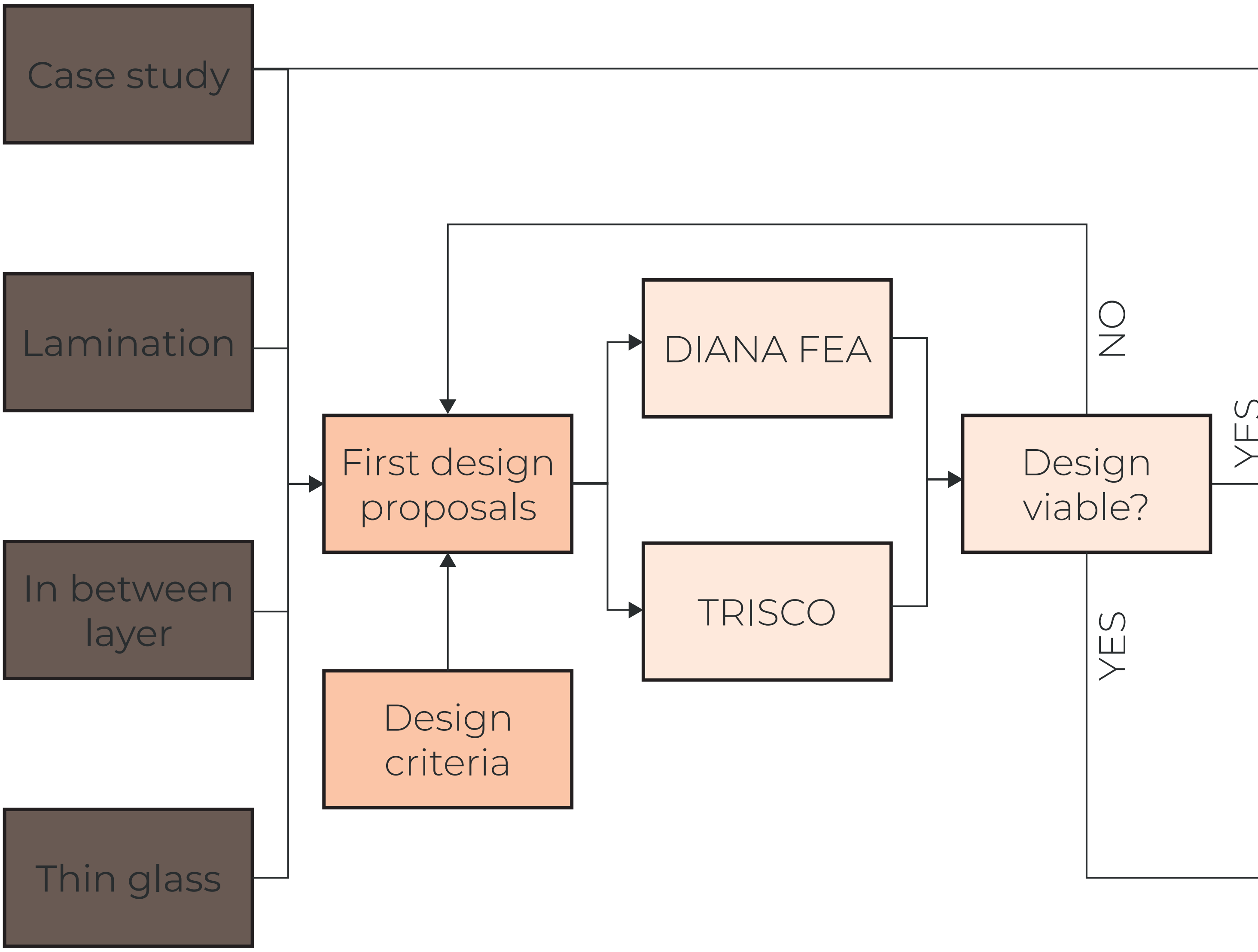
Scale (1:5)


Honeycomb pattern
6.8

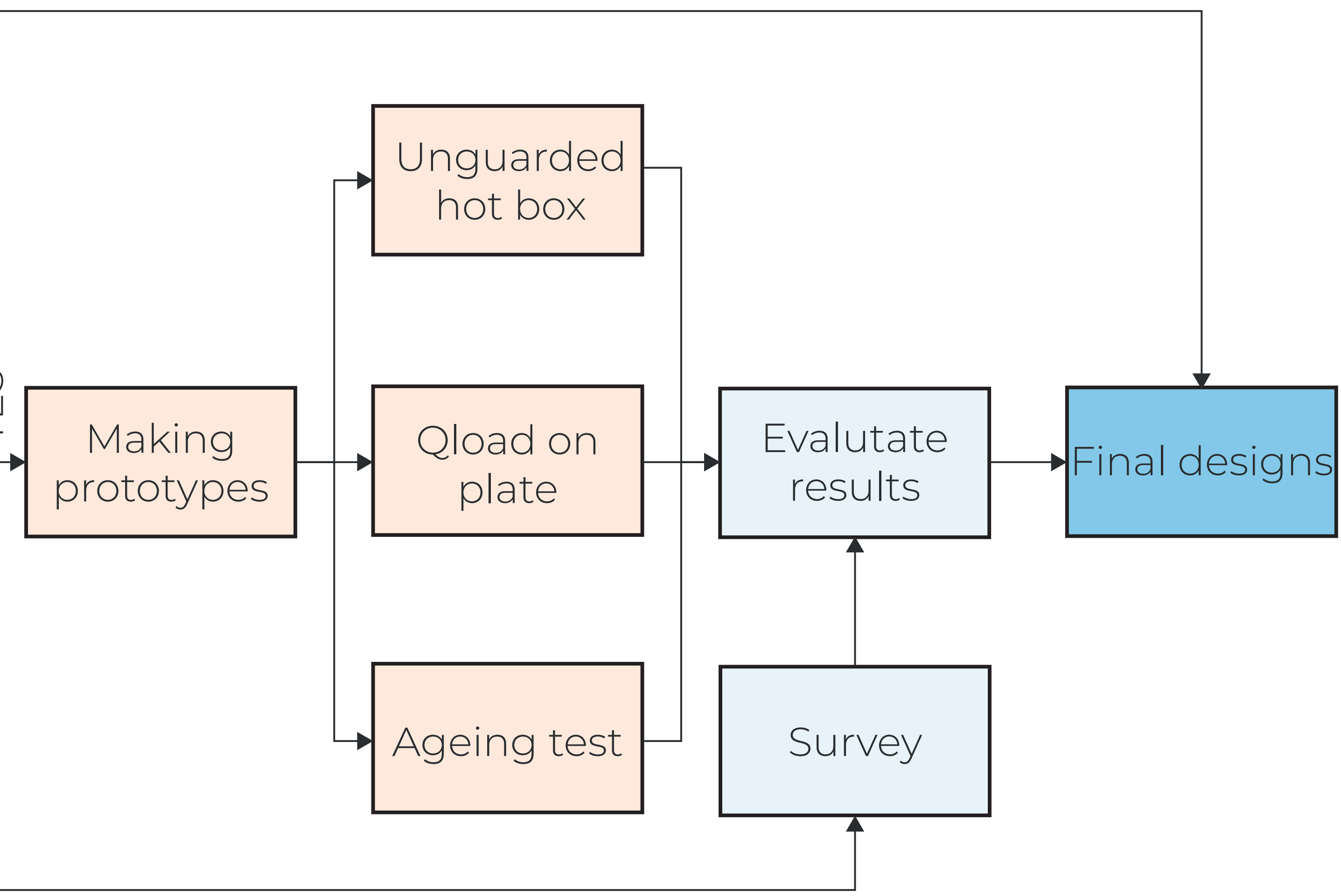


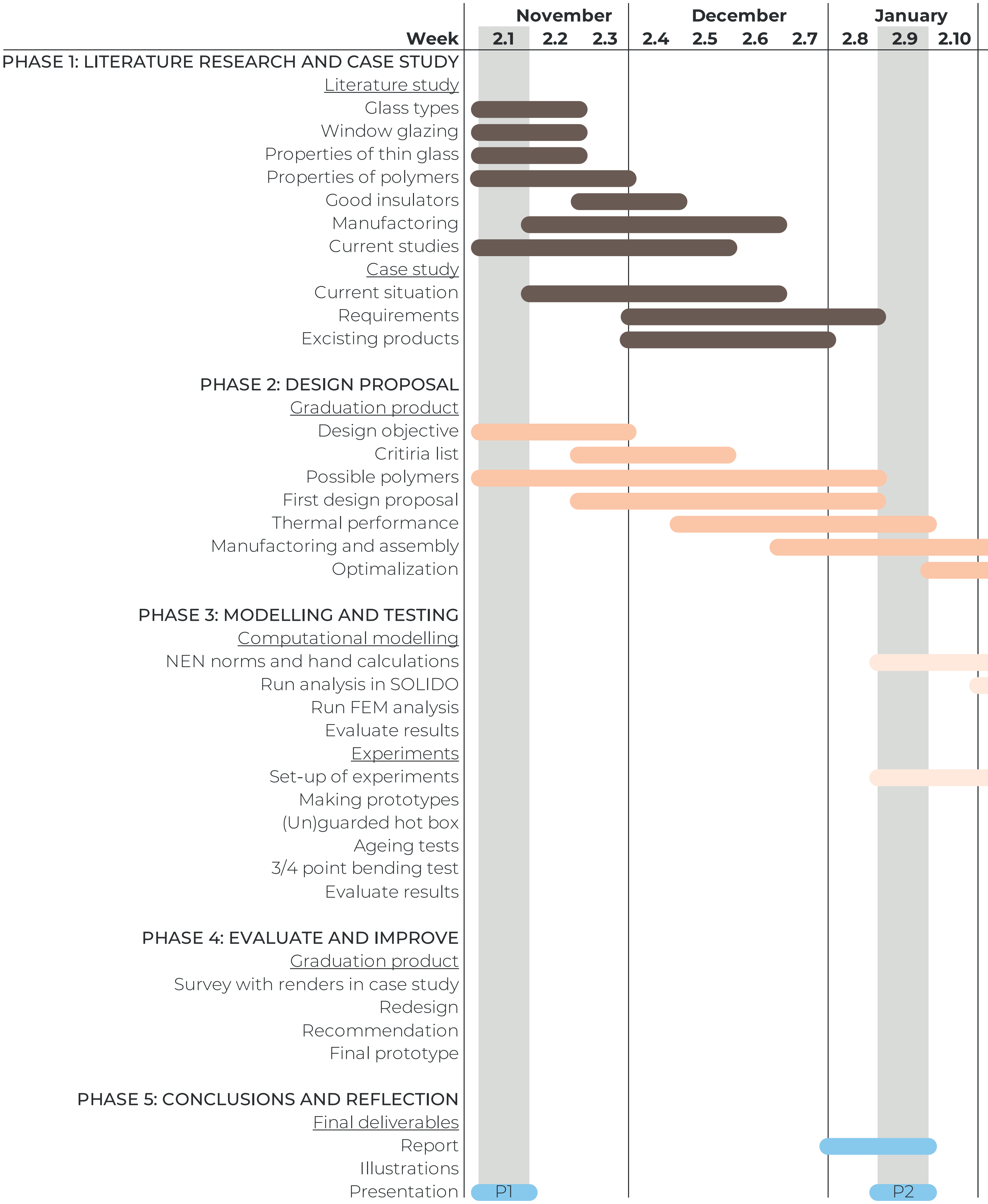
Scale (1:5)

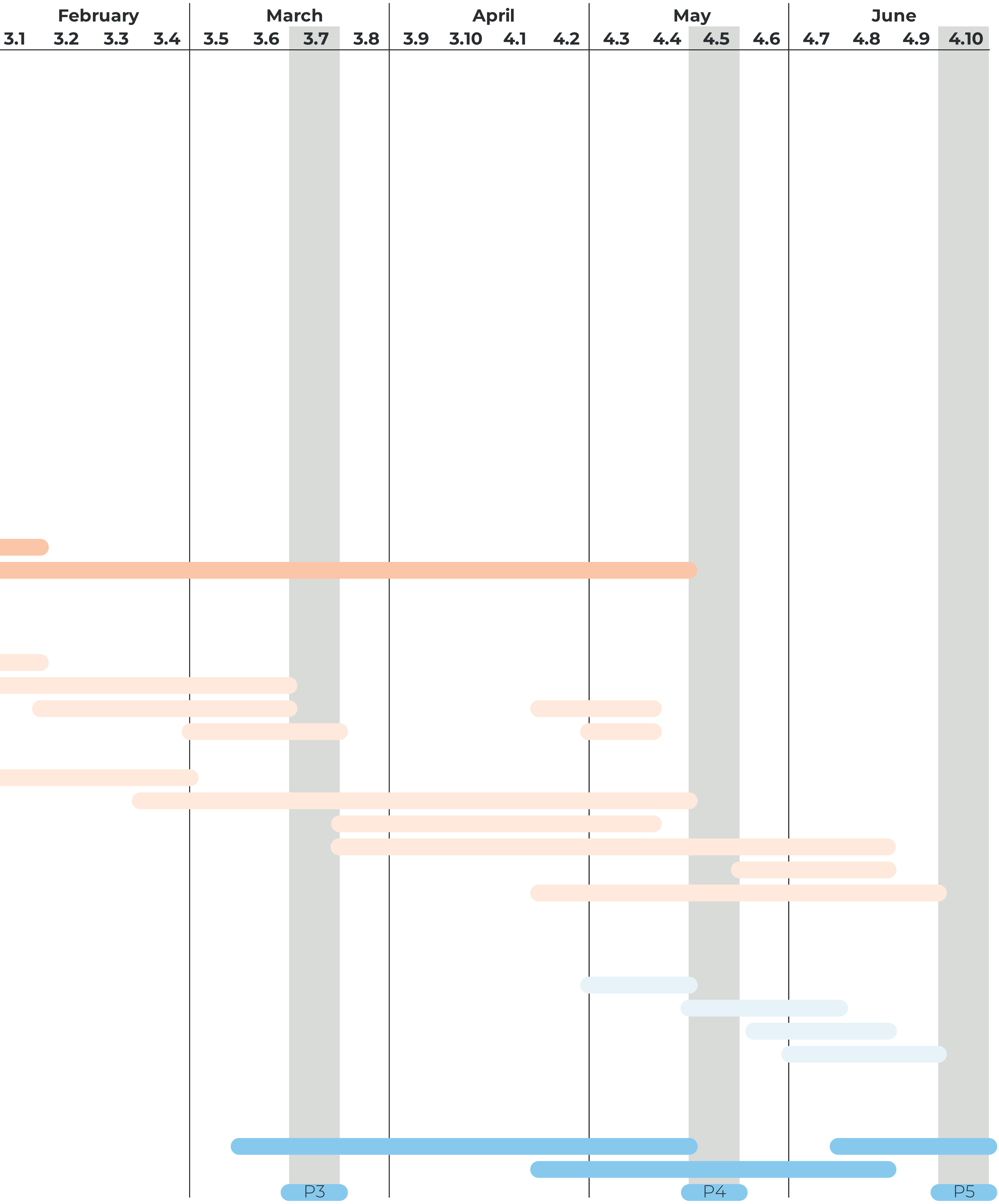
Appendix B



Case study
Lamination
In between layer
Thin glass
First design proposals
Design criteria
DIANA FEA
TRISCO
Design viable?
NO
YES


Unguarded hot box
Making prototypes
Qload on plate
Evalutate results
Final designs
Ageing test
Survey


November
December
January
Week
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
2.9
2.10
PHASE 1: LITERATURE RESEARCH AND CASE STUDY
Literature study
Glass types
Window glazing
Properties of thin glass
Properties of polymers
Good insulators
Manufactoring
Current studies
Case study
Current situation
Requirements
Excisting products
PHASE 2: DESIGN PROPOSAL
Graduation product
Design objective
Critiria list
Possible polymers
First design proposal
Thermal performance
Manufactoring and assembly
Optimalization
PHASE 3: MODELLING AND TESTING
Computational modelling
NEN norms and hand calculations
Run analysis in SOLIDO
Run FEM analysis
Evaluate results
Experiments
Set-up of experiments
Making prototypes
(Un)guarded hot box
Ageing tests
3/4 point bending test
Evaluate results
PHASE 4: EVALUATE AND IMPROVE
Graduation product
Survey with renders in case study
Redesign
Recommendation
Final prototype
PHASE 5: CONCLUSIONS AND REFLECTION
Final deliverables
Report
Illustrations
Presentation
P1
P2



February
March
April
May
June
3.1 3.2 3.3 3.4 3.5 3.6 3.7 3.8 3.9 3.10 4.1 4.2 4.3 4.4 4.5 4.6 4.7 4.8 4.9 4.10
P3
P4
P5

Appendix C

For the following hand calculations, equations 3, 4, 5 and 6 are used. These are described in the approach and methodology chapter.

Design 1

E modulus glass	70	GPa
Width glass	500	mm
Height glass	0,7	mm
Total moment of Inertia	14,29	mm^4
Length of beam	500	mm
Q wind total	1000	N/m^2
Q wind per glass sheet	0,0005	N/mm^2
Q beam	0,25	N/mm
Deflection beam	**40,67**	**mm**
Max allowable deflection	*10,88*	*mm*
Max moment	5208,3	Nmm
Moment centre	2604,2	Nmm
Distance y	0,35	mm
Max stress mid	63,78	N/mm^2
Max stress end	**127,55**	**N/mm^2**
Max allowable stress glass	*40*	*N/mm^2*

Design 2

E modulus glass	70	GPa
Width glass	500	mm
Height glass	1,4	mm
Total moment of Inertia	114,33	mm^4
Length of beam	500	mm
Q wind total	1000	N/m^2
Q wind per glass sheet	0,0005	N/mm^2
Q beam	0,25	N/mm
Deflection beam	**5,08**	**mm**
Max deflection	*10,88*	*mm*
Max moment	5208,3	Nmm
Moment centre	2604,2	Nmm
Distance y	0,7	mm
Max stress mid	15,94	N/mm^2
Max stress end	**31,89**	**N/mm^2**
Max allowable stress glass	*40*	*N/mm^2*

Design 3

E modulus glass	70	GPa
E modulus PC	2,2	GPa
E modulus PC	2200	N/mm²
Eglas / Epc	31,8	-

Width glass (M&N)	500	mm
Width glass E	15909	mm
Height glass	0,7	mm
Height PC (top&bottom)	0,1	mm
Width PC (walls)	0,1	mm
Height PC	3,8	mm
Amount of 'walls'	125	-

	I (mm⁴)	**A (mm²)**	**y (mm)**	**A*y² (mm⁴)**
First last PC	0,08	100	1,95	380,25
In between PC	57	47,5	0	0
Glass	909	22273	2,35	123001
Total	*967*	-	-	*123381*

Total moment of Inertia	124348	mm⁴

Length of beam	500	mm
Q wind	1000	N/m²
Q wind	0,001	N/mm²
Q beam	0,5	N/mm
Deflection beam	**0,297**	**mm**

Max allowable deflection	*10,88*	*mm*

Max moment	10417	Nmm
Max moment centre	5208	Nmm
Distance y PC	2	mm
Distance y glass	2,7	mm
Max stress PC	**0,17**	**N/mm²**
Max stress DIANA	0,23	N/mm²
Max stress mid	0,11	N/mm²
Max stress glass	**7,20**	**N/mm²**

Max allowable stress PC	*75*	*N/mm²*	*(tensile)*
Max allowable stress glass	*40*	*N/mm²*	*(annealed)*

Design 4a

E modulus glass	70	GPa
E modulus PMMA	2,855	GPa
E modulus PMMA	2855	N/mm^2
Eglas / Epmma	24,5	-

Width glass (M&N)	500	mm
Width glass E	12259	mm
Height glass	0,7	mm
Width PMMA (first&last wall)	5	mm
Width PMMA (walls)	2	mm
Height PMMA	4	mm
Amount of 'walls'	25	-

	I (mm^4)	**A (mm^2)**	**y (mm)**	**A*y² (mm^4)**
First last PMMA	53	40	0	0
In between PMMA	267	200	0	0
Glass	701	17163	2,35	94782
Total	*1021*	-	-	*94782*

Total moment of Inertia	95803	mm^4

Length of beam	500	mm
Q wind	1000	N/m^2
Q wind	0,001	N/mm^2
Q beam	0,5	N/mm
Deflection beam	**0,298**	**mm**

Max allowable deflection	*10,88*	*mm*

Max moment	10417	Nmm
Max moment centre	5208	Nmm
Distance y PMMA	2	mm
Distance y glass	2,7	mm
Max stress PMMA	**0,22**	**N/mm^2**
Max stress DIANA	0,29	N/mm^2
Max stress mid	0,15	N/mm^2
Max stress glass	**7,20**	**N/mm^2**

Max allowable stress PMMA	*75*	*N/mm^2*	*(tensile)*
Max allowable stress glass	*40*	*N/mm^2*	*(annealed)*

Design 4b

E modulus glass	70	GPa		
E modulus PMMA	2,855	GPa		
E modulus PMMA	2855	N/mm²		
Eglas / Epmma	24,5	-		
Width glass (M&N)	500	mm		
Width glass E	12259	mm		
Height glass	0,7	mm		
Width PMMA (first&last wall)	5	mm		
Width PMMA (walls)	2	mm		
Height PMMA	4	mm		
Amount of 'walls'	13	-		
	I (mm⁴)	**A (mm²)**	**y (mm)**	**A*y² (mm⁴)**
First last PMMA	53	40	0	0
In between PMMA	139	104	0	0
Glass	701	17163	2,35	94782
Total	*893*	-	-	*94782*
Total moment of Inertia	95675	mm⁴		
Length of beam	500	mm		
Q wind	1000	N/m²		
Q wind	0,001	N/mm²		
Q beam	0,5	N/mm		
Deflection beam	**0,298**	**mm**		
Max allowable deflection	*10,88*	*mm*		
Max moment	10417	Nmm		
Max moment centre	5208	Nmm		
Distance y PMMA	2	mm		
Distance y glass	2,7	mm		
Max stress PMMA	**0,22**	**N/mm²**		
Max stress DIANA	0,29	N/mm²		
Max stress mid	0,15	N/mm²		
Max stress glass	**7,21**	**N/mm²**		
Max allowable stress PMMA	*75*	*N/mm²*	*(tensile)*	
Max allowable stress glass	*40*	*N/mm²*	*(annealed)*	

Design 4c

E modulus glass	70	GPa		
E modulus PMMA	2,855	GPa		
E modulus PMMA	2855	N/mm²		
Eglas / Epmma	24,5	-		
Width glass (M&N)	500	mm		
Width glass E	12259	mm		
Height glass	0,7	mm		
Width PMMA (first&last wall)	5	mm		
Width PMMA (walls)	2	mm		
Height PMMA	4	mm		
Amount of 'walls'	9	-		
	I (mm⁴)	**A (mm²)**	**y (mm)**	**A*y² (mm⁴)**
First last PMMA	53	40	0	0
In between PMMA	96	72	0	0
Glass	701	17163	2,35	94782
Total	*850*	-	-	*94782*
Total moment of Inertia	95632	mm⁴		
Length of beam	500	mm		
Q wind	1000	N/m²		
Q wind	0,001	N/mm²		
Q beam	0,5	N/mm		
Deflection beam	**0,298**	**mm**		
Max allowable deflection	*10,88*	*mm*		
Max moment	10417	Nmm		
Max moment centre	5208	Nmm		
Distance y PMMA	2	mm		
Distance y glass	2,7	mm		
Max stress PMMA	**0,22**	**N/mm²**		
Max stress DIANA	0,29	N/mm²		
Max stress mid	0,15	N/mm²		
Max stress glass	**7,21**	**N/mm²**		
Max allowable stress PMMA	*75*	*N/mm²*	*(tensile)*	
Max allowable stress glass	*40*	*N/mm²*	*(annealed)*	

Appendix D

Hi,

Thank you in advance for filling in this survey!
It will take about 10 minutes.

You can fill in your name, but you can also leave it empty and remain anonymous.

1.1 What is your name?

____

1.2 What is your gender? *

0 Male
0 Female
0 Other

1.3 What is your age? *

0 18-30
0 30-40
0 40-50
0 50-60
0 60-70

1.4 Which description fits you best? *

0 Company for building products
0 Architecture student
0 Home owner or building owner
0 Tenant
0 None of the above

Two different designs are placed in a heritage building. The next photos will give an impression. Please note that design 1 is slightly less transparent than the other.

Figure 64: a) Current situation, b)Design 1: Horizontal lines, c) Design 2: A honeycomb pattern (Author)

Figure 65: a) Current situation, b) Design 1: Horizontal lines, c) Design 2: A honeycomb pattern (Author)

2.1 Which design do you prefer, based on looks? *

0 Design 1: Horizontal lines
0 Design 2: A honeycomb pattern

2.2 Why? *

The U-value is a value that measures the thermal performance of a product. The lower the U-value, the better the product insulates. The U-value for single glazing is 5.6 W/m^2*K. This is pretty bad if you compare this to double glazing which has a U-value of 2.8 W/m^2*K. This can even be optimized to lower U-values with the use of gasses and a special coating. However, these solutions do not fit the heritage window frames, since their thickness is too thick.

The U-value of design 1 is 3.4 W/m^2*K.
The U-value of design 2 is 3.6 W/m^2*K.

This means that design option 1 is a better insulator.

3.1 Now knowing their U-value, which design do you prefer? *

0 Design 1: Horizontal lines
0 Design 2: A honeycomb pattern

3.2 Why? *

____

3.3 Did your choice switch due to the U-value? *

0 Yes
0 No

~~ For this section, please forget the U-value stated before. ~~

The glazing that is researched will be placed in heritage buildings. For instance, this can be houses, offices or churches.

4.1 Which design do you prefer in these situations? *

		Design 1	Design 2
a)	A housing building; the **living room** window	0	0
b)	A housing building; the **bathroom** window	0	0
c)	A housing building; the window in the **utility room**	0	0
d)	An **office** window	0	0
e)	An office building; the **toilet** window	0	0
f)	An office building; the **corridor** window	0	0
g)	A **church** window	0	0
h)	A **library** window	0	0
i)	A **museum** window	0	0
j)	A **shop** window	0	0

4.2 Please explain your choices. *

____