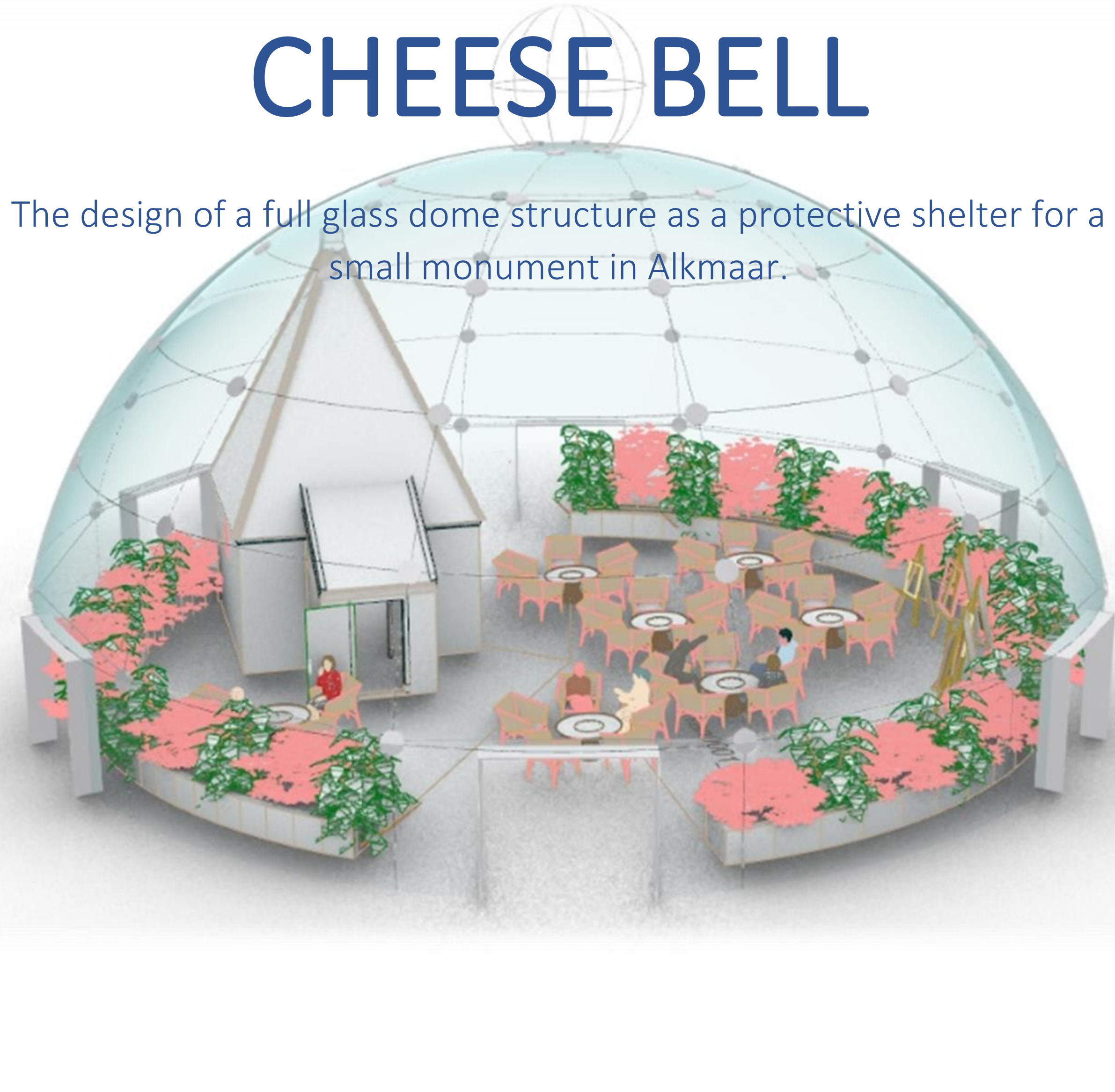
CHEESE BELL

The design of a full glass dome structure as a protective shelter for a small monument in Alkmaar.



MSc. Thesis | Delft University of Technology
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ABSTRACT

A building manager of a small monument in Alkmaar wants to give the monument a new function as a restaurant. His idea is to place a glass structure over his monument, like a huge cheese bell, in Alkmaar as a famous cheese city.

The main question that is central in this research is:

"How can a full glass dome structure be built, to cover 'Het Kruithuisje' in Alkmaar, The Netherlands, in which the thermal comfort is maintained in the most passive manner, without impeding the visual benefits of glass?".

To answer this question this research is divided into four parts: literature, designs, analysis and final design and conclusion. Various coarse designs will be made that will be analyzed. Based on the analyzed designs, a final design can be made in which the structural performance and thermal comfort are known. These results will lead to a design with building plans that can ultimately be built, with guidelines, recommendations and conclusions for possible upcoming similar structures.

A dome structure, or a cupula structure, is a form of shell structures. A shell structure is a structure where the surface can bear the loads, because the surface is shaped and supported in a certain way (Flügge, 1973).

Glass can be used as a construction material, but it has a number of properties as standard that are not entirely suitable for a construction material. To make glass a safer construction material and to give it a greater bearing capacity, it must be strengthened.

The dome is a suitable shape for constructing glass structures because most of the internal dome forces are in compression. A shell structure can be built in as a completely smooth surface or built from various separate components. To build this entire construction, the shape must be divided into panels. To approximate the dome shape hot bended double curved panels will be used.

To be able to build with glass, connections are needed between the various glass components. (Santarsiero et al., 2016). To achieve high transparency and low peak voltages, a combination of adhesive connections and dry assembly connections can be used.

Designing with glass creates problems, especially for thermal comfort problems. These problems can be easily solved by using a lot of energy, which is not a sustainable solution. With passive strategies, a large part of this requested energy can be removed. In order to take away as much energy as possible in a passive manner, there must be compromised on transparency.

PREFACE

It was a long journey from looking for a graduation project to writing the thanks. It is not only the end of the thesis, but also the end of my studies at TU Delft. From the first day of my bachelor at the Faculty of Architecture and the Built Environment I knew that my interests were in building physics and structural design. This is the reason why I chose the master track Building Technology. In the course structural design I fell in love with engineering with glass. So for my graduation topic I was looking for a topic where I could combine structural glass and building physics. Thanks to ir. Eric van den Ham I was introduced to the building manager of a small monument in Alkmaar, who wants to add a "real" function to the monument and thereby put Alkmaar on the map.

I am very proud of my end products and it wouldn't be the same without the good feedback and support from my mentors. I would like to thank my supervisors, Prof. James O'Callaghan and Dr. Regina Bokel for guiding my entire project. They supported me throughout the process, with their patience, their knowledge and their precious time. They made sure that I was put back on track from time to time, so that I was busy with the things I had to do. They were there to advise and encourage me to continue my work. They have explained to me fundamental aspects and the limitations of their fields, making my end product what it is.

For this research, I went to the utmost of different disciplines: the fields of structure (dome construction) with glass as construction material and climate design for thermal comfort in glass buildings. Structural Design and Architectural Glass were easy to combine in this study, since glass was the construction material. Climate design was separate from the structural research in this research. The two studies came together in the final design. So the road went separately. Researching in this way therefore took double effort for me, which ultimately resulted in the final design. By looking at the utmost of the different disciplines, I challenged myself to get acquainted with both disciplines and created guidelines for myself, which I can use in the future. As I thought it was a challenging project, where I encountered several obstacles and tried to solve them as best as possible.

"Designing with glass creates problems, but this does not mean that it should therefore be avoided."

Delft, July 2020
Ronald Rijsterborgh

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1 INTRODUCTION

1 INTRODUCTION

Say cheese say Alkmaar! Alkmaar is known as "the cheese city". In Alkmaar there is a cheese route. This route passes various characteristic monuments of Alkmaar. One monument is forgotten in this route, if we can believe the building manager of this small monument: Het Kruithuisje ("The Little Powder House"), see figure 1. The building manager of this monument wants to add his monument to the cheese route and wants to place a glass structure over it. His idea is to place a glass structure over his monument, like a huge cheese bell, in Alkmaar as a famous cheese city.

The monument is currently used as a coffee and tea house and as a little exhibition space. The problem with this monument is that it has no real function. This is because it is small and there are no sanitary facilities. Because it has the status of a national monument, it is not allowed to place a structure next to the building to create a covered terrace to give it a real hospitality function. That is why a more drastic measure is needed: placing a glass dome, a cheese bell, over the monument.

Figure 1: Het Kruithuisje (Het Kruithuisje, 2017)

Glass is a theme that has long been involved in architecture. The best solution to avoid thermal comfort problems is by applying less glass, but many students and architects do not want that. In this graduation research, possible solutions will come forward for building physical comfort problems. Especially for buildings with a lot of glass, where thermal comfort complaints often arise. These solutions can hopefully also be used in other buildings with a lot of glass, so that it does not have to be a full glass structure.

With the transparency of glass structures, things can be shown that are not visible with other structures. Even wider, high transparency can be achieved with glass constructions. This graduation research can provide tools for projects where high transparency is required, while also taking physical problems into account.

With the design of a dome over a small monument in Alkmaar, a function is added to this monument. At the moment the problem with this monument is that it has no real function. This is because it is a small monument and there are no sanitary facilities. This construction will be a new eyecatcher in Alkmaar. The monument is located in a recreation area. Nowhere in this area are facilities for these holidaymakers. Getting better facilities in this area is a must.

The main goal of this research is to design a fully glass dome to cover a small monument in Alkmaar, to create a place where people can stay dry and with thermal comfort for a longer period. The focus of this research is on the structural design with glass and on the thermal comfort design (specified on preventing overheating in the summer). Achieving high transparency is central to both focuses.

The main question that is central in this research, based on the research objectives, is:

"How can a full glass dome structure be built, to cover 'Het Kruithuisje' in Alkmaar, The Netherlands, in which the thermal comfort is maintained in the most passive manner, without impeding the visual benefits of glass?".

To answer this main question this research question is divided into sub research questions:

- What is the **optimal shape** of the dome to cover the monument as cheese bell?
- What kind of **connections** can be used to build the dome without compromising **transparency**?
- What kind of **passive strategies** can be used to create **thermal comfort** without impeding the **transparency**?

This research can be roughly divided into four parts: literature, designs, analysis and final design and conclusion. Figure 2 shows the general methodology framework of this research. Various coarse designs will be made that will be analyzed. The constructive simulations will be run in Diana. The thermal simulations will be run in DesignBuilder. To validate the different values, hand and computer based calculations will be combined and compared. Based on the analyzed designs, a final design can be made in which the structural performance and thermal comfort are known. These results will lead to a design with building plans that can ultimately be built, with guidelines, recommendations and conclusions for possible upcoming similar structures.

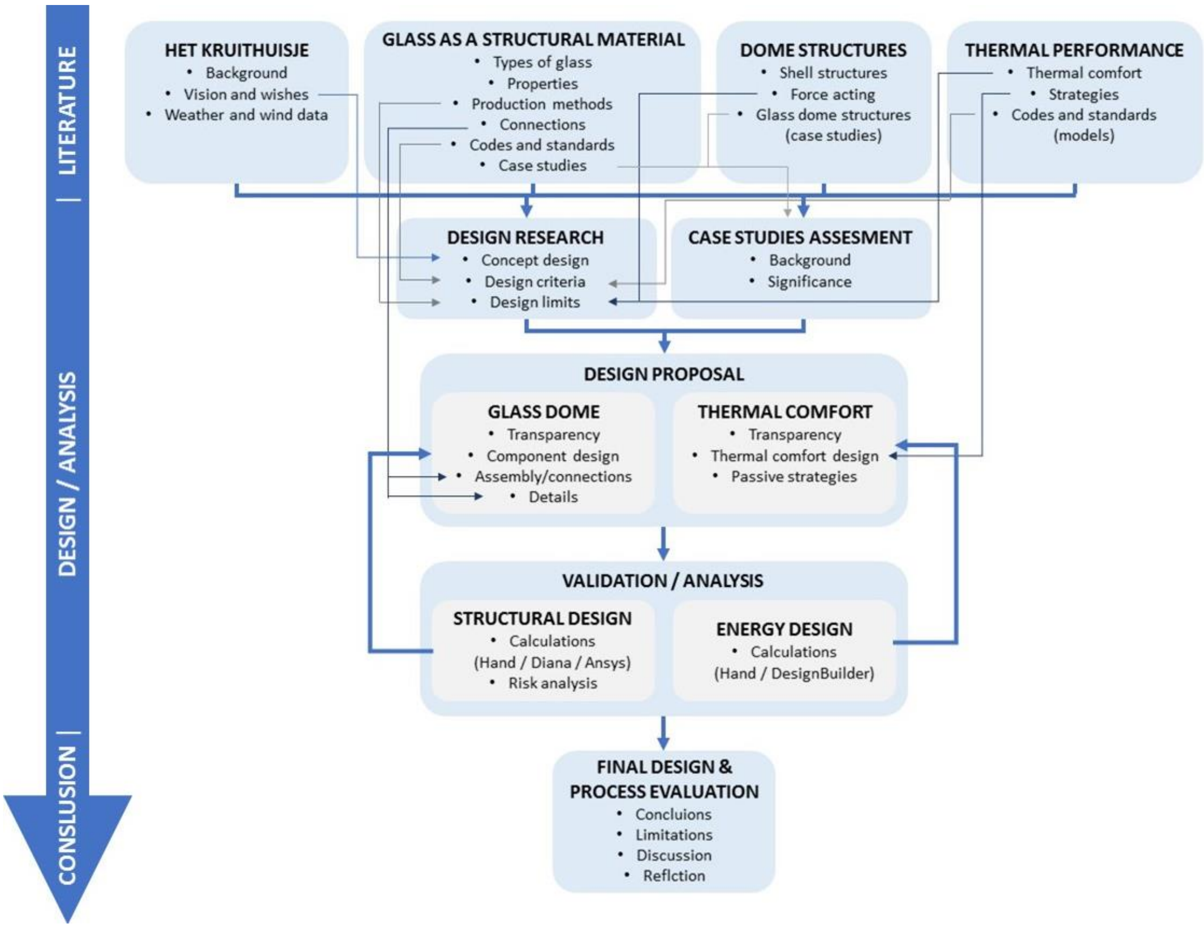


Figure 2: Research methodology (own figure)

2 LITERATURE STUDY

2 LITERATURE STUDY

2.1 Het Kruithuisje

Alkmaar is a city dating from the tenth century, with almost 90,000 inhabitants (CBS, 2019), located in the province of Noord-Holland, see figure 3. The historic center contains many national monuments and municipal moments. One of these national monuments, located in the historic center, is Het Kruithuisje (figure 4). The city has two train stations. A traditional cheese market is held weekly in most of the year, see figure 5. Alkmaar is known as "the cheese city".

Figure 3: Location Het Kruithuisje in The Netherlands (own figure)

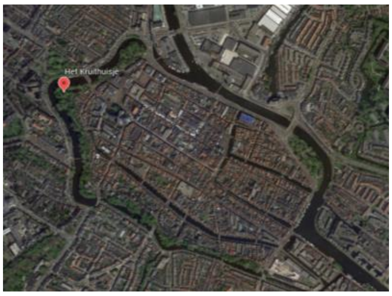


Figure 4: Location Het Kruithuisje in Alkmaar (own figure)


Figure 5: Cheese market Alkmaar (Chatelaine, 2017)

2.1.1 History

The historic city center of Alkmaar, the Netherlands, is surrounded by a canal and ramparts. On top of the Clarissenbolwerk, which is part of these ramparts, is a five by five meter moment; Het Kruithuisje ("The Little Powder House"), see figure 6.


Figure 6: Het Kruithuisje (Soeting, 2017)

The 16th century defense belt of the city; the stronghold, was converted into a park in the 19th century. The stronghold is located on the old and high city wall in which the church is built. The defensive belt surrounds the historic center, the part of Alkmaar where it all started (Gemeente Alkmaar, 2016).

In times of war the powder house stock was distributed to civilians, from an ammunition store located in the center. In the eighteenth century, the growing number of inhabitants and the number of houses in the center made it no longer safe for citizens to store the ammunition in the center of the city. The municipality decided to store the ammunition safely outside the built area on the ramparts. At the end of the eighteenth century, a powder cellar and a powder house were built on the Clarissenbolwerk. "Het Kruithuisje" probably served as a shelter for the sentries, who had to protect the nearby powder cellar. In the beginning of the nineteenth century the land administration took over the gunpowder storage and the local stores became superfluous. The powder cellar and powder house located on the Clarissenbolwerk became empty (Het Kruithuisje, 2017).

Halfway the nineteenth century the powder cellar was converted into an ice cellar. Here, until every household got its own refrigerator, large pieces of ice were stored. Due to the constant temperature, the pieces of ice chopped from the frozen canal in the winter were preserved well until into the summer (Het Kruithuisje, 2017).

Current usage

After being empty for years, neglected and even withstanding a fire, the small monument was renovated. Since the early 1960s, Het Kruithuisje has the status of a national monument. It has been in use for a while by various artists, until in 2013 the current building manager established his mini-gallery annex coffee and tea house. Where, in addition to changing exhibitions every month, lectures and small cultural performances take place. It is a beautiful meeting place where you can enjoy the surroundings, the art and a good conversation, see figure 7 (Het Kruithuisje, 2017).

Figure 7: Het Kruithuisje in use (Colmjon, 2019)

2.1.2 Weather and wind data

Figure 8 shows the average temperatures and precipitation of Alkmaar. The solid red line shows the average daily maximum temperatures and the solid blue line shows the average daily minimum temperatures. The dotted lines show the hottest days (red) and the coldest nights (blue). The coldest months are January and February. The hottest months are July and August. The most precipitation is in July and December.

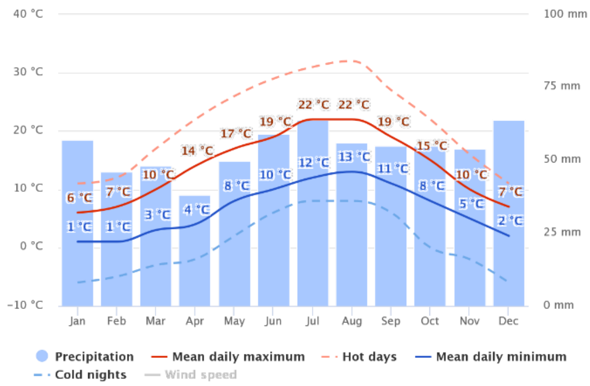


Figure 8: Average temperatures and precipitation (Meteoblue, 2020)

The amount of sun, overcast and precipitation days for each month are shown in figure 9. Sunny means the sky has less than 20% cloud cover. Partly cloudy is defined as the sky has between 20% and 80% clouds. The sky with more than 80% cloud cover is stated as overcast. The blue line shows the number of days per month with precipitation. The sunniest days are in June and September. The most cloudy days are in January and December. The months with the most rainfall days are also January and December.

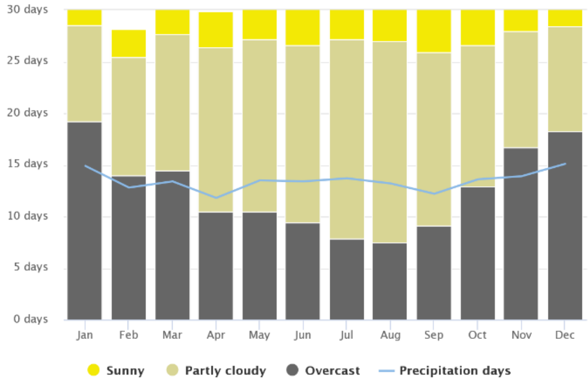


Figure 9: Cloudy, sunny and precipitation days (Meteoblue, 2020)

Figure 10 shows the number of days and correlated wind speeds varying for each month from Alkmaar. From October to April strong winds may occur with a related wind speeds of more than 50 km/h. In the calmer months, the dominant wind speed is between 19 and 28 km/h.

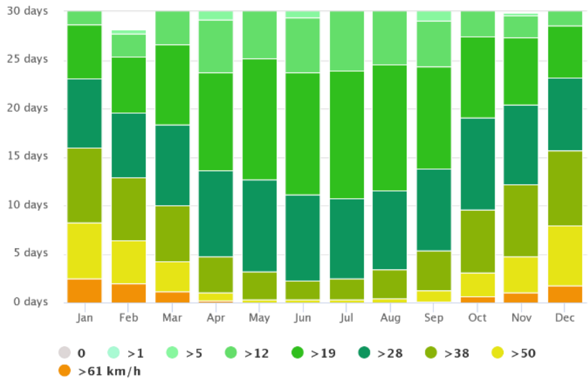


Figure 10: Wind speed (Meteoblue, 2020)

Figure 11 shows the wind rose of Alkmaar. The hourly wind direction varies through the year. The main dominant wind direction is the southwest direction. 563 hours of wind come from this direction annually with a speed between 19 and 28 km/h.

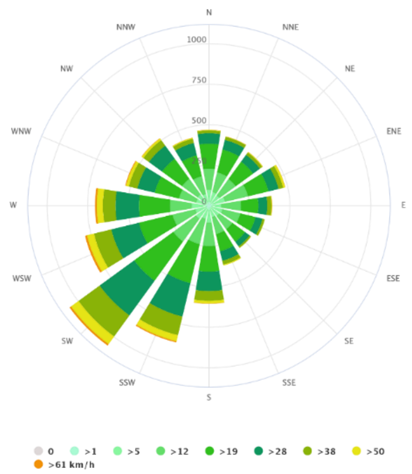


Figure 11: Wind rose (Meteoblue, 2020)

Figure 12 shows the relative humidity data from 2015 to 2020. The relative humidity varies between 68% and 89% over these years. It is therefore a humid climate. The highest relative humidity is in the winter months and the lowest relative humidity in the spring / summer months.

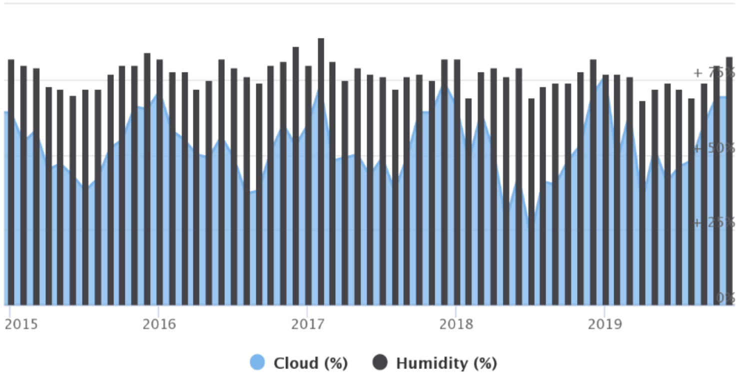


Figure 12: Relative humidity data from 2015-2020 for each month (World Weather Online, 2020)

2.2 Glass

2.2.1 What is glass?

The word glass comes from the Germanic word for amber, glare or shimmer; "glaza" (Schittich, Staib, Balkow, Schulder & Sobek, 2007). Glass is a solid and transparent material that is used in many different applications in daily life. But what is glass and what can be done with it? To design a structure with glass, first this question must be answered.

Glass is formulated in the scientific language as a homogeneous and amorphous material (Schittich et al, 2007). Glass can be found in different forms and in different places in nature. These natural forms of glass are formed when sand and / or stone are heated at a high temperature and then quickly cooled down (Lambert, 2005). Artificially produced glass is a combination of a mixture of sand and other minerals melted at a high temperature. To be even more specific, glass is a produced combination of a mixture of silicon oxides, alkaline oxides and alkaline earth oxides heated up to temperatures exceeding 1100 °C (Schittich et al, 2007).

In general, in nature the molecular structure of a material exist in three states of aggregation; gas, liquid and solid. The same applies to glass. Glass is a solid material under "normal" conditions and temperature and can therefore be used as a material with various applications. The process from liquid to solid is important for these applications. When a material cools down from liquid state to solid state; crystallization, lattice structures are formed; atomic bonds. Glass and quartz (crystal) can show different bonds, see figure 13. Glass has a random non-crystalline solid, structurally disordered structures; amorphous bonds. In contrast to crystal that has a crystalline solid, structurally ordered structures; crystalline bonds. These fundamental differences in structures can be explained by the different ways of cooling. The quartz is cooled in a very slow way. The atoms have time to achieve a highly ordered way. Unlike glass, which is a combination of sand and other minerals that are melted together and then cooled quickly. As a result, disordered molecular position of the ions and molecules an disordered bonds arise (Szabo, 2018). Because of the controlled cooling down process during the primary production of glass, the molten state cools to a solid amorphous form without crystallization (Schittich et al, 2007). Glass does not have a melting point, glass becomes viscous and liquid when heat is applied. Glass does have a melting temperature, which depends on the composition of the glass (Weller, Härth, Tasche, & Unnewehr, 2009).

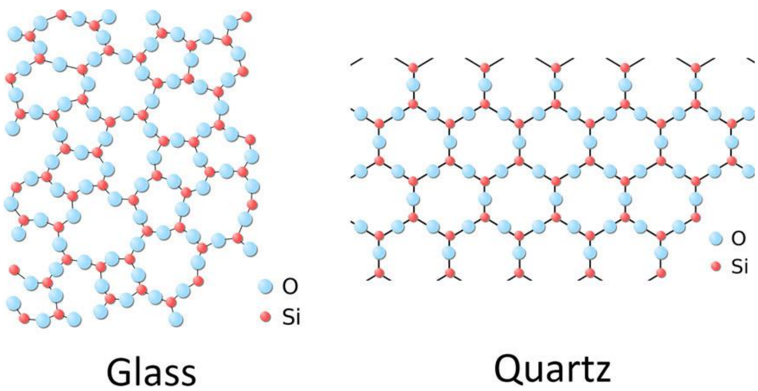


Figure 13: The atomic-level of glass and quartz (Szabo, 2018, p. 14)

2.2.2 Types of glass

Because there are different chemical compositions to manufacture glass, there are many different types of glass, each with different chemical and physical properties. Since each type of glass has different types of properties, it is important to choose the right type for the specialized applications. The most important and most commonly used groups of glass, which are used for glass products, are listed below. In general, glass has a three-dimensional structure of silicon (Si) and oxide (SiO_4) with cations in their apertures.

- *Soda lime glass*
  The principal component of soda lime glass is silicon dioxide (SiO_2). Other components of soda lima glass are calcium oxide (CaO), sodium oxide (Na_2O), magnesium oxide (MgO), aluminum oxide (Al_2O_2) and less than 5% other components. Soda lime glass is the most common type of glass that is produced (Janssens, 2018). So the main glasses that are used in the building industry are in the soda lime group. A typical use of this group of glass are windows, bottles, containers, tubing, lamp bulbs, lenses, mirrors, bells, glazes and tiles (Szabo, 2018).

  Soda lime glass is a cost-effective glass to produce, because it can be processed at lower temperatures (1000-1200 °C). Therefore it is a relatively inexpensive group of glass. The manufacturing time is affected by the required considerably longer annealing time, due the higher thermal expansion coefficient of soda lime glass (Szabo, 2018).

- *Borosilicate glass*
  Borosilicate glass is made by replacing the calcium oxide (CaO) for boric oxide (B_2O_3) (7-15%). Other components of borosilicate glass are Silicon dioxide (SiO_2), Sodium oxide (Na_2O), Potassium oxide (MgO) and Aluminum oxide (Al_2O_3) (Janssens, 2018).

  In de building industry borosilicate glass is often used, especially for fire resistant glazing, due to the high chemical resistance and better resistance to thermal shock. The Boron oxide provides enhanced durability and diminished coefficient of thermal expansion. The working temperature is significantly higher than soda-lime glass, approximately 1200-1400°C. Borosilicate glass is often used in the building industry, but also for laboratory apparatus, optics, lighting applications and ovenware (Szabo, 2018).

- *Alumino silicate glass*
  Alumino silicate glass has a composition of silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), calcium oxide (CaO), magnesium oxide (MgO), barium oxide and boric oxide (B_2O_3).

  Alumino silicate glass has similar properties as borosilicate glass. This type of glass is also often used for fire resistant glazing. This type of glass has better chemical resistance and higher operating temperature of up to 600°C. Alumino silicate glass is able to withstand high temperatures and thermal shocks. It is more difficult and more expensive to manufacture it in comparison to borosilicate glass. This type of glass is often used in combustion tubes, gauge glasses for high-pressure steam boilers an halogen-tungsten lamps (Szabo, 2018).

- *Quartz glass*
  Quartz glass is a pure material. Quartz glass is made from pure quartz, which containing almost no other components. Because there are no other ingredients which are normally added in traditional glass for lowering the melting temperature, quarts glass has a high melting temperature and a low coefficient of thermal expansion. Because of the exceptional properties it is a material for variety of applications in several industries (Szabo, 2018).

- *Lead glass*
  Lead glass is made by replacing the calcium oxide (CaO) for lead oxide (PbO) and potassium oxide (Janssens, 2018). If the glass contains more than 24% PbO, it can be considered as lead crystal, less than 24% PbO is known as crystal. If the glass contains a lot of lead oxide (> 65%) then it can stop different types of radiation. Lead glass in not often used in the building industry. It is mainly used to make decorative glass objects and glass objects for the medical industry.

The properties of these most important and most commonly used groups of glass are presented in the following table.

Table 1: *Properties of the different glass types* (Schittich et al, 2007)

	Basic types of glass				
	Quartz	Soda lime	Borosilicate	Lead	Alumino silicate
Price (€/kg)	5140-8580	1160-1370	3430-5150	3300-5100	1170-1370
Density (kg/m³)	2170-2200	2440-2490	2200-2300	3950-3990	2490-2300
Young's modulus (GPa)	68-74	68-72	61-64	53-55	85-89
Hardness (kg/mm²)	450-950	440-485	84-92	472-525	68-75
Tensile strength (MPa)	45-155	30-35	22-32	23-24	40-44
Compressive strength (MPa)	1100-1600	360-420	264-348	232-244	400-440
Yield strength elongation 0% (MPa)	45-155	30-35	22-32	23-24	40-44
Thermal expansion coefficient (10^{-6}/K)	0.55-0.75	9.1-9.5	3.2-4	8.82-9.18	4.11-4.28
Thermal conductivity (W/(m·K))	1.4-1.5	0.7-1.3	1-1.3	0.82-0.86	1-1.5
Poisson's ratio	0.15-0.19	0.21-0.22	0.19-0.21	0.23-0.24	0.23-0.24
Softening point (°C)	1665	726	820	631	
Strain point (°C)	1070	510	510		

2.2.3 Material properties

To meet all project-specific requirements, including the complex performance requirements for the design; construction and building physics, it is important to understand the mechanical and physical properties of glass. The most common mechanical and physical properties are explained in this section.

Mechanical properties

If the mechanical properties of glass are compared with other known building materials, glass is stiffer, stronger in tension and less brittle, see figure 14 for the comparison of modulus of elasticity of different building materials. Glass can handle a high tensile strength, up to 92 GPa. Glass is a isotropic material that deforms in a linear elastic way (Fröling, 2013). A disadvantage of glass is that it has a brittle fracture, since it does not show any plastic deformation prior to failure and breaks in a complete way without any visible warning, compared to other materials. This is due to the high percentage of silicate. Silicate, on the other hand, it ensures the hardness and strength of glass. The associated Youngs modulus is equal to 7000 N/mm^2. See figure 15 for the comparison of the mechanical behavior of glass compared to steel (Wurm, 2007).

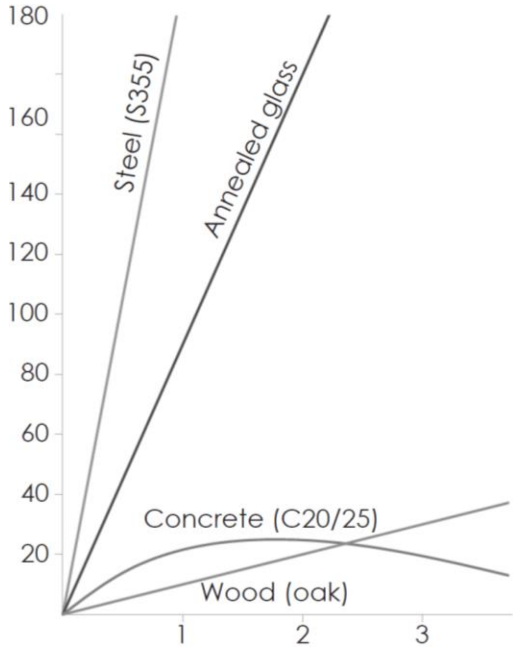


Figure 14: Modulus of Elasticity of steel, glass, concrete and wood (Felekou, 2016, p. 31)

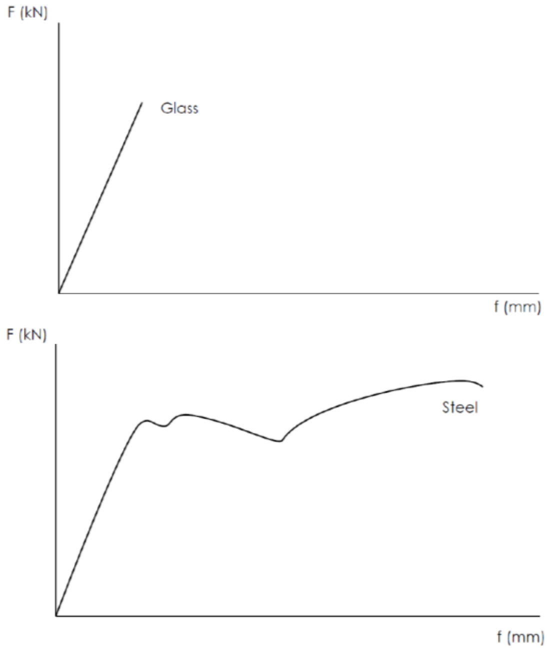


Figure 15: Mechanical behavior of glass (top) and steel (bottom) (Doulkari, 2013, p. 36)

Tensile strength

In theory, glass could achieve a tensile strength of 8000 N/mm^2 (30 times larger than steel), but due to the brittleness of glass and micro-errors, this value is not achieved in practice. Glass has a characteristic value that is between 30 and 80 N/mm^2. During manufacturing, treatments and handling, micro flaws occur in the material. Micro flaws, called Griffit flaws, are faults in the microstructure (small cracks on the surface) of a material, so that glass is not a compact solid anymore. This has the consequence that the tensile strength of the glass decreases considerably. When glass is pulled (tensile strength), peak tensions arise around these Griffit flaws, which ultimately leads to failure. Because glass does not deform plastically, the cracks spread due to peak stresses. When glass is compressed (compressive strength), these peak stresses do not occur. The tensile strength of glass depends on the following aspects and therefore has it no constant value, but a characteristic value: (Wurm, 2007; Weller et al., 2009)

- Duration of load
- Size
- Properties of glass
- Glass type
- Environment
- Age

Compressive strength

As mentioned earlier, no peak stresses around the micro flaws occur during compression. So the compressive strength is at least ten times the tensile strength. The compressive strength is between 400 and 900 N / mm2 (Weller et al., 2009).

Physical properties

Glass is often used in facades due to the transparency of the glass. This can lead to advantages, but certainly also to disadvantages. In this section the physical properties of glass are discussed; the optical and thermal properties.

Transmission, reflection and absorption

It is said that glass is transparent, but looking at the definition of transparency, this can be interpreted differently, since glass reflects and absorbs part of the light so that a color of the glass can be observed. Transparency is a broad concept, but in physics there is transparency when complete transmission occurs: the complete transmission of all wavelengths of light (Weller et al., 2009). In the case of transparency of glass, there is transmission of light in which there is no perceptible disturbance (Wurm, 2007).

Since glass is not completely transparent, disadvantages may arise. If light falls on a glass surface at a certain angle, it may be that there is even less transmission, causing reflection. Reflection reduces transparency and disrupts optical properties, which can lead to the blinding of people. Reflection, refractions and permeability depend on the angle of incidence, this increases when the angle is flattened. By increasing the texture of the surface of the glass, the direct light changes into diffuse light, which causes a decrease in the reflective reflection, but also the transparency of the glass (Wurm, 2007).

Light consists of a spectrum of wavelengths. What people are able to see is only 50% of the full light spectrum. A portion of this invisible light is not transmitted through the glass, but is absorbed. The absorption of light is caused by the iron oxide in the glass. The metal oxides therefore ensure the absorption factor of the glass, which determines the color of the glass. A disadvantage of the incomplete occurrence of transmission is that certain wavelengths are transmitted through the glass. Some of these short wavelengths of light change inside, behind the glass, into long wavelengths (heat wavelengths) that are then no longer transmitted through the glass, due to the incomplete transmission. These longer wavelengths are absorbed and transmitted by convection or radiation, which causes heat. If this heat cannot leave the room behind the glass, this can lead to overheating of the room. This principle is called the greenhouse effect. In some applications, therefore, glass is chosen to get this effect. The thicker the glass, the more heat is absorbed by the glass (Wurm, 2007).

Thermal insulation

With single glass in buildings it can be seen that the thermal resistance of glass is low, because frost and condensation occur on the surface. The thermal resistance of glass depends on the thermal resistance of the material and the thermal resistance of the surface. Because glass has a high thermal conductivity, it is desirable to increase the thermal resistance of glass. A known solution is to use several layers of glass with a certain type of gas between them. Another solution or combination can be by using coatings. Coating reduces emissivity, thereby improving the radiation properties. The radiation transmission is absorbed or reflected. The insulating effect of coatings is improved, with a reduced U-value (Schittich et al., 2007).

2.2.4 Production methods

At high temperatures glass is fluid. When the temperature reduces, the glass becomes solid. Melting the raw materials together is the start of the production. There are different manufacturing processes of glass. To arrive at these different manufacturing methods, there has been an evolution of manufacturing techniques. The many production processes lead to different types of glass with different batch sizes and properties. The chosen production technique depends on various factors; the raw materials and what heat energy is required (Wurm, 2007). The four primary and promising production methods used in the building environment are discussed below.

- *Float glass*

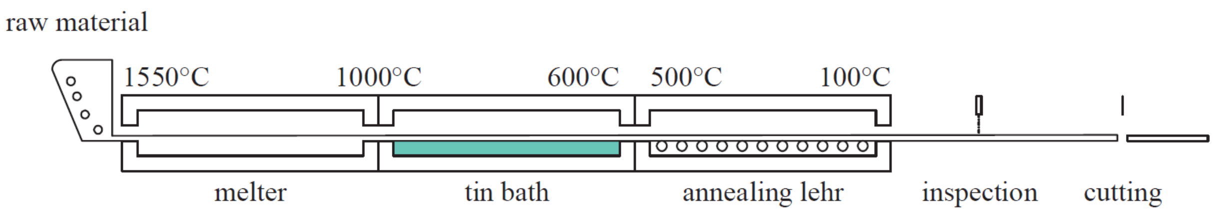
  The most common production method is the production of float glass, approximately 90% of the glass production. Around the world float glass companies produce 750 tons (50.000 m^2) of glass per day. This method is a relatively cheap method and it gives a high optical quality (Weller et al., 2009).

  This production technique was invented by Alastiar Pilkington in 1952. It has 6 stages and are shown in figure 16 (Weller et al., 2009; Wurm, 2007):

  1. Melting and refining

     The raw materials are controlled, mixed and added to the melter and heated to a temperature of 1550°C. When the materials are melted, and there are no more bubbles in the glass, the glass is cooled down to the temperature of 1000-1200°C.
  2. Float bath

     The solid glass of 1000-1200°C flows onto a molten bath of tin and the atmosphere is filled with nitrogen and hydrogen to prevent the oxidation of the tin and coatings. After approximately 50 meters the cooled down solidified glass leaves the bath and goes to the annealing lehr with a temperature of 600°C.
  3. Annealing lehr
  4. Cooling to 100°C
  5. Inspection
  6. Cutting to size



Fiugre 16: Schematic illustration of the float production process (Oikonomopoulou, 2019, p. 56)

- *Cast glass*

  A big advantage of cast glass is the high form flexibility (freedom in forming) and a strong unique monolithic structure, because the shape is created by pouring glass into a preformed mould (Janssens, 2018). Two basic techniques for casting glass are hot-pouring and kiln-pouring (Sombroek, 2016):

  - Hot-pouring

    Liquid glass (molten glass), at the temperature of 1200°C, is poured into a preformed heated mould directly. The mould is heated to avoid temperature changes. The glass is removed from the mould when the glass is cooled down to a temperature of 700°C. The glass is then placed in an oven to cool slowly to room temperature.
  - Kiln-casting

    There are two similar ways to do the kiln casting. The first way is when broken glass pieces are placed in a mould in a kiln. While the kiln is heating the viscosity of the glass decreases and will fill the mould everywhere. The second way of doing it is to put the broken glass pieces in a pot, above the mould in a kiln. While the kiln is heating the glass pieces melt and fill the mould. When the mould is totally filled with the molten glass, the kiln is slowly cooled down to avoid cracking due heat changes.

In comparing to hot-pouring, the mould is placed into a kiln and remains during the process of kiln-casting. Because the mould has to withstand high temperatures, the mould is usually made of a solid material (Sombroek, 2016).

- *Extruded glass*
  The extrusion production is known in the metal, plastic industry and also for glass. The glass is heated and pressed through a small opening by a punch. The glass is shaped by changing the diameter of the opening. By adding an extrusion mandrel in the opening, tubes can be created. There is a difference in direct and indirect extrusion. With indirect extrusion, a hollow punch is used, whereby the glass goes in the opposite direction of pressing. The latter method is complex and is therefore only used in special cases. The advantage of this technique is that different cross-sectional shapes are possible. Extruded glass products are not often used, but sometimes it is the only way to get the desired diameter in products (Janssens, 2018).

- *3D printed glass*
  3d Printing is a well-known method, but 3d printing with glass is still unknown and needs further elaboration. The Mediated Matter group (G3DP) has worked on additive manufacturing or optically transparent glass. They were the first to print 3d precise, optically transparent glass in association with the Glass lab at MIT (G3DP, 2018). G3DP has a "printer" with a double heating chamber. There is a kiln cartridge in the upper chamber. The lower chambers act as annealing kilns. The molten glass comes from an alumina-silica nozzle. So far, only small decorative objects have been printed. It has not yet been applied in the building industry, because it is still experimental (Janssens, 2018).

2.2.5 Conclusion

Because there are different chemical compositions to manufacture glass, there are many different types of glass, each with different chemical and physical properties. In general, glass has a three-dimensional structure of silicon (Si) and oxide (SiO_4) with cations in their apertures. The most important and most commonly used groups of glass, which are used for glass products, are: soda lime glass, borosilicate glass, alumino silicate glass, quartz glass and lead glass.

If the mechanical properties of glass are compared with other known building materials, glass is stiffer, stronger in tension and less brittle. Glass can handle a high tensile strength. Glass is a isotropic material that deforms in a linear elastic way (Fröling, 2013). A disadvantage of glass is that it has a brittle fracture, since it does not show any plastic deformation prior to failure and breaks in a complete way without any visible warning, compared to other materials.

Glass is often used in facades due to the transparency of the glass. This can lead to advantages, but certainly also to disadvantages. If light falls on a glass surface at a certain angle, it may be that there is even less transmission, causing reflection. Reflection reduces transparency and disrupts optical properties, which can lead to the blinding of people. A portion of this invisible light is not transmitted through the glass, but is absorbed. A disadvantage of the incomplete occurrence of transmission is that certain wavelengths are transmitted through the glass. These longer wavelengths are absorbed and transmitted by convection or radiation, which causes heat. If this heat cannot leave the room behind the glass, this can lead to overheating of the room (Wurm, 2007) Because glass has a high thermal conductivity, it is desirable to increase the thermal resistance of glass (Schittich et al., 2007)

There are different manufacturing processes of glass. The most common production method is the production of float glass. This method is a relatively cheap method and it gives a high optical quality (Weller et al., 2009). Casting glass has a high form of flexibility and the glass has a strong unique monolithic structure, because the shape is created by pouring glass into a preformed mould (Janssens, 2018). The extrusion production is known in the metal, plastic industry and also for glass. The glass is heated and pressed through a small opening by a punch. 3d Printing is a well-known method, but 3d printing with glass is something that is still unknown and needs further elaboration.

2.3 Glass as a structural material

As described in the previous chapter, glass is an elastic, isotropic material and exhibits brittle fracture that can absorb a high tensile strength. Glass can certainly compete with other materials such as structural materials. This chapter discusses what should be taken into account with glass as a structural material.

2.3.1 Case studies

A good way to find out what can be done with glass as a structural material is by looking at projects that have already been completed; case studies. Different existing examples with different types of glass will be discussed in this section.

- *Apple Fifth Avenue Mark II, New York, 2011, Eckersley O'Callaghan*

  The entrance to the Apple's underground store in Manhattan, NY, is a 9.8x9.8x9.8 m transparent cube. The original cube, completed in 2006, had 106 panels and 250 primary fittings. The second re-constructed cube, completed in 2011, has 15 panels and 40 fittings.

  Because of the glass innovation in those five years, there was the opportunity to improve the transparency of this cube by using larger glass panels and applying more sophisticated details, so that the connections are embedded in the glass. This case study is an exemplifying of the latest thinking in construction glass.

Figures 17, 18 & 19: Apple Fifth Avenue Mark II (Eckersley O'Callaghan, 2011)

- *The glass house, Milan,2010 , Carlo Santambrogio*

  A blue-tinged glass cube house on a private enough place, in the middle of the woods, is almost entirely made out of glass. The cube is made of 30 to 60 mm tempered and laminated extra-clear glass panels. The glass can be specially heated for different types of weather.

  Almost everything in the house is made out of glass, from the dining table, to the stairs, to the bookcase.

Figure 20: The glass house (Santambrogiomilano, 2013)

- *Crystal house, Amsterdam, 2016, MVRDV*

  The entirely transparent facade of a store in Amsterdam is made of glass bricks, glass windows frames and glass architraves. There are 3 sizes of cast glass blocks/bricks made for this project. A transparent adhesive layer was used between these bricks. One rigid unit that uses monolithically against loading was used. There are buttresses behind the facade to counteract lateral loads.



Figures 21, 22 & 23: Crystal house (MVRDV, 2016)

- *Atocha station memorial, Madrid, 2015, FAM Arquitectura y Urbanismo*

  The Atocha station memorial is a 11 m high memorial monument, that commemorates the victims of train bombings. The 11 m high cupola has 2 layers: transparent colorless glass blocks and an ETFE membrane. The cupola is made of approximate 15000 round-shaped solid cast glass, convex on the one side and concave on the other side, blocks. Due the shape of the blocks it is possible to bond them together in circular rows to create the cylindrical shape of the monument. The blocks are connected by a transparent adhesive layer.


Figure 24 & 25: Atocha station memorial (Lomholt, 2019)

2.3.3 Strengthening of glass

Glass can be used as a construction material, but it has a number of properties as standard that are not entirely suitable for a construction material. To make glass safer, to give glass a greater bearing capacity, it must be strengthened. There are different ways to reduce the brittle and unpredictable failure behavior of glass under certain circumstances. The three primary methods for reinforcing glass will be discussed below. The methods to make the glass safer and stronger can be carried out during basic production (Louter, 2011).

- *Chemical treatment*

  With the chemical treatment, the glass is immersed in a hot potassium chloride bath, at 3000°C, where sodium ion exchange takes place. The sodium ions in the glass are replaced by potassium ions from the bath. This gives the surface of the glass a compact molecular structure (Swift Glass, 2020). This treatment gives the glass a higher pressure surface strength, because the surface comes into compression and the core is under tension. This glass is therefore called chemically reinforced glass. Chemically reinforced glass breaks into large pieces (Wurm, 2007).

- *Thermal treatment*

  The principle of thermal treatment of glass or tempering of glass is fairly simple. The produced glass is reheated and then cooled in a controlled manner and within a certain time. This cools the outside of the glass faster than the inside. The outer surfaces of the glass coming under compression and the core under tension. This results in internal stresses with a parabolic stress diagram across the section: a pressure zone on the surfaces and a stress zone in the core as shown in figure 26. This makes the glass better protected against temperature differences and mechanical shocks (Wurm, 2007).

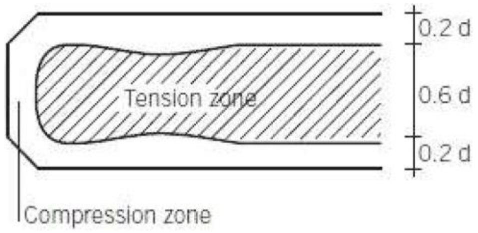


Figure 26: Cross section tempered glass with tension and compression zone (Wurm, 2007)

  There are different ways to thermally treat the glass. Each way yields a specific type of glass. Each type of thermally treated glass has its own breaking pattern of the glass. The different types of thermally treated glass are discussed below.

  - *Annealed glass*

    The glass produced as float glass is heated to 1500 °C and is then slowly cooled under controlled conditions. Glass that has not been annealed can crack with small temperature differences or mechanical shocks. The characteristic tensile strength of annealed glass is 45 MPa. The shards of annealed glass are large and sharp and can therefore be dangerous (Leitch, 2005).

  - *Heat strengthened glass (HS)*

    To make this glass, normal (annealed) glass is heated again to above 600 °C. This is then cooled by blowing cold air over it. This causes shrinkage of the surfaces of the glass. This has improved thermal shock resistance. Heat-reinforced glass has a lower surface pre-pressure. The characteristic tensile strength is approximately twice as high as annealed glass, 70 MPa. The fracture pattern are different cracks from a point that divides the glass into larger pieces and islands (Leitch, 2005).

- *Fully tempered glass (FT)*
  The process of thermal treatment of fully tempered glass is comparable to that of heat strengthened glass, but it is cooled many times faster. The finish has less flatter surfaces than heat strengthened glass. This type of glass has the highest characteristic tensile strength, approximately twice as high as heat strengthened glass, 110 MPa. A disadvantage of this glass is that there is a risk of the glass splashing spontaneously. Fully tempered glass has a fracture pattern of many small, less dangerous pieces (Leitch, 2005).

With heat strengthened glass, fully tempered glass and chemically strengthened glass, the surface is put under compression and the core under tension. With chemically strengthened glass, the compression does not go deep into the material, compared to the other two. Figure 27 shows stress cross sectional diagrams of the three different variants. Fully tempered glass and reinforced glass are considered safety glass and chemically reinforced glass is not considered safety glass (Wurm, 2007).

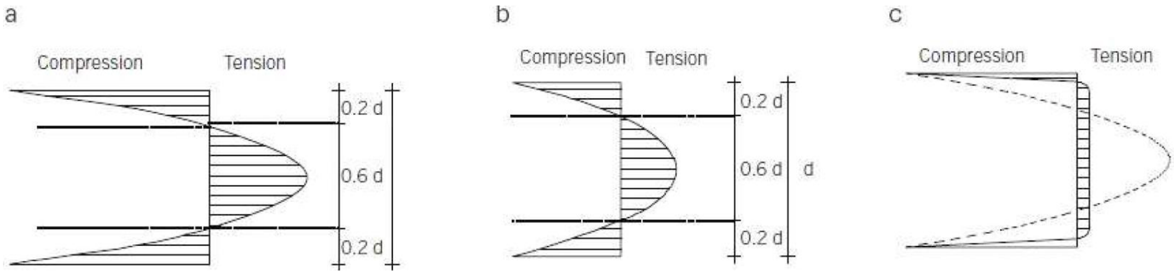


Figure 27: Stress cross sectional diagram for: a) fully tempered glass ,b) heat strengthened glass, c) chemically strengthened glass (Wurm, 2007)

- *Lamination of glass*
  Laminated glass are sheets of glass that consist of at least 2 glass layers, which are connected with a (plastic) intermediate layer. Because the various glass layers are combined (permanently) with a thin layer of foil and / or glue under a temperature of between 140 °C and 250 °C and compression, the composition of several sheets will behave as a single panel. The type of intermediate layer and the thickness of the glass layers determine the mechanical and optical properties. The load-bearing capacity is strengthened by laminating, if a glass layer breaks, the other glass layer(s) still has a load-bearing capacity. The fragments of a broken glass layer are held by the intermediate layers, so that the pieces of glass interlock and the broken glass layer still has a bearing capacity. Laminated glass is seen as safety glass (Louter, 2011).

  There are different types of materials for the interlayers, usually soft polymers. The most common intermediate layers are films. These different film layers are discussed below:

  - Polyvinyl butyral (PVB)
    PVB is connected under elevated temperature and pressure between the glass layers in an autoclave, see figure 28. This material is only used to hold the glass fragments together. Because PVG has little strength and stiffness, this intermediate layer offers no additional bearing capacity (Bos, 2009).

Figure 28: The largest glass industry autoclave (lamination up to 15m), Sedak Industry (Sedak, 2020)

- Ethylene vinyl acetate (EVA)
  If EVA is applied, this enters into a complete limitation (cross-linking) with the material. This does not necessarily have to be with glass, it can also be polycarbonate, for example. The production method for laminating with EVA is comparable to PVB. The difference is that EVA is a resin, so that it is poured onto the glass in different places with different thicknesses, because the resin has to distribute evenly during pressing. This process is not an automated process, so different sheet thicknesses are allowed (Gatsiou, 2015).

- DuPont's Sentryglass (SGP)
  SGP has been developed for burglary, vandalism and hurricane. It has a high tear strength, 5 times higher than PVB. It makes the laminate component stronger, 100 times stiffer than PVB. SGP also has a higher transparency. The price for this are therefore higher (Ungureanu, 2011).

Layered glass can have different thicknesses. The construction of laminated glass can also consist of various thicknesses of glass. The various laminated glass plates can be made from heat-treated glass, annealed glass or the combination of both (Szabo, 2018).

If the entire laminated glass panel is broken, the remaining structural capacity of the panel depends on the fragmentation of the glass. This capacity depends on the fragment size of the glass. The type of glass therefore plays a role in this. View figure 29 for the breakage behavior or different strengthened glass types (Ungureanu, 2011).

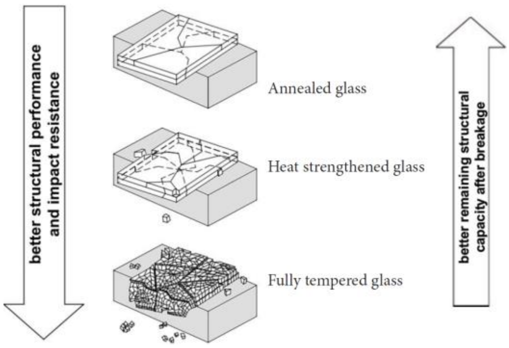


Figure 29: Breakage behavior of different strengthened glass types (Ungureanu, 2011)

The transparent interlayers of the laminated glass can absorb and refract sunlight. The intermediate layers can be designed to save energy in the building. For example, the intermediate algae can block the high summer sun radiation and let through the low winter sun radiation. The intermediate layer can also have a sound-damping effect (Schimmelpenningh, 2012).

2.3.4 Bending of glass

Flat panes of glass can be curved. Curved (tempered) glass can also be used for laminated safety glass or insulating units. Double curved panes are also possible. The load-bearing effect is even more favorable than for single-curved glass panes, because uneven loads can also be carried as axial forces without bending (Schittich et al., 2007).

There are different techniques of bending flat panes of glass:

- *Cold bending*
  The panes of glass are run at the factory room temperature. By placing the glass in a frame, the glass is mechanically bent into the desired shape. With this method, the glass is screwed or glued directly into the frame. This frame therefore remains around the glass, also in construction and must therefore be a structural element instead of the glass (Äppelqvist, 2015).

- *Hot bending*
  Hot bending is a technique where the glass is heated beyond the transformation point (640 °C). The glass becomes a "soft" ("doughy") material, so that it can be bent into the shape of a desired mold. Cylindrical, conical, spherical or other curved shapes are possible here. The curved glass is then cooled or the curved glass is prestressed (Schittich et al., 2007). There are two methods of getting glass into the mold in hot bending (Äppelqvist, 2015):

  - *Gravity*
    By using gravity the glass turns into the mold.

  - *Mechanical bending*
    A mechanical bending press forces the glass into the target shape.

Glass producers should be consulted about which dimensions of curved glass are possible: these depend on the production furnaces available but also the shape. Type of glass, length, width, bending radius or bending angle play a role in this (Schittich et al., 2007). Sedak, manufacturer leader of premium oversized glass, can supply cold curved panes of glass with the maximum dimensions of 20 by 3.6 meters, hot bended gravity curved panes of glass with the maximum dimensions of 11.5 by 3.3 meters and hot bended tempered curved panes of glass (double-bended) with the maximum dimensions of 6.5 by 3.6 meters (Sedak, 2020).

2.3.5 Connections

To be able to build with glass, connections are needed between the various glass components. These are the critical parts of a glass design, because glass is fragile and does not redistribute the stress peaks where forces are transferred between the different components. There are three options for connecting glass components to each other. These three are described below: (Santarsiero, Louter, & Nussbaumber, 2016)

- *Bolted connections*
  For bolted connections, holes must be drilled through the glass, through which metal bolts are placed to transfer the forces properly. A soft material is placed between the glass and the metal component, so that both hard surfaces do not connect directly to each other (Santarsiero et al.,2016).

The holes drilled in the glass cause stress concentrations around the hole. These stress concentrations can cause cracks in the glass with component failure as result. Therefore, the area around the hole must also be hardened uniformly (Szabo, 2015).

Stainless steel, aluminum and titanium are used for these applications. To reduce drilling of holes in the glass, metal parts can also be laminated in the glass, so that the stress concentration is distributed differently over the glass. Titanium is generally used for this application due to the comparable thermal coefficient of glass, resulting in fewer stresses during the laminating process (Felekou, 2016).

- *Adhesive connections*
  Adhesive connections between glass components is also possible. An intermediate layer of a liquid adhesive or adhesive film is applied between the glass elements. These adhesives must meet the structural requirements to keep the various glass components together (Santarsiero et al., 2016).

  Bonding the glass components is a sensitive process, because any dirt can deteriorate adhesion. This can cause failure in the structure in the longer term. The glue must be applied evenly with a certain thickness for proper operation and it is an irreversible process. An adhesive connection ensures a watertight and airtight connection (Szabo, 2015).

  The adhesive joints are able to evenly transfer stress concentrations on the joints across the various components, which is positive for the glass construction (Szabo, 2015).

- *Dry assembly connections*
  History has shown that masonry work with a special way of stacking and interlocking can work without a mortar connection. This dry assembly method can also be used for glass elements. However, due to unevenness of the glass surface, peak stresses could occur which could cause cracks, this method of glass connections is not yet considered a safe method. In order to distribute the forces between the various elements properly, so that no peak stresses arise, an intermediate layer would have to be applied (Szabo, 2015).

2.3.2 Codes and standards

Because glass is not yet a standardized construction material, there are no extensive design codes or independent control elements for glass as construction material. There are some loose guidelines or rules of thumb from national governments or local municipalities. Since architects and engineers do work with glass as construction material, more extensive codes and standards must be introduced (Connor, 2011).

Different manufacturers provide simple design tables for different glazing systems. Since these offered guidelines are often patented, it is difficult to standardize these guidelines. Furthermore, more research needs to be done to draw up standardized codes and guidelines. An umbrella authoritative organization should be formed for this, according to Connor (2011).

The most detailed design guidelines have so far been published in the United Kingdom by the Institute of Structural Engineers, since European countries are at the forefront of structural glass technology. The Netherlands offers various remarkable examples of construction glass (Connor, 2011).

Limit state design

One of the most commonly used methods for designing with glass is the method for limit state design. This method takes into account various statistical distributions about the strength of the material and load, for example wind and snow. This is a difficult method, because the failure behavior of individual components must be explicitly considered, with different failure scenarios per component. The method means that the structure is viewed under different scenarios, with the remaining components still having to provide stability after the failure of individual components (Badalassi, Biolzi, Royer-Carfagni, & Salvatore, 2014).

The lifespan of the various components plays a role here, since it is not feasible to offer a lifetime guarantee for each component. Therefore, when designing with glass, it is important to divide the parts that require a lifetime warranty into different components that can fail locally, without affecting structural behavior seriously (Gatsiou, 2015).

There are two main goals when designing a safe structure of glass (Weller et al., 2009):

- A great residual loadbearing capacity
  The remaining load capacity is the safety limit for the complete failure of a partially broken system. What this means is that the structure must remain in position and bear other loads for an acceptable period of time if the structure is damaged.

- Redundancy
  Glass structures must also be designed with redundancies. This means that an element must bear the loads of a defective element when an element fails. To include this in the design, failure diagrams must be included in the structural analysis of structural systems to ensure their safety.

Risk analysis

A certain level of stability and safety against failure is required for any kind of structure. In the Dutch code NEN-EN 1990 there are three classes that categorize the different constructions according to their importance, depending on the possible consequences of the failure of a structure: houses, offices, agricultural buildings. Herein, a statistical assessment is made of the likelihood of collapse, from which the acceptability of the associated function with the possible consequences is assumed.

Glass structural elements can be subdivided into different classes, see table 2. As each class corresponds to an increasingly important and more serious impact as a function of the design life of the structure in question, it can generally be assigned as a decreasing probability of collapse in this class (Badalassi et al., 2014).

Table 2: *Proposal of classes of consequences and probability of collapse for glass elements* (Badalassi et al., 2014)

Class:	Definition:	Probability of collapse:
CC0	Specifically non-structural elements. Following failure, negligible economic, social and environmental consequences and practically null risk of loss of human life.	Probability of collapse to be evaluated in consideration of costs of maintenance and repair.
CC1	Following failure, low risk of loss of human life and modest or negligible economic, social and environmental consequences. Glass structural elements whose failure involves scarce consequences fall into to this category.	$4.83 \cdot 10^{-4}$ over 50 years; $1.335 \cdot 10^{-5}$ in 1 year
CC2	Following failure, moderate risk of loss of human life, considerable economic, social and environmental consequences. Glass structural elements whose failure involves medium-level consequences belong to this category.	$7.235 \cdot 10^{-5}$ over 50 years; $1.301 \cdot 10^{-6}$ in 1 year
CC3	High risk of loss of human life, serious economic, social and environmental consequences: for instance, the structures of public buildings, stages and covered galleries, where the consequences of failure can be catastrophic (concert halls, crowded commercial centers, etc.). Glass structural elements whose failure involves high-level consequences fall into this category.	$8.54 \cdot 10^{-6}$ over 50 years; $9.960 \cdot 10^{-8}$ in 1 year

The Dutch code NEN 2608 has included the Fine & Kinney method to classify risks. The risk is defined as the factor RD = PD · ED · SD. PD is the probability that damage will occur. ED is the exposure of the object to possible damage. SD is the severity of the injury when the object completely collapses.

This risk analysis calculates the chance of failure due to the variation in factors. The risk is defined as the expected consequences of a certain activity. Considering only one incident with a potential impact risk is therefore the probability that this incident will occur multiplied by the structural exposure element and the consequences given that the incident occurs. See table 3 for the determination of the different values. Table 4 shows the RD factor with the relationship with the glass breakage.

Table 3: *Determination of RD-value* (Ten Brincke, 2019)

Probability intentionally or unintentionally	WS	Exposure of the structural element	BS	Consequence at complete failure	ES
Virtual impossible	0.1	Very rarely	0.5	First aid	1
Practically impossible	0.2	Several times a year	1	Minor injury	3
Possible, but very unlikely	0.5	Monthly	2	Serious injury	7
Only possible in the longer term	1	Weekly	3	One dead	15
Uncommon, but possible	3	Daily	6	More than one dead	40
The best possible	6	Constantly	10	Catastrophe, many deaths	100
Can be expected	10				

Table 4: *RD factor with the relationship with the glass breakage* (Ten Brincke, 2019)

RD < 70	Glass layer breakage, single sided
70 < RD < 400	Glass layer breakage, double sided
RD > 400	Complete breakage of the construction

A possible option to make the structure safer is to use external objects or structures that defend the main structure (Szabo, 2018).

2.3.6 Maintenance

Glass is a construction material that generally lasts a long time because it is resistant to weather influences. Glass can incur aging effects. These include small cracks or scratches. This results in the glass becoming dull, but generally has no effect on the structural performance of the glass. A reason to replace glass parts is if the cracks are too large and / or too wide, which can cause moisture to penetrate, if parts are likely to fail or if the connections are poor (Neumann, Stockbridge, & Kaskel, 1995).

If the glass is so damaged as a result of a thermal shock or due to an impact load occurrence, these damaged parts must be replaced. The adjacent glass components must be taken into account in order not to damage them (Gatsiou, 2018). The connection between the various glass parts therefore plays an important role for the replacement of parts, how easily this is or is not.

By sealing the seams and / or joints between glass parts with a water and aging resistant kit or glue, the seams and / or joints are protected against the ingress of moisture and dirt (Gatsiou, 2018)

To clean the glass surface from dirt with only rainwater and without the necessary extra cleaning, a hydrophilic coating can be applied to the surface. This must then be repeated every 10 years (Gatsiou, 2018).

2.3.7 Conclusion

Glass can be used as a construction material, but it has a number of properties as standard that are not entirely suitable for a construction material. The three primary methods for reinforcing glass are chemical treatment, thermal treatment and lamination of glass.

Flat panes of glass can be (double) curved. There are different techniques of bending flat panes of glass; cold bending and hot bending. Glass producers should be consulted about which dimensions of curved glass are possible: these depend on the production furnaces available but also the shape (Schittich et al., 2007).

To be able to build with glass, connections are needed between the various glass components. There are three options for connecting glass components to each other; bolted connections, adhesive connections and dry assembly connections (Santarsiero et al., 2016).

Because glass is not yet a standardized construction material, there are no extensive design codes or independent control elements for glass as construction material. One of the most commonly used methods for designing with glass is the method for limit state design (Connor, 2011). There are two main goals when designing a safe structure of glass; a great residual loadbearing capacity and redundancy (Weller et al., 2009). The Dutch code NEN 2608 has included the Fine & Kinney method to classify risks.

2.4 Dome structures

To arrive at the desired shape of a dome, it must first be understood what a dome is and how its structure works. This chapter discusses shell structures, domes and the force acting in domes. In addition, only examples will be shown.

2.4.1 Shell structures

A shell structure is a structure where the surface can bear the loads, because the surface is shaped and supported in a certain way. So only the surface of the structure, the shell, is load bearing (Flügge, 1973). The thickness of the shell does not really matter, because the stiffness of the structure is determined by the shape of the surface and the support conditions. The construction remains intact, because the stiffness of the surface is greater than the bending stiffness. The thickness of the surface depends on the buckling behavior of the shape and on the bending moments, usually at the support points. If a shell structure is efficiently designed, it can span 500 to 1500 times the thickness of the surface. This can be achieved because the inherent weight of the thin structure is low. The force flow of the structure is virtually impossible to calculate by hand. Here, FE analysis tools provide help to calculate and analyze the structural response of a shell structure (Bagger, 2010).

A shell structure can be built in various ways. Figures 30 and 31 show concrete shell structures, the surface consisting of a completely smooth surface. When building such a type of structure, careful consideration must be given to how it should be built, since it is one large surface.

Figure 30: Deitingen Raststätte, Deitingen, Switzerland, by Heinz Isler (Bagger, 2010, p. 2)

Figure 31: Los Manantiales Restaurant, Mexico City, by Félix Candela (Bagger, 2010, p. 2)

Another way to build a shell structure is to build it from various separate components. Figures 32 and 33 show shell structures that are made up of loose flat triangles. It must be said that the glass only serves as a covering material and the steel structure carries the load.

Figure 32: Great court at British Museum, by Foster and Partners (Bagger, 2010, p. 2)

Figure 33: BG Bank courtyard, Berlin, by Frank Gehry (Bagger, 2010, p. 2)

Dome structures

A dome structure, or a cupula structure, is a form of shell structures. One of the oldest and best-known dome techniques is the igloo (Janssens, 2018). The Geodesic Dome, see figure 34, is a good example of a strong, light and competent building structure. This project from 1951 led to major changes in dome designs. This spherical surface is made up of many triangular surfaces (Prenis, 1973).

Figure 34: Geodesic dome from Buckminster Fuller (Wikipedia, 2020)

2.4.2 Force acting in domes

A dome shape can be described as an arch or vault and can take various forms. The structural performance of such a structure can be assessed with the help of the Hooke hanging chain. An inverted hanging flexible chain presents a stiff arc, the principle of then the hanging chain of Hooke, see figure 35 (Heyman, 1995).

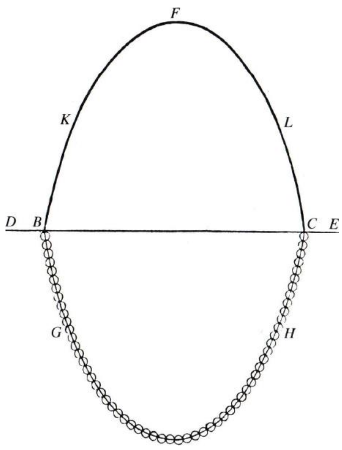


Figure 35: Hooke's hanging chain (Heyman, 1995)

The dome structure must withstand its own weight and other external loads by its internal forces; membrane forces. In the membrane theory it is described that the thickness of a surface is small compared to the rise and span of the entire dome. As previously described, the shape of the dome can be described as an inverted chain; arch, but the force within an arch and a dome is different. The dome structure must be able to accept a wider range of loads without changing its shape. The loads must be resisted by the membrane forces. The inverted chain represents the thrust. This applies to both the arc and dome. The structure is stable if the thrust remains in the material, see figure 36. In addition, no tensile stresses will occur if the trust line remains within the middle third of the cross-section (Heyman, 1995).

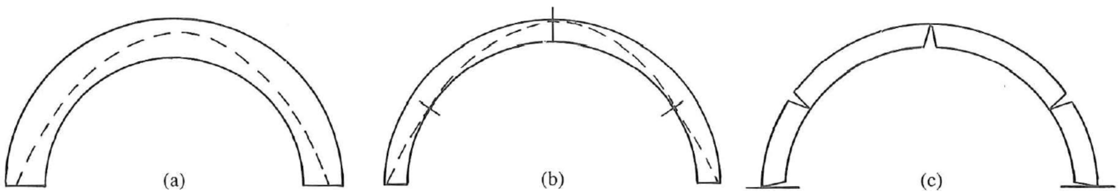


Figure 36: The semicircular arch (a) stable and (b),(c) of minimum thickness (Heyman, 1995)

The compressive stress in a dome can be calculated using formula 1 (Heyman, 1995).

$$\sigma(2 \cdot \pi \cdot a \cdot t) = \rho(4 \cdot \pi \cdot a \cdot t) \text{ or } \sigma = \rho \cdot a \qquad (1)$$

a: radius
t: thickness cross section
$2\pi at$: area of the diametrical ring
$4\pi at$: volume of the dome
σ: supporting stress / distributed compressive stress
ρ: unit weight

Stress resultants are used in the membrane theory of domes instead of stresses (σ), where $N = \sigma \cdot t$. Self-weight (w) loads are defined per unit area, where $w = \rho \cdot t$. Substitution leads to the new equation 2:

$$N = w \cdot a \qquad (2)$$

2.4.3 Glass dome structures

Interesting realized glass dome references are discussed below in chronological order by year of manufacture: (Wurm, 2007)

- *Spherical homogeneous shell structure, Glasstec, 1998*

  The spherical homogeneous shell structure supported by steel, see figure 37, is a dome structure with a steel circumferential ring. The dome is less transparent due to the steel construction, made up of 27 different triangular components. There are 282 laminated glass panels in this steel structure, with a total thickness of 20 mm. There are steel cables under each panel to enable permanent compressive strength.

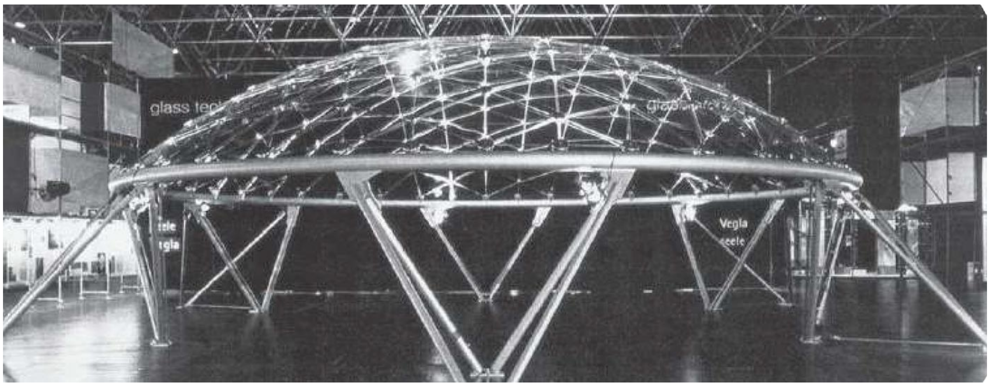


Figure 37: Multi-faceted steel and glass shell (Wurm, 2007)

- *Delft glass dome, 2002-2004*

  This transparent glass dome with its 5-meter wingspan, thanks to its integrated connections, is a prototype of an original with a 25-meter span glass dome. It is an annular dome with an open top, consisting of rings, 16 meridians and 4 different types of plate elements. Because of the rings and meridians, the dome is a completely compressive structure.

  The glass panels are connected with two types of connections; mechanical and bonded connections. Only linear connections have been used to safeguard the evenly distributed forces on the edges of the joints. To handle tolerances in the meridian direction, the stress equalization is ensured by using a PUR resin that bonded the connections.

Figure 38: The all-glass dome outside of the former Bouwkunde building (Eekhouts, Staaks, 2010)

- *Stuttgart glass shell, 2002*

  This, in 2002 built and larger in 2003, spherical dome prototype, see Figure 39, consists of 4 identical curved laminated glass panels and has a span of 8,5 m. These glass panels has a total thickness of 10 mm and consists of float glass and chemically reinforced glass. There is a very high transparency since a minimal construction has been applied, because it uses 10 mm epoxy butt joints. It is therefore difficult to replace broken panels.

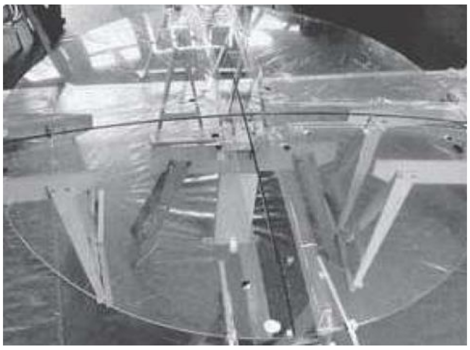


Figure 39: Prototype Glasstec 2002 (Wurm, 2007)

- *Glasstex dome, 2003*

  This glass dome has a span of 8.5 m. The spherical dish consists of 5 rings, 20 meridians and 5 different types of trapezoidal panels, see figure 40. The top is open. The 10 mm thick panels are made up of 2 layers; 8 mm float glass and 2 mm chemically reinforced glass. The ultimate slenderness and transparency is achieved by connecting the panels with a glued butt joint, with a width of 10 mm. Determined by FE analysis the maximum stress in the adhesive is 0.6 N/mm^2 (Bagger, 2010). The correct position of the glass, bearing capacity and the prevention of damage is realized because the bent edges of the glass are screwed against aluminum profiles. These are attached to the ring elements, an extruded continuous profile along the meridians. This whole provides a fully compressive structure.

Figure 40: Fully glaze dome on the experimental site at ILEK (Emami, 2013, p. 6)

2.4.4 Conclusion

A shell structure is a structure where the surface can bear the loads, because the surface is shaped and supported in a certain way. So only the surface of the structure, the shell, is load bearing (Flügge, 1973). A shell structure can be built in as a completely smooth surface or built from various separate components.

A dome structure, or a cupula structure, is a form of shell structures. A dome shape can be described as an arch or vault and can take various forms. The structural performance of such a structure can be assessed with the help of the Hooke hanging chain (Heyman, 1995). The dome structure must withstand its own weight and other external loads by its internal forces. The inverted chain represents the thrust. The structure is stable if the thrust remains in the material (Heyman, 1995).

A good example of a glass dome is Glasstex dome in Stuttgard. This glass dome has a span of 8.5 m. The 10 mm thick panels are made up of 2 layers. The ultimate slenderness and transparency are achieved by connecting the panels with a glued butt joint, with a width of 10 mm. Determined by FE analysis the maximum stress in the adhesive is 0.6 N/mm2 (Bagger, 2010).

2.5 Thermal performance

Thermal comfort is an important aspect in buildings. This is certainly the case in a glass dome with restaurant functions, where guests stay for a longer period of time. It is one of the aspects that makes guests feel comfortable or not. Thermal comfort is discussed in this chapter. What steps must be taken to achieve thermal comfort?

2.5.1 Thermal comfort

Because the thermal comfort is different for everyone, it is difficult to define it properly. The combination of different factors plays a role in thermal comfort, namely (ASHRAE Standard 55, 2010):

- air temperature
- mean radiant temperature
- air velocity
- humidity
- clothing
- metabolic rate

With the perception of the combination of these terms, the following definition may possibly be given to thermal comfort:

"that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation." (ASHRAE Standard 55, 2010, p.3)

To realize thermal comfort for people, it is important where these people are located and who or what must take care of realizing it. Therefore, a distinction can be made between three different "layers" (Nakano, & Tanabe, 2004):

- *Indoor*
  With the inner layer is meant the indoor environment where the heating, ventilation and / or cooling (HVAC systems) provide the thermal comfort. To create a higher quality and efficiency of the environmental control, the inner layer can be further divided into:
    - Occupied zone
    - Personal task zone
- *Outdoor*
  The outer layer means the outside environment where there are no environmental regulations. People need to take adaptive actions to get thermal comfort.
- *Semi outdoor*
  The layer between the inner layer and the outer layer means semi-outer environment. This environment acts as a (thermal) buffer space during the transition from the indoor environment to the outdoor environment, or vice versa, to the step change, change of a thermal environment. This "transition phase" can be divided into two types of phases:
    - Processing phase
    - Short occupation phase (for a period of less than an hour)

The thermal control in this layer therefore depends on the use. The thermal comfort criteria of the semi-outdoor environment must therefore be investigated for this specific function.

2.5.2 Thermal indoor climate requirements

Guidelines for the thermal indoor climate are laid down in the Dutch NEN-EN-ISO 7730. These requirements are a minimum that must in any case be met. The requirements will therefore be higher to achieve higher quality of thermal indoor climate. To achieve this higher quality, three classes / categories have been established (Boerstra, Coffeng, van der Minne, & Scheers, 2008):

- *Category A: 'very good'*
  High expectations regarding the quality of the indoor environment; report grade approx. 8.5.
- *Category B: 'good':*
  Average expectations regarding the quality of the indoor environment; report mark approx. 7.
- *Category C: 'acceptable'*
  Moderate expectations with regard to the quality of the indoor environment, at least necessary from the point of view of public health and ca level of the statutory minimum for new buildings; report grade approx. 5.5.

Below is a list of the (average) requirements for category A for various aspects of the thermal indoor climate that apply to the room type restaurant that come from NEN-EN-ISO 7726. In some aspects, a distinction is made between summer and winter. For the summer a heat resistance of the clothing (clo) of 0.5 is used and in a winter 1.0.

- *Operative temperature*
  For category A, the operative temperature in summer must be between 23 °C and 26 °C and in winter between 20 °C and 24 °C, both with the possibility of individually influencing the temperature . In both cases, without the possibility of individually influencing the temperature, they belong to category B.

  These maximum (and minimum) temperatures depend on a weighted average outdoor temperature over the previous 5 days, with yesterday weighing heavier than the day before yesterday, etc.

  The ISSO / SBR publication specifies the limit values of the weighing hours for computer simulations (summer comfort). The maximum number of weighing hours in category A is 100 hours (Boerstra et al., 2008).
- *Maximum mean air velocity*
  For category A, the maximum mean air velocity should be 0.12 m/s in summer and 0.10 m/s in winter. These maximum mean air velocities are based on a turbulence intensity of 40% and air temperature equal to the operative temperature. Figure 41 shows for each category the graph from which these maximum mean are derived, where:

  $t_{a,l}$ local air temperature, °C
  $v_{a,l}$ local mean air velocity, m/s
  T_u turbulence intensity, %

  On hot summer days, when the air temperature is considerably higher, it can be deduced from these graphs the maximum air speed may be considerably higher.

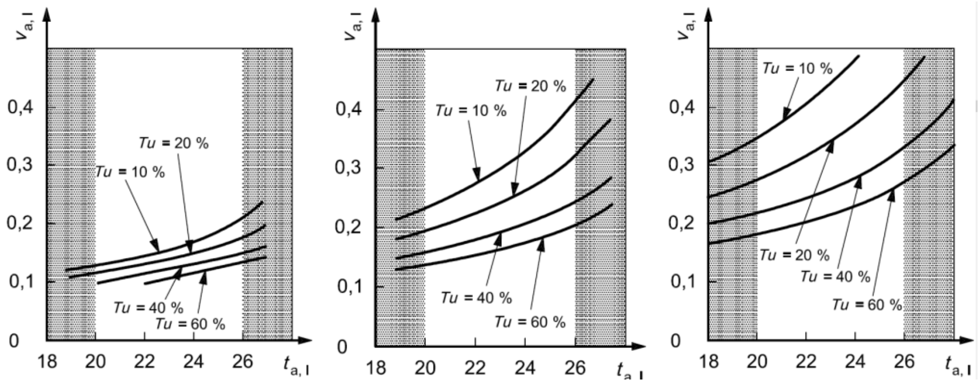


Figure 41: Max. allowable mean air velocity as function of local air temperature and turbulence intensity (left: category A, middle: category B, right: category C) (NEN-EN-ISO 7730, 2005, p. 16)

- *Vertical difference in air temperature*

  The vertical difference in air temperature between the head and ankles (1.1 and 0.1 m above the floor) must be less than 2 °C for Category A.

- *Radiation temperature asymmetry*

  For the maximum radiation temperature asymmetry, a distinction is made between 4 types of surfaces:

  - For a warm ceiling in category A, the radiation temperature asymmetry must be less than 5 °C.
  - For a cold wall (glass) in category A, the radiation temperature asymmetry must be less than 10 °C.
  - For a cold ceiling in category A, the radiation temperature asymmetry must be less than 14 °C.
  - For a warm wall in category A, the radiation temperature asymmetry must be less than 23 °C.

- *Floor temperature*

  For category A, the floor temperature must be between 19 °C and 26 °C.

When interpreting and applying these requirements, it is especially important to use common sense. Not all requirements are measurable and should therefore be used as a guideline. In some cases, some requirements are not realistic, since they are theoretical values, in practice it can turn out differently.

2.5.3 Thermal comfort steps

There are seven important steps to create thermal comfort. These different steps are listed below. Ultimately, these steps must be taken in relation to the design (Regnier, 2012).

1. *Defining the thermal environment*

   In section 2.3.2 Thermal comfort, there has been talked about the realization of thermal comfort by determining the location of the people and who or what must take care of realizing thermal comfort. A distinction could be made between three different layers, or the definition of the thermal environment.

2. *Select weather and wind data*

   The local weather plays an important factor to realize thermal comfort. Every specific location has different weather conditions and therefore different measures must be taken to realize the thermal comfort.

3. *Select thermal comfort standard*
   There are different ways and models to determine the thermal comfort. Because of this, every authority or country can have its own standards, which influences the final design.

4. *Define conditioning systems*
   The best way would be to use passive energy to be minimally invasive for the local environment in this way. In some cases it is not possible to passively obtain the entire thermal comfort design.

5. *Determine environmental comfort conditions*
   There are cases where the environmental comfort conditions are fixed, but in some cases certain values are open for the specific functions. In those cases, personal preferences are important, together with the use of common sense.

6. *Determine occupant control standard*
   Depending on the function, it is determined who has to take care how the thermal comfort is regulated. This can be arranged centrally, but also locally. Since the thermal comfort differs for everyone, a decision must be made as to who controls what and when and with what values.

7. *Determine number of exceeding hours*
   The number of exceeding hours includes the performance of the conditioning systems.

2.5.4 Thermal comfort models

There are many different thermal comfort models to predict the degree of satisfaction of users / visitors for a specific thermal environment. In the Dutch standard NEN-EN16798-1 (the former Dutch standard NEN-EN 15251) and Dutch practice guideline NPR-CEN / TR 16798-2 indoor environmental input parameters for design and assessment of energy performance or buildings addressing indoor air quality, thermal environment, lighting and acoustics. This standard uses data from five European countries obtained from the ASHRAE 55 standard, which collected data from 30 different buildings from different countries, using uniform experimental measurements and instruments. The adaptive model from ASHRAE, introduced in 1986, is an adaptive model that results in comfort temperature. This adaptive model has been proposed to interpret thermal comfort for, for example, free running buildings (Nicol, Humphreys, & Roaf, 2012).

2.5.5 Conclusions

The (average) guidelines of category A for various aspects of the thermal indoor climate that apply to the room type restaurant, the new function of Het Kruithuisje, are: the operative temperature in summer must be between 23 °C and 26 °C and in winter between 20 °C and 24 °C, the maximum mean air velocity should be 0.12 m/s in summer and 0.10 m/s in winter, the vertical difference in air temperature between the head and ankles must be less than 2 °C, for a warm ceiling the radiation temperature asymmetry must be less than 5 °C, for a cold wall (glass) the radiation temperature asymmetry must be less than 10 °C, for a cold ceiling the radiation temperature asymmetry must be less than 14 °C, for a warm wall in the radiation temperature asymmetry must be less than 23 °C and the floor temperature must be between 19 °C and 26 °C.

2.6 Passive strategies

The aim of this research is to achieve thermal comfort in the most passive way as possible. It is important to know what passive strategies are and which means can be used for this.

2.6.1 What are passive strategies?

Mechanical systems (active systems) can be used to create a comfortable indoor environment. These active systems have a high energy consumption. The 2010 guideline for (Near to) Zero Energy Buildings ((Near to) ZEB) describes that (new) buildings with a high energy performance must achieve an energy demand from very low to zero, by using renewable, preferably locally, sources. Different conditions are described about energy-neutral buildings. An important condition is to reduce energy consumption and improve system efficiency in buildings by initially identifying the need for thermal comfort (Rodriguez-Ubinas et al., 2014). In order to reduce the high energy consumption of the mechanical systems, passive design strategies (passive systems) must be sought by mapping out the (local) available natural resources.

Passive strategies (and hybrid solutions) make use of local climate conditions, such as wind, solar radiation, daylight, ground temperature, clear skies and thermal variance. Therefore, passive strategies do not require external energy. The ZEB approach provides ways to achieve (Near to) Zero Energy Buildings by using passive strategies, which essentially means reducing the cooling and heat load (Rodriguez-Ubinas et al., 2014). Examples of passive strategies (and hybrid solutions) are shown in figure 42.

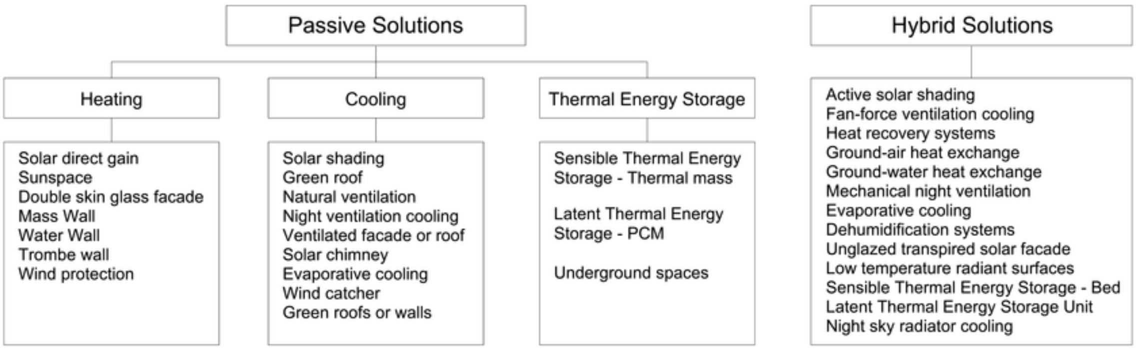


Figure 42: Possible passive and hybrid solutions (Rodriguez-Ubinas et al., 2014, p. 13).

2.6.2 Thermal mass

The capacity of a material to absorb, store and release heat is called thermal mass (Tuohy, McElroy, & Johnstone, 2004). Large amounts of thermal mass, large temperature differences (day and night, summer and winter) and the correct location are required to use thermal mass as a passive design strategy. Applying it correctly can be positive for energy savings. The dominant (mean) temperature is stored and releases as a constant temperature (Tuohy et al., 2004). In summer this would mean that the thermal mass has a cooling effect and the winter a warming effect, which leads to an increased thermal comfort.

Every (building) material has a thermal conductivity. Table 5 shows various (building) materials with the associated thermal conductivity. The higher this value, the density and the specific heat, the greater thermal mass effect can be achieved. Heavy and solid materials absorb and store larger amounts of temperatures (Tuohy et al., 2004). Since every (building) material has a specific heat, every material in a building already contributes to this effect. To really notice it, the specific heat value is important (dense and heavy), but also the execution (quantity, size and thickness).

Table 5: *Thermal conductivity (building) materials* (The Engineering ToolBox, n.d.)

Material	Thermal conductivity (W/m·K)
Concrete	0.75
Brick (common)	0.9
Glass	0.84
Soil (dry)	0.8
Water (20°C)	0.6

2.6.3 Natural ventilation

Ventilation is necessary to remove bad particles, heat and moisture and to add oxygen (Bokel, 2018). Openings in the building are required to ventilate. A passive way of ventilation is by using natural ventilation. Natural ventilation can be created by having / getting an air pressure difference. An air pressure difference can be created by temperature differences (Bokel, 2018).

Natural ventilation due to temperature differences is called stack ventilation (stack effect); the stack effect creates convection streams driven by temperature differences. To create the effect, openings (inlets and outlets of air) are needed at different heights.

To calculate the air pressure difference created, use can be made of formula 3 (Bokel, 2018).

$$(\Delta P)(h) = \frac{ghP_{0,0}}{R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right) \approx \rho g h \frac{\Delta T}{T} \qquad (3)$$

ΔP : Air pressure difference (Pa)

g : The gravitational or fall acceleration on the earth's surface. In the Netherlands it averages $9.81\ m/s^2$

h : Height difference openings (m)

$P_{0,0}$: The mean air pressure at sea level: $101{,}325\ Pa$

R : The gas constant of air: $287\ J/kg \cdot K$

T : Air temperatures (K)

ρ : The density of dry air at sea level: $1.293\ kg/m^3$

To calculate how much can be ventilated with this created air pressure difference can be calculated with formula 4 (Bokel, 2018).

$$Q = C_d \cdot A_{eff} \cdot \sqrt{\frac{2 \cdot \Delta P}{\rho}} \qquad (4)$$

Q : Amount of ventilation (m^3/s)

C_d : Discharge coefficient, consider as a constant value of ~ 0.8

A_{eff} : Effective cross sections, calculated by using formula 5

$$\frac{1}{{A_{eff}}^2} = \frac{1}{A_1^2} + \frac{1}{A_2^2} \quad (5)$$

$A_{1,2}$: Opening sizes (m^2)

When determining the sizes of the openings it is important to take into account the air speed of the air through this opening. This air speed will be felt immediately at this opening. The air will spread over space and the airspeed will decrease. The Beaufort scale indicates which air speed belongs to which wind force. The air speed through the openings will probably have to be between wind force 2 and 3. Wind force 2 is characterized as weak. The air speed is between 1.6 and 3.3 m/s. The wind can be felt in the face. Wind force 3 is characterized as moderate. The air speed is between 3.4 and 5.4 m/s. The wind will blow up dust and flutter flags.

2.6.4 Low-E coatings

One of the important ways heat transfer occurs with windows is radiant energy. All materials, including windows, radiates heat, depending on the emissivity, in the form of long wave infrared energy. Emissivity is the relative ability of a material surface to radiate energy. In general highly reflective materials have a low emissivity and darker colored materials have a high emissivity. A solution to improve the glass performance and insulating properties is reducing the emissivity of the glass. To minimize the amount of ultraviolet and infrared light that can pass through glass, Low-E coatings have been developed. For example uncoated glass has an emissivity of 0.84, while low-E coated glass can reach an emissivity of 0.02. Low-E coating is a microscopically thin transparent coating reflects long wave infrared energy (or heat). In the summer when the sun tries to heat the interior the Low-E coating reflects the heat back outside and in the winter vice versa. An advantage of Low-E coatings is it does not compromise the amount of visible light that is transmitted. To perform even better, several layers of this microscopically thin coating can be applied (Vitro Architectural Glass, 2018).

There are two different types of manufacturing processes to apply the Low-E coating to the glass, which leads to two kinds of Low-E coatings (Vitro Architectural Glass, 2018):

- *Passive Low-E coating - pyrolytic, or “hard coat”*
  Most passive Low-E coatings are manufactured using the pyrolytic process. The coating is applied to the glass ribbon while it is being produced on the float line. The coating then fuses to the hot glass surface; creating a strong bond or a hard coat that is durable during fabrication. Finally the glass is cut into stock sheets of various sizes for shipment to fabricators. Passive Low-E coatings are good for very cold climates, because they allow some of the sun’s shortwave infrared, to pass through and help heat the building during the winter, but still reflect the interior long wave infrared back inside.

- *Solar control Low-E coating - Magnetron Sputter Vacuum Deposition (MSVD), or “soft coat”*
  Most solar control low-E coating are manufactured using the MSBD process: The coating is applied offline to pre-cut glass in a vacuum chamber at room temperature. This coating needs to be sealed in an insulated glazing of laminated unit and has lower emissivity and superior solar control. The best performing solar control coatings are MSVD and they are ideal for mild to hot climates, that are dominated by air conditioning use.

To measure the effectiveness of glass with a Low-E coating and to choose between the different types of Low-E coating, the following values are important (Vitro Architectural Glass, 2018):

- *U-Value* is the rating given to a window based on how much heat loss it allows.
- *Visible Light Transmittance* is a measure of how much light passes through a window.

- *Solar Heat Gain Coefficient* is the fraction of incident solar radiation admitted through a window. The lower a window's solar heat gain coefficient, the less solar heat it transmits.
- *Light to Solar Gain* is the ratio between the window's Solar Heat Gain Coefficient and its visible light transmittance rating.

Low-E coatings can be applied to the various surfaces of a glass unit. In standard insulated double glazing there are four potential surfaces where the coating can be applied (Vitro Architectural Glass, 2018):

- The surface faces outdoors (1) never has a coating, because of its exposure to the outside elements.
- The two surfaces face each other inside (2, 3) the insulating glazing, which are separated by an insulating airspace.
- The surface faces directly indoors (4).

The best surfaces for the passive Low-E coating are the surfaces which are the furthest away from the sun, so surface 3 and 4. The best surface for solar control Low-E coating is the surface that is the closest to the, so the surface number 2 (Vitro Architectural Glass, 2018).

2.6.5 Fritted glass

Another (passive solution), which does affect transparency but with respect to the glass, is fritting of the glass (enameled glass). This can reduce the large amount of solar gain. Fritted glass gives the glass a UV shield and makes the sunlight diffuse. By firing an enamel image into the surface of glass during the curing process, different patterns in (possibly) different colors are created on the glass surface, digital ceramic printing (Oikonomopoulou, 2012).

The different patterns that can be created with this can give a playful shadow effect in the design. For architects, this is a different kind of design tool in terms of shape and visible texture of the facade for their design. Figure 43 shows an applied example of fritted glass.

Figure 43: Inssbruck's Town Hall (Oikonomopouloi, 2012, p.76)

2.6.6 Switchable glass

Switchable glass (smart glass) is glass whose light transmission properties (transparency) can be changed, from transparent to translucent and vice versa, to transmit or block certain wavelengths of light. Switchable glass can be used to reduce glare, solar heat gain and UV exposure (Baetens, Jelle, & Gustavsen, 2010). It can therefore be used as an alternative to sun shading equipment. An advantage of switchable glass is that the transparency for heat radiation can be varied. A disadvantage is that a voltage is required to achieve the desired effect. There are different types of switchable glazing:

- *Suspended particle devices (SPDs)*
  SPD uses a thin layer of foil with a liquid where nanoparticles are suspended. These nanoparticles float (arbitrary location) through the liquid, so that they absorb and block light. When a voltage is applied to the liquid, the particles move in a certain orientation and allow light to pass through. By varying the voltage, the amount of transmitted light can also be varied and the tint of the glass is also determined (Santamouris, 2007).

- *Electrochromic*
  An electrochromic coating is placed in laminated glass. When voltage is applied to the coating, the coating is activated and it will darken. In idle state, without tension, the glass will be transparent. In order to "activate" the glass, it is only necessary to apply voltage to the coating once. The glass will then slowly become transparent again. To maintain the sun protection effect, voltage must be applied again for a certain time. The effect of this coating has a slow effect, so it can take a few minutes before the desired effect is achieved (Santamouris, 2007).

- *Polymer-dispersed liquid crystal (PDLC)*
  PDLC is a liquid polymer in which liquid crystals are processed in a foil. Without tension, the liquid crystals will be arranged randomly, giving the glass a translucent white surface. When tension is applied to the foil, the liquid crystals will be arranged in order, making the glass transparent again (Santamouris, 2007).

- *Micro-blinds*
  Micro-blinds are very small rolled thin metal strips, which are invisible to the eye. These micro-blinds control the amount of light passing through the surface by applying a voltage. By varying the voltage, these micro-blinds will roll up or roll out, and so let light through or block light. Without a voltage the metal strips are rolled and let the light through. The opposite effect is achieved by applying a voltage to it (Lamontagne, Barrios, Py, & Nikumb, 2009).

2.6.7 Case studies

Example case study projects where a lot of glass is used, where mainly passive strategies are applied are:

- *European Patent Office, Rijswijk, 2019, Jean Nouvel and Dam & Partners Architecten*
  The EPO building in Rijswijk, the Netherlands, is an iconic mirage in the area, see figure 44. This project uses a double skin facade, which gives the iconic appearance, protects the work spaces from noise pollution, creates a thermal buffer and the light remains excellent.

  Iron-poor single glass is used for the second skin, to achieve high transparency. A COOL-LIGHT ST BRIGHT SILVER coating on the glass reflected the environment. This coating has sun protection properties, but also a high light penetration of almost 70%. For the 1st facade, the thermal shell, thermally insulating, solar heat-resistant glazing was used.

Figure 44: The European Patent Office (Glassolutions, n.d.)

- *Greenhouse houses, Culemborg, 2009, KWSA Karssenberg Wienberg Samenwerkende Architecten*

  A greenhouse house consists of two temperature zones: one in the heavy construction and one in the greenhouse section, see figure 45. The house itself consists of the usual furnishings. In the greenhouse, the temperature fluctuates between 15°C and 25°C.

  The greenhouse has an insulating effect on cold days; as soon as the sun shines, the greenhouse heats up space. On average it is 30 days above 20°C in the greenhouse section. In summer, part of the facade of the greenhouse and part of the roof of the greenhouse can be opened. The warm air is then diverted by a convection current and cooler in the greenhouse.

Figure 45: Greenhouse house (Frissewind, 2016)

2.6.8 Conclusions

In order to reduce the high energy consumption of the mechanical systems, passive design strategies (passive systems) must be sought by mapping out the (local) available natural resources. Passive strategies (and hybrid solutions) make use of local climate conditions, such as wind, solar radiation, daylight, ground temperature, clear skies and thermal variance. Therefore, passive strategies do not require external energy (Rodriguez-Ubinas et al., 2014).

Passive strategies that can be used in a glass construction are:

- Thermal mass is the capacity of a material to absorb, store and release heat (Tuohy, McElroy, & Johnstone, 2004). The higher this value, density and the specific heat, the greater thermal mass effect can be achieved. Heavy and solid materials absorb and store larger amounts of temperatures (Tuohy et al., 2004).
- Natural ventilation is a passive way of ventilation. Ventilation is necessary to remove bad particles, heat and moisture and to add oxygen (Bokel, 2018). Natural ventilation can be created by having / getting an air pressure difference. An air pressure difference can be created by temperature differences (Bokel, 2018).
- Low-E coatings are a solution to improve the window performance and insulating properties to reducing the emissivity of the window. Emissivity is the relative ability of a material surface to radiate energy. In general highly reflective materials have a low emissivity and darker colored materials have a high emissivity. For example uncoated glass has an emissivity of 0.84, while low-E coated glass can reach an emissivity of 0.02 (Vitro Architectural Glass, 2018). There are two kinds of Low-E coatings: passive Low-E coating and solar control Low-E coating.
- Fritting of glass can reduce a large amount of solar gain. It does affect transparency but with respect to the glass (Oikonomopoulou, 2012). The different patterns that can be created with this can give a playful shadow effect in the design.

- Switchable glass (smart glass) is glass whose light transmission properties (transparency) can be changed, from transparent to translucent and vice versa, to transmit or block certain wavelengths of light. Switchable glass can be used to reduce glare, solar heat gain and UV exposure (Baetens, Jelle, & Gustavsen, 2010). An advantage of switchable glass is that the transparency for heat radiation can be varied. A disadvantage is that a voltage is required to achieve the desired effect.

2.7 Conclusions

2.7.1 Literature study conclusions

From the entire literature study and the studied case studies, main conclusions, the design criteria, can be formulated for the glass structure and thermal comfort.

Glass structure

A dome structure, or a cupula structure, is a form of shell structures. A shell structure is a structure where the surface can bear the loads, because the surface is shaped and supported in a certain way (Flügge, 1973). The structural performance of such a structure can be assessed with the help of the Hooke hanging chain (Heyman, 1995). A shell structure can be built in as a completely smooth surface or built from various separate components. A good example of a glass dome is Glasstex dome in Stuttgard.

Glass can handle a high tensile strength. Glass is an isotropic material that deforms in a linear elastic way (Fröling, 2013). If the mechanical properties of glass are compared with other known building materials, glass is stiffer, stronger in tension and less brittle. There are many different types of glass, each with different chemical and physical properties. The most commonly used groups of glass in the built environment are: soda lime glass, borosilicate glass. There are different manufacturing processes of glass. The most common production method is the production of float glass.

Because glass is not yet a standardized construction material, there are no extensive design codes or independent control elements for glass as construction material. One of the most commonly used methods for designing with glass is the method for limit state design (Connor, 2011). Glass can be used as a construction material, but it has a number of properties as standard that are not entirely suitable for a construction material. The three primary methods for reinforcing glass are chemical treatment, thermal treatment and lamination of glass. Flat panes of glass can be (double) curved. To be able to build with glass, connections are needed between the various glass components. There are three options for connecting glass components to each other; bolted connections, adhesive connections and dry assembly connections (Santarsiero et al., 2016).

Thermal performance

Because the thermal comfort is different for everyone, it is difficult to define thermal comfort properly. The combination of different factors plays a role (ASHRAE Standard 55, 2010). Guidelines for the thermal indoor climate are laid down in the Dutch NEN-EN-ISO 7730. There are seven important steps to create thermal comfort (Regnier, 2012). There are many different models to predict the degree of satisfaction of users / visitors for a specific thermal environment. The Dutch standards use data from five European countries obtained from the ASHRAE 55 standard (Nicol, Humphreys, & Roaf, 2012).

In order to reduce the high energy consumption of the mechanical systems, passive design strategies (passive systems) must be sought by mapping out the (local) available of natural resources. Passive strategies (and hybrid solutions) make use of local climate conditions. Therefore, passive strategies do not require external energy (Rodriguez-Ubinas et al., 2014).

2.7.2 Design criteria

Glass structure

- *Shape*

  To get the shape of a cheese bell, a spherical double-curved surface is required. A dome structure should make this possible.

- *Glass type*

  Two types of glass are possible to build the glass structure: soda lime glass and borosilicate glass. Since the glass in the structure is not exposed to extremely high temperatures, soda lime glass is sufficient. This is a cheaper alternative and costs less energy to produce as it has a lower processing temperature.

- *Production method*

  To give the glass a high optical quality float glass is a good production method. This most common production method and is a relatively cheap method.

- *Plate type*

  To build this entire construction, the shape must be divided into panels. To approximate the dome shape hot bended double curved panels will be used.

- *Strengthening method*

  To make glass safer, to give glass a greater bearing capacity, it must be strengthened. To makes the glass better protected against temperature differences and mechanical shocks thermal treatment will be used as strengthening method. For safety reasons, the glass will consist of several layers. To increase the load-bearing capacity, strengthening by laminating is also used. The interlayer between the glass layers will be a SGP interlayer, to reduce the deflection of the panel, the panel will remain intact in the event that it fractures completely and the SGP material has a high transparency.

- *Connection type*

  To achieve high transparency and low peak voltages, a combination of adhesive connections and dry assembly connections can be used.

Thermal performance

The (average) requirements for category A for various aspects of the thermal indoor climate that apply to the room type restaurant are:

- *Operative temperature*

  The operative temperature in summer must be between 23 °C and 26 °C and in winter between 20 °C and 24 °C.

- *Maximum mean air velocity*

  The (average) maximum mean air velocity should be 0.12 m/s in summer and 0.10 m/s in winter. On hot summer days, when the air temperature is considerably higher, this value can be considerably higher.

- *Vertical difference in air temperature*

  The vertical difference in air temperature between the head and ankles must be less than 2 °C.

- *Radiation temperature asymmetry*
  - For a warm ceiling the radiation temperature asymmetry must be less than 5 °C.
  - For a cold wall (glass) the radiation temperature asymmetry must be less than 10 °C.

- For a cold ceiling the radiation temperature asymmetry must be less than 14 °C.
- For a warm wall in the radiation temperature asymmetry must be less than 23 °C.
- The floor temperature must be between 19 °C and 26 °C.

Seven important steps to create thermal comfort are defining the thermal environment, select weather and wind data, select thermal comfort standard, define conditioning systems, determine environmental comfort conditions, determine occupant control standard and determine number of exceeding hours.

Passive strategies that can be used in a glass construction are thermal mass, natural ventilation, low-E coatings, fritting of glass and switchable glass.

3 DESIGN

3 DESIGN

3.1 Introduction

The reason for this research was to make a design to cover Het Kruithuisje with a fully glass construction, a dome: a cheese bell. The building manager and his friend made a sketch design for this construction. This sketch design is shown in figure 46. The dome of this sketch design has a diameter of 21.2 meters and a height of 10.6 meters. Steel columns have been used to realize the shape. The wish is to have as less construction as possible, to make it a real huge cheese bell. This sketch design will form the basis for the design in this research.

Based on the literature study, design proposals are made in this chapter and alternatives are offered. In the next chapter, the various suggestions and alternatives are validated. These results will show which proposals can be included in the final design. Some of the results of the validation have already been included in this chapter in order to make further design suggestions. These two chapters are closely linked.

Figure 46: Sketch design (provided by: Hollenberg, 2019)

3.2 General design

The basis of the design is laid in the sketch design. It will be a dome structure with a diameter of 21.2 meters and a height of 10.6 meters and will be made entirely out of glass (except for any connections).

Different shapes are possible to get a dome. These options consist of two standard shapes: a paraboloid and a hemisphere. Because people will be entering the construction, as much free height as possible is required to get an efficient and useful floor area. The paraboloid and the hemisphere are both shapes with much free height. By deriving the correct formulas, the given dimensions can be achieved. Figure 47 provides an overview of this. The final choice will depend on the constructive behavior of the shapes. This analysis is done in the next chapter; Validation. The result of this is that the two forms do not differ much from each other. The hemisphere is therefore chosen, as it most closely approximates the shape of a cheese bell.

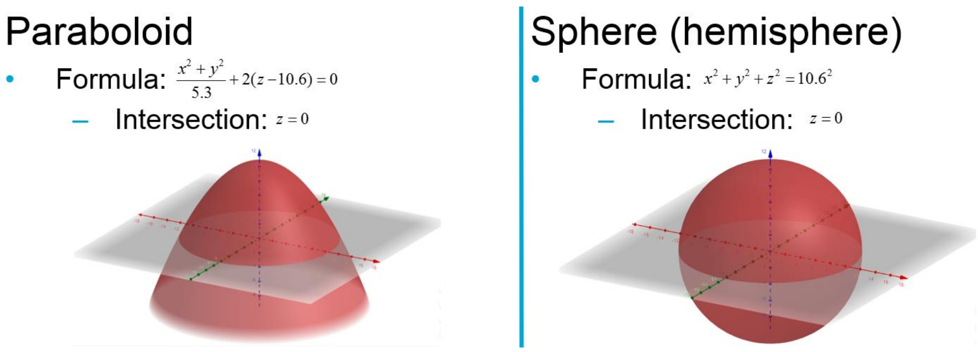


Figure 47: Shapes with derived formulas (own figure)

It is the intention that people can get into the construction. The construction must be interrupted. For a shell structure, this has consequences to the behavior. A solution is to lift the hemisphere. The height of the lifting has an effect on the horizontal forces, but also on the final design result. The less lifting height the better this is to reduce the horizontal forces. To still meet the requirements for diameter and height, it is no longer a complete hemisphere. This means that not all forces run vertically anymore, but also some horizontally. These lateral forces will push the structure apart. Since glass is stronger in pressure than tension, it is not possible to come up with a slim glass solution with this. A possible slim and simple idea which can be used as a compression ring is a steel rod. Since a rod is very good for absorbing tensile forces, this rod can be relatively thin. Further elaborations of this are discussed in the details. In figure 48, the difference is shown in the appearance of the effect of the lifting. The less lifted height, the smoother the shape will be. Therefore, work will continue with an elevated height of 2.5 meters. Figure 49 shows the correct derivative formula to maintain the required dimensions.

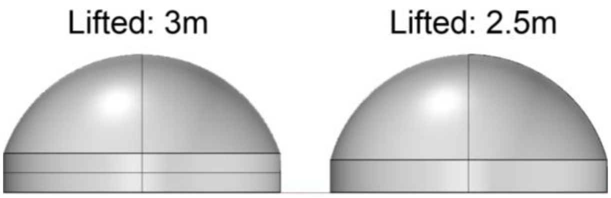


Figure 48: Difference in the appearance (own figure)

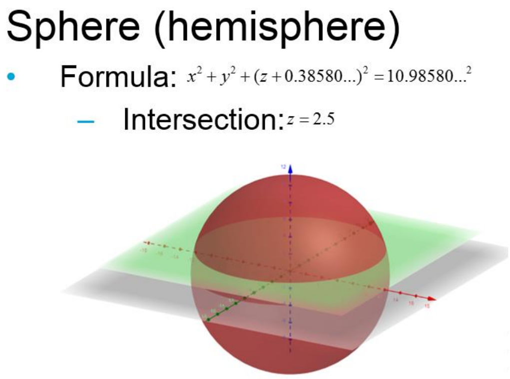


Figure 49: Derived formula new shape (own figure)

The general design can be divided into three parts. From now on, these parts will be further named in the report:

- *Dome*
  This includes the double curved surface of the structure. This is the part of the hemisphere.
- *Base*
  This is the part where the dome is on. This is the part that lifts the dome, so that openings can be made in the construction.
- *The connection between dome and base*
  This connection is necessary to absorb the horizontal forces and to connect the dome to the base. The detail is mainly important for this part.

Because there will be natural ventilation, openings are required in the construction. By making the height difference as large as possible between the inlet and the outlet openings, the largest possible air pressure difference can be created. The opening sizes and the air pressure difference determine the maximum amount of natural ventilation. Analysis must show how much natural ventilation is needed and how much can be created. On the base of this, hand calculations can be used to calculate the size of the openings for ventilation, the effective area of the openings.

3.3 Component design

To build this entire construction, the shape must be divided into panels. Because double curved panels will be used, the original shape of the hemisphere will be approximated as much as possible. When dividing the construction into panels, the maximum dimensions of the panels that the manufacturer can supply must be taken into account. As mentioned earlier, these maximum dimensions for thermally hardened double curved glass are 6500 by 3600 mm.

The floorplan of the entire construction is a circle with a radius of 10.6 meters. This means the floorplan has a circumference of 66.60 meters. Dividing the floorplan into 12 equal parts creates panels with a maximum width of 5.55 meters. The base of the structure has a height of 2.5 meters, which ensures there are 12 panels with the dimensions of 5.55 by 2.5 meters.

By using the same floorplan grid when dividing the dome, the dome can be divided into rings from 12 panels. Dividing the dome into the rings from the center of the sphere into parts of 14 degrees creates the cross section as shown in figure 50. By doing this, the size of the curvature of each ring, and so the curvature of each double curved panel, is the same.

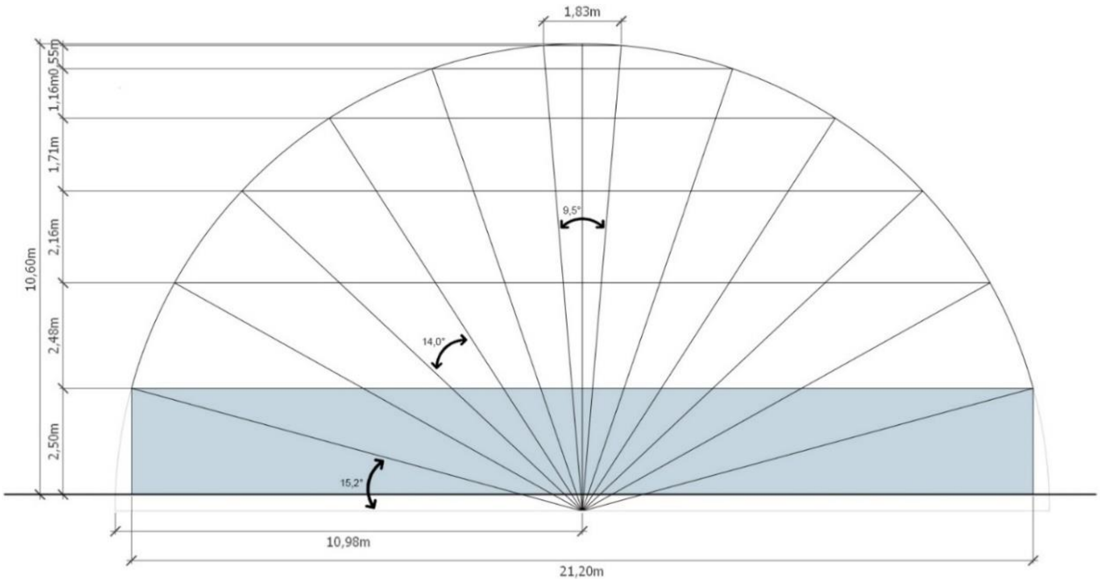


Figure 50: Vertical section dividing the rings form center point (own figure)

This produces the following result, see figure 51. A construction consisting of 60 panels divided into 6 rings. At the top of the dome, the panels become smaller. By joining multiple smaller panels, there are fewer connections, which provides a more transparent result and a stiffer construction. An opening remains at the top: an oculus. This can be used for natural ventilation. Table 6 shows the maximum sizes of all the panels of the whole structure.

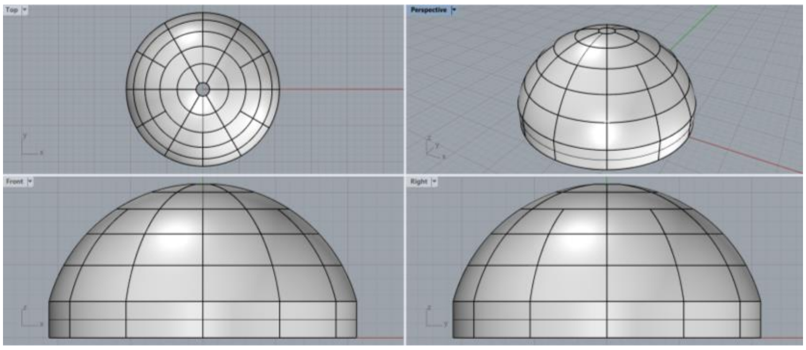


Figure 51: Shape divided in panels (own figure)

Table 6: *Maximum sizes panels* (own table)

Quantity:	Length (mm):	Width (mm):
12	5550	2500
12	5550	2684
12	5201	2684
12	4194	2684
6	6220	2684
6	3707	2684

The interlayer between the glass layers will be a SGP interlayer. The SGP interlayer is chosen for three reasons. The first reason is to reduce the deflection of the panel because this is a stiffer interlayer than PVB. The second reason is that the panel will remain intact in case it fractures, causing no harm to the people that are in the construction. The third reason is that the SGP material has a higher transparency. This contributes to the transparency of the construction.

Since most threats according to the risk analysis, see next chapter, come from the outside, it is wise to place the thinnest glass plate on the outside. If it is damaged, the thickest glass plate will still take the most forces. Due to the fracture pattern and the lamination, the broken glass plate will always be able to take forces.

A solution to improve the glass performance and insulating properties is reducing the emissivity of the glass by using coatings. Different types of glass and coatings from different manufacturers have specific values. Table 7 shows an overview of different types of glass with or without coating and the associated values, which can be applied and simulated for this project. These values come from DesignBuilder.

Table 7: *Properties different types of glass* (own table)

Type of glass		Light		Solar Energy		U value
Name	Coated	Transmittance	Reflectance	Direct Transmittance	Reflectance	$W/m^2 \cdot K$
Generic Clear 10mm	No	0.860	0.081	0.74	0.075	5.666
Generic Tinted 10mm	No	0.378	0.081	0.305	0.075	5.666
Optitherm SN 10mm	Yes	0.842	0.049	0.548	0.301	5.534
Suncool HP Silver 50/30 10mm	Yes	0.527	0.260	0.302	0.535	5.528

This table clearly shows the effect of tint and coating on the transparency, reflection and U value of the glass. Generic Clear glass has the highest transparency, but the lowest U value and the highest SHGC. Tinted glass reduces the SHGC greatly, but this expenses the transparency. Coated glass does not compromise on transparency, but reduces SHGC and U-value. Coated glass with a high reflection value compromises transparency, but lowers the SHGC the most and also insulates the best. Optitherm SN would be the best option for this design, as it is highly transparent and has a low SHGC and better insulation. The analysis must show whether this glass actually blocks enough solar energy, otherwise it will be necessary to look at other solutions at the expense of transparency.

As mentioned earlier, openings are needed in the construction to be able to ventilate by natural ventilation. In order to create the largest possible air pressure difference for natural ventilation, the inlet openings for ventilation must be as low as possible in the construction. Since the dome has already been lifted to create an entrance opening, without interrupting the shell structure, it is wise to also locate the inlet openings in this section. By evenly distributing several openings at the bottom of the construction, the air will also enter the construction in a divided manner, which ensures that the fresh air is distributed evenly throughout the space. Because the construction is divided into 6 parts, it makes sense to also place the openings for natural ventilation on 6 sides of the construction, see figure 52. The height of the openings will be the total height of the base. The width will contain half of the panel. This amounts to 6 openings with the dimensions of 2.75 by 2.5 meters. The maximum inlet opening area is therefore 41.25 m^2. Since the maximum outlet opening is known (2.76 m^2), the minimum inlet opening can be calculated. Because the maximum outlet opening is fixed, the A_{eff} cannot become smaller than this fixed opening. This means the minimum air pressure difference that can be used for natural ventilation is also fixed.

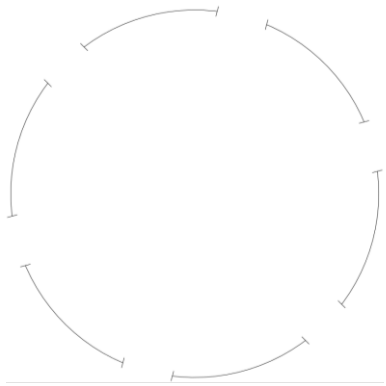


Figure 52: Floor plan with 6 openings (own figure)

An advantage of glass is that it is a transparent material. At the same time, this can also be a disadvantage, for example with openable parts. Since there are many connections to create openable windows this will all be visible through the glass. Every screw will be seen. To prevent this, it is wise to make the frames of the open parts of a non-transparent material. At the same time, this frame will have to serve as a structural part, since the openable parts will have no load-bearing function. An aluminum portal will serve this purpose well. Since aluminum has a higher compression and tensile strength than glass, the bridge can be worn. These portals allow the openings in the base. The portals will be the same height as the panels of the base, so that no small pieces of load bearing glass remain above the portals. These portals should therefore replace parts of the base's panels. Since the base has a round shape and the portals will be straight, the portals should have a certain depth , see figure 53. The portals will therefore protrude both outside and inside the construction. By giving the portals a depth of 500 mm, they get a certain appearance of a portal. Structural verification should show the thickness of the portals. In these portals, everything can be freely arranged, for example for doors or openable windows.

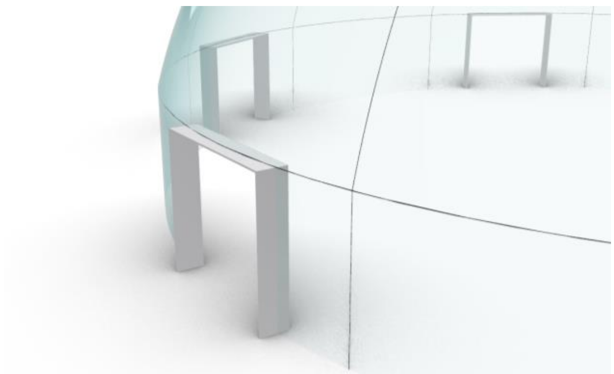


Figure 53: Aluminum portal (own figure)

As indicated, the oculus can be used as an opening for natural ventilation. Since this oculus is located at the highest point of the construction, this is positive for the height difference. Because this opening is horizontal, rain can enter through it. Since the temperature is lower on rainy days, because there is less direct sunlight, and therefore less natural ventilation is required, this iris will be closed and minimal rain will enter.

This can be prevented by closing this opening. Since it is desirable in some cases to vary this opening size, this should be possible. A solution is to use a diaphragm, a mechanical iris, known from optics, see figure 54. In this way, the opening can be opened and closed in the horizontal plane.

Figure 54: Operation of mechanical iris, closed and open (Haynie, 2018)

To finish the cheese bell, a handle, with a diameter of about 3 meters, has to be added on top of the construction. In order not to add extra weight to the construction, it should be as light as possible. Natural ventilation must also take place via the mechanical iris. It has therefore been decided to try to achieve the shape of a handle with a steel wireframe, see figure 55. In this way it is a very light addition to the construction, without the wind blowing against it, which can generate extra forces on the construction and the mechanical iris remains open for natural ventilation.

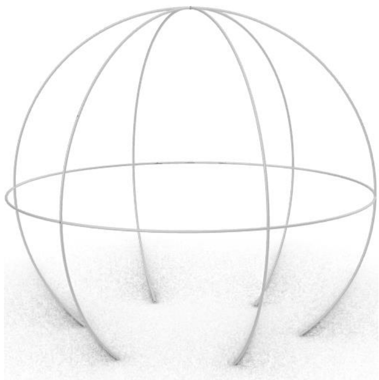


Figure 55: Wireframe (diameter 3 m) as handle of cheese bell (own figure)

3.4 Detailing

The connections between the different panels of the dome are the weak spots of the structure in several aspects. It will compromise the transparency of the design and the connection may have a lower insulation value than the rest of construction, but more importantly the connections are likely to be less strong than the panels. The appearance of the connections is important for the design. The purpose of this design is to make the design as transparent as possible. The connections should appear slim and light there. Since the connections will absorb large parts of the forces, the connections must be strong enough to withstand the loads.

There are a number of things to consider when designing the connections. The structure must be able to be put together, but it must also be possible to take it apart again. Repair work should be possible, which can be made easier by the connection design. It would be best if the connections can be disassembled per panel, making it easy to replace a single panel. The design should be watertight so that it does not leak water during a heavy rain shower. Before design suggestions are made, the requirements for the connections will first be examined.

3.4.1 Connections of the dome

Different options for the connections of the dome are possible. Below, four connections are presented with explanatory information, advantages and disadvantages. The proposed connection details are global outlined details. The actual curvature of the dome is applied in the drawing, but any dimensions of the connections may ultimately differ.

Glued-in plate connection

A minimum of three layers of laminated glass is required per panel to use this type of joint. In a middle layer, a plate is glued to the edges with a structural glue, as shown in figure 56. This type of connection provides a high rotational stiffness. This rotational stiffness can be adjusted by changing the thickness of the plate. This plate can be made over the entire length of the glass panels, but length divisions are also possible. The gaps between the different panels can be filled with a silicone, to get the same appearance in each seam. The silicone will protect the connection from weathering and the silicone ensures a water tightness of the construction.

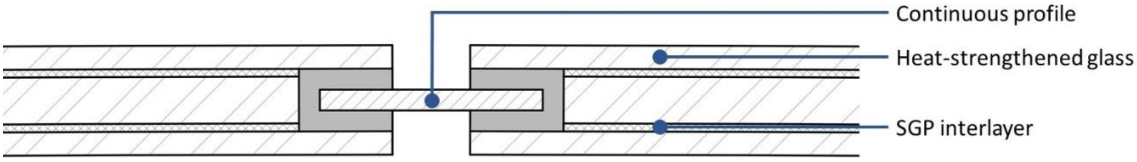


Figure 56: Glued-in plate connection (own figure)

An advantage of this type of connection is the connection does not protrude from the glass surface, so that the glass remains a smooth surface. A drawback is that this connection has an estimated width of about 70 mm. As a result, the connection is visibly present in the entire design, and compromises transparency. Only half of the connections can be prepared in a workshop. On site, the other glass panel must be placed on the connection. Because the design is a double curved surface, this will cause problems with the last panels to complete the total shape. Replacing a glass panel will be difficult, as parts of the entire construction has to be dismantled.

Glued-in hinge connection

A variant of the previous connection suggestion is the glued-in hinge connection, see figure 57. The rotational stiffness is expected to be very low and the axial stiffness is relatively high. This connection reduces some of the disadvantages of the glued-in plate connection. The hinge consists of two separate fittings, glued into opposing edge canals in the workshop, and assembled mechanically on site. The width of this connection is expected to become even wider than the previous suggestion, thus further diminishing the transparency of the design.

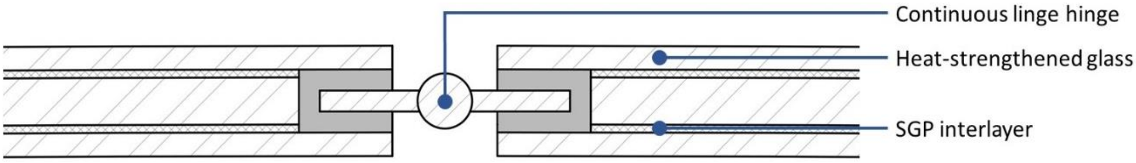


Figure 57: Glued-in hinge connection (own figure)

Clamp connection

Two profiles are clamped on the edge or corners of a glass panel, tightened with a screw, see figure 58. A softer material is placed between the profiles as an intermediate layer to prevent peak stresses in the glass due to unevenness. The greater the rotational stiffness in the connection, the greater the bending moment in the connection. The gaps between the different panels can be filled with silicone, to get the same appearance in every seam. The silicones ensure a water tightness of the construction.

An advantage is that these types of connections are easy to place on the side and a glass panel is easy to replace by just unscrewing the connections. A drawback is that this connection protrudes above and below the glass surface, so that the glass surface is no longer smooth. Depending on the size of the connection, the transparency of the construction is affected. Since this connection is expected to be used only in the corners of each glass panel, it will not compromise transparency a lot.

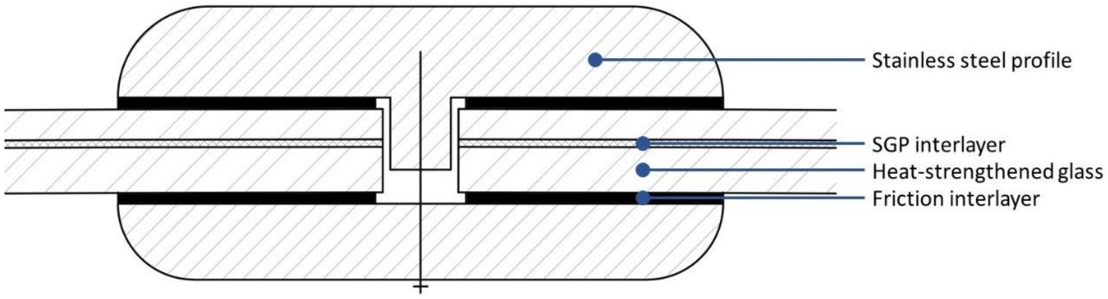


Figure 58: Clamp connection (own figure)

Glued butt joint

To achieve the ultimate in slenderness and transparency, just like the glass dome from ILEK in Stuttgart, the glass panels must be joined together with a glued butt joint. The glued butt joint is fitted against the glass panels, see figure 59. Since this design, just like the dome of ILEK, is a dome, the predominant load in the connection forces will be in the plane. These forces will lead to relatively low stress levels. In the ILEK dome, the maximum stress in the adhesive is 0.6 N/mm^2, determined by FE analysis (Bagger, 2010).

The advantage of this type of connection is that ultimate slenderness and transparency can be achieved. The panels can be easily replaced individually by cutting open the glued butt joint. Since it is a flexible material, it is important to consider how the entire structure will be built, since the connection will only work when the entire structure is standing.

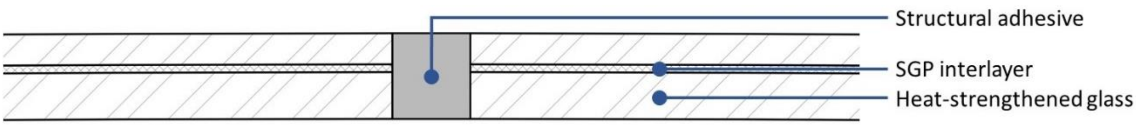


Figure 59: Glued but joint (own figure)

Only clamp connection and glued butt joint will be included for further investigation. These two were chosen for three reasons. These two connections are quite feasible to build a double curved shape. Replacing a panel is easier, since the connections per panel can be removed. The last reason is that these connections have the least influence on transparency. Structural verification will have to show which type of connection is most suitable for this design.

3.4.2 Connection between dome and base

Because the dome is not a complete hemisphere not all the forces run vertically, but also some horizontally. These lateral forces will push the structure apart. Since glass is stronger in pressure than tension, it is not possible to come up with a slim solution with this. A possible slim and simple idea which can be used as a compression ring is a steel rod. Since a rod is very good for absorbing tensile forces, this rod can be relatively thin. A thin steel rod will serve as a compression ring and absorb these horizontal forces, so that the base only needs to carry the dome. Since it is a relatively thin rod, this will have minimal influence on transparency. Figures 60 and 61 show a 3d view of the proposed detail between the dome and the base. Structural verification, next chapter, will have to show which minimum diameter steel rod is needed to absorb these horizontal forces.

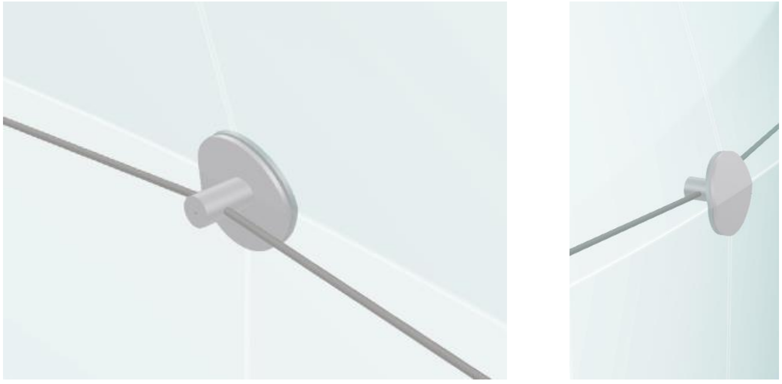


Figure 60 & 61: 3d detail connection between dome and base (own figures)

The principle of this connection works the same as the clamp connection of the dome. Two profiles clamped on the corners of 4 panels. This type of detail was chosen because the steel rod has to be connected in a way at the bottom edge of the dome. The profile on the inside of the construction will have a solid profile through which the steel rod will run, see figure 62. Tensioning the rod will pull the connection inward, eliminating the horizontal forces of the dome. This type of connection detracts from the transparency of the design, since the horizontal forces have to be absorbed, this is a solution without a continuous interrupting of the glass and transparency.

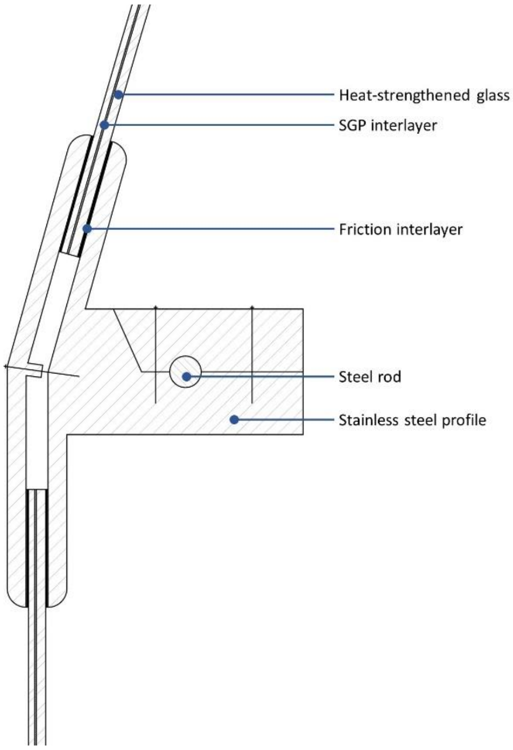


Figure 62: Connection between dome and base (own figure)

3.4.3 Connection to the ground floor

To connect the entire construction to the ground floor, the foundation, a connection to the ground floor is required, see figure 63. It concerns the base, only curved glass panels, which must be connected to the ground floor. By clamping these panels in a U-profile, the entire construction will be supported by the foundation. Since the panels are curved in a circle, the horizontal forces will take place in all directions, 360 degrees. This will minimize the deformation of this U-profile. And because the horizontal forces of the dome are already absorbed by the compression ring at the top of the base, in this connection mainly vertical forces will have to be able to transfer due to the self-weight.

To prevent drilling through the glass or obstructing bolts for the glass, the U-profile must be connected to the foundation. By welding flanges to the profile, these can be attached to the foundation.

To give the glass enough contact surface with the profile, it is placed about 300mm in the profile, under the ground, so that it is not visible. This means that the panels of the base have to be bigger to maintain the 2.5 m of the base.

Since a glass panel of the base must be replaced without removing the entire construction, it must be possible to remove a panel from this U-profile. The glass panel can be removed by removing the outer plate of the U-profile. In order to do this, the surrounding soil must be dug.

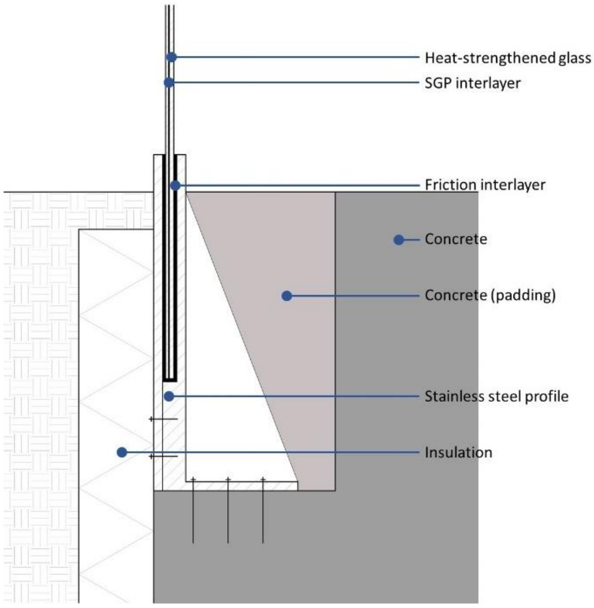


Figure 63: Connection to the ground floor (own figure)

3.5 Passive strategies

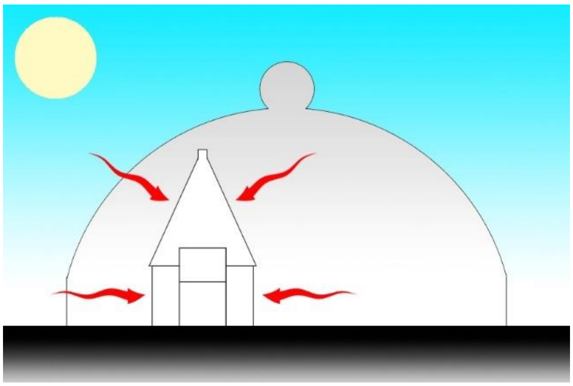
By getting the summer temperatures in the dome as close as possible to the outside temperature in a passive way, passive strategies must be applied in the design. The literature study addressed a number of strategies that can be applied. Below will be described how each strategy will be applied in this design.

3.5.1 Thermal mass

A small monument is situated in the glass construction. The monument consists of a square masonry block measuring 4.92 by 4.92 m with a height of 2.9. On top of this is a pointed roof with roof tiles. The masonry block is constructed from masonry with a thickness of 29 cm. The ground floor of the dome must be insulated to ensure that it does not get too cold in the construction in winter. This insulation will have a concrete floor that can be finished as desired.

Because there is a small monument and a concrete ground floor in the dome, these will contribute to the thermal mass effect. Because the summer temperatures in the dome are higher during the day than at night, the thermal mass will reduce the temperature fluctuations, see the effect between day and night shown in figures 64 and 65. The peak temperatures will be lowered by the thermal mass.

By increasing the thermal mass, this effect can also be increased. Since the monument exists, nothing can be added to it. The only thing that can be adjusted for the thermal mass is the thickness of the concrete ground floor.



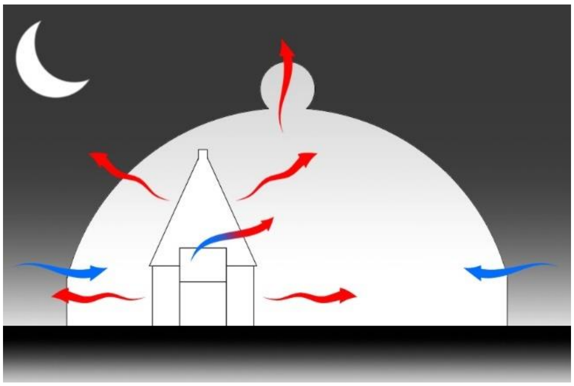


Figure 64 & 65: Thermal mass principles day and night (own figures)

3.5.2 Natural ventilation

Ventilation is necessary not only to refresh the air in a room, but also to lower the temperature. By making use of the temperature difference between inside and outside and the height difference of the design, natural ventilation in the form of stack ventilation can be applied, to create convective cooling air streams. The dome shape ensures natural air circulation due to an accelerated air flow.

By letting the cooler air in at the bottom of the construction, the air will move through the room, warm up and move upwards. By letting out the heated air at the top of the construction, stack ventilation is created in this way, see figure 66 for the principle of this operation.

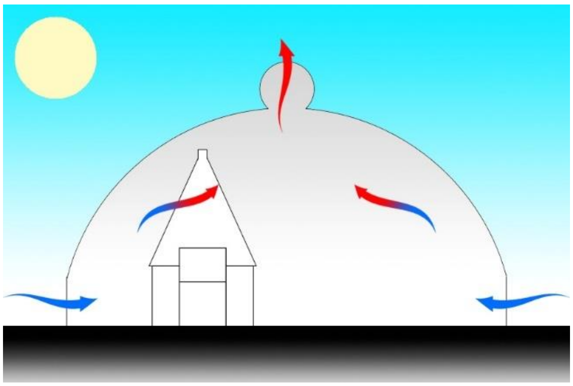


Figure 66: Natural ventilation principle (own figure)

By playing with the sizes of the different openings, the amount of natural ventilation can be adjusted. As indicated earlier, the maximum size of the outlet opening is fixed. This can vary in size in the horizontal plane. By evenly distributing several openings at the bottom of the construction, the air will also enter the construction in a divided manner, which ensures that the fresh air is distributed evenly throughout the space. Because the construction is divided into 6 parts, it makes sense to also place the openings for natural ventilation on 6 sides of the construction.

3.5.3 Fritting

Since large surfaces of glass are used in this design, a large huge amount of solar gain will also be caused. By using fritted glass this can be reduced, with respect to the glass. By choosing a pattern that fits well with the design, this intervention does not have to be noticed.

The sun is higher in summer than in winter. In the summer, most sun should be blocked and in winter it is desirable to let the sun through. The best for this design will therefore be a gradient of fritting. By applying more fritting at the top of the construction than at the bottom, this effect can be achieved.

By using for example small circles that each cover little surface individually, these will be barely visible from a distance. By varying the density or diameters of these circles, a gradient can be created, see figure 67 for an example of a gradient.

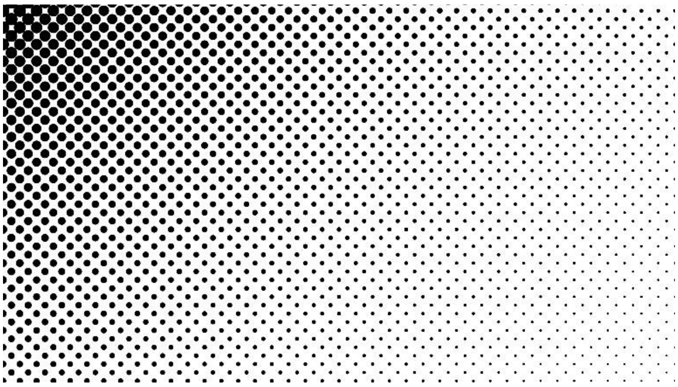


Figure 67: Gradient created by varying diameter circles (own figure)

By using a maximum fritting percentage of 50% on top of the construction, the furthest away from the sight, a lot of solar gain is prevented in the summer. By pulling the fritting down to a fritting percentage of 0%, this will not be visible at all at the bottom of the construction. Nevertheless, a total of 25% of the glass surface is covered with fritting in this way, which leads to a 25% decrease in the total visible transmittance and solar transmittance value of the glass.

Another possibility is to show the fritted glass by making fritted drawings on the glass of, for example, the history of Alkmaar or various iconic buildings of Alkmaar. This can give a playful shadow effect in the cheese bell.

3.5.4 Switchable glass

Switchable glass can be used to reduce glare, solar heat gain and UV exposure by changing the light transmission properties (transparency), to transmit or block certain wavelengths of light. Because this affects full transparency, this is only used as an emergency measure when the solar gain is too much. So this is only used at the hottest time of the day and the hottest days of summer to show the rest of the day a transparent design. An advantage of switchable glass is that the transparency for heat radiation can be varied. A disadvantage is that a voltage is required to achieve the desired effect. By using a switchable glass type that only requires voltage in the active state, the energy consumption can be reduced, for example electrochromic switchable glass. This type does not require constant voltage even in an active state. The glass will then slowly become transparent again. To maintain the sun protection effect, voltage must be applied again for a certain time.

3.5.5 Additional mechanical cooling

The DesignBuilder simulations, in the next chapter, show that with the proposed passive strategies, the operative temperature on the hottest summer day can be reduced from 88.07 °C to 45.39 °C. This covers most of the energy demand of achieving thermal comfort in the cheese bell by using passive strategies. To achieve thermal comfort in the dome, the additional cooling must be achieved by using mechanical systems. Here the main principles of the applied mechanical systems will be discussed. The extensive design study and dimensioning of these mechanical systems is not covered by this research, because this research focuses on passive strategies.

A more sustainable application of a mechanical system for cooling (and heating) is by using a heat pump. A heat pump absorbs coolness (or heat) from an environment and releases this coolness (or heat) into another environment by using a heat exchanger, see figure 68 for the principle of a heat pump. On a hot day, this means the heat pump gives coolness from a colder environment to the inside environment of the cheese bell and transfers the heat from the cheese bell to the colder environment. This coolness (or heat) is transferred via a medium to another medium, for example water to water. The monument is located at a rampart surrounded by a canal. It makes sense to use this water for the heat pump. Due to the large amount of water in this canal and the thermal conductivity of water, the temperature of this water (on the bottom of the canal) in the summer is considerably lower than the outside temperature (the other way around in the winter) and is therefore suitable for use with the heat exchanger . The temperature of the water is delivered by the heat exchanger to the water in the heat pump. In the cheese bell, this cold (or heat) must be delivered to another medium, for example air or water. Fan coils can be used for air. Since (visible) interventions must be applied in the cheese bell, it may be wiser to use water via the ground floor to be installed as a cooling floor in the summer and floor heating in the winter. The performance coefficient (CoP) gives the efficiency of the heat pump: the ratio between the amount of energy that the heat pump delivers and the amount of energy that the heat pump absorbs. A CoP of 3.5 for cooling is a safe average. This means that the required cooling capacity can be reduced 3.5 times by using a heat pump.

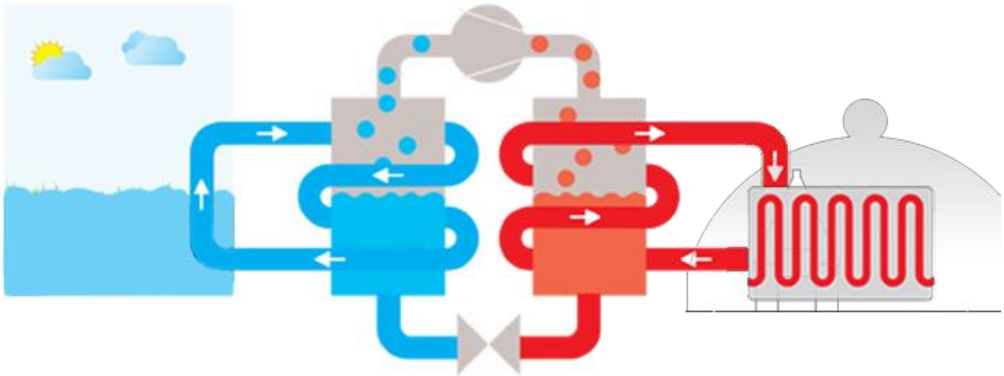


Figure 68: Principle of heat pump (own figure)

3.6 Construction and maintenance

3.6.1 Construction

To build the entire glass construction, work will have to be done from bottom to top, with care to the monument. The construction order is therefore simple:

1. Foundation
2. Base
3. Dome

The foundation and base can be built in a traditional way without any problems. The dome needs to be built in a special way, because it is a shell structure with a span of 21.2 m.

Because the dome will function as a shell structure when the construction is complete, the construction cannot be built panel by panel, as tensions then arise due to gravity, which the glass cannot handle. In order to be able to build the dome, a support structure is required under the final dome, over the monument. It might be wise to build the support structure for the base construction, since then all the space is left without damaging anything. By giving the support structure the shape of the dome, all panels and connectors can be placed in the right place. By mounting the connectors on the panels, the glass is slightly lifted and prestressed. By slowly lowering the support construction evenly, the dome will take over all forces and the dome will function as a full shell construction. The support structure can be broken down. The various smaller parts can then be removed through the openings in the structure.

By cleverly designing the support structure or by making the support structure from a recyclable material, this structure can later be used for other purposes, since this glass construction will only be built once. For example a wooden support structure.

3.6.2 Maintenance

A glass panel may break. Because the glass consists of several layers and is laminated, the panel will still be structural due to the whole layers of glass and the fracture pattern of the broken layer. A broken glass panel will therefore have little influence on the structural behavior of the entire construction. It is always better to replace a broken glass panel in case this panel breaks further and for the appearance of the design. Since all panels are constructive, removing a panel influences the structural behavior of the entire construction, especially in a shell structure. It is therefore necessary to place a temporary local support structure near the surrounding panels. Once the surrounding panels are supported, the broken panel can be removed. Due to the simple connection method, this panel can be easily and quickly replaced.

Glass is a construction material that generally lasts a long time because it is resistant to weather influences. Glass can incur aging effects. These include small cracks or scratches. This results in the glass becoming dull, but generally has no effect on the structural performance of the glass.

Because the design does not consist of horizontal surfaces, most of the dirt of the glass panels will flow away with the rainwater due to the angle of inclination and gravity. To clean the glass surface from dirt with only rainwater and without the necessary extra cleaning, a hydrophilic coating can be applied to the surface. This self-cleaning coating can be applied to remove fungus, water and pollution to keep the design transparent and shiny. The coating is applied by spray to the glass surfaces, both outside and inside. A disadvantage is that these types of coatings do not work for a long time, so applying of the coating should be repeated every many years.

4 VALIDATION

4 VALIDATION

4.1 Introduction

In the previous chapter, various design proposals were made based on the possibilities from the literature study. To make informed decisions about the proposed parts of the design, this chapter validates the proposals. These validations show which proposals meet the requirements and which proposals actually work. Design suggestions are compared to see which are best implemented to achieve high transparency.

There are several techniques to validate. Common sense, computer simulations and hand calculations are used to apply, modify or reject the proposed design suggestions. Each independent verification / analysis has its own different factors that play a role in the result. Each verification or analysis is made up of the specific inputs for the simulations or analysis and the results.

4.2 Structural verification

4.2.1 Risk analysis

To assess what and where possible risks are in the design, a safety analysis is necessary. The risk factor has been calculated according to the Fine & Kinney method from the Dutch code NEN 2608. With this RD-value it is possible to determine how much of the structure could be damaged in case a risk becomes reality.

According to the risk assessment, see table 8, there are several risks that have to be taken into account for the design. In the table the risks are split between natural and human causes.

Table 8: *Risk analysis* (own table)

Safety risk	Description	WS	BS	ES	RD	Explanation	Precaution to reduce risk
Fault by people							
Vandalism on glass facade pane		10	0.5	7	35	Unlikely in the area of the dome (pedestrian area)	Create barrier around building
Error in construction	Contractor	10	1	40	**400**		Periodic inspection of constructive elements
Fire		3	0.5	3	4.5		
Car/lorry crashes into façade	Accident	3	0.5	15	22.5	Unlikely in the area of the dome (pedestrian area)	Create barrier around building
Construction crane falls on building		3	0.5	100	**150**		Check when installing
Degradation of the construction	In secondary construction elements by local element in the air	1	10	7	**70**		Periodic inspection of constructive elements
Terror attack inside building	Bomb	0.5	0.5	100	25		
Bullet hits façade		0.5	0.5	1	0.25		Laminated glass is standard
Car crashes into façade	On purpose	0.2	0.5	100	10		

Natural cause							
Bird	Bird crashes into façade	10	3	1	30		
Hail		10	1	1	10		
Snow on roof	More snow on the roof than expected/calculated	3	0.5	40	60		
Wind on façade	More snow on the facade than expected/calculated	3	0.5	40	60		
Meteorite		0.5	0.5	40	10		
Earthquake		0.2	0.5	40	60		

4.2.2 Form finding

Two shapes have been proposed as a dome for over the small monument as a cheese bell. To determine which shape has the best structural behavior for this construction, analysis in Diana FEA is performed. All global analysis will initially be carried out with 10 mm thick glass.

Inputs

To analyze the different shapes, different properties must be assigned to the shape:

- Diana settings:
  - Dimensions: Three dimensional
  - Model size: 100 m
  - Default mesher type: Hexa/Quad
  - Default mesh order: Quadratic
  - Shape type: Sheets
  - Element class: Regular curved shell elements
  - Thickness chosen dimension: 10 mm
  - Mesh operation: Edge (all edges)
  - Element size: 350 mm (smallest mesh possible with this model and student license)
- Material properties (glass):
  - Young's modulus: 68 kN/mm^2
  - Poisson's ratio: 0.21
  - Mass density: 2500 kg/m^3
- Load cases:
  - Self-weight: Specific weight
  - Wind load: 1 kN/m^2 (y-direction)
  - Snow load: -1 kN/m^2 (z-direction) (Applied to all surfaces at an angle less than 30°)
- Support:
  - Support target type: Edge (all bottom edges)
  - Coordinate system: X Y
  - Fixed translations: X Y Z
  - Fixed rotation: none

Results

Since both shapes are a solid model, the results will be very positive, eventually if the shape is divided into panels, the values will be many times higher. At the moment, the two different shapes can be compared to see how they differ in behavior. Most extreme conditions are considered; where all three loads are applied. Table 9 shows the results in difference. Appendix A shows all values and behavior of both shapes. The figures in the appendix show a normalized deformation, so that it is easy to see how the construction and this is exaggerated.

Table 9: *Results different shapes* (own table)

Shape:	Paraboloid	Hemisphere
Maximum deflection:	0.36 mm	0.66 mm
Maximum stress (tension):	1.31 N/mm^2	2.68 N/mm^2
Maximum stress (compression):	1.68 N/mm^2	2.34 N/mm^2

There is a difference in results. The paraboloid comes out the best from this equation, but the values are close together. So in terms of behavior it does not matter which form is chosen. The shape with the most aesthetics can be chosen.

4.2.3 Dome connections

For the dome, different connections have been proposed to keep the different panels together. In this analysis, two types of connections will be analyzed. The smaller the connection, the less this effects the transparency of the design. With a small clamp connection it can be imagined that high peak stresses will occur in the vicinity of these connections. That's why four different sizes will be simulated for the clamp connection (150 mm, 300 mm, 450 mm and 600 mm diameter). The clamp connections will only be applied to the corners of the panels, as round profiles. The space between the panels will be 10 mm. Since a compression ring will be applied later, all edges at the bottom will be simulated as supports.

To shorten the modulation time and simulation time, only one-sixth of the entire dome is simulated. The other parts of the entire dome are modulated as solid blocks, see figure 69. In this one-sixth part all sizes of the panels of the dome occur, so that all connections also occur multiple. This can therefore provide valuable insights into how the entire construction will behave.

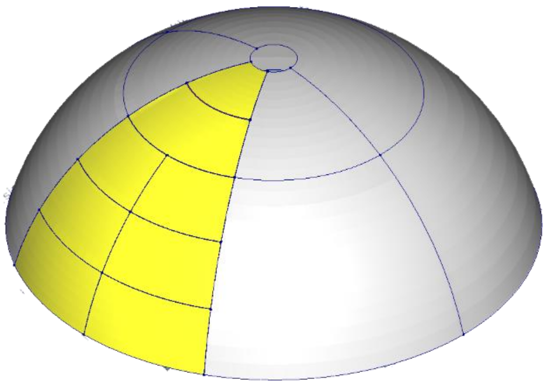


Figure 69: One-sixth of the entire dome (own figure)

To get an impression of how the entire construction will behave the entire model is simulated in 3 directions, in order to allow the influences of the wind to play along, see figure 70.

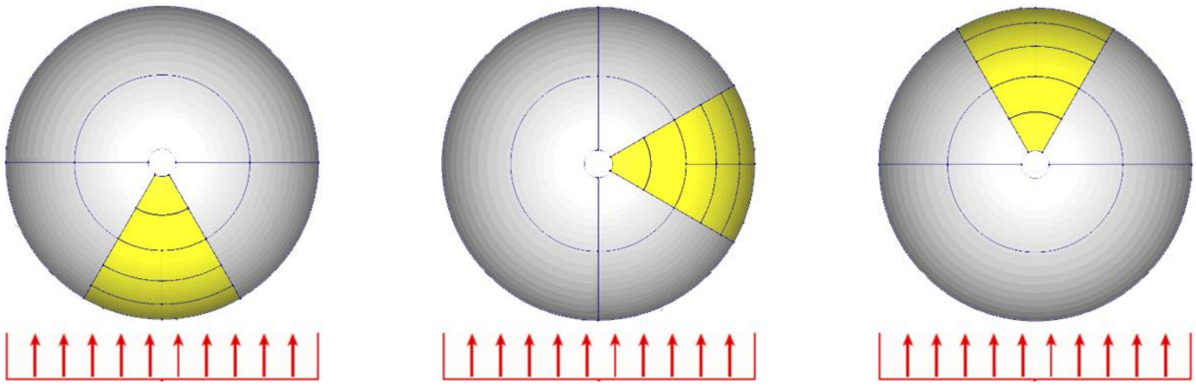


Figure 70: Simulated directions, left: direction 1, middle: direction 2, right: direction 3 (own figure)

Inputs

The inputs will be the same as the previous simulations. Only two materials need to be added:

- Material properties (clamp connection) (Bagger, 2010):
  - Young's modulus: 69 kN/mm^2
  - Poisson's ratio: 0.3
  - Mass density: 2755 kg/m^3
- Material properties (glued butt joint) (Bagger, 2010):
  - Young's modulus: 1 kN/mm^2
  - Poisson's ratio: 0.45
  - Mass density: 1200 kg/m^3

Results

With the clamp connections, all forces run through the corners, via the clamp connection of the panels, so the simulation therefore has high stress peaks. Since the connections can be adjusted in thickness and material, these values will not be shown in the simulations. The simulations only look at the behavior of the glass. Table 10 shows all maximum values of the glass with the different connection types. All different values per direction are shown in appendix B. The results of the clamp connections show that the largest deflections are in the middle of the edges of the panels. This is because there are no connections here. All forces go through the connections in the corners. In reality there will be nylon blocks between panels, with a maximum length of 200 mm and a thickness of 2/3 of the thickness of the glass. There will be a maximum of 3 of these blocks along the length of each panel. These blocks ensure that the vertical forces due to the self-weight and snow load are transferred via these blocks to the next panel. By filling the other openings with a black silicone (and over the blocks), these blocks will not be visible, but will participate in the transfer of forces. The values of the simulations will therefore be bigger than in reality, because these nylon blocks are not included in the simulations.

Table 10: *Results different connections* (own table)

Connection type:	Clamp connection (150 mm)	Clamp connection (300 mm)	Clamp connection (450 mm)	Clamp connection (600 mm)	Glued butt joint (10 mm)
Maximum deflection:	31.87 mm	20.70 mm	16.70 mm	14.80 mm	0.76 mm
Maximum stress (tension):	73.41 N/mm^2	60.34 N/mm^2	30.79 N/mm^2	22.90 N/mm^2	2.53 N/mm^2
Maximum stress (compression):	76.57 N/mm^2	67.90 N/mm^2	43.48 N/mm^2	33.91 N/mm^2	3.25 N/mm^2

The predominant load in the glued butt joint connections are in-plane forces, which lead to a relatively low stress level. The simulations also show that the glued butt joint gives the lowest values. The simulations show that the clamp connection with the diameters of 450 mm and 600 mm are also possible as a connection type, but these will influence the transparency of the design, as these will be relatively large connections.

Since only a sixth has been simulated and the entire construction will eventually behave differently, values will increase. The best connection type from these simulations is the glued butt joint connection. The risk analysis shows that errors in the construction has the largest RD value. By taking this into account in the design, this risk will decrease. The two proposed connection types play a role in this. Regardless of which connection type comes better from the structural verification, it must also be considered which type of connection provides the least chance of error in construction. The glued butt joint will be most sensitive to error in construction, as the glued butt joint is a movable connection. Since this is a connection that can be performed the slenderest, few tolerances may occur. Since it is applied as a liquid, these less tolerances can only be achieved under the most optimal conditions. Therefore, this may not be the most optimal connection to limit the errors in the construction. The clamp connection is a pre-fabricated part, which can be made with the utmost precision. The tolerances of this type of connection will be many times lower and therefore better suited to prevent errors in the construction. It is decided to include this type of connection in the design. Therefore, it is needed to look further into the clamp connection. Since a clamp connection with a diameter between 450mm and 600mm is too large, it must be reduced. By taking thicker glass, the values of the smaller clamp connections will decrease. The smallest variant will be used for this optimization in the following simulations.

Inputs

To analyze the different shapes, different properties must be assigned to the shape:

- Diana settings:
    - Thickness chosen dimension: 10 mm and 20 mm

Results

With the clamp connections, all forces run through the corners, via the connection of the panels, so the simulation therefore has high stress peaks. Since the connections can be adjusted in thickness and material, these values will not be shown in the simulations. The simulations only look at the behavior of the glass. Table 11 shows all maximum values of the glass with the different glass thickness. All different values per direction are shown in appendix B.

Table 11: *Results different glass thickness* (own table)

Connection type:	Clamp connection, (diameter 150 mm, glass thickness 10 mm)	Clamp connection, (diameter 150 mm, glass thickness 20 mm)	Clamp connection, (diameter 150 mm, glass thickness 30 mm)
Maximum deflection:	31.87 mm	6.62 mm	2.76 mm
Maximum stress (tension):	73.41 N/mm^2	17.95 N/mm^2	9.79 N/mm^2
Maximum stress (compression):	76.57 N/mm^2	34.33 N/mm^2	26.34 N/mm^2

This shows that the use of thicker glass has a significant effect on the stress peaks. Glass with a thickness between 20 and 30 mm can be applied to a clamp connection with a diameter of 150 mm. If 30 mm glass is chosen, the diameter of the clamp connection would be even smaller.

4.2.4 Dimensioning of the steel rods

To determine the diameter of the steel rod to absorb the horizontal forces from the dome, the magnitude of these horizontal forces must be determined. The diameter can be calculated depending on the strength, length and maximum elongation of the stem rot.

Inputs

To determine these horizontal forces, the same Diana model is used with the same settings. In these simulations there will not be looked at the stresses of the glass, but at the distributed forces at the bottom clamp connection in all three directions.

Results

By determining the amount of the distributed forces, Nxx or Nyy, in the middle of the clamp connection, to which the steel rods are attached, it is possible to determine how many forces the steel rods have to handle. The simulations show that the largest distributed forces in the middle of the clamp connection is 98.19 N/mm. All different values per direction are shown in appendix C. Since the clamp connection has a diameter (width) of 150 mm, the largest and therefore normative horizontal force that the steel rod must absorb is 14.73 kN.

This force is divided between two steel rods per clamp connection. Since these steel rods are at an angle to this horizontal force, factors need to be decomposed. Per clamp connection there is 7.36 kN force at an angle on 1 steel rod. Figure 71 shows, by factorizing, that 28.45 kN is pulled on the steel rod per clamp connection. Since a steel rod is connected to two clamp connections, pulling is done on both sides, in the opposite direction, with a force of 28.45 kN. So a total tensile force of 56.91 kN is applied per steel rod.

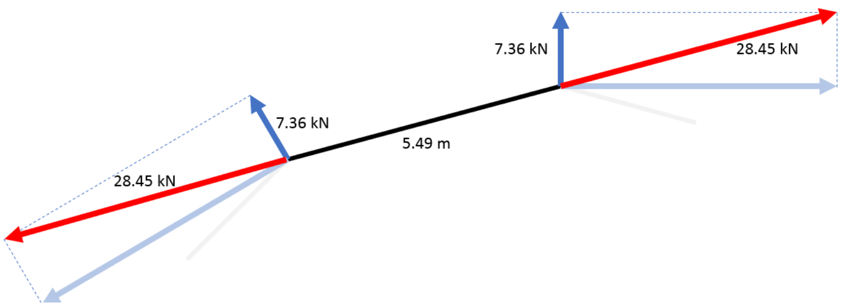


Figure 71: Factorizing of the forces (own figure)

Hand calculations

By calculating with a steel rod of 5.49 m with a Young's modulus of 210 Gpa, where the maximum allowable elongation is 5 mm, the diameter of the steel rod can be calculated with formula 6 (Eigenraam, 2018).

$$\delta = \frac{P \cdot L}{A \cdot E} \qquad (6)$$

δ : Elongation (mm)

P : Applied force (kN)

L : Length steel rod (mm)

E : Elastic modulus (kN/mm^2)

A : Cross section area, calculated by using formula 7

$$A = \frac{\pi}{4} \cdot D^2 \qquad (7)$$

To calculate the diameter (D) of the steel rod, formulas 6 and 7 can be converted to formula 8.

$$D = \sqrt{\frac{P \cdot L}{\delta \cdot E \cdot \frac{\pi}{4}}} \qquad (8)$$

The diameter of the steel rod can be calculated on the basis of the above mentioned values.

$$D = \sqrt{\frac{56.91 \cdot 5490}{5 \cdot 210 \cdot \frac{\pi}{4}}} = 19.46\,mm$$

19.46 mm is the minimum size of diameter rod that is needed, so that the deformation, elongation in this case, does not exceed 5 mm. Anything larger than this diameter would be fine, because anything larger would have a larger cross section area and the elongation would be less. In this design a steel rod with a diameter of 20 mm will be used. This is a bit oversized, but that causes an elongation smaller than 5 mm.

4.2.5 Dimensioning of the portals

In order to dimension the portals as structural elements, it must be calculated how much these portals must carry and what dimensions the portals must have. There will be a total of 6 portals. The base consists of 12 glass panels. 1 portal is half a panel. Each portal must be able to support 1/24 of the forces of the dome. A portal spans a length of 2.75 m and has a width of 0.5 m. The portals have the same height as the panels of the base: 2.5 m. Since the span will be the most decisive for the sizing of the portals, it will be included in the calculation as a beam. The dome has an area of 1708 m^2 consisting of glass. This amounts to a total weight of 1250 kN. The surface of the dome at an angle of less than 30 degrees, on which snow can remain, is 285 m^2. This amounts to a total weight of 285 kN. The total vertical weight of the dome is 1535 kN. Each portal must carry a weight of 64 kN distributed over a length of 2.75 m. This equates to a q-load of 23.3 kN/m. The material and thickness of the portals will depend of the calculations. Since the span will be the most decisive for the sizing of the portals, it will be included in the calculation as a beam, see figure 72.

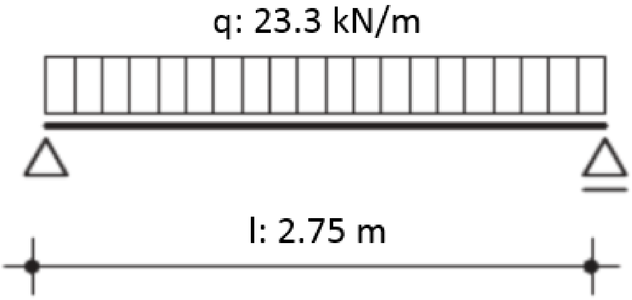


Figure 72: Span of the portal as a beam (own figure)

The bending stress of a beam can be calculated with formula 9 (Eigenraam, 2018).

$$\sigma = \frac{M \cdot c}{I} \qquad (9)$$

σ : Bending stress (kN / mm^2)

M : Maximum bending moment ($kNmm$), calculated by using formula 10

c : Distance from the neutral axis (mm)

I : Moment of inertia (mm^4), calculated by using formula 11

$$M = \tfrac{1}{8} \cdot q \cdot l^2 \qquad (10)$$

q : Distributed force (kN / mm)

l : Beam length (mm)

$$I = \frac{b \cdot h^3}{12} \qquad (11)$$

b : Beam width (mm)

h : Beam height (mm)

Since the cross section of the tree is a simple rectangle, c is equal to $\tfrac{1}{2}h$. This simplifies the merged formulas to formula 12.

$$\sigma = \frac{M}{\tfrac{1}{6} \cdot b \cdot h^2} = \frac{3 \cdot q \cdot l^2}{4 \cdot b \cdot h^2} \qquad (12)$$

In the previous chapter it was proposed to make the portals of aluminum. The calculation must show that the portals of this material can be made, in other words that the portals of this material will have an acceptable thickness. Aluminum has a tensile strength of 250 MPa. σ should therefore not exceed 250 kN/mm^2. The only variable of the portal is still the thickness. Formula 12 can be converted to formula 13.

$$h = \sqrt{\frac{3 \cdot q \cdot l^2}{4 \cdot \sigma \cdot b}} \qquad (13)$$

The minimum thickness of the portals can be calculated on the basis of the above mentioned values.

$$h = \sqrt{\frac{3 \cdot 0.0233 \cdot 2750^2}{4 \cdot 0.25 \cdot 500}} = 32.52mm$$

32.52 mm is the minimum thickness of the portals made out of aluminum. Anything thicker than this thickness would be fine. In this design a portal with a thickness of 35 mm made out of aluminum will be used. Any other material with a higher tensile strength will result in thinner portals.

4.3 Energy Plus analysis

4.3.1 Baseline measurement

The baseline measurements will serve as the starting point of the Energy Plus analysis. These baseline results will indicate the most extreme values. The situation without any climate control. The can be worked from here to realize the indoor thermal comfort.

Inputs

The inputs in DesignBuilder for the baseline measurements will be the start of the further simulations. See figure 73 for the standard model in DesignBuilder. Work will continue from here:

- DesignBuilder settings:
    - Analysis type: 1-EnergyPlus
    - Location: AMSTERDAM AP SCHIPH
      Since Alkmaar is not supplied as a standard location template by DesignBuilder, Amsterdam is chosen. These two cities are 30 km apart and the results will therefore differ only a little.
    - Activity Template: Eating/drinking area
    - Number of people: 75
    - Occupancy Schedule: Entered manually
      In the winter months, an opening time is from 10am to 9pm, 7 days a week. In the summer months, an opening time is from 9:00 am to 11:00 pm, 7 days a week.
- Geometry properties: two stacked blocks
    - Block type: 1-Building block
    - Form: 1-Extruded and 4-Dome
    - Shape: 3-Circle (diameter: 21.2 m)
    - Opening type: 5-Fill surface (100%)
- Materialization:
    - Glazing type: Entered manually
      For the first simulations, a glazing of 1 layer of Generic Clear 30mm glass will be applied.
    - Frame and Dividers: none
    - Construction Ground floor: Project ground floor
      This consists of 4 layers: Urea Formaldehyde Foam (0.2393 m), Cast Concrete (0.1 m), Floor/Roof Screed (0.07 m) and Timber Flooring (0.03 m).

- Monument:
  The monument will be simulated as a very simplified adiabatic component block.
  - Block type: 3-Component block
  - Component block type: 3-Adiabatic
  - Form: 1-Extruded (2.9 m)
  - Shape: 2-Rectangle (4.92 by 4.92 m)
  - Material Category: Brick and blockwork
  - Default thickness: 0.145 m
    Since it is an adiabatic block, half of the actual wall thickness (0.29 m) will contribute to the thermal mass.

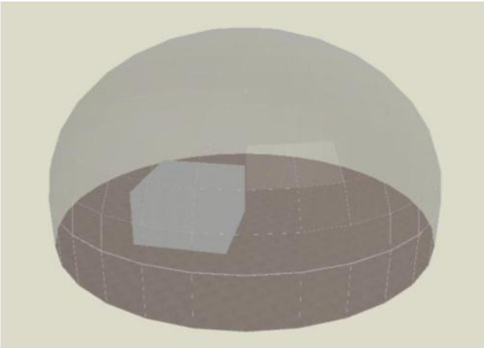


Figure 73: Standard model in DesignBuilder (own figure)

Results

Looking at what happens to the temperatures in the dome over a whole year, it can be seen that the highest operative temperature is reached on June 7 (70.35°C) and the lowest operative temperature is reached on February 14 (-7.71°C), see figure 74. This figure clearly shows that the majority of the year the temperatures are above the comfort limits. Drastic interventions must therefore be taken to lower the temperatures in the dome to make this fully glass dome functional.

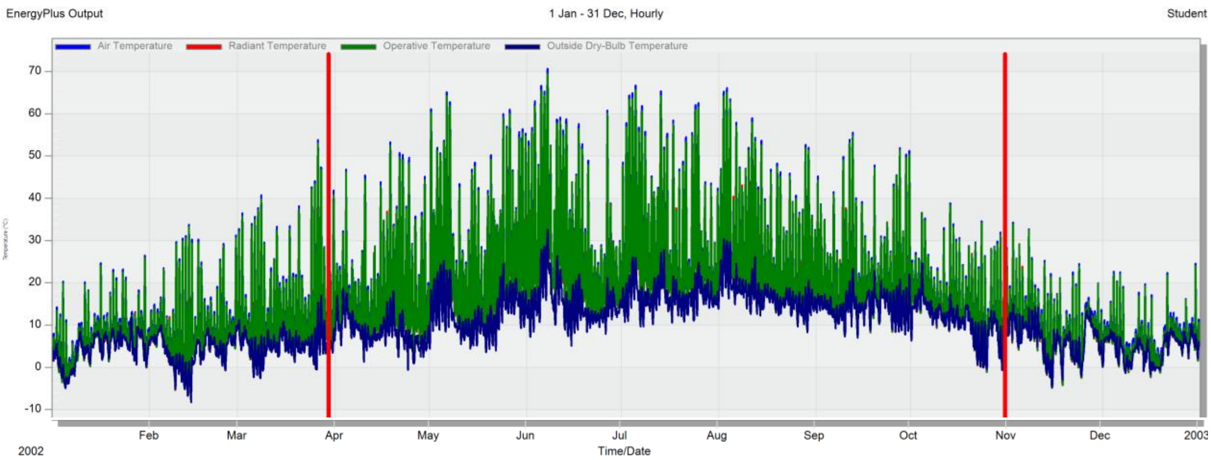


Figure 74: Temperatures over a year in the cheese bell (own figure)

Since the glass only has a U-value of 5,077 W/(m²·K), it becomes very cold in the dome in winter. A simple solution for this is to give the glass a higher U value, for example by using double glazing. Figure 75 shows the temperatures in the dome over a whole year with double glazing, built from the inside out is 30 mm generic clear glass, 12 mm air cavity and 4mm generic clear glass, which will influence the self-weight of the construction and thus also the behavior of the construction. Since the U-value is now higher, less cold will come in and less heat will come out in winter, but less heat will go out in summer, which will make it even hotter in summer. From now on this is the new baseline measurement, with which work will continue. Because the U-value is higher in this case, it is more difficult for the incoming heat to leave the construction, so the summer temperatures are higher than in the previous situation.

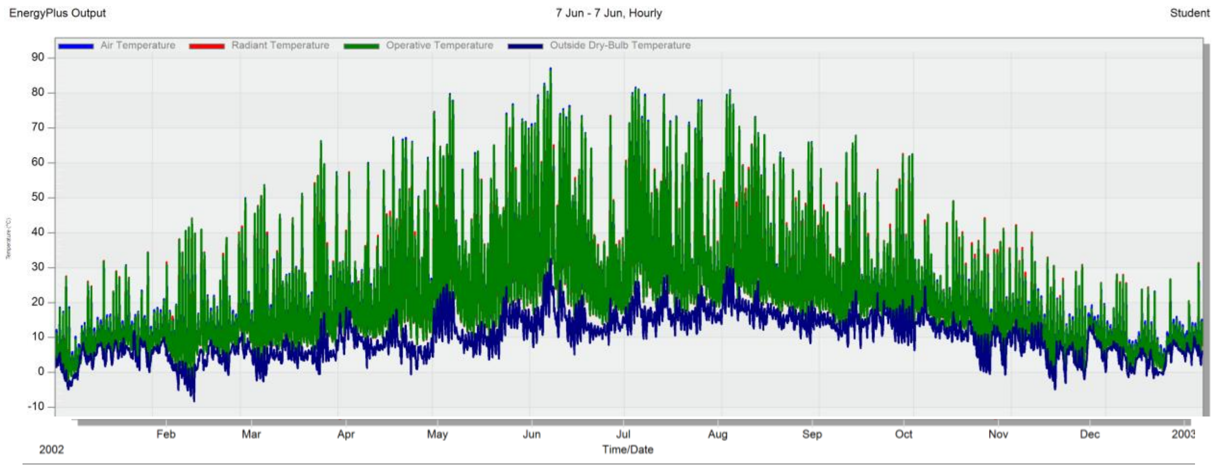


Figure 75: Temperatures over a year in the cheese bell using double glazing (own figure)

Since this study focuses mostly on the hottest summer day, figure 76 shows the temperatures in the dome over the hottest day: June 7. Hottest time of the day is 88.07°C.

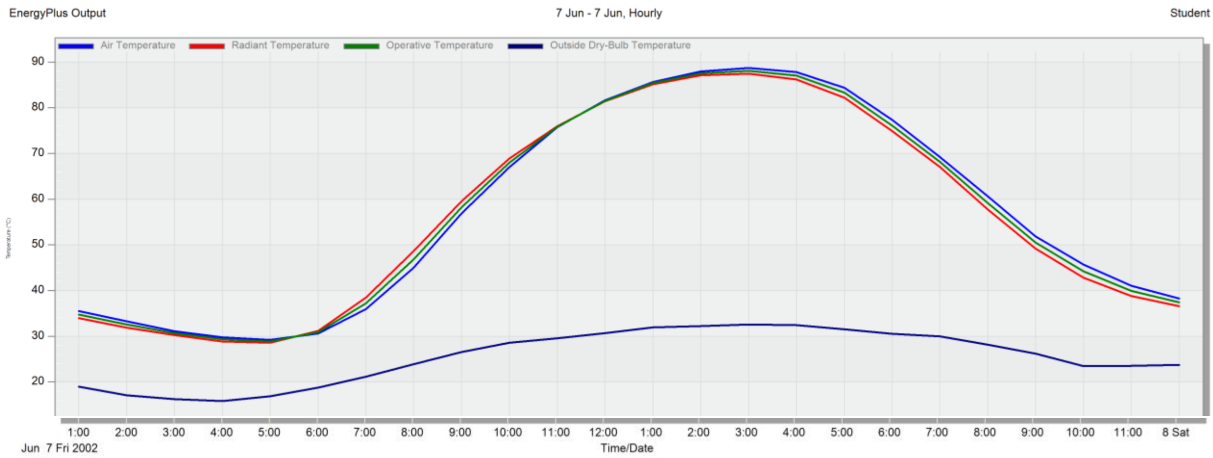


Figure 76: Temperatures over the hottest in the cheese bell (own figure)

4.3.2 Natural ventilation

If the heat cannot escape from the construction, this heat accumulates. So before interventions can be applied, ventilation must first be applied in the simulations. Since natural ventilation was already a strategy that was going to be applied, this works out well.

Minimum ventilation requirement

By applying the minimum ventilation requirement at full occupancy, which amounts to a ventilation rate of approximately 1.45, insight can be obtained what ventilation does with the temperature in the dome.

Inputs

- DesignBuilder settings:
  - Natural Ventilation Outside air (ac/h): 1.45
  - Operation Schedule: On 24/7

Results

With the minimum ventilation requirement, a maximum operative temperature of 71.84°C is achieved in the cheese bell. Table 12 shows the different maximum temperatures and maximum gains. In appendix D all values for the whole day are shown.

Table 12: *Maximum temperatures and gains minimum ventilation requirements* (own table)

Outside Dry-Bulb Temperature:	32.58 °C
Air Temperature:	66.56 °C
Radiant Temperature:	77.50 °C
Operative Temperature:	71.84 °C
Solar Gains Exterior Windows:	204.06 kW
External Vent.:	43.67 kW

Hand calculations

The air pressure difference can be calculated on the basis of the obtained temperatures.

$$\Delta P = \frac{9.81 \cdot 10.6 \cdot 101,325}{287}\left(\frac{1}{305.73} - \frac{1}{339.71}\right) = 12.01 Pa$$

The effective area of the ventilation openings can be calculated on the basis of this calculated air pressure difference and the amount of ventilation.

$$A_{eff} = \frac{3750}{0.8 \cdot \sqrt{\frac{2 \cdot 12.01}{1.293}} \cdot 3600} = 0.30 m^2$$

Since the maximum opening of the outlet for the ventilation is fixed (2,76 m2), the minimum opening of the inlet for the ventilation can be calculated.

$$A_{inlet} = \sqrt{\frac{1}{0.30^2} - \frac{1}{2.76^2}} = 0.30 m^2$$

Based on this calculated minimum inlet opening for ventilation and the amount of ventilation, the maximum air speed through this opening can be calculated. Note: This is the maximum air speed. This speed can be reduced by varying the sizes of the inlet and outlet openings.

$$v = \frac{3750}{0.30 \cdot 3600} = 3.43 m / s$$

This air speed corresponds to a wind force of 3, characterized as moderate. The wind will blow up dust and flutter flags.

Ventilation rate of 5

By applying a ventilation rate of 5, insight can be obtained what ventilation does with the temperature in the dome.

Inputs

- DesignBuilder settings:
  - Natural Ventilation Outside air (ac/h): 5

Results

With a ventilation rate of 5, a maximum operative temperature of 59.84°C is achieved in the cheese bell. Table 13 shows the different maximum temperatures and maximum gains. In appendix D all values for the whole day are shown.

Table 13: *Maximum temperatures and gains ventilation rate of 5* (own table)

Outside Dry-Bulb Temperature:	32.58 °C
Air Temperature:	50.09 °C
Radiant Temperature:	69.73 °C
Operative Temperature:	59.84 °C
Solar Gains Exterior Windows:	204.06 kW
External Vent.:	78.70 kW

Hand calculations

The air pressure difference can be calculated on the basis of the obtained temperatures.

$$\Delta P = \frac{9.81 \cdot 10.6 \cdot 101,325}{287}\left(\frac{1}{305.73} - \frac{1}{323.24}\right) = 6.50 Pa$$

The effective area of the ventilation openings can be calculated on the basis of this calculated air pressure difference and the amount of ventilation.

$$A_{eff} = \frac{12952}{0.8 \cdot \sqrt{\frac{2 \cdot 6.50}{1.293}} \cdot 3600} = 1.42 m^2$$

Since the maximum opening of the outlet for the ventilation is fixed (2,76 m2), the minimum opening of the inlet for the ventilation can be calculated.

$$A_{inlet} = \sqrt{\frac{1}{1.42^2} - \frac{1}{2.76^2}} = 1.65 m^2$$

Based on this calculated minimum inlet opening for ventilation and the amount of ventilation, the maximum air speed through this opening can be calculated.

$$v = \frac{12952}{1.65 \cdot 3600} = 2.18 m/s$$

This air speed corresponds to a wind force of 2, characterized as weak. The wind can be felt in the face.

Ventilation rate of 8

By applying a ventilation rate of 8, insight can be obtained what ventilation does with the temperature in the dome.

Inputs

- DesignBuilder settings:
  - Natural Ventilation Outside air (ac/h): 8

Results

With a ventilation rate of 8, a maximum operative temperature of 66.81°C is achieved in the cheese bell. Table 14 shows the different maximum temperatures and maximum gains. In appendix D all values for the whole day are shown.

Table 14: *Maximum temperatures and gains ventilation rate of 8* (own table)

Outside Dry-Bulb Temperature:	32.58 °C
Air Temperature:	45.04 °C
Radiant Temperature:	66.81 °C
Operative Temperature:	56.08 °C
Solar Gains Exterior Windows:	204.06 kW
External Vent.:	90.64 kW

Hand calculations

The air pressure difference can be calculated on the basis of the obtained temperatures.

$$\Delta P = \frac{9.81 \cdot 10.6 \cdot 101{,}325}{287}\left(\frac{1}{305.73} - \frac{1}{318.19}\right) = 4.70 Pa$$

The effective area of the ventilation openings can be calculated on the basis of this calculated air pressure difference and the amount of ventilation.

$$A_{eff} = \frac{20723}{0.8 \cdot \sqrt{\frac{2 \cdot 4.70}{1.293}} \cdot 3600} = 2.67 m^2$$

Since the maximum opening of the outlet for the ventilation is fixed (2,76 m2), the minimum opening of the inlet for the ventilation can be calculated.

$$A_{inlet} = \sqrt{\frac{1}{2.67^2} - \frac{1}{2.76^2}} = 10.37 m^2$$

Based on this calculated minimum inlet opening for ventilation and the amount of ventilation, the maximum air speed through this opening can be calculated.

$$v = \frac{20723}{10.37 \cdot 3600} = 0.56\, m/s$$

The upcoming simulations will be carried out further with a ventilation rate of 5. As stated earlier, only natural ventilation can take place with a fixed minimum air pressure difference. As a result of the coming strategies, the temperature in the dome will decrease, which will also decrease the air pressure difference. By taking a ventilation rate of 5, there is still a margin in the air pressure difference. If all strategies are applied, the ventilation rate could increase to cause the last bit of extra temperature decrease.

4.3.3 Low-E coating

By applying glass with special coatings to reducing the emissivity of the glass the light and solar transmittance and with that the SHGC will be reduced. This will also improve the insulation value of the glass.

Inputs

- Materialization:
  - Glazing type: Entered manually
    A glazing of 2 layer will be applied. From the inside to the outside the construction is: Generic Clear 30 mm glass, air cavity of 12 mm and Pilkington Optitherm S1 Plus 4mm (coating faced to inside). The property of the glazing of this structure is shown in table 15.

Table 15: *Properties of the glazing* (own table)

SHGC	Direct solar transmission	Light transmission	U-Value ($W/m^2 \cdot K$)
0.490	0.410	0.715	2.507

Results

With the low-E coating, a maximum operative temperature of 53.95°C is achieved in the cheese bell. Table 16 shows the different maximum temperatures and maximum gains. In appendix D all values for the whole day are shown.

Table 16: *Maximum temperatures and gains using coatings* (own table)

Outside Dry-Bulb Temperature:	32.58 °C
Air Temperature:	45.87 °C
Radiant Temperature:	62.11 °C
Operative Temperature:	53.95 °C
Solar Gains Exterior Windows:	137.54 kW
External Vent.:	59.56 kW

4.3.4 Thermal mass

The baseline simulation used the existing situation, where the monument and the standard concrete floor have already been applied as thermal mass. In the design, the thermal mass can only be influenced by one thing, namely the concrete floor. By giving the *concrete* floor a thickness of 1 m instead of 0.1 m, the effect of the thermal mass can be viewed.

Inputs

- Materialization:
  - Construction Ground floor: Project ground floor
    This consists of 4 layers: Urea Formaldehyde Foam (0.2393 m), Cast Concrete (1.0 m), Floor/Roof Screed (0.07 m) and Timber Flooring (0.03 m).

Results

With the added thermal mass, a maximum operative temperature of 52.87°C is achieved in the cheese bell. Table 17 shows the different maximum temperatures and maximum gains. In appendix D all values for the whole day are shown.

Table 17: *Maximum temperatures and gains adding thermal mass* (own table)

Outside Dry-Bulb Temperature:	32.58 °C
Air Temperature:	45.11 °C
Radiant Temperature:	60.70 °C
Operative Temperature:	52.87 °C
Solar Gains Exterior Windows:	137.54 kW
External Vent.:	56.10 kW

4.3.5 Fritting

The glass panels have a gradient fritting density of 0% to 50%. The total surface area of the glass panels of the dome has an average fritting density of 25%. Into the analysis this can be interpreted as a 25% reduction of the visible transmittance and solar transmittance value of the glass.

Inputs

- Materialization:
    - Glazing type: Entered manually
      A glazing of 2 layer will be applied. From the inside to the outside the construction is: Generic Clear 30 mm glass, air cavity of 12 mm and Pilkington Optitherm S1 Plus 4mm (coating faced to inside). The property of the fritted glazing of this structure is shown in table 18.

Table 18: *Properties of the glazing* (own table)

Fritting	SHGC	Direct solar transmission	Light transmission	U-Value ($W/m^2 \cdot K$)
0 – 50% (gradient)	0.452	0.308	0.536	2.507

Results

With the fritted glass, a maximum operative temperature of 53.35°C is achieved in the cheese bell. Table 19 shows the different maximum temperatures and maximum gains. In appendix D all values for the whole day are shown.

Table 19: *Maximum temperatures and gains using fritted glass* (own table)

Outside Dry-Bulb Temperature:	32.58 °C
Air Temperature:	45.14 °C
Radiant Temperature:	61.69 °C
Operative Temperature:	53.35 °C
Solar Gains Exterior Windows:	100.37 kW
External Vent.:	56.26 kW

4.3.6 Switchable glass

If the heat cannot escape from the construction, this heat accumulates. So before interventions can be applied, ventilation must first be applied in the simulations. Since natural ventilation was already a strategy that was going to be applied, this works out well.

Inputs

- DesignBuilder settings:
    - Window shading Type: Electrochromic reflective 6mm
    - Window shading Position: 4-Switchable
    - Control type: 1-Always on

Results

With the switchable glass, a maximum operative temperature of 46.14°C is achieved in the cheese bell. Table 20 shows the different maximum temperatures and maximum gains. In appendix D all values for the whole day are shown.

Table 20: *Maximum temperatures and gains minimum ventilation requirements* (own table)

Outside Dry-Bulb Temperature:	32.58 °C
Air Temperature:	40.21 °C
Radiant Temperature:	52.10 °C
Operative Temperature:	46.14 °C
Solar Gains Exterior Windows:	18.23 kW
External Vent.:	35.45 kW

4.3.7 Natural ventilation

By trial and error it can be determined how much natural ventilation can still be created. With the applied passive strategies, natural ventilation can still be added up to a ventilation rate of 6.05.

Inputs

- DesignBuilder settings:
  - Natural Ventilation Outside air (ac/h): 6.05

Results

With a ventilation rate of 6.05, a maximum operative temperature of 45.39°C is achieved in the cheese bell. Table 21 shows the different maximum temperatures and maximum gains. In appendix D all values for the whole day are shown.

Table 21: *Maximum temperatures and gains maximum natural ventilation* (own table)

Outside Dry-Bulb Temperature:	32.58 °C
Air Temperature:	39.21 °C
Radiant Temperature:	51.61 °C
Operative Temperature:	45.39 °C
Solar Gains Exterior Windows:	18.23 kW
External Vent.:	36.44 kW

Hand calculations

The air pressure difference can be calculated on the basis of the obtained temperatures.

$$\Delta P = \frac{9.81 \cdot 10.6 \cdot 101,325}{287}\left(\frac{1}{305.73} - \frac{1}{312.36}\right) = 2.55Pa$$

The effective area of the ventilation openings can be calculated on the basis of this calculated air pressure difference and the amount of ventilation.

$$A_{eff} = \frac{15672}{0.8 \cdot \sqrt{\frac{2 \cdot 2.55}{1.293}} \cdot 3600} = 2.74m^2$$

Since the maximum opening of the outlet for the ventilation is fixed (2,76 m2), the minimum opening of the inlet for the ventilation can be calculated.

$$A_{inlet} = \sqrt{\frac{1}{2.74^2} - \frac{1}{2.76^2}} = 22.55m^2$$

Based on this calculated minimum inlet opening for ventilation and the amount of ventilation, the maximum air speed through this opening can be calculated.

$$v = \frac{15672}{22.55 \cdot 3600} = 0.19\, m/s$$

4.3.8 Additional mechanical cooling

The operative temperature in summer must be between 23 °C and 26 °C and in winter between 20 °C and 24 °C to achieve thermal comfort.

Inputs

- DesignBuilder settings:
    - Cooling Setpoint Temperatures Cooling (°C): 23.0
    - Temperature control: 2-Operative temperature

Results

Table 22 shows the different maximum gains. In appendix D all values for the whole day are shown.

Table 22: *Maximum temperatures and gains maximum natural ventilation* (own table)

Outside Dry-Bulb Temperature:	32.58 °C
Air Temperature:	21.19 °C
Radiant Temperature:	44.28 °C
Operative Temperature:	28.14 °C
Solar Gains Exterior Windows:	17.93 kW
External Vent.:	18.97 kW
Sensible Cooling:	352.44 kW

By using a heat pump with a CoP of 3.5 for cooling, a cooling requirement of 76.95 kW equates to power demand of 352.44 / 3.5 = 100.70 Kw.

5 FINAL DESIGN

5 FINAL DESIGN

5.1 General design

The hemisphere is chosen as shape to get a dome, because it approximates the shape of a cheese bell. It will be a hemisphere with a diameter of 21.2 meters and a height of 10.6 meters. The construction must be interrupted to get openings in de construction to enter the construction and to create natural ventilation. For a shell structure, this has consequences to the behavior. A solution is to lift the hemisphere 2.5 meters. To still meet the requirements for diameter and height, it is no longer a complete hemisphere. This means that not all forces run vertically anymore, but also some horizontally. These lateral forces will push the structure apart. The correct derivative formula to maintain the required dimension of the hemisphere is $x^2 + y^2 + (z + 0.38580...)^2$, with the intersection with the z-plane $z = 2.5$, see figure 77.

Figure 77: Lifted hemisphere (own figure)

5.2 Component design

To build this entire construction, the shape must be divided into panels. Because double curved panels will be used, the original shape of the hemisphere will be approximated as much as possible. The floorplan of the entire construction is a circle with a radius of 10.6 meters. This means the floorplan has a circumference of 66.60 meters. Dividing the floorplan into 12 equal parts creates panels with a maximum width of 5.55 meters. By using the same floorplan grid when dividing the dome the dome can be divided into rings from 12 panels. Dividing the dome into the rings from the center of the sphere into parts of 14 degrees creates the same size of the curvature of each ring, see figure 50. This produces a construction consisting of 60 panels divided into 6 rings, see figure 78. At the top of the dome, the panels become smaller. By joining multiple smaller panels, there are fewer connections, which provides a more transparent result and a stiffer construction. An opening remains at the top: an oculus. This can be used for natural ventilation. Because the bottom ring must be connected to the foundation, these panels will partly go into the ground. Table 23 shows the maximum sizes of all the panels of the whole structure.

Table 23: *Maximum sizes panels* (own table)

Quantity:	Length (mm):	Width (mm):
12	5550	2750
12	5550	2684
12	5201	2684
12	4194	2684
6	6220	2684
6	3707	2684
6	3707	2684

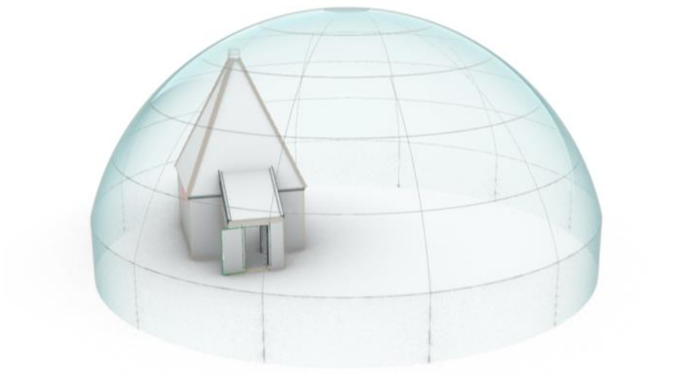


Figure 78: Shape divided in panels (own figure)

The interlayer between the glass layers will be a SGP interlayer to reduces the deflection of the panel, to remain intact in case if it fractures, causing no harm to the people who are in the construction and it has a higher transparency. To improve the glass performance and insulating properties, the emissivity has to be reduced by using coatings. Optitherm SN would be the best option for this design, as it is highly transparent and has a low SHGC and a better insulation value.

To be able to ventilate by natural ventilation openings are needed. Since the dome has already been lifted to create an entrance opening, without interrupting the shell structure, it is wise to locate the inlet openings in this section. By evenly distributing several openings at the bottom of the construction, the air will also enter the construction in a divided manner. Because the construction is divided into 6 parts, it makes sense to also place the openings for natural ventilation on 6 sides of the construction, with the dimensions of 2.75 by 2.5 meters (maximum inlet opening area of 41.25 m^2)

Aluminum portals with a thickness of 35 mm will allow the openings in the base, see figure 79. The portals will be the same height as the panels of the base. By giving the portals a depth of 500 mm, these portals get a certain appearance of a portal. In these portals, everything can be freely arranged, for example for doors or openable windows. The oculus can be used as an outlet opening for natural ventilation. Since it is desirable in some cases to vary this opening size, this should be possible. A solution is to use a diaphragm, a mechanical iris, known from optics. In this way, the opening can be opened and closed in the horizontal plane.

To finish the cheese bell, a handle, with a diameter of about 3 meters, has to be added on top of the construction, see figure 79. To get a light addition to the construction, without the wind blowing against it, and to keep the mechanical iris open to generate natural ventilation, it has been decided to try to achieve the shape of a handle with a steel wireframe.

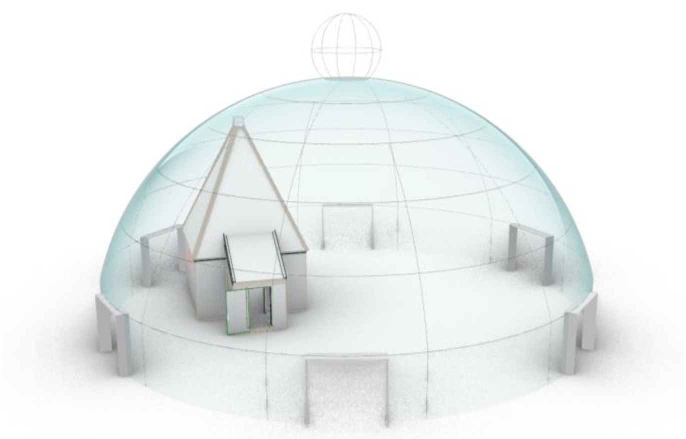


Figure 79: Cheese bell included openings and a handle (own figure)

5.3 Detailing

All details are shown bigger in Appendix E.

Clamp connection

The risk analysis shows that errors in the construction has the largest RD value. By taking this into account in the design, this risk will decrease. Two profiles are clamped on the edge of corners of a glass panel, tightened with a screw, see figure 80 and 81. A softer material is placed between the profiles as an intermediate layer to prevent peak stresses in the glass due to unevenness. The greater the rotational stiffness in the connection, the greater the bending moment in the connection. The gaps between the different panels can be filled with black silicone, to get the same appearance in every seam. The silicones ensure a water tightness of the construction. Figure 82 shows a 3D exploded view of the connection.

An advantage is that these types of connections are easy to place on side and a glass panel is easy to replace by just unscrewing the connections per panel. A drawback is that this connection protrudes above and below the glass surface, so that the glass surface is no longer smooth. Depending on the size of the connection, the transparency of the construction is affected. Since this connection is expected to be used in the corners of each glass panel, it will not compromise transparency a lot.

In the structural verification, for the simplicity of modeling, circles are used as a connection between the 4 panels. In reality this will become a diamond, so only 1 cutting line per corner will have to be applied. In this way there is also more surface between the glass and the clamp. This can be seen in the horizontal detail.

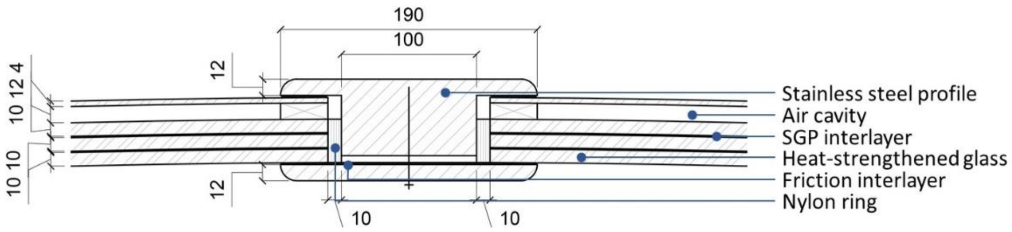


Figure 80: Detail clamp connection vertical (own figure)

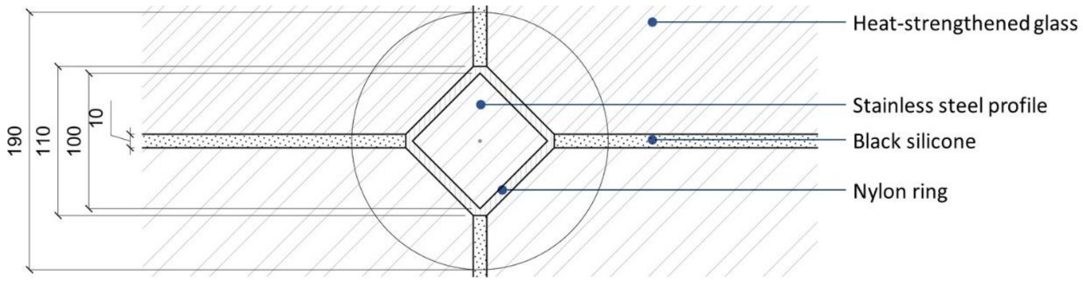


Figure 81: Detail clamp connection horizontal (own figure)

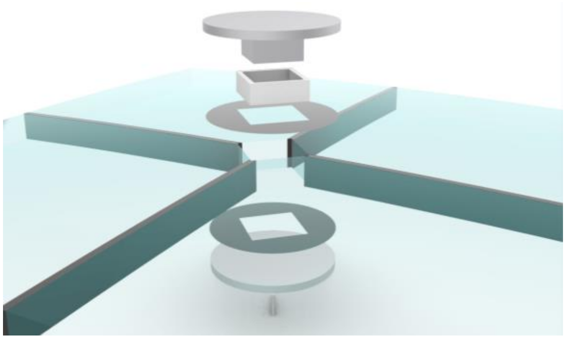


Figure 82: 3D exploded view of the clamp connection (own figure)

Connection between dome and base

Because the dome is not a complete hemisphere not all the forces run vertically, but also some horizontally. These lateral forces will push the structure apart. A thin steel rod with a diameter of 20 mm, obtained from the structural verification, will serve as a compression ring and absorb these horizontal forces, so that the base only needs to carry the dome, see figure 83.

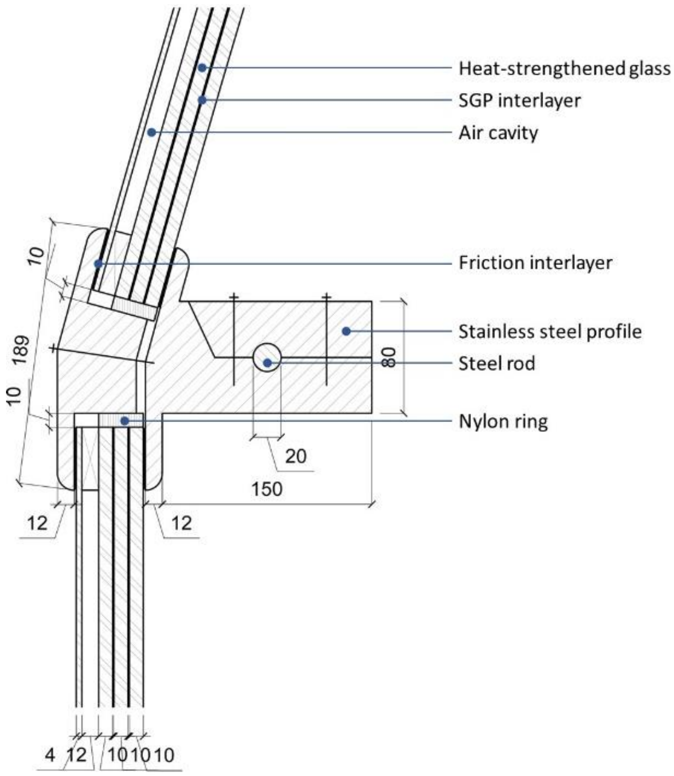


Figure 83: Detail connection between dome and base vertical (own figure)

The profile on the inside of the construction will have a solid profile, existing of two parts, of through which the steel rod will run. Tensioning the rod will pull the connection inward, eliminating the horizontal forces of the dome. By making the ends of the rods larger, they will fall into a hollow in the profile, so that they cannot go away, see figure 84. The rods are attached by attaching the two parts of the profile together. Figure 85 shows a 3D exploded view of the connection. This type of connection detracts from the transparency of the design, since the horizontal forces have to be absorbed, this is a solution without a continuous interrupting of the glass and transparency.

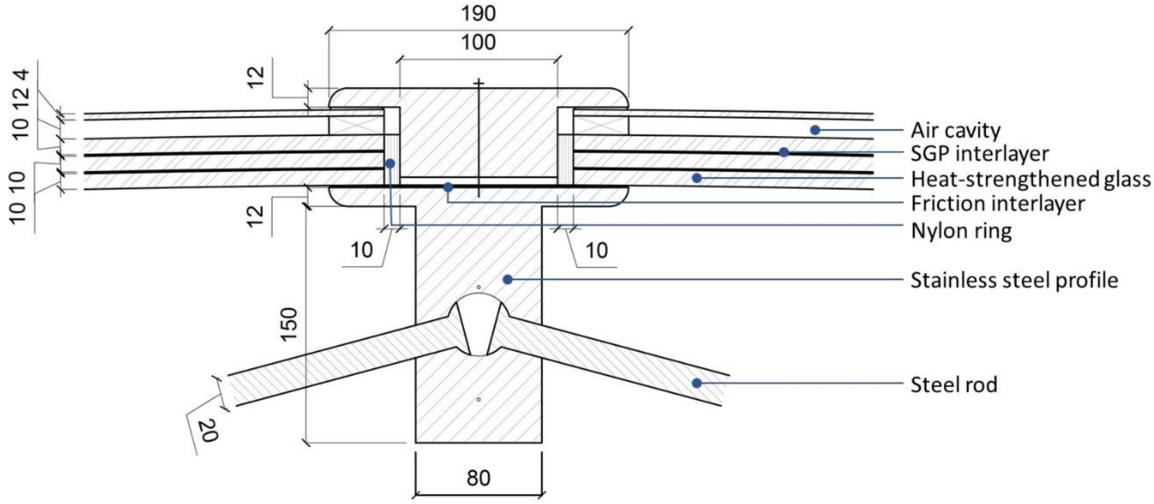


Figure 84: Detail connection between dome and base horizontal (own figure)

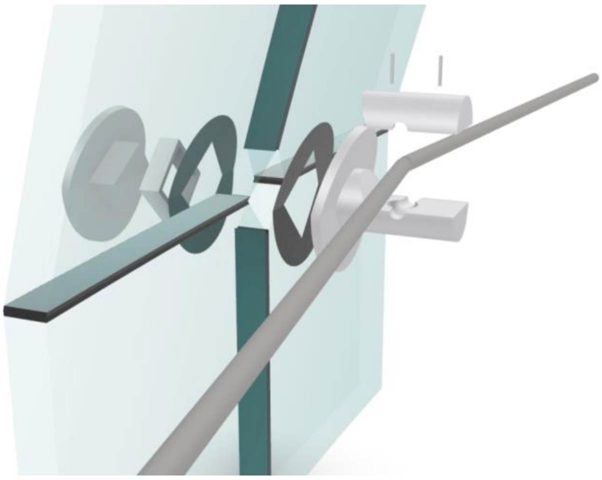


Figure 85: 3D exploded view of the connection between dome and base (own figure)

Connection to the ground floor

To connect the entire construction to the foundation, a connection to the ground floor is required, see figure 86 and 87. By clamping these panels in a U-profile, the entire construction will be supported by the foundation. To prevent drilling through the glass or obstructing bolts for the glass, the U-profile must be connected to the foundation. By welding flanges to the profile, these can be attached to the foundation.

To give the glass enough contact surface with the profile, it is placed about 300mm in the profile, under the ground, so that it is not visible. This means that the panels of the base have to be bigger to maintain the 2.5 m of the base. Since a glass panel of the base must be replaced without removing the entire construction, it must be possible to remove a panel from this U-profile. The glass panel can be removed by removing the outer plate of the U-profile. In order to do this, the surrounding soil must be dug. Figure 88 shows a 3D exploded view of the connection. Figures 89 shows the design included all the connections.

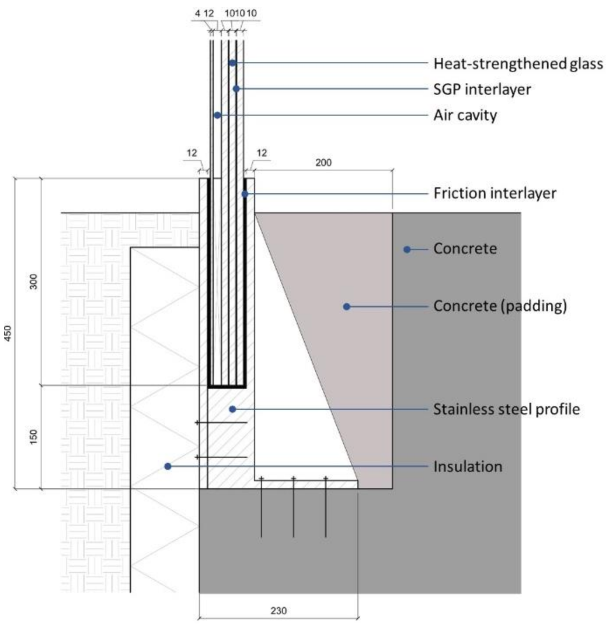


Figure 86: Detail connection to the ground floor vertical (own figure)

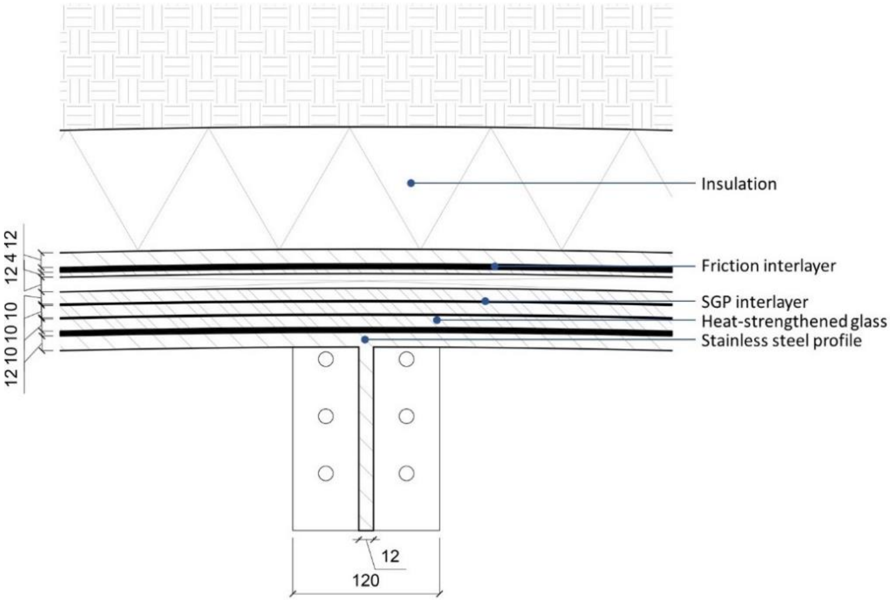


Figure 87: Detail connection to the ground floor horizontal (own figure)

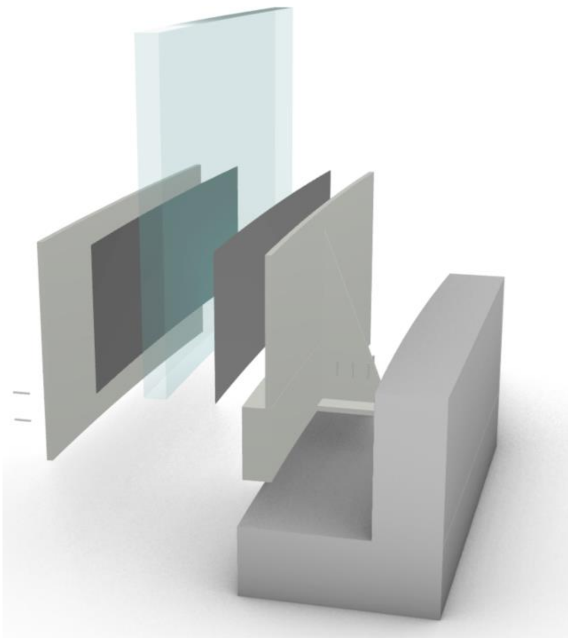


Figure 88: 3D exploded view of the connection to the ground floor (own figure)

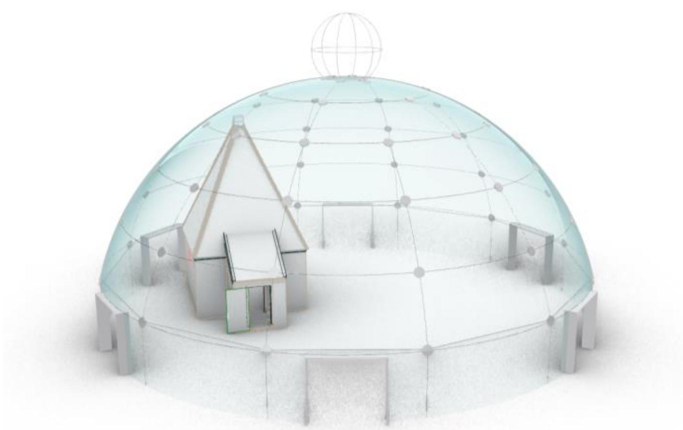


Figure 89: Design included connections (own figure)

5.4 Passive strategies

Thermal mass

Because there is a small monument and a concrete ground floor (to insulate the dome) in the dome, these will contribute to the thermal mass effect. Because the summer temperatures in the dome are higher during the day than at night, the thermal mass will reduce the temperature fluctuations. The peak temperatures will be lowered by the thermal inertia. By increasing the thermal mass, this effect can also be increased. Since the monument exists, nothing can be added to it. Only the concrete ground floor can be adjusted in thickness to adding thermal mass.

Natural ventilation

By making use of the temperature difference between inside and outside and the height difference of the design, natural ventilation in the form of stack ventilation can be applied, to create convective cooling air streams. The dome shape ensures natural air circulation due to an accelerated air flow. By letting the cooler air in at the bottom of the construction, the air will move through the room, warm up and move upwards. By letting out the heated air at the top of the construction, stack ventilation is created. By playing with the sizes of the different openings, the amount of natural ventilation can be adjusted. By evenly distributing several openings at the bottom of the construction, the air will also enter the construction in a divided manner, which ensures that the fresh air is distributed evenly throughout the space.

Fritting

Since large surfaces of glass are used in this design, a large amount of solar gain will also be caused. By using fritted glass this can be reduced, with respect to the glass. The sun is higher in summer than in winter. In the summer, most sun should be blocked and in winter it is desirable to let the sun through. By applying more fritting at the top of the construction than at the bottom, this effect can be achieved. The best for this design will therefore be a gradient of fritting. By using small circles that each cover little surface individually, these will be barely visible from a distance. By varying the density or diameters of these circles, a gradient can be created. By using a maximum fritting percentage of 50% on top of the construction a lot of solar gain is prevented in the summer. By pulling the fritting down to a fritting percentage of 0%, this will not be visible at all at the bottom of the construction. Nevertheless, a total of 25% of the glass surface is covered with fritting in this way, which leads to a 25% decrease in the total visible transmittance and solar transmittance value of the glass. See figure 90 for the look of the fritted glass design. Another possibility is to show the fritted glass by making fritted drawings on the glass of, for example, the history of Alkmaar or various iconic buildings of Alkmaar. This can give a playful shadow effect in the cheese bell.

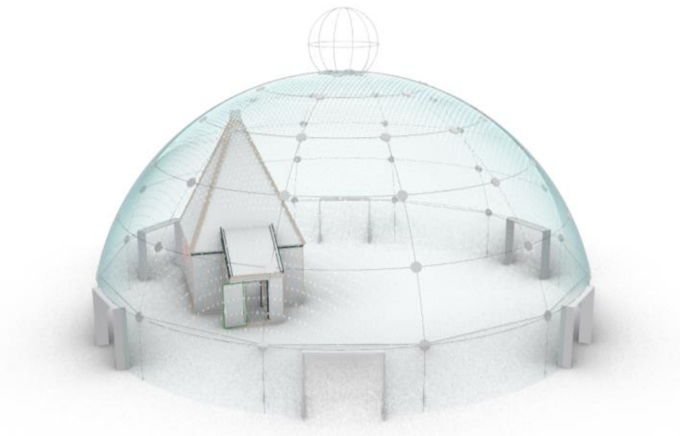


Figure 90: Design included fritted glass (own figure)

Switchable glass

Switchable glass can be used to reduce glare, solar heat gain and UV exposure by changing the light transmission properties (transparency), to transmit or block certain wavelengths of light. An advantage of switchable glass is that the transparency for heat radiation can be varied. By using a switchable glass type that only requires voltage in the active state, the energy consumption can be reduced by using this system. Because switchable glass affects full transparency in active state, this is only used as an emergency measure when the solar gain is too much. So this is only used at the hottest time of the day and the hottest days of summer to show the rest of the day a transparent design. See figure 91 for the appearance of the design with the active switchable glass.

Figure 91: Design included active switchable glass (own figure)

Additional mechanical cooling

In case the passive strategies do not remove enough heat from the dome, the thermal comfort should be achieved by using mechanical systems. A sustainable application of a mechanical system for cooling (and heating) is by using a heat pump. By using a heat pump with a high CoP, many of the requested cool needs can be reduced.

5.5 Construction and maintenance

To build the entire glass construction, work will have to be done from bottom to top, with care to the monument. The construction order is therefore simple:

1. Foundation
2. Base
3. Dome

The foundation and base can be built in a traditional way without any problems. Because the dome will function as a shell structure when the construction is complete. In order to be able to build the dome, a support structure is required under the final dome, over the monument.

A glass panel may break. Because the glass consists of several layers and is laminated, the panel will still be structural due to the whole layers of glass and the fracture pattern of the broken layer. To replace a broken panel it is necessary to install a temporary local support structure near the surrounding panels.

Because the design does not consist of horizontal surfaces, most of the dirt of the glass panels will flow away with the rainwater due to the angle of inclination and gravity. To clean the glass surface from dirt with only rainwater and without the necessary extra cleaning, a hydrophilic coating can be applied to the surface.

5.6 Structural verification

Because it has been found that the glass must be insulating, double glass is used. The 4 mm glass layer is added to the glass panels, but does not cooperate constructively. Only the weight influences the behavior of the construction. The mass density is therefore adjusted for the verification (1.13 times bigger).

Inputs

- Material properties (glass):
  - Mass density: 2833 kg/m^3

Results

Table 24 shows all maximum values of the glass in the dome of the final design. All different values per direction are shown in appendix E. The results of the clamp connection show that the largest deflections are in the middle of the edges of the panels. This is because there are no connections here. All forces go through the connections in the corners. In reality there will be nylon blocks between panels, with a maximum length of 200 mm and a thickness of 2/3 of the thickness of the glass. There will be a maximum of 3 of these blocks along the length of each panel. These blocks ensure that the vertical forces due to the self-weight and snow load are transferred via these blocks to the next panel. By filling the other openings with a black silicone (and over the blocks), these blocks will not be visible, but will participate in the transfer of forces. The values of the simulations will therefore be bigger than in reality, because these blocks are not included in the simulations.

Table 24: *Results maximum values dome* (own table)

Maximum deflection:	2.88 mm
Maximum stress (tension):	10.17 N/mm^2
Maximum stress (compression):	27.23 N/mm^2

5.7 Energy Plus analysis

The situation without any climate control will indicate the most extreme values. The hottest operative temperature in the dome over the hottest summer day, June 7, is 88.07°C. Figure 92 shows the temperatures during this day with all passive strategies applied. The maximum operative temperature in the dome is then only 45.39 °C. All temperatures and gains throughout the day can be seen in Appendix E.

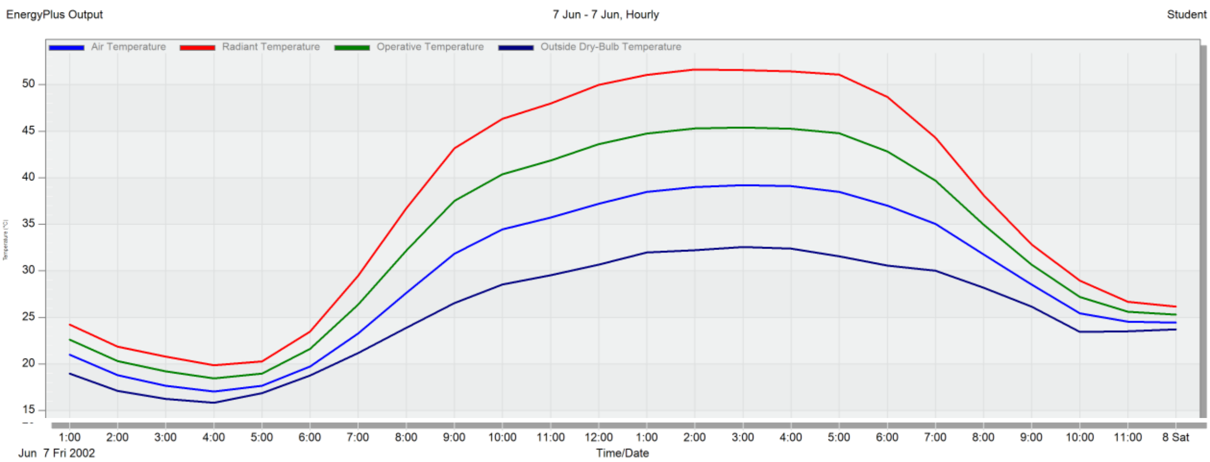


Figure 92: Temperatures over the hottest in the cheese bell including all passive strategies (own figure)

Figure 93 shows the temperatures during this day by using mechanical cooling. All temperatures and gains throughout the day can be seen in Appendix E.

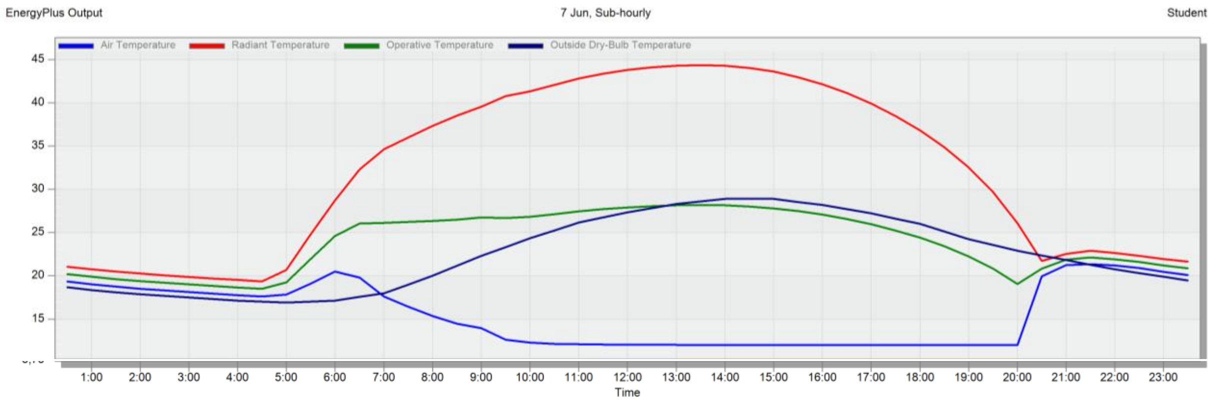


Figure 93: Temperatures over the hottest in the cheese bell using mechanical cooling (own figure)

By using a heat pump with a CoP of 3.5 for cooling, a cooling requirement of 352.44 kW equates to power demand of 352.44 / 3.5 = 100.70 Kw.

Figure 94: Final design (own figure)

6 DISCUSSION

6 DISCUSSION

For the structural verification, one-sixth of the total construction has been simulated, to save modeling time and simulation time. The actual values may therefore deviate, because the whole construction will probably behave differently. The values shown will give an indication of how the construction behaves.

The shown values of the structural verification are based on the used mesh. The used mesh was the maximum possible mesh with a student license. If the mesh is even smaller, more precise values will come out.

The Energy Plus simulations did not use surrounding design factors. The temperatures will therefore actually be lower, since the plot is surrounded by a lot of greenery and trees. This is positive because the temperatures will therefore actually be lower.

The hand calculations for natural ventilation will differ in reality, because the hand calculations do not take the wind into account. The wind that blows the air against and into the building influences the amount of natural ventilation.

Switchable glass can be used in curved surfaces. The developments in glass technology are not yet ready to apply this in double curved surfaces, with the assumed result of the design. In this research, switchable glass has been applied to achieve the desired result. If the glass technique is innovative enough, this can also be applied in double curved surfaces in the future.

The temperatures shown in the Energy Plus simulations give average temperatures in the entire dome. Since people are only in the lower part of the dome, temperatures will probably be lower here, because heat rises. This is good for the actual temperatures, because the showed temperatures are too high to provide the desired thermal comfort, with the given passive strategies.

7 CONCLUSION

7 CONCLUSION

This research focused on this main question:

"How can a full glass dome structure be built, to cover 'Het Kruithuisje' in Alkmaar, The Netherlands, in which the thermal comfort is maintained in the most passive manner, without impeding the visual benefits of glass?".

In order to answer this question, a design has been made in this research. The question can be answered based on the design.

Because a dome structure is a structure where the surface can bear the loads, there is no construction required to support the surface. A dome structure is suitable to construct glass structures, because most of the internal dome forces are in compression and glass can handle a high tensile strength. Because glass has a number of properties that are not entirely suitable for a construction material the glass must to be strengthened to make glass a safer construction material and to give glass a greater bearing capacity. Thermal treatment makes the glass better protected against temperature differences and mechanical shocks. For safety reasons, the glass has to consist of several glass layers. To increase the load-bearing capacity, strengthening by laminating is also needed. To get the shape of a cheese bell, a spherical double-curved surface is required. To build this entire construction, the shape must be divided into panels. To approximate the dome shape hot bended double curved panels are needed. To be able to build with glass, connections are needed between the various glass components. To achieve high transparency and low peak stresses, a combination of adhesive connections and dry assembly connections can be used. A risk analysis must determine the probability that damage will occur. If this probability is too high, adjustments must be made in the design.

Designing with glass creates thermal comfort problems, especially in the summer. These problems can be easily solved by using a lot of energy, which is not a sustainable solution. With passive strategies, a large part of this requested energy can be removed. For the design with the used passive strategies; thermal mass, natural ventilation, low-E coatings, fritting of glass and switchable glass, the operative temperature on the hottest day of summer is reduced from 88.07 °C to 45.39 °C. The remaining temperature reduction required to achieve thermal comfort must be solved by mechanical systems. A more sustainable application of a mechanical system for cooling (and heating) is by using a heat pump. In order to take away as much energy as possible in a passive manner, there must be compromised on transparency.

7.1 Recommendations

In this research, a dome was designed by building it from double curved panels. No research has been conducted into other ways of building it from panels. Perhaps building it form segmented flat panels will provide other structural results.

In this research is focused on the building physical aspect of thermal comfort. There are more aspects to ensure comfort in a building. Designing with glass does not only cause thermal comfort problems. Any subsequent research can investigate another building physics aspect, such as acoustics or humidity management.

This design was created to house a restaurant under the dome. Is it possible to accommodate another function here in the future? Should major changes be made to do this?

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APPENDIXES

APPENDIXES

Table of contents

Appendix A: Form finding

Table 1: *Structural verification paraboloid shape* (own table)

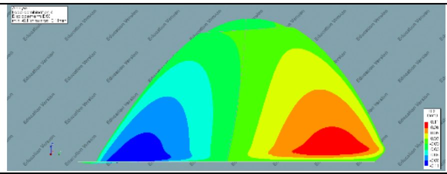
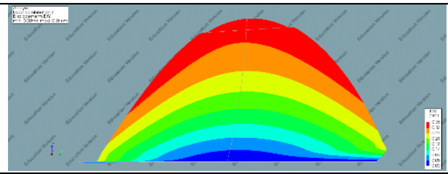
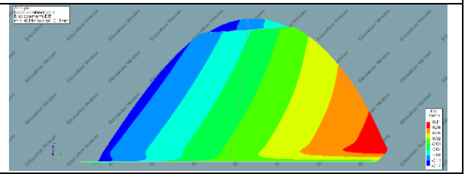
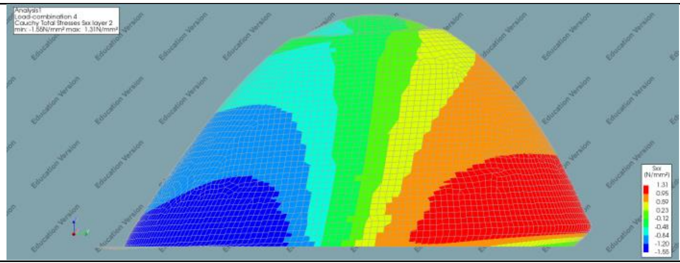
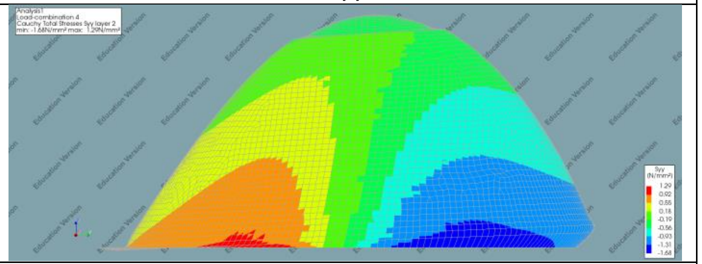
<table>
<tr><th colspan="4">Deflection:</th></tr>
<tr><td>Type deflection:</td><td>DtX</td><td>DtY</td><td>DtZ</td></tr>
<tr><td>Result:</td><td></td><td></td><td></td></tr>
<tr><td>Maximum deflection:</td><td>0.11 mm</td><td>0.36 mm</td><td>0.14 mm</td></tr>
<tr><th colspan="4">Stress:</th></tr>
<tr><td>Type stress:</td><td colspan="2">Sxx</td><td>Syy</td></tr>
<tr><td>Result:</td><td colspan="2"></td><td></td></tr>
<tr><td>Maximum stress (tension):</td><td colspan="2">1.31 N/mm^2</td><td>1.29 N/mm^2</td></tr>
<tr><td>Maximum stress (compression):</td><td colspan="2">1.55 N/mm^2</td><td>1.68 N/mm^2</td></tr>
</table>

Table 2: *Structural verification hemisphere shape* (own table)

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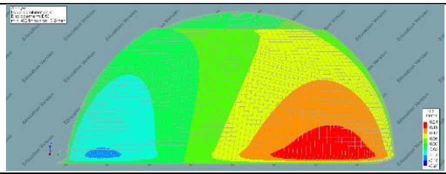
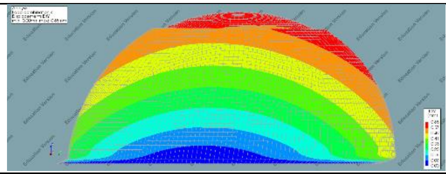
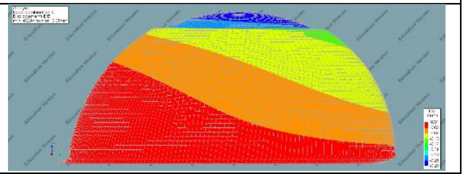
<tr><td>Result:</td><td></td><td></td><td></td></tr>
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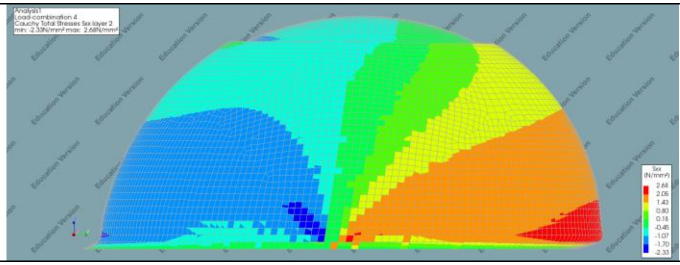
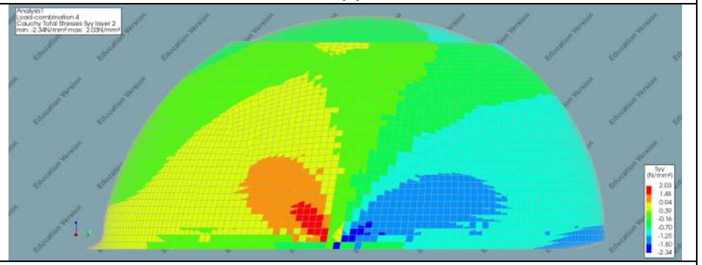
<tr><td>Result:</td><td colspan="2"></td><td></td></tr>
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<tr><td>Maximum stress (compression):</td><td colspan="2">2.33 N/mm^2</td><td>2.34 N/mm^2</td></tr>
</table>

Appendix B: Dome connections

Table 1: *Structural verification dome connection clamp connection 150 mm diameter direction 1* (own table)

<table>
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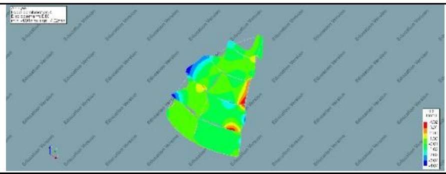
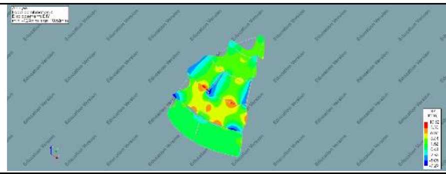
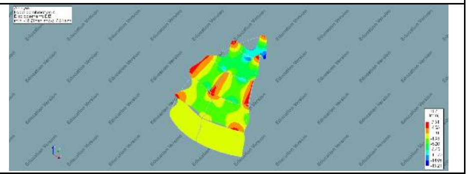
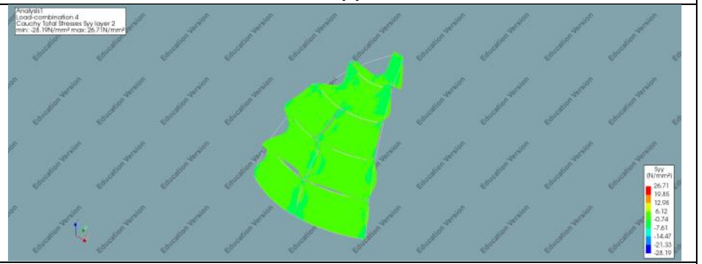
<tr><td>Type deflection:</td><td colspan="2">DtX</td><td colspan="2">DtY</td><td colspan="2">DtZ</td></tr>
<tr><td>Result:</td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>Maximum deflection:</td><td colspan="2">4.04 mm</td><td colspan="2">10.52 mm</td><td colspan="2">18.21 mm</td></tr>
<tr><th colspan="7">Stress:</th></tr>
<tr><td>Type stress:</td><td colspan="3">Sxx</td><td colspan="3">Syy</td></tr>
<tr><td>Result:</td><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td>Maximum stress (tension):</td><td colspan="3">17.16 N/mm^2</td><td colspan="3">26.71 N/mm^2</td></tr>
<tr><td>Maximum stress (compression):</td><td colspan="3">31.26 N/mm^2</td><td colspan="3">28.19 N/mm^2</td></tr>
</table>

Table 2: *Structural verification dome connection clamp connection 150 mm diameter direction 2* (own table)

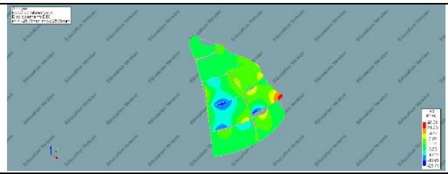
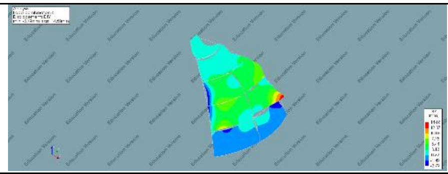
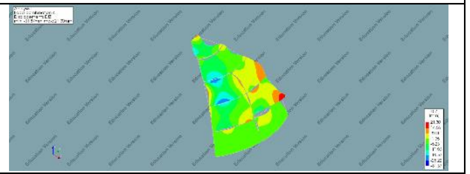
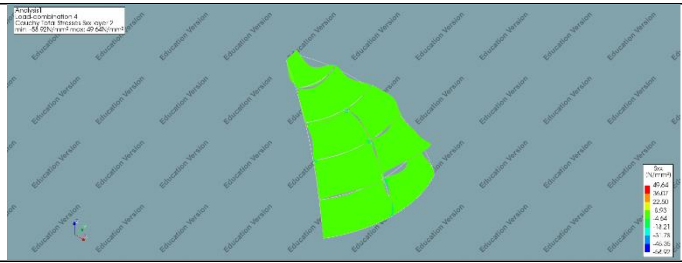
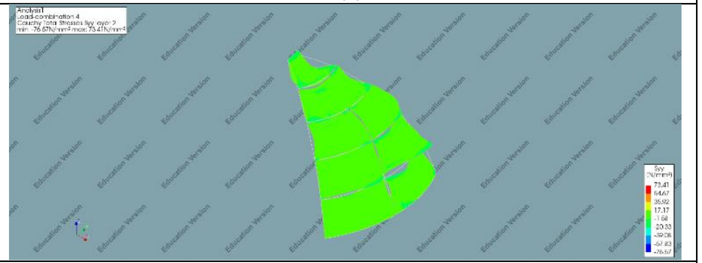
<table>
<tr><td colspan="7">Deflection:</td></tr>
<tr><td>Type deflection:</td><td colspan="2">DtX</td><td colspan="2">DtY</td><td colspan="2">DtZ</td></tr>
<tr><td>Result:</td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>Maximum deflection:</td><td colspan="2">28.05 mm</td><td colspan="2">14.68 mm</td><td colspan="2">31.87 mm</td></tr>
<tr><td colspan="7">Stress:</td></tr>
<tr><td>Type stress:</td><td colspan="3">Sxx</td><td colspan="3">Syy</td></tr>
<tr><td>Result:</td><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td>Maximum stress (tension):</td><td colspan="3">49.64 N/mm^2</td><td colspan="3">73.41 N/mm^2</td></tr>
<tr><td>Maximum stress (compression):</td><td colspan="3">58.92 N/mm^2</td><td colspan="3">76.57 N/mm^2</td></tr>
</table>

Table 3: *Structural verification dome connection clamp connection 150 mm diameter direction 3* (own table)

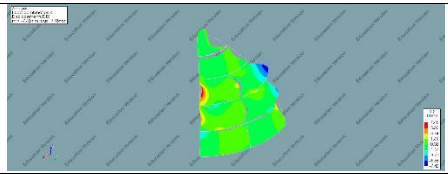
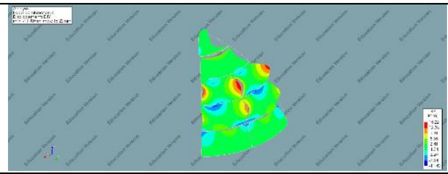
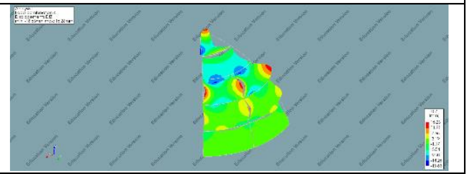
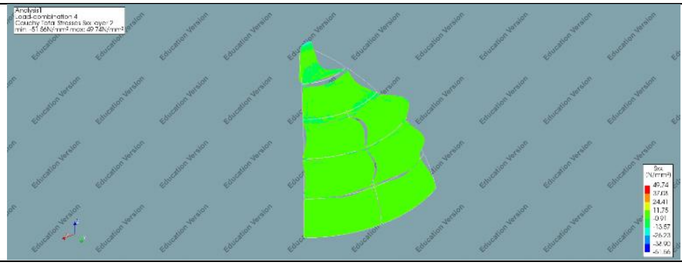
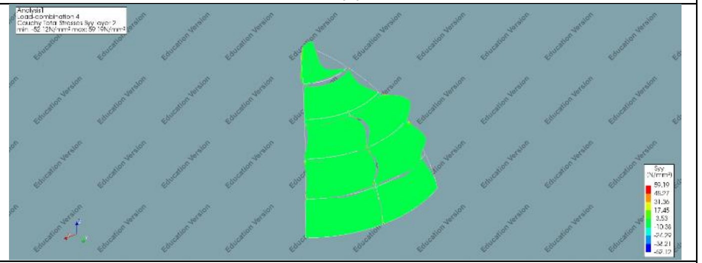
Deflection:			
Type deflection:	DtX	DtY	DtZ
Result:			
Maximum deflection:	7.46 mm	16.22 mm	18.63 mm
Stress:			
Type stress:	Sxx	Syy	
Result:			
Maximum stress (tension):	49.74 N/mm^2	59.19 N/mm^2	
Maximum stress (compression):	51.56 N/mm^2	52.12 N/mm^2	

Table 4: *Structural verification dome connection clamp connection 300 mm diameter direction 1* (own table)

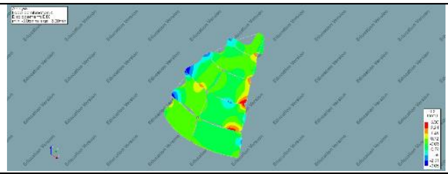
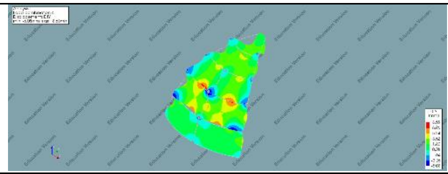
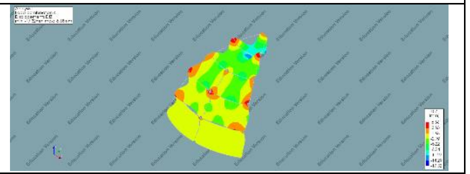
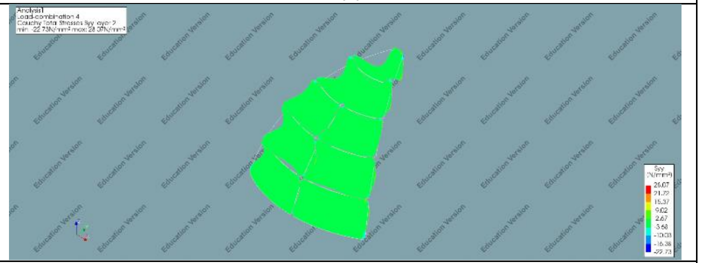
<table>
<tr><th colspan="4">Deflection:</th></tr>
<tr><td>Type deflection:</td><td>DtX</td><td>DtY</td><td>DtZ</td></tr>
<tr><td>Result:</td><td></td><td></td><td></td></tr>
<tr><td>Maximum deflection:</td><td>3.06 mm</td><td>8.68 mm</td><td>17.32 mm</td></tr>
<tr><th colspan="4">Stress:</th></tr>
<tr><td>Type stress:</td><td colspan="2">Sxx</td><td>Syy</td></tr>
<tr><td>Result:</td><td colspan="2"></td><td></td></tr>
<tr><td>Maximum stress (tension):</td><td colspan="2">17.78 N/mm^2</td><td>28.07 N/mm^2</td></tr>
<tr><td>Maximum stress (compression):</td><td colspan="2">22.58 N/mm^2</td><td>22.73 N/mm^2</td></tr>
</table>

Table 5: *Structural verification dome connection clamp connection 300 mm diameter direction 2* (own table)

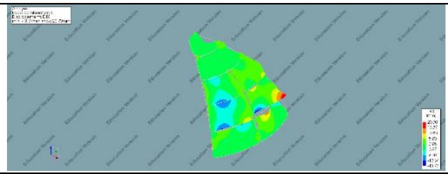
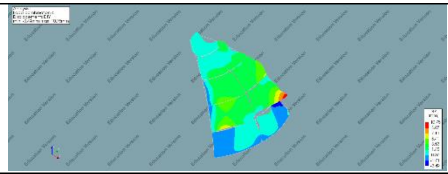
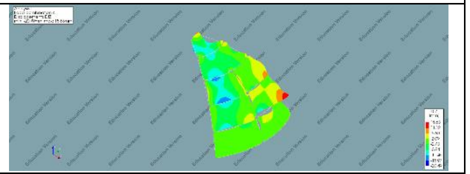
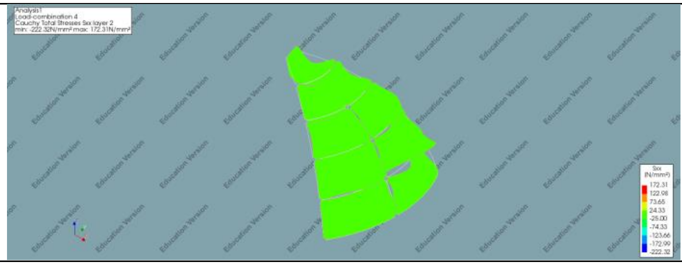
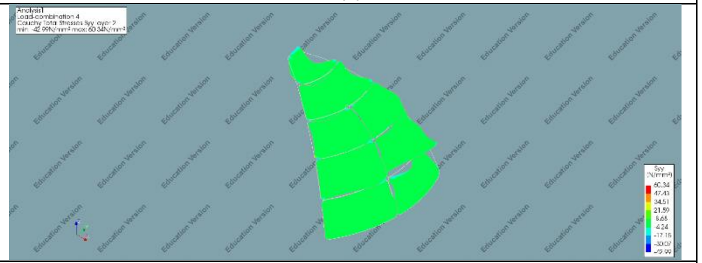
Deflection:			
Type deflection:	DtX	DtY	DtZ
Result:			
Maximum deflection:	20.70 mm	10.75 mm	20.49 mm
Stress:			
Type stress:	Sxx		Syy
Result:			
Maximum stress (tension):	28.20 N/mm^2		60.34 N/mm^2
Maximum stress (compression):	33.27 N/mm^2		42.99 N/mm^2

Table 6: *Structural verification dome connection clamp connection 300 mm diameter direction 3* (own table)

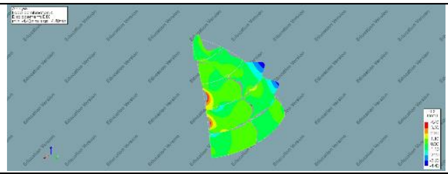
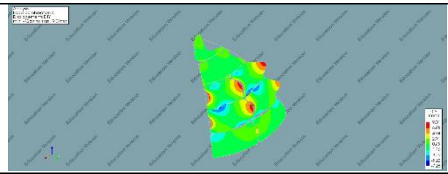
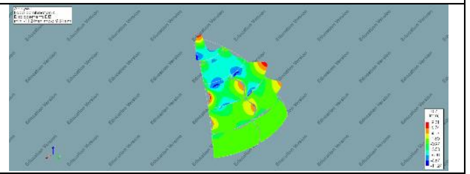
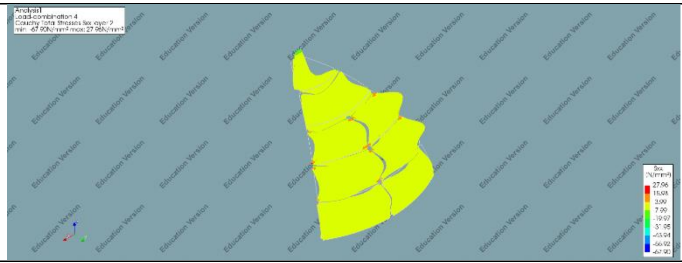
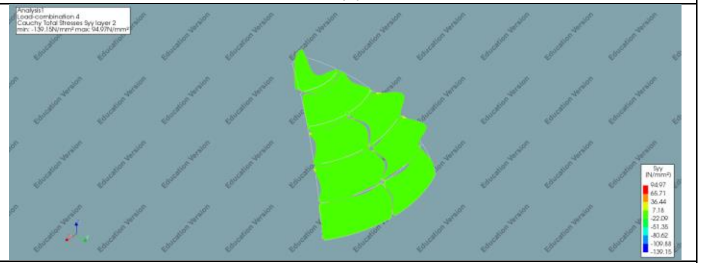
Deflection:			
Type deflection:	DtX	DtY	DtZ
Result:			
Maximum deflection:	4.40 mm	9.01 mm	11.24 mm
Stress:			
Type stress:	Sxx	Syy	
Result:			
Maximum stress (tension):	27.96 N/mm^2	49.07 N/mm^2	
Maximum stress (compression):	67.90 N/mm^2	29.39 N/mm^2	

Table 7: *Structural verification dome connection clamp connection 450 mm diameter direction 1* (own table)

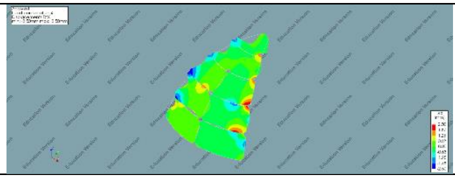
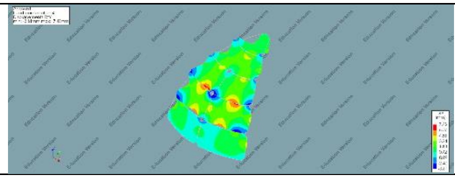
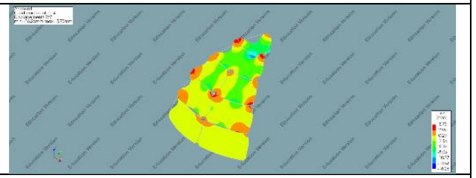
Deflection:			
Type deflection:	DtX	DtY	DtZ
Result:			
Maximum deflection:	2.50 mm	7.48 mm	16.26 mm
Stress:			
Type stress:	Sxx	Syy	
Result:			
Maximum stress (tension):	15.60 N/mm^2	13.35 N/mm^2	
Maximum stress (compression):	14.84 N/mm^2	18.54 N/mm^2	

Table 8: *Structural verification dome connection clamp connection 450 mm diameter direction 2* (own table)

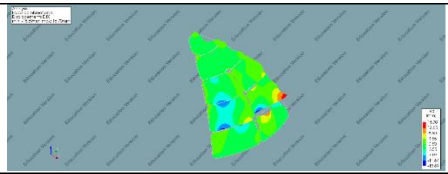
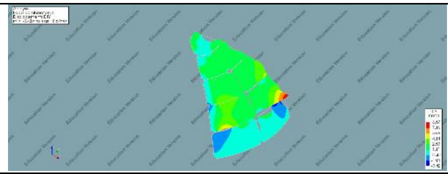
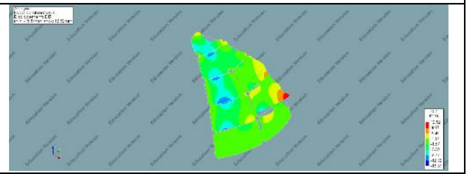
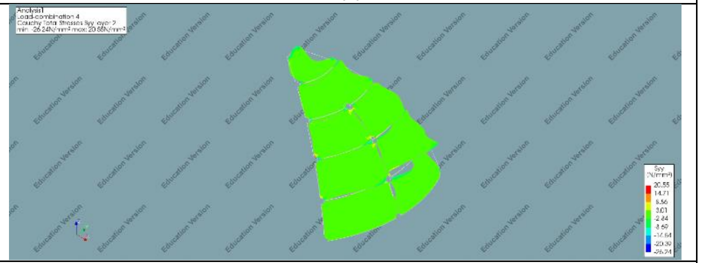
Deflection:			
Type deflection:	DtX	DtY	DtZ
Result:			
Maximum deflection:	16.70 mm	8.67 mm	15.87 mm
Stress:			
Type stress:	Sxx	Syy	
Result:			
Maximum stress (tension):	21.03 N/mm^2	20.55 N/mm^2	
Maximum stress (compression):	43.48 N/mm^2	26.24 N/mm^2	

Table 9: *Structural verification dome connection clamp connection 450 mm diameter direction 3* (own table)

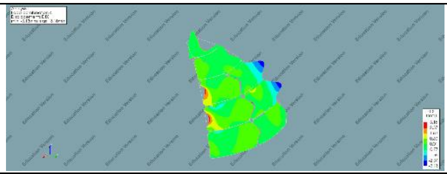
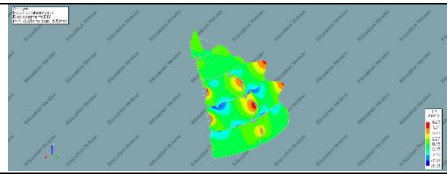
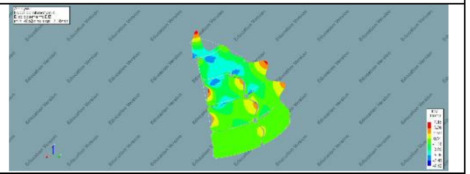
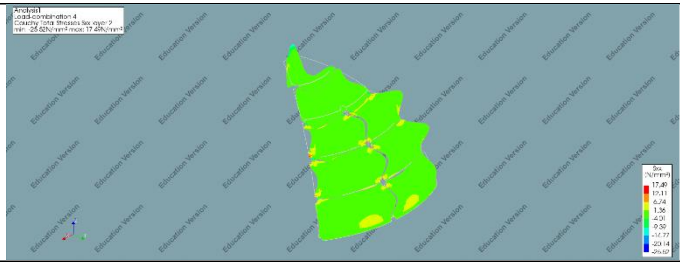
<table>
<tr><th colspan="7">Deflection:</th></tr>
<tr><td>Type deflection:</td><td colspan="2">DtX</td><td colspan="2">DtY</td><td colspan="2">DtZ</td></tr>
<tr><td>Result:</td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>Maximum deflection:</td><td colspan="2">3.16 mm</td><td colspan="2">6.83 mm</td><td colspan="2">9.52 mm</td></tr>
<tr><th colspan="7">Stress:</th></tr>
<tr><td>Type stress:</td><td colspan="3">Sxx</td><td colspan="3">Syy</td></tr>
<tr><td>Result:</td><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td>Maximum stress (tension):</td><td colspan="3">17.49 N/mm^2</td><td colspan="3">30.79 N/mm^2</td></tr>
<tr><td>Maximum stress (compression):</td><td colspan="3">25.52 N/mm^2</td><td colspan="3">32.44 N/mm^2</td></tr>
</table>

Table 10: *Structural verification dome connection clamp connection 600 mm diameter direction 1* (own table)

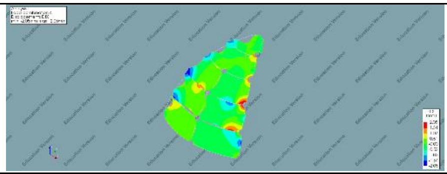
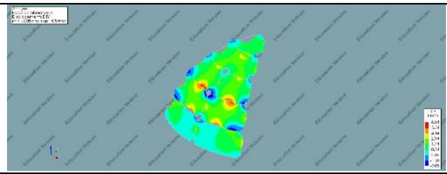
<table>
<tr><th colspan="4">Deflection:</th></tr>
<tr><td>Type deflection:</td><td>DtX</td><td>DtY</td><td>DtZ</td></tr>
<tr><td>Result:</td><td></td><td></td><td></td></tr>
<tr><td>Maximum deflection:</td><td>2.05 mm</td><td>6.54 mm</td><td>14.80 mm</td></tr>
<tr><th colspan="4">Stress:</th></tr>
<tr><td>Type stress:</td><td colspan="2">Sxx</td><td>Syy</td></tr>
<tr><td>Result:</td><td colspan="2"></td><td></td></tr>
<tr><td>Maximum stress (tension):</td><td colspan="2">12.08 N/mm^2</td><td>11.66 N/mm^2</td></tr>
<tr><td>Maximum stress (compression):</td><td colspan="2">11.58 N/mm^2</td><td>17.95 N/mm^2</td></tr>
</table>

Table 11: *Structural verification dome connection clamp connection 600 mm diameter direction 2* (own table)

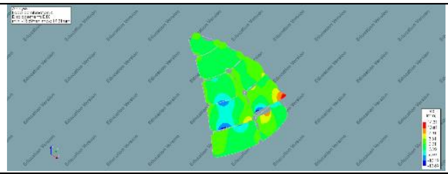
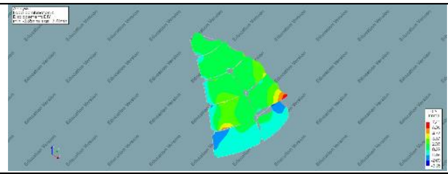
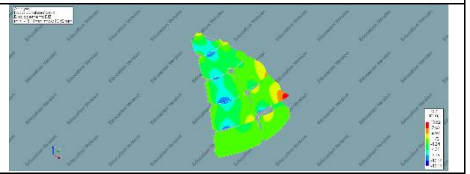
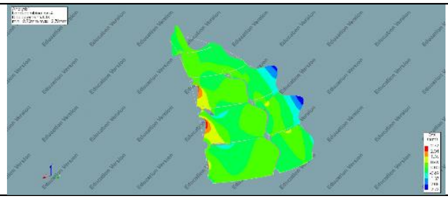
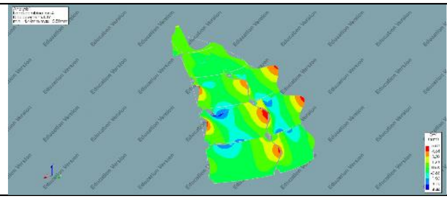
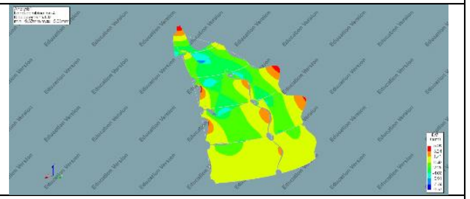
<table>
<tr><th colspan="7">Deflection:</th></tr>
<tr><td>Type deflection:</td><td colspan="2">DtX</td><td colspan="2">DtY</td><td colspan="2">DtZ</td></tr>
<tr><td>Result:</td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>Maximum deflection:</td><td colspan="2">14.31 mm</td><td colspan="2">7.41 mm</td><td colspan="2">13.11 mm</td></tr>
<tr><th colspan="7">Stress:</th></tr>
<tr><td>Type stress:</td><td colspan="3">Sxx</td><td colspan="3">Syy</td></tr>
<tr><td>Result:</td><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td>Maximum stress (tension):</td><td colspan="3">17.58 N/mm^2</td><td colspan="3">11.22 N/mm^2</td></tr>
<tr><td>Maximum stress (compression):</td><td colspan="3">33.91 N/mm^2</td><td colspan="3">23.05 N/mm^2</td></tr>
</table>

Table 12: *Structural verification dome connection clamp connection 600 mm diameter direction 3* (own table)

Deflection:			
Type deflection:	DtX	DtY	DtZ
Result:			
Maximum deflection:	2.73 mm	5.59 mm	9.57 mm

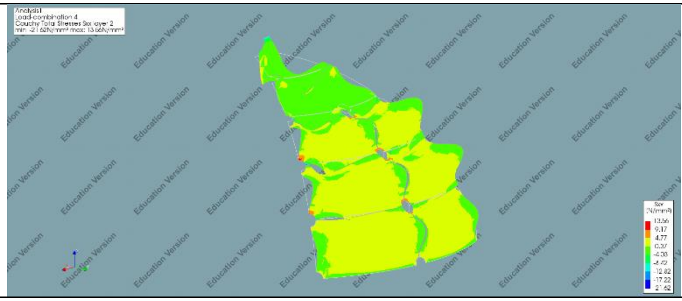
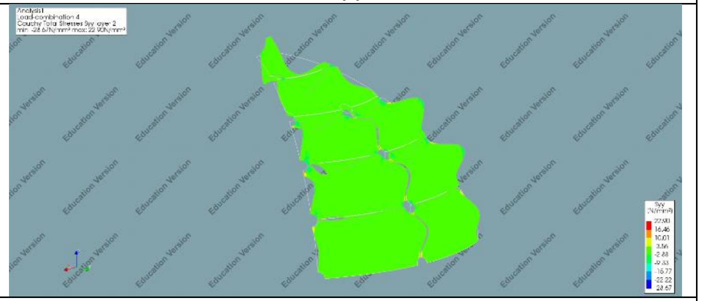
Stress:		
Type stress:	Sxx	Syy
Result:		
Maximum stress (tension):	13.56 N/mm^2	22.90 N/mm^2
Maximum stress (compression):	21.62 N/mm^2	28.67 N/mm^2

Table 13: *Structural verification dome connection glued butt joint connection direction 1* (own table)

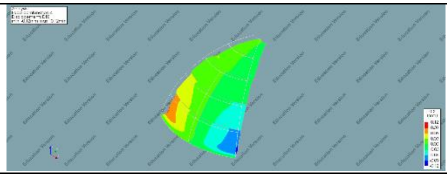
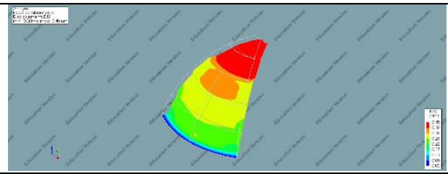
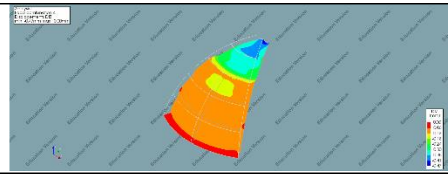
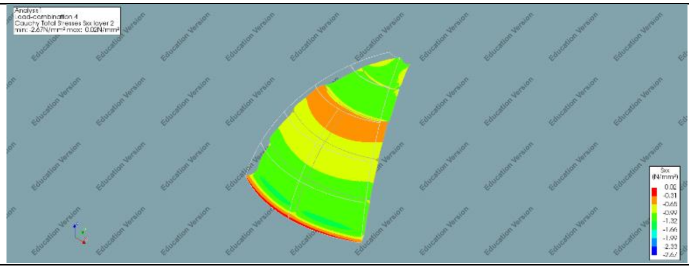
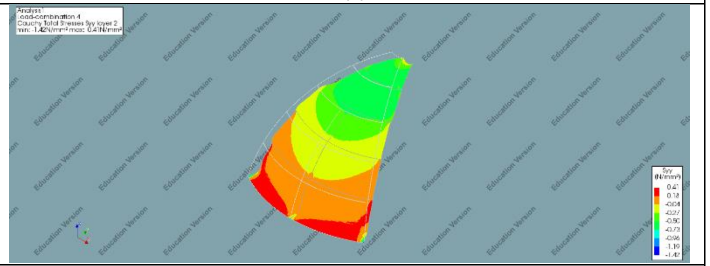
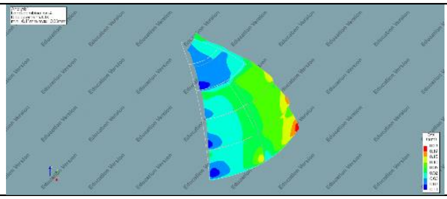
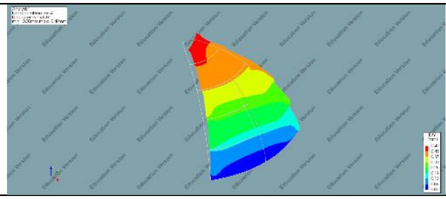
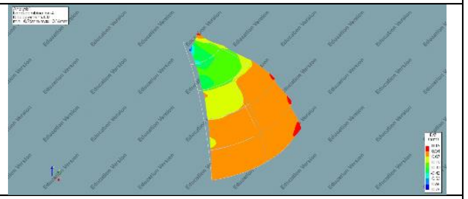
<table>
<tr><th colspan="7">Deflection:</th></tr>
<tr><td>Type deflection:</td><td colspan="2">DtX</td><td colspan="2">DtY</td><td colspan="2">DtZ</td></tr>
<tr><td>Result:</td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>Maximum deflection:</td><td colspan="2">0.12 mm</td><td colspan="2">0.45 mm</td><td colspan="2">0.47 mm</td></tr>
<tr><th colspan="7">Stress:</th></tr>
<tr><td>Type stress:</td><td colspan="3">Sxx</td><td colspan="3">Syy</td></tr>
<tr><td>Result:</td><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td>Maximum stress (tension):</td><td colspan="3">0.02 N/mm^2</td><td colspan="3">0.41 N/mm^2</td></tr>
<tr><td>Maximum stress (compression):</td><td colspan="3">2.67 N/mm^2</td><td colspan="3">1.42 N/mm^2</td></tr>
</table>

Table 14: *Structural verification dome connection glued butt joint connection direction 2* (own table)

Deflection:			
Type deflection:	DtX	DtY	DtZ
Result:			
Maximum deflection:	0.23 mm	0.49 mm	0.76 mm

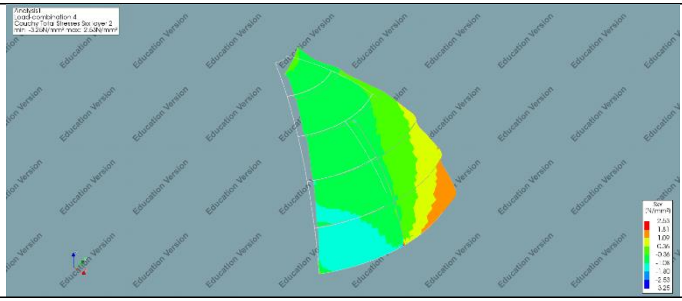
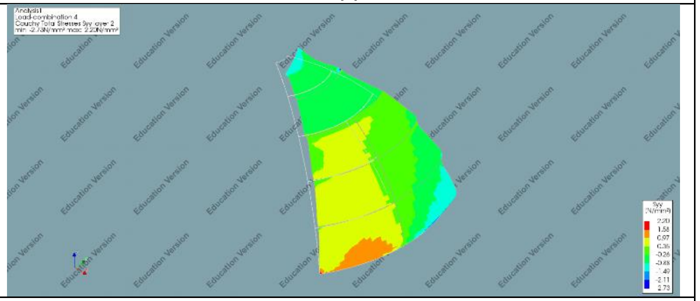
Stress:		
Type stress:	Sxx	Syy
Result:		
Maximum stress (tension):	2.53 N/mm^2	2.20 N/mm^2
Maximum stress (compression):	3.25 N/mm^2	2.73 N/mm^2

Table 15: *Structural verification dome connection glued butt joint connection direction 3* (own table)

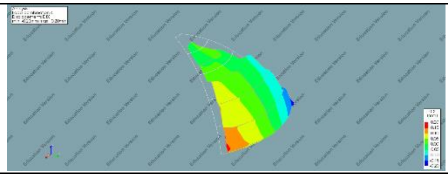
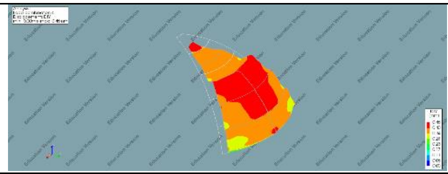
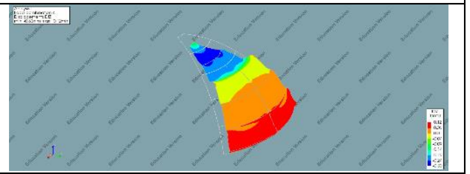
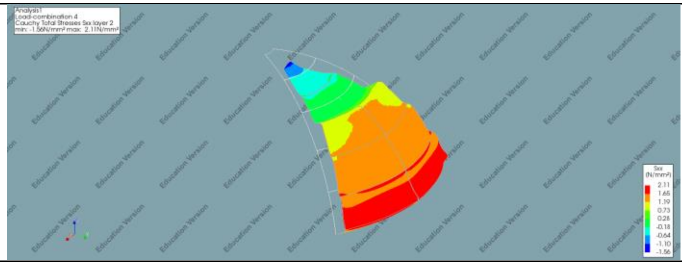
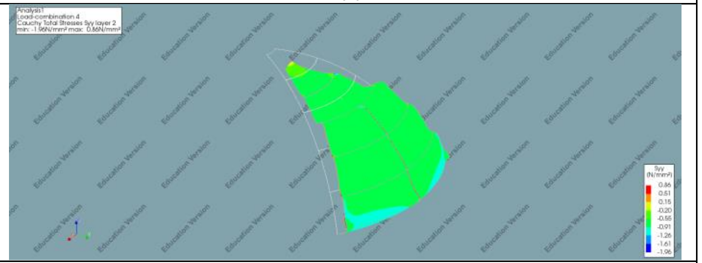
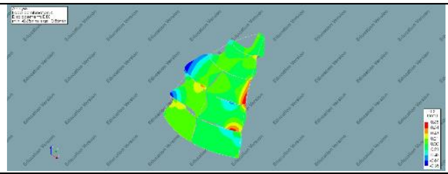
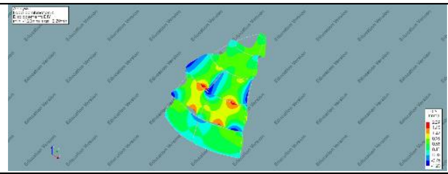
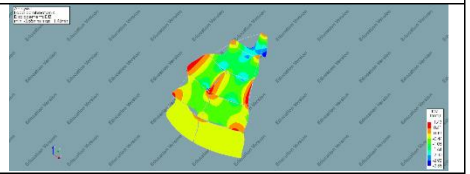
Deflection:			
Type deflection:	DtX	DtY	DtZ
Result:			
Maximum deflection:	0.20 mm	0.46 mm	0.30 mm
Stress:			
Type stress:	Sxx		Syy
Result:			
Maximum stress (tension):	2.11 N/mm^2		0.86 N/mm^2
Maximum stress (compression):	1.56 N/mm^2		1.96 N/mm^2

Table 16: *Structural verification dome connection clamp connection 150 mm diameter glass thickness 20mm direction 1* (own table)

Deflection:			
Type deflection:	DtX	DtY	DtZ
Result:			
Maximum deflection:	0.85 mm	2.29 mm	3.55 mm

Stress:		
Type stress:	Sxx	Syy
Result:		
Maximum stress (tension):	4.68 N/mm^2	5.99 N/mm^2
Maximum stress (compression):	11.43 N/mm^2	8.03 N/mm^2

Table 17: *Structural verification dome connection clamp connection 150 mm diameter glass thickness 20mm direction 2* (own table)

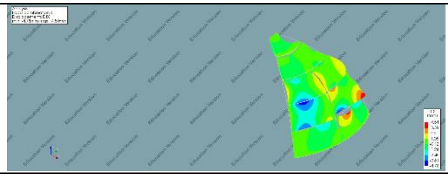
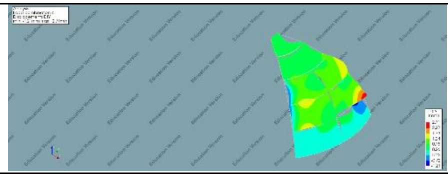
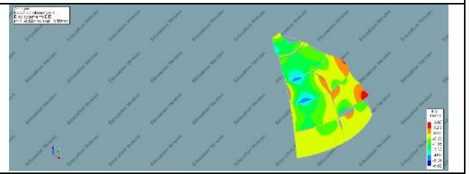
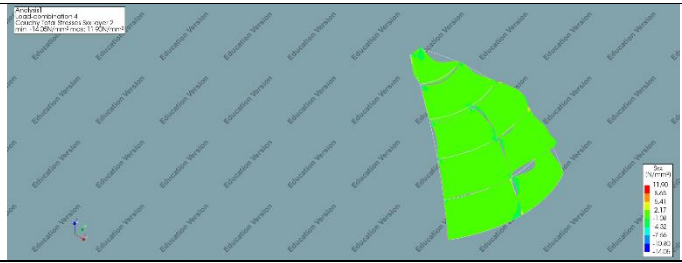
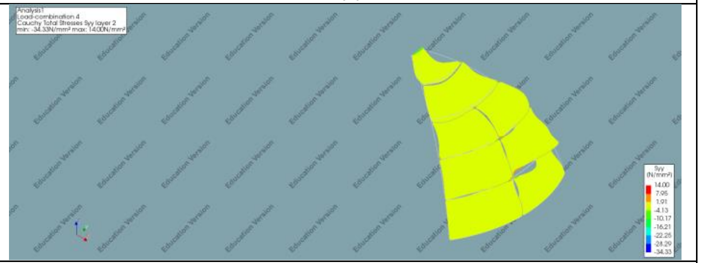
<table>
<tr><td colspan="7">Deflection:</td></tr>
<tr><td>Type deflection:</td><td colspan="2">DtX</td><td colspan="2">DtY</td><td colspan="2">DtZ</td></tr>
<tr><td>Result:</td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>Maximum deflection:</td><td colspan="2">4.78 mm</td><td colspan="2">2.71 mm</td><td colspan="2">6.62 mm</td></tr>
<tr><td colspan="7">Stress:</td></tr>
<tr><td>Type stress:</td><td colspan="3">Sxx</td><td colspan="3">Syy</td></tr>
<tr><td>Result:</td><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td>Maximum stress (tension):</td><td colspan="3">11.90 N/mm^2</td><td colspan="3">14.00 N/mm^2</td></tr>
<tr><td>Maximum stress (compression):</td><td colspan="3">14.05 N/mm^2</td><td colspan="3">34.33 N/mm^2</td></tr>
</table>

Table 18: *Structural verification dome connection clamp connection 150 mm diameter glass thickness 20mm direction 3* (own table)

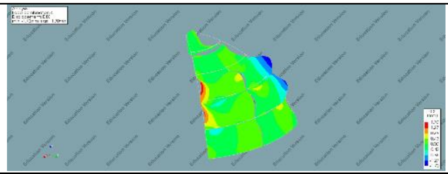
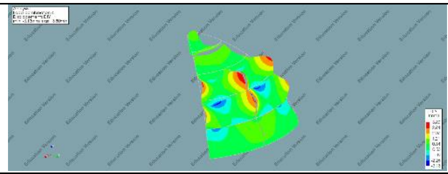
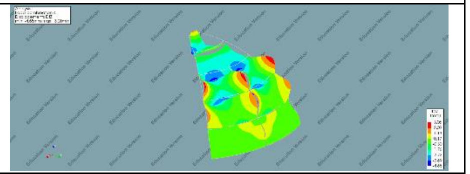
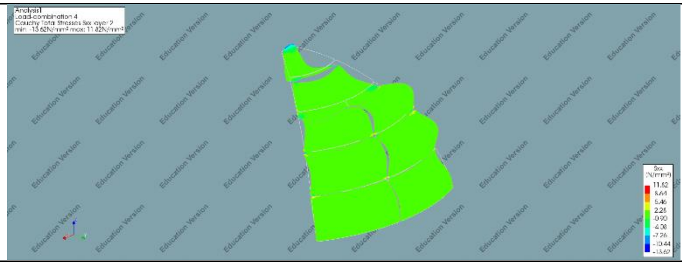
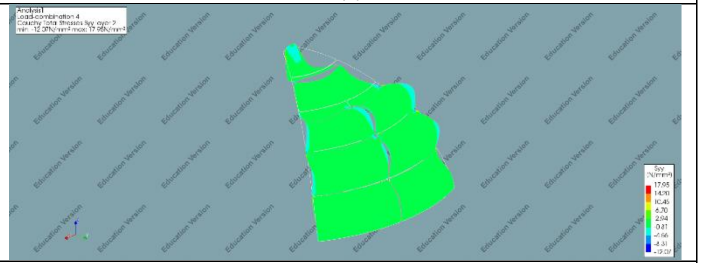
<table>
<tr><th colspan="6">Deflection:</th></tr>
<tr><td>Type deflection:</td><td>DtX</td><td colspan="2">DtY</td><td colspan="2">DtZ</td></tr>
<tr><td>Result:</td><td></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>Maximum deflection:</td><td>1.70 mm</td><td colspan="2">3.80 mm</td><td colspan="2">4.65 mm</td></tr>
<tr><th colspan="6">Stress:</th></tr>
<tr><td>Type stress:</td><td colspan="2">Sxx</td><td colspan="3">Syy</td></tr>
<tr><td>Result:</td><td colspan="2"></td><td colspan="3"></td></tr>
<tr><td>Maximum stress (tension):</td><td colspan="2">11.82 N/mm^2</td><td colspan="3">17.95 N/mm^2</td></tr>
<tr><td>Maximum stress (compression):</td><td colspan="2">13.62 N/mm^2</td><td colspan="3">12.07 N/mm^2</td></tr>
</table>

Table 19: *Structural verification dome connection clamp connection 150 mm diameter glass thickness 30mm direction 1* (own table)

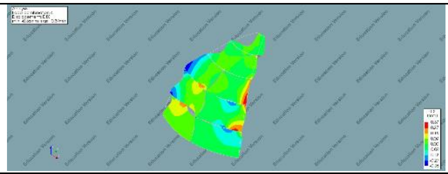
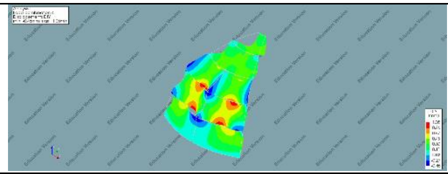
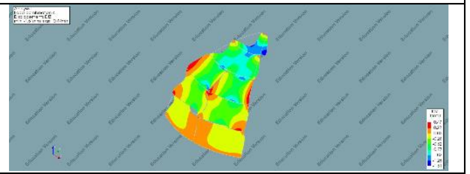
<table>
<tr><th colspan="7">Deflection:</th></tr>
<tr><td>Type deflection:</td><td colspan="2">DtX</td><td colspan="2">DtY</td><td colspan="2">DtZ</td></tr>
<tr><td>Result:</td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>Maximum deflection:</td><td colspan="2">0.37 mm</td><td colspan="2">1.05 mm</td><td colspan="2">1.51 mm</td></tr>
<tr><th colspan="7">Stress:</th></tr>
<tr><td>Type stress:</td><td colspan="3">Sxx</td><td colspan="3">Syy</td></tr>
<tr><td>Result:</td><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td>Maximum stress (tension):</td><td colspan="3">3.29 N/mm^2</td><td colspan="3">3.90 N/mm^2</td></tr>
<tr><td>Maximum stress (compression):</td><td colspan="3">7.46 N/mm^2</td><td colspan="3">5.47 N/mm^2</td></tr>
</table>

Table 20: *Structural verification dome connection clamp connection 150 mm diameter glass thickness 30mm direction 2* (own table)

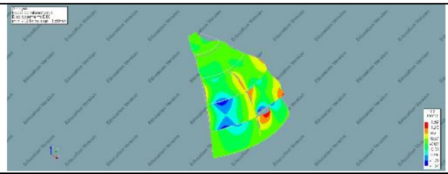
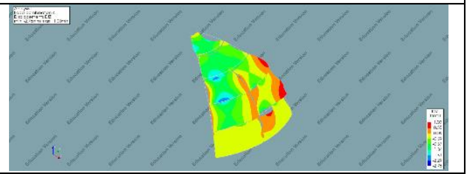
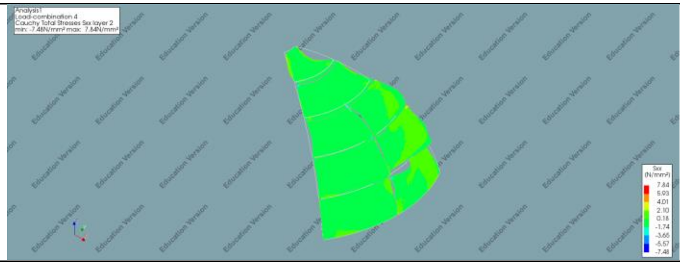
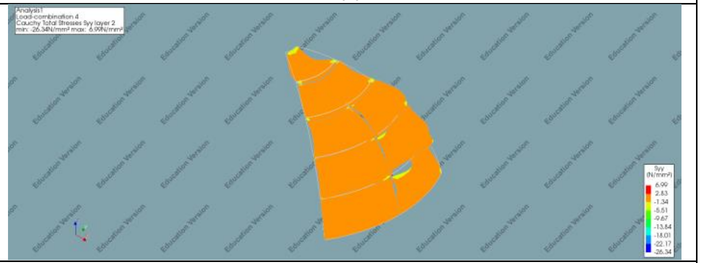
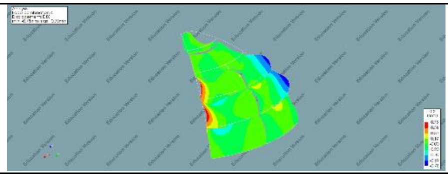
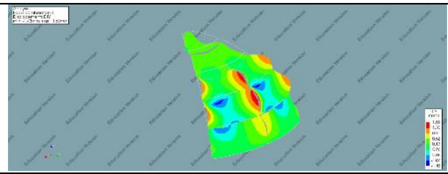
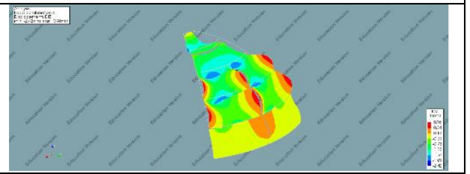
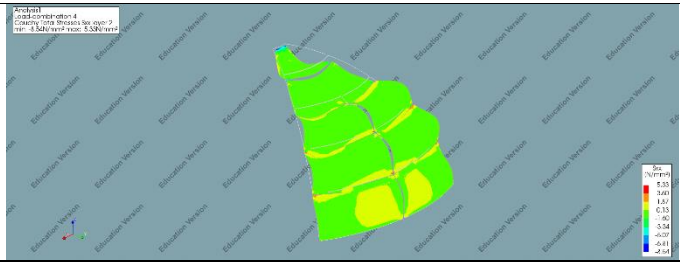
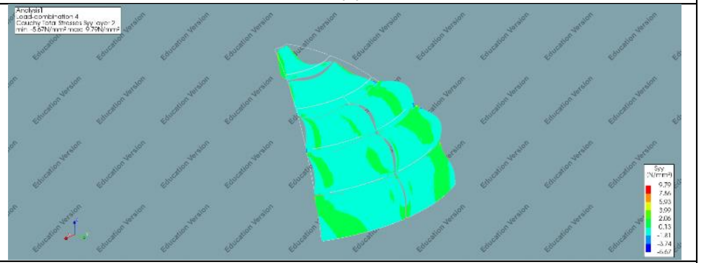
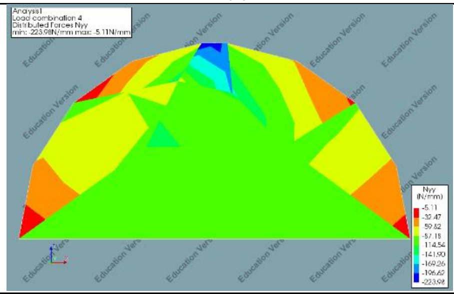
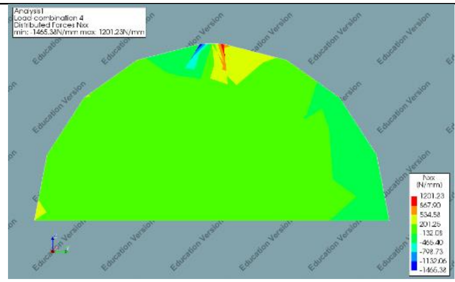
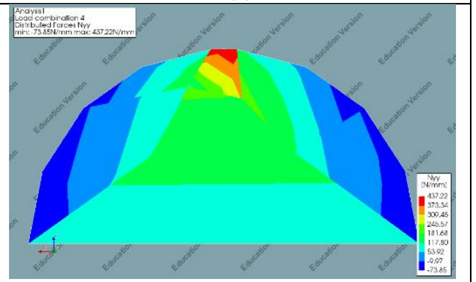
<table>
<tr><th colspan="4">Deflection:</th></tr>
<tr><td>Type deflection:</td><td>DtX</td><td>DtY</td><td>DtZ</td></tr>
<tr><td>Result:</td><td></td><td></td><td></td></tr>
<tr><td>Maximum deflection:</td><td>1.84 mm</td><td>0.99 mm</td><td>2.76 mm</td></tr>
<tr><th colspan="4">Stress:</th></tr>
<tr><td>Type stress:</td><td colspan="2">Sxx</td><td>Syy</td></tr>
<tr><td>Result:</td><td colspan="2"></td><td></td></tr>
<tr><td>Maximum stress (tension):</td><td colspan="2">7.84 N/mm^2</td><td>6.99 N/mm^2</td></tr>
<tr><td>Maximum stress (compression):</td><td colspan="2">7.48 N/mm^2</td><td>26.34 N/mm^2</td></tr>
</table>

Table 21: *Structural verification dome connection clamp connection 150 mm diameter glass thickness 30mm direction 3* (own table)

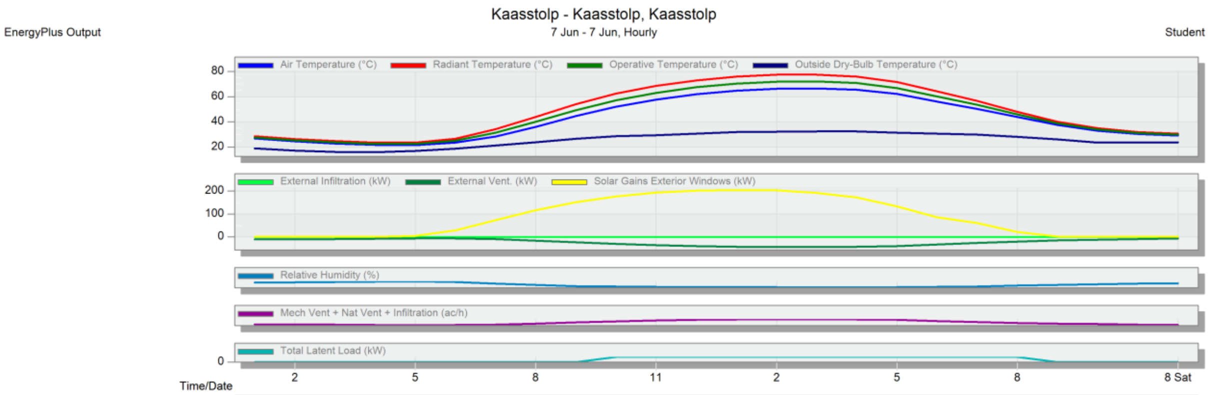
<table>
<tr><th colspan="4">Deflection:</th></tr>
<tr><td>Type deflection:</td><td>DtX</td><td>DtY</td><td>DtZ</td></tr>
<tr><td>Result:</td><td></td><td></td><td></td></tr>
<tr><td>Maximum deflection:</td><td>0.78 mm</td><td>1.68 mm</td><td>2.42 mm</td></tr>
<tr><th colspan="4">Stress:</th></tr>
<tr><td>Type stress:</td><td colspan="2">Sxx</td><td>Syy</td></tr>
<tr><td>Result:</td><td colspan="2"></td><td></td></tr>
<tr><td>Maximum stress (tension):</td><td colspan="2">5.33 N/mm^2</td><td>9.79 N/mm^2</td></tr>
<tr><td>Maximum stress (compression):</td><td colspan="2">8.54 N/mm^2</td><td>5.67 N/mm^2</td></tr>
</table>

Appendix C: Distributed forces connection between dome and base

Table 1: *Distributed forces connection between dome and base* (own table)

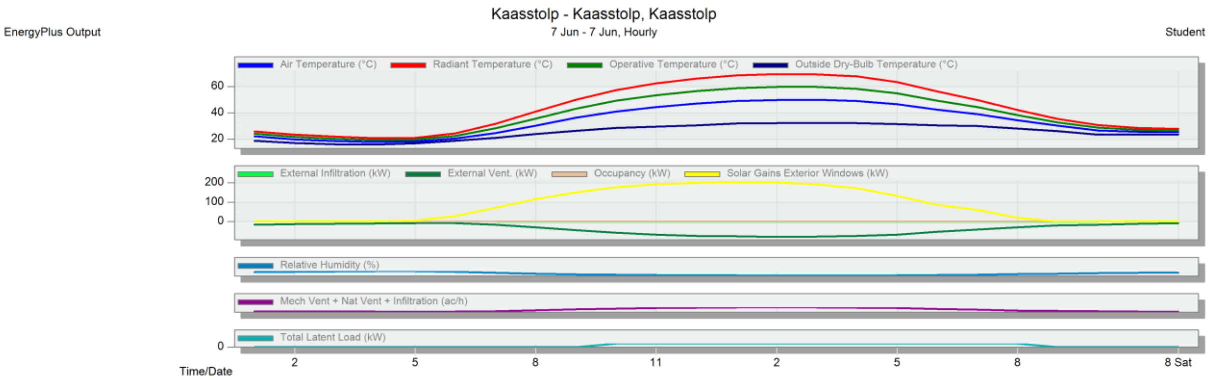
Distributed forces:			
Direction:	1	2	3
Type distributed force:	Nyy	Nxx	Nyy
Result:			
Maximum distributed force:	223.98 N/mm	1201.23 N/mm	437.22 N/mm
Minimum distributed force:	5.11 N/mm	-1465.38 N/mm	-73.85 N/mm
Distributed force in the midpoint:	96.66 N/mm	15.45 N/mm	98.19 N/mm

Appendix D: Energy Plus Output



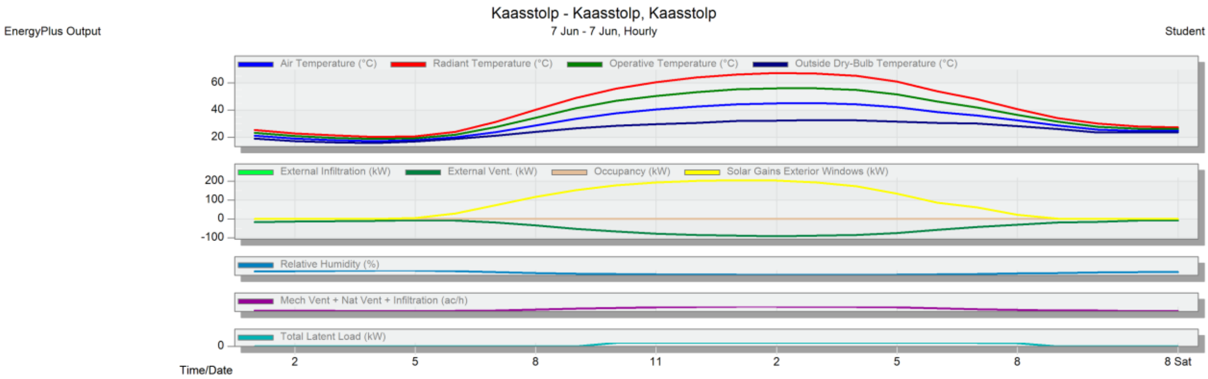
Time/Date																								
Air Temperature (°C)	26,78	24,48	22,78	21,76	21,52	23,48	28,49	36,00	44,53	52,00	57,53	61,94	64,80	66,18	66,56	65,48	62,08	55,96	50,32	43,76	37,54	32,84	30,36	29,10
Radiant Temperature (°C)	28,59	26,32	24,77	23,55	23,53	26,66	34,15	43,91	54,05	62,35	68,40	72,95	75,99	77,50	77,45	75,91	71,61	64,09	56,69	47,92	40,17	34,90	32,00	30,68
Operative Temperature (°C)	27,69	25,40	23,77	22,65	22,52	25,07	31,32	39,96	49,29	57,17	62,97	67,45	70,39	71,84	72,00	70,70	66,85	60,02	53,50	45,84	38,85	33,87	31,18	29,89
Outside Dry-Bulb Temperature (°C)	18,98	17,10	16,25	15,85	16,85	18,77	21,17	23,90	26,55	28,55	29,52	30,67	31,98	32,22	32,58	32,40	31,55	30,55	30,00	28,17	26,17	23,45	23,52	23,73
External Infiltration (kW)	-0,36	-0,35	-0,31	-0,28	-0,22	-0,22	-0,34	-0,55	-0,81	-1,05	-1,26	-1,39	-1,46	-1,51	-1,51	-1,47	-1,36	-1,13	-0,91	-0,70	-0,51	-0,43	-0,31	-0,25
External Vent. (kW)	-10,52	-10,02	-8,90	-8,06	-6,35	-6,36	-9,79	-16,03	-23,60	-30,58	-36,41	-40,45	-42,27	-43,67	-43,67	-42,49	-39,32	-32,81	-26,29	-20,29	-14,91	-12,43	-9,06	-7,11
Solar Gains Exterior Windows (kW)	0,00	0,00	0,00	0,00	5,23	28,16	72,61	116,45	151,97	177,02	193,06	201,09	204,06	202,90	192,52	172,58	132,76	86,14	60,57	21,27	1,37	0,00	0,00	0,00
Relative Humidity (%)	54,41	59,14	62,96	66,13	67,68	61,69	46,84	31,35	20,73	16,00	13,22	10,87	9,41	8,53	7,88	8,15	9,53	13,12	17,80	25,57	33,76	40,89	45,91	49,33
Mech Vent + Nat Vent + Infiltration (ac/h)	1,54	1,54	1,54	1,53	1,52	1,53	1,54	1,56	1,59	1,62	1,64	1,66	1,66	1,67	1,67	1,66	1,65	1,63	1,60	1,58	1,56	1,55	1,54	1,53
Total Latent Load (kW)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	6,92	6,92	6,92	6,92	6,92	6,92	6,92	6,92	6,92	6,92	6,92	0,00	0,00	0,00	0,00

Figure 1: Temperatures and gains, ventilation rate of 1.45 (own figure)



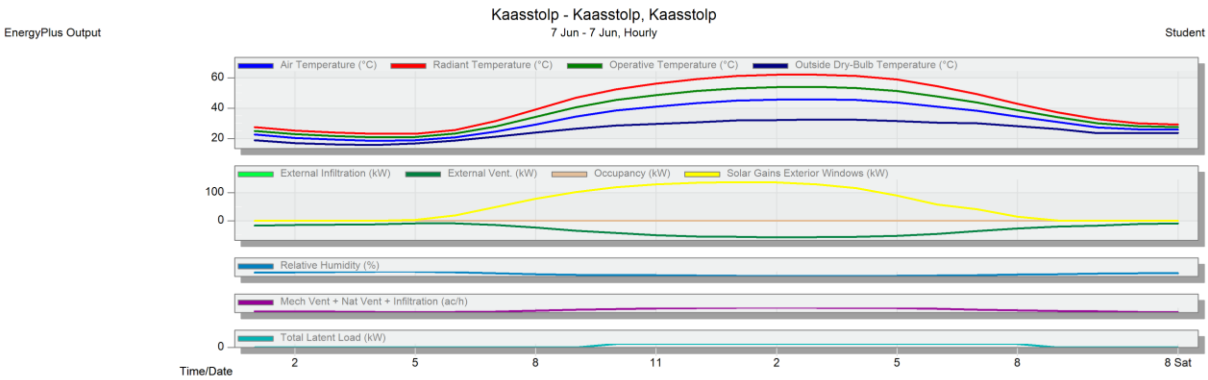
Time/Date																								
Air Temperature (°C)	22,32	19,93	18,69	17,89	18,37	20,54	24,74	30,32	36,40	41,17	44,50	47,22	49,14	49,96	50,09	49,21	46,59	42,47	39,02	34,51	30,40	26,80	25,78	25,48
Radiant Temperature (°C)	26,08	23,56	22,03	20,92	21,13	24,52	31,90	41,01	50,14	57,34	62,43	66,12	68,56	69,73	69,44	67,81	63,51	56,36	49,92	42,25	35,36	30,91	28,74	27,99
Operative Temperature (°C)	24,20	21,75	20,36	19,41	19,75	22,53	28,32	35,66	43,27	49,25	53,46	56,67	58,85	59,84	59,77	58,51	55,05	49,42	44,47	38,38	32,88	28,85	27,26	26,74
Outside Dry-Bulb Temperature (°C)	18,98	17,10	16,25	15,85	16,85	18,77	21,17	23,90	26,55	28,55	29,52	30,67	31,98	32,22	32,58	32,40	31,55	30,55	30,00	28,17	26,17	23,45	23,52	23,73
External Infiltration (kW)	-0,16	-0,13	-0,12	-0,10	-0,07	-0,08	-0,16	-0,29	-0,45	-0,57	-0,67	-0,74	-0,76	-0,79	-0,78	-0,74	-0,67	-0,53	-0,40	-0,28	-0,19	-0,15	-0,10	-0,08
External Vent. (kW)	-15,61	-13,31	-11,52	-9,64	-7,20	-8,24	-16,46	-29,34	-44,62	-56,77	-67,14	-73,85	-76,26	-78,70	-77,64	-74,49	-66,82	-53,12	-40,30	-28,48	-19,15	-15,33	-10,33	-8,07
Occupancy (kW)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,19	0,00	0,00	0,00	0,00
Solar Gains Exterior Windows (kW)	0,00	0,00	0,00	0,00	5,23	28,16	72,61	116,45	151,97	177,02	193,06	201,09	204,06	202,90	192,52	172,58	132,76	86,14	60,57	21,27	1,37	0,00	0,00	0,00
Relative Humidity (%)	68,26	74,26	79,28	82,77	83,54	75,30	59,16	43,54	32,92	28,18	24,29	20,12	17,67	15,77	14,69	15,45	17,92	23,43	28,99	38,32	46,27	54,82	59,22	60,88
Mech Vent + Nat Vent + Infiltration (ac/h)	5,11	5,10	5,10	5,09	5,08	5,09	5,12	5,17	5,22	5,27	5,31	5,33	5,34	5,34	5,34	5,33	5,30	5,25	5,21	5,16	5,13	5,11	5,09	5,08
Total Latent Load (kW)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	6,92	6,92	6,92	6,92	6,92	6,92	6,92	6,92	6,92	6,92	6,72	0,00	0,00	0,00	0,00

Figure 2: Temperatures and gains, ventilation rate of 5 (own figure)



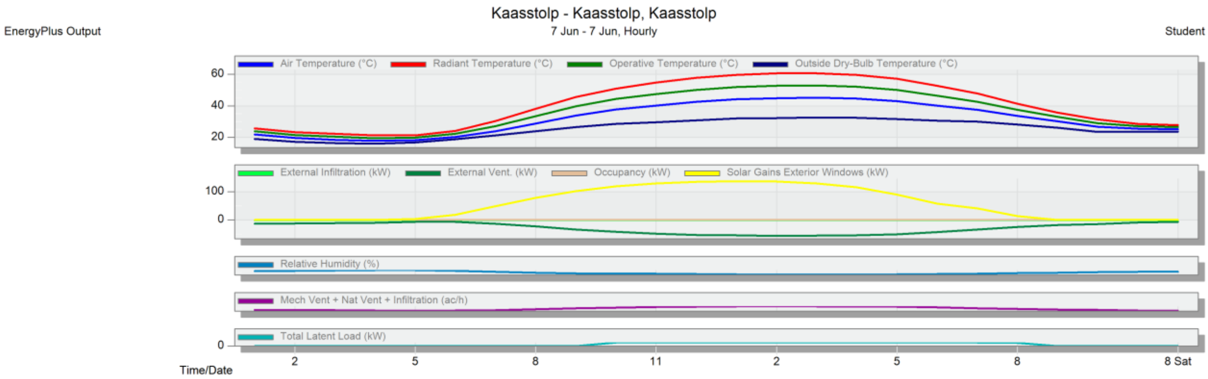
Air Temperature (°C)	21,22	18,96	17,81	17,14	17,81	19,94	23,71	28,60	33,71	37,69	40,33	42,55	44,29	44,99	45,04	44,30	42,05	38,67	35,99	32,34	28,77	25,53	24,71	24,83
Radiant Temperature (°C)	25,50	22,89	21,40	20,31	20,60	24,02	31,31	40,15	48,89	55,70	60,45	63,85	66,10	67,16	66,81	65,17	60,92	53,97	47,91	40,66	34,14	29,99	27,98	27,37
Operative Temperature (°C)	23,36	20,93	19,61	18,73	19,20	21,98	27,51	34,38	41,30	46,70	50,39	53,20	55,20	56,08	55,92	54,73	51,48	46,32	41,95	36,50	31,46	27,76	26,35	26,10
Outside Dry-Bulb Temperature (°C)	18,98	17,10	16,25	15,85	16,85	18,77	21,17	23,90	26,55	28,55	29,52	30,67	31,98	32,22	32,58	32,40	31,55	30,55	30,00	28,17	26,17	23,45	23,52	23,73
External Infiltration (kW)	-0,10	-0,09	-0,07	-0,06	-0,05	-0,05	-0,12	-0,22	-0,32	-0,41	-0,48	-0,53	-0,55	-0,57	-0,55	-0,53	-0,47	-0,36	-0,27	-0,19	-0,12	-0,10	-0,05	-0,05
External Vent. (kW)	-16,76	-14,00	-11,83	-9,80	-7,26	-8,76	-18,78	-34,43	-51,91	-65,82	-77,58	-84,84	-87,59	-90,64	-88,40	-84,38	-74,70	-57,93	-42,84	-30,01	-18,87	-15,28	-8,78	-8,12
Occupancy (kW)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,13	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,88	0,00	0,00	0,00	0,00
Solar Gains Exterior Windows (kW)	0,00	0,00	0,00	0,00	5,23	28,16	72,61	116,45	151,97	177,02	193,06	201,09	204,06	202,90	192,52	172,58	132,76	86,14	60,57	21,27	1,37	0,00	0,00	0,00
Relative Humidity (%)	72,16	78,44	83,83	86,74	87,33	78,36	62,96	48,12	38,54	33,86	29,82	25,02	22,15	19,73	18,58	19,45	22,25	28,33	33,68	42,52	50,34	58,90	62,98	63,22
Mech Vent + Nat Vent + Infiltration (ac/h)	8,12	8,11	8,10	8,09	8,08	8,09	8,13	8,19	8,25	8,31	8,35	8,37	8,38	8,39	8,38	8,37	8,34	8,28	8,22	8,17	8,13	8,12	8,09	8,08
Total Latent Load (kW)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	6,79	6,92	6,92	6,92	6,92	6,92	6,92	6,92	6,92	6,92	6,04	0,00	0,00	0,00	0,00

Figure 3: Temperatures and gains, ventilation rate of 8 (own figure)



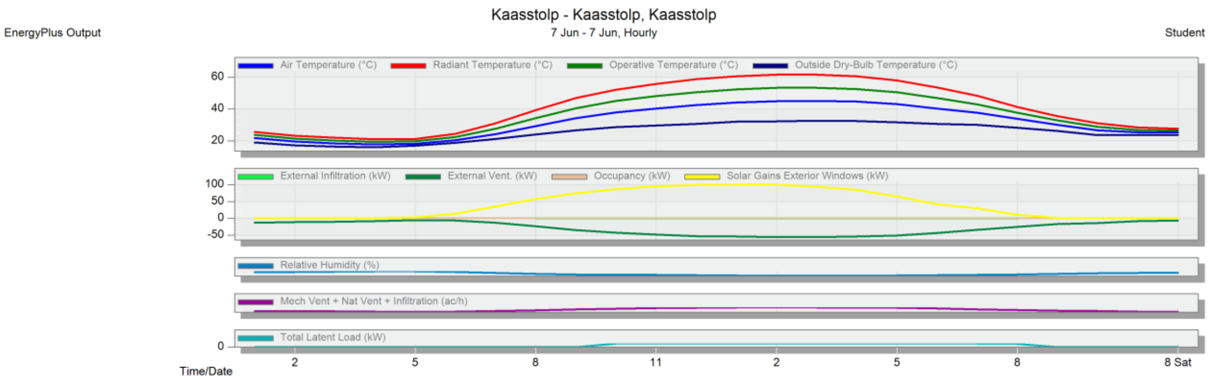
Air Temperature (°C)	22,64	20,44	19,25	18,58	18,93	20,87	24,49	29,31	34,51	38,38	40,97	43,25	44,95	45,64	45,87	45,37	43,75	41,06	38,28	34,47	30,82	27,32	26,09	25,76
Radiant Temperature (°C)	27,50	25,24	24,03	23,01	23,09	25,64	31,53	39,18	46,80	52,31	56,10	59,13	61,09	62,11	62,03	61,14	58,82	54,50	49,26	42,89	37,29	32,83	30,04	29,21
Operative Temperature (°C)	25,07	22,84	21,64	20,79	21,01	23,26	28,01	34,25	40,66	45,34	48,54	51,19	53,02	53,88	53,95	53,25	51,28	47,78	43,77	38,68	34,05	30,07	28,06	27,49
Outside Dry-Bulb Temperature (°C)	18,98	17,10	16,25	15,85	16,85	18,77	21,17	23,90	26,55	28,55	29,52	30,67	31,98	32,22	32,58	32,40	31,55	30,55	30,00	28,17	26,17	23,45	23,52	23,73
External Infiltration (kW)	-0,17	-0,16	-0,14	-0,13	-0,10	-0,10	-0,15	-0,25	-0,36	-0,44	-0,51	-0,56	-0,58	-0,60	-0,59	-0,57	-0,54	-0,47	-0,37	-0,28	-0,21	-0,18	-0,12	-0,09
External Vent. (kW)	-17,08	-15,69	-14,15	-12,85	-9,80	-9,79	-15,32	-24,73	-36,08	-44,23	-51,34	-56,13	-57,64	-59,56	-58,95	-57,50	-54,20	-46,85	-36,98	-28,32	-21,05	-17,68	-11,74	-9,31
Occupancy (kW)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,22	0,00	0,00	0,00	0,00
Solar Gains Exterior Windows (kW)	0,00	0,00	0,00	0,00	3,52	18,98	48,95	78,49	102,44	119,33	130,14	135,54	137,54	136,77	129,78	116,34	89,49	58,07	40,83	14,34	0,93	0,00	0,00	0,00
Relative Humidity (%)	66,94	72,11	76,72	79,34	80,70	73,74	59,97	46,09	36,50	32,67	29,19	24,68	21,84	19,60	18,17	18,76	20,71	25,19	30,29	38,37	45,22	53,14	58,11	59,91
Mech Vent + Nat Vent + Infiltration (ac/h)	5,12	5,11	5,11	5,10	5,09	5,09	5,11	5,15	5,19	5,22	5,25	5,26	5,27	5,27	5,27	5,27	5,26	5,23	5,19	5,16	5,13	5,12	5,10	5,08
Total Latent Load (kW)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	6,92	6,92	6,92	6,92	6,92	6,92	6,92	6,92	6,92	6,92	6,70	0,00	0,00	0,00	0,00

Figure 4: Temperatures and gains, making use of Low-E coating (own figure)



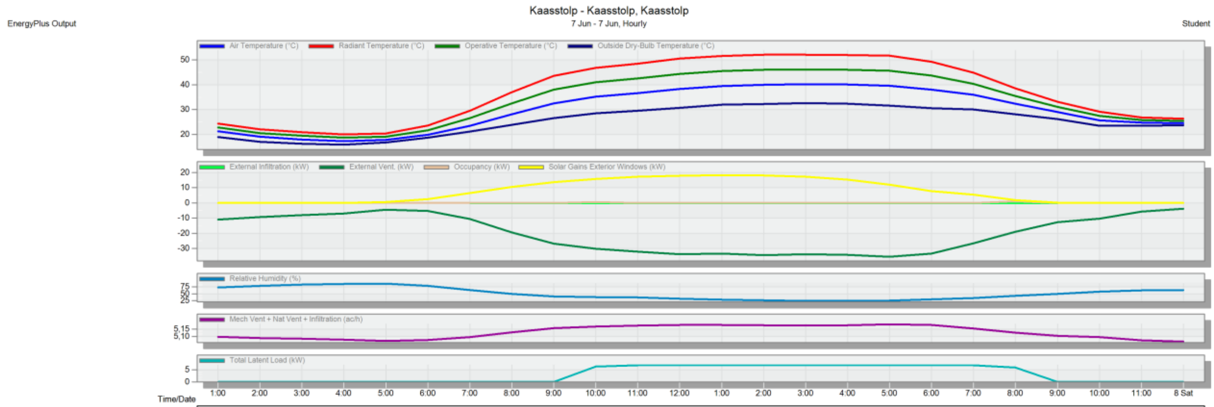
Air Temperature (°C)	21,90	19,61	18,46	17,79	18,17	20,20	23,90	28,76	33,86	37,68	40,19	42,45	44,16	44,86	45,11	44,59	42,90	40,17	37,51	33,71	30,10	26,66	25,45	25,16
Radiant Temperature (°C)	25,74	23,31	22,17	21,17	21,30	24,14	30,32	38,10	45,58	50,95	54,66	57,67	59,68	60,70	60,64	59,69	57,22	52,77	47,72	41,25	35,71	31,36	28,59	27,79
Operative Temperature (°C)	23,82	21,46	20,31	19,48	19,74	22,17	27,11	33,43	39,72	44,31	47,43	50,06	51,92	52,78	52,87	52,14	50,06	46,47	42,61	37,48	32,90	29,01	27,02	26,48
Outside Dry-Bulb Temperature (°C)	18,98	17,10	16,25	15,85	16,85	18,77	21,17	23,90	26,55	28,55	29,52	30,67	31,98	32,22	32,58	32,40	31,55	30,55	30,00	28,17	26,17	23,45	23,52	23,73
External Infiltration (kW)	-0,14	-0,12	-0,10	-0,09	-0,06	-0,07	-0,13	-0,22	-0,33	-0,41	-0,48	-0,53	-0,54	-0,56	-0,56	-0,54	-0,50	-0,43	-0,34	-0,25	-0,18	-0,15	-0,09	-0,07
External Vent. (kW)	-13,63	-11,80	-10,41	-9,18	-6,26	-6,67	-12,62	-22,23	-33,12	-41,08	-47,85	-52,55	-54,17	-56,10	-55,56	-54,02	-50,45	-42,87	-33,53	-24,88	-17,80	-14,68	-8,85	-6,61
Occupancy (kW)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,04	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,41	0,00	0,00	0,00	0,00
Solar Gains Exterior Windows (kW)	0,00	0,00	0,00	0,00	3,52	18,98	48,95	78,49	102,44	119,33	130,14	135,54	137,54	136,77	129,78	116,34	89,49	58,07	40,83	14,34	0,93	0,00	0,00	0,00
Relative Humidity (%)	70,06	75,89	80,64	83,34	84,62	76,87	62,13	47,57	37,95	33,96	30,43	25,74	22,74	20,41	18,90	19,53	21,64	26,41	31,59	40,01	47,09	55,24	60,34	62,06
Mech Vent + Nat Vent + Infiltration (ac/h)	5,11	5,10	5,09	5,09	5,08	5,08	5,10	5,14	5,18	5,21	5,23	5,25	5,26	5,26	5,26	5,25	5,24	5,22	5,18	5,15	5,12	5,11	5,09	5,07
Total Latent Load (kW)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	6,88	6,92	6,92	6,92	6,92	6,92	6,92	6,92	6,92	6,92	6,51	0,00	0,00	0,00	0,00

Figure 5: Temperatures and gains, adding thermal mass (own figure)



Air Temperature (°C)	21,80	19,52	18,37	17,71	18,11	20,23	24,10	29,09	34,21	37,94	40,36	42,54	44,20	44,90	45,14	44,64	43,04	40,35	37,63	33,80	30,00	26,52	25,39	25,06
Radiant Temperature (°C)	25,51	23,09	21,96	20,97	21,20	24,38	31,08	39,28	46,90	52,22	55,84	58,75	60,68	61,69	61,57	60,59	58,12	53,53	48,27	41,36	35,48	31,05	28,32	27,55
Operative Temperature (°C)	23,66	21,31	20,16	19,34	19,66	22,31	27,59	34,19	40,55	45,08	48,10	50,65	52,44	53,30	53,35	52,61	50,58	46,94	42,95	37,58	32,74	28,78	26,85	26,31
Outside Dry-Bulb Temperature (°C)	18,98	17,10	16,25	15,85	16,85	18,77	21,17	23,90	26,55	28,55	29,52	30,67	31,98	32,22	32,58	32,40	31,55	30,55	30,00	28,17	26,17	23,45	23,52	23,73
External Infiltration (kW)	-0,13	-0,11	-0,10	-0,09	-0,06	-0,07	-0,14	-0,24	-0,35	-0,42	-0,49	-0,53	-0,54	-0,56	-0,56	-0,54	-0,51	-0,44	-0,34	-0,25	-0,17	-0,14	-0,09	-0,06
External Vent. (kW)	-13,19	-11,38	-10,00	-8,80	-5,98	-6,83	-13,54	-23,77	-34,71	-42,28	-48,62	-52,96	-54,35	-56,26	-55,69	-54,25	-51,08	-43,67	-34,10	-25,28	-17,34	-14,06	-8,54	-6,16
Occupancy (kW)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,41	0,00	0,00	0,00	0,00
Solar Gains Exterior Windows (kW)	0,00	0,00	0,00	0,00	2,57	13,83	35,67	57,22	74,70	87,03	94,94	98,91	100,37	99,78	94,66	84,83	65,23	42,32	29,76	10,45	0,67	0,00	0,00	0,00
Relative Humidity (%)	70,47	76,32	81,08	83,77	84,94	76,72	61,40	46,66	37,21	33,48	30,15	25,61	22,69	20,37	18,87	19,48	21,48	26,16	31,37	39,74	47,36	55,68	60,61	62,43
Mech Vent + Nat Vent + Infiltration (ac/h)	5,10	5,10	5,09	5,08	5,07	5,08	5,11	5,14	5,19	5,21	5,24	5,25	5,26	5,26	5,26	5,25	5,25	5,22	5,18	5,15	5,12	5,11	5,08	5,07
Total Latent Load (kW)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	6,92	6,92	6,92	6,92	6,92	6,92	6,92	6,92	6,92	6,92	6,51	0,00	0,00	0,00	0,00

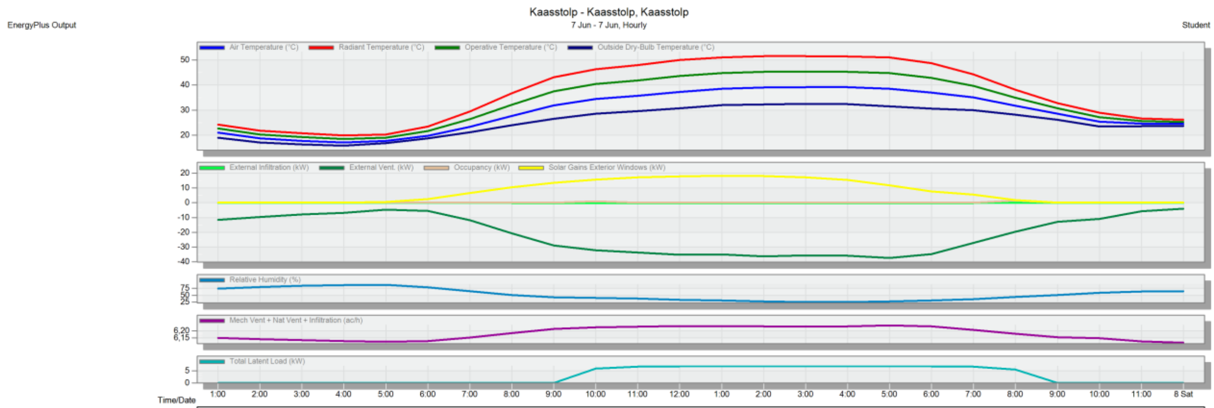
Figure 6: Temperatures and gains, making use of fritting (own figure)



Time/Date	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00
Air Temperature (°C)	21,35	19,09	17,96	17,33	17,78	19,89	23,48	28,13	32,47	35,25	36,66	38,23
Radiant Temperature (°C)	24,38	22,03	20,96	20,03	20,42	23,59	29,60	36,96	43,51	46,71	48,39	50,44
Operative Temperature (°C)	22,86	20,56	19,46	18,68	19,10	21,74	26,54	32,55	37,99	40,98	42,53	44,34
Outside Dry-Bulb Temperature (°C)	18,98	17,10	16,25	15,85	16,85	18,77	21,17	23,90	26,55	28,55	29,52	30,67
External Infiltration (kW)	-0,11	-0,09	-0,08	-0,07	-0,04	-0,05	-0,11	-0,19	-0,27	-0,30	-0,32	-0,34
External Vent. (kW)	-11,07	-9,35	-8,09	-7,01	-4,42	-5,24	-10,66	-19,36	-26,84	-30,19	-32,05	-33,77
Occupancy (kW)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,57	0,00	0,00
Solar Gains Exterior Windows (kW)	0,00	0,00	0,00	0,00	0,47	2,52	6,49	10,40	13,56	15,79	17,23	17,96
Relative Humidity (%)	72,46	78,41	83,18	85,81	86,73	78,36	63,72	49,37	40,87	38,58	36,78	32,21
Mech Vent + Nat Vent + Infiltration (ac/h)	5,10	5,09	5,08	5,08	5,07	5,07	5,10	5,13	5,16	5,17	5,17	5,18
Total Latent Load (kW)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	6,35	6,92	6,92

Time/Date	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	8 Sat
Air Temperature (°C)	39,49	39,98	40,21	40,10	39,52	38,03	35,94	32,41	28,99	25,73	24,78	24,58
Radiant Temperature (°C)	51,53	52,10	52,07	51,92	51,60	49,25	44,82	38,56	33,18	29,21	26,89	26,31
Operative Temperature (°C)	45,51	46,04	46,14	46,01	45,56	43,64	40,38	35,48	31,08	27,47	25,84	25,45
Outside Dry-Bulb Temperature (°C)	31,98	32,22	32,58	32,40	31,55	30,55	30,00	28,17	26,17	23,45	23,52	23,73
External Infiltration (kW)	-0,33	-0,34	-0,34	-0,34	-0,35	-0,33	-0,27	-0,19	-0,13	-0,10	-0,06	-0,04
External Vent. (kW)	-33,40	-34,46	-33,85	-34,15	-35,45	-33,37	-26,53	-19,04	-12,77	-10,46	-5,78	-3,95
Occupancy (kW)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,99	0,00	0,00	0,00	0,00
Solar Gains Exterior Windows (kW)	18,23	18,12	17,18	15,40	11,85	7,70	5,42	1,90	0,12	0,00	0,00	0,00
Relative Humidity (%)	29,00	26,44	24,42	24,74	25,87	29,56	34,24	42,86	50,15	58,33	62,83	64,26
Mech Vent + Nat Vent + Infiltration (ac/h)	5,18	5,18	5,18	5,18	5,18	5,18	5,15	5,13	5,10	5,10	5,07	5,06
Total Latent Load (kW)	6,92	6,92	6,92	6,92	6,92	6,92	6,92	5,92	0,00	0,00	0,00	0,00

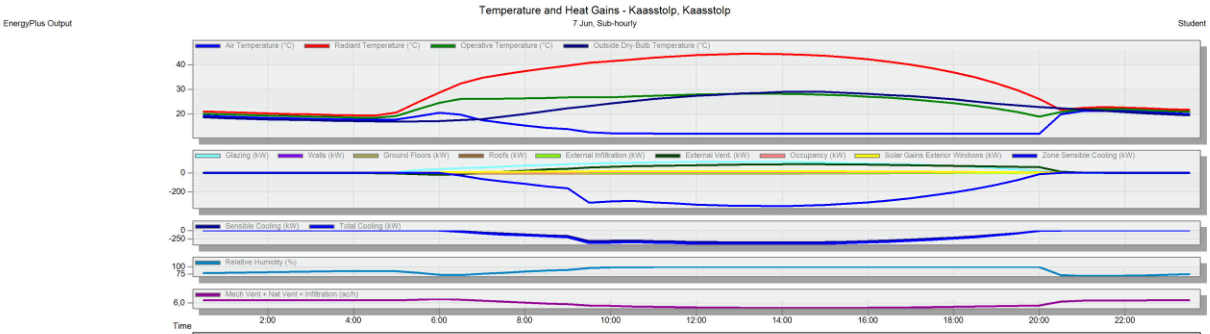
Figure 7: Temperatures and gains, making use of switchable glass (own figure)



Time/Date	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00
Air Temperature (°C)	21,01	18,78	17,65	17,03	17,65	19,74	23,27	27,64	31,83	34,45	35,73	37,21
Radiant Temperature (°C)	24,25	21,85	20,78	19,87	20,28	23,47	29,45	36,73	43,17	46,31	47,97	49,98
Operative Temperature (°C)	22,63	20,31	19,22	18,45	18,96	21,60	26,36	32,18	37,50	40,38	41,85	43,60
Outside Dry-Bulb Temperature (°C)	18,98	17,10	16,25	15,85	16,85	18,77	21,17	23,90	26,55	28,55	29,52	30,67
External Infiltration (kW)	-0,10	-0,08	-0,07	-0,06	-0,04	-0,05	-0,10	-0,17	-0,24	-0,27	-0,28	-0,29
External Vent. (kW)	-11,52	-9,59	-8,01	-6,80	-4,59	-5,48	-11,76	-20,70	-29,00	-32,17	-33,74	-35,35
Occupancy (kW)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,97	0,19	0,00
Solar Gains Exterior Windows (kW)	0,00	0,00	0,00	0,00	0,47	2,52	6,49	10,40	13,56	15,79	17,23	17,96
Relative Humidity (%)	73,57	79,64	84,63	87,42	87,88	79,24	64,59	50,84	42,53	40,27	38,38	33,77
Mech Vent + Nat Vent + Infiltration (ac/h)	6,15	6,14	6,13	6,13	6,12	6,13	6,15	6,18	6,22	6,23	6,23	6,24
Total Latent Load (kW)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	5,95	6,73	6,92

Time/Date	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	8 Sat
Air Temperature (°C)	38,47	39,00	39,21	39,11	38,49	36,99	35,04	31,78	28,53	25,43	24,54	24,43
Radiant Temperature (°C)	51,04	51,61	51,57	51,41	51,06	48,67	44,29	38,14	32,84	28,95	26,69	26,16
Operative Temperature (°C)	44,75	45,31	45,39	45,26	44,78	42,83	39,67	34,96	30,68	27,19	25,61	25,29
Outside Dry-Bulb Temperature (°C)	31,98	32,22	32,58	32,40	31,55	30,55	30,00	28,17	26,17	23,45	23,52	23,73
External Infiltration (kW)	-0,29	-0,30	-0,29	-0,30	-0,31	-0,29	-0,23	-0,16	-0,11	-0,09	-0,05	-0,03
External Vent. (kW)	-34,95	-36,44	-35,66	-36,00	-37,36	-34,74	-27,29	-19,67	-12,94	-10,99	-5,68	-3,94
Occupancy (kW)	0,00	0,00	0,00	0,00	0,00	0,00	0,09	1,29	0,00	0,00	0,00	0,00
Solar Gains Exterior Windows (kW)	18,23	18,12	17,18	15,40	11,85	7,70	5,42	1,90	0,12	0,00	0,00	0,00
Relative Humidity (%)	30,54	27,49	25,50	25,86	27,11	31,22	35,87	44,07	51,27	59,46	63,79	64,83
Mech Vent + Nat Vent + Infiltration (ac/h)	6,23	6,23	6,23	6,23	6,24	6,24	6,21	6,18	6,16	6,15	6,12	6,11
Total Latent Load (kW)	6,92	6,92	6,92	6,92	6,92	6,92	6,83	5,63	0,00	0,00	0,00	0,00

Figure 8: Temperatures and gains, ventilation rate of 6.05 (own figure)



Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	18,51	17,78	20,50	15,37	12,30	12,04	12,01	12,00	12,00	12,00	21,19
Radiant Temperature (°C)	20,27	19,52	28,71	37,33	41,31	43,79	44,28	42,14	36,82	26,08	22,65
Operative Temperature (°C)	19,39	18,65	24,61	26,35	26,81	27,91	28,14	27,07	24,41	19,04	21,92
Outside Dry-Bulb Temperature (°C)	17,86	17,14	17,14	20,02	24,34	27,34	28,90	28,18	26,02	22,90	20,74
Glazing (kW)	-2,49	-2,39	40,60	77,07	105,11	116,82	116,70	103,06	74,67	20,98	-2,14
Walls (kW)	-0,05	-0,06	-0,07	0,12	0,21	0,22	0,25	0,30	0,31	0,21	-0,04
Ground Floors (kW)	4,85	5,04	-5,30	-9,20	-8,74	-9,34	-8,41	-5,60	-0,75	7,83	3,71
Roofs (kW)	-0,17	-0,17	-0,22	0,18	0,57	0,78	0,83	0,71	0,49	0,22	-0,14
External Infiltration (kW)	-0,03	-0,03	-0,16	0,21	0,55	0,69	0,75	0,72	0,63	0,50	-0,02
External Vent. (kW)	-3,74	-3,66	-18,97	25,82	66,01	83,08	91,25	87,59	76,44	60,01	-2,58
Occupancy (kW)	0,00	0,00	0,00	0,00	6,92	6,92	6,92	6,92	6,92	6,92	0,00
Solar Gains Exterior Windows (kW)	0,00	0,00	6,48	12,97	16,48	17,93	17,65	15,55	11,17	2,90	0,00
Zone Sensible Cooling (kW)	0,00	0,00	0,00	-117,02	-304,11	-335,61	-352,44	-311,27	-207,83	-13,32	0,00
Sensible Cooling (kW)	0,00	0,00	0,00	-117,03	-304,11	-335,61	-352,44	-311,27	-207,83	-13,32	0,00
Total Cooling (kW)	0,00	0,00	0,00	-148,17	-354,99	-382,87	-398,42	-353,12	-240,59	-16,34	0,00
Relative Humidity (%)	81,58	85,44	72,14	83,39	98,27	99,79	99,97	99,99	100,00	99,98	68,94
Mech Vent + Nat Vent + Infiltration (ac/h)	6,11	6,11	6,18	6,01	5,86	5,79	5,76	5,78	5,82	5,88	6,11

Figure 9: Temperature and gains, mechanical cooling (own figure)

Appendix E: Final design

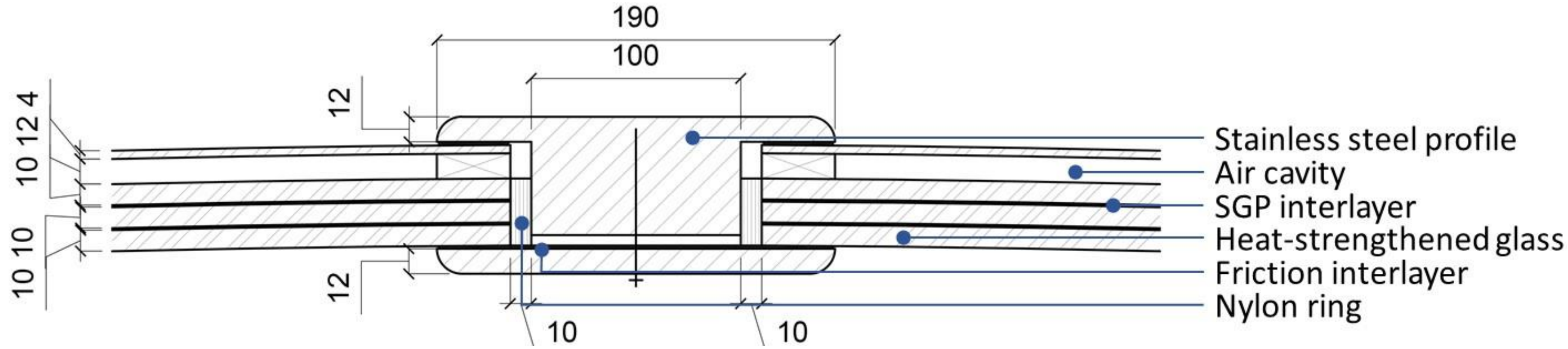


Figure 1: Detail clamp connection vertical (own figure)

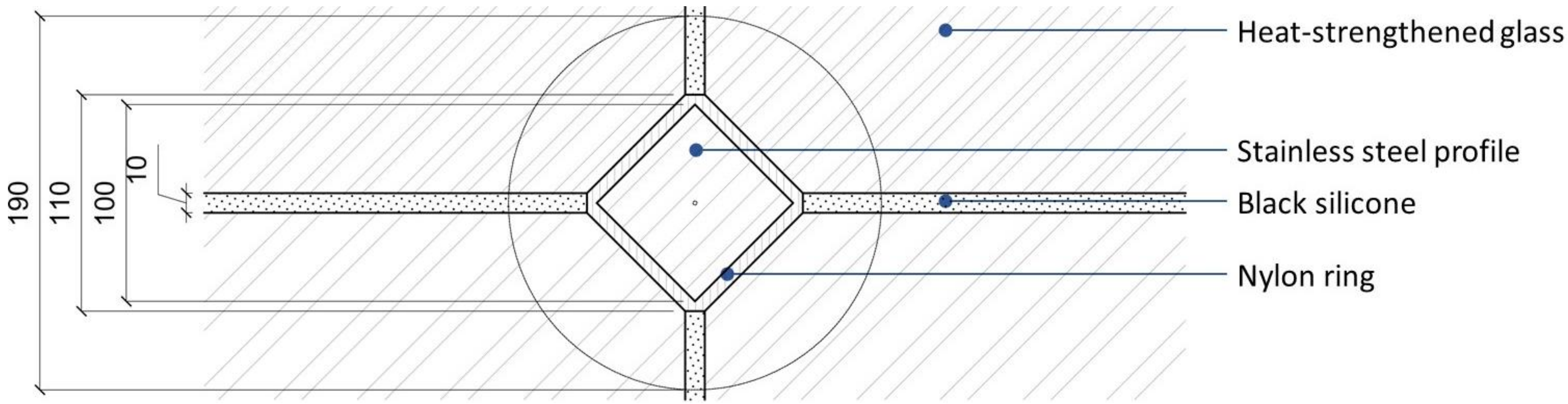


Figure 2: Detail clamp connection horizontal (own figure)

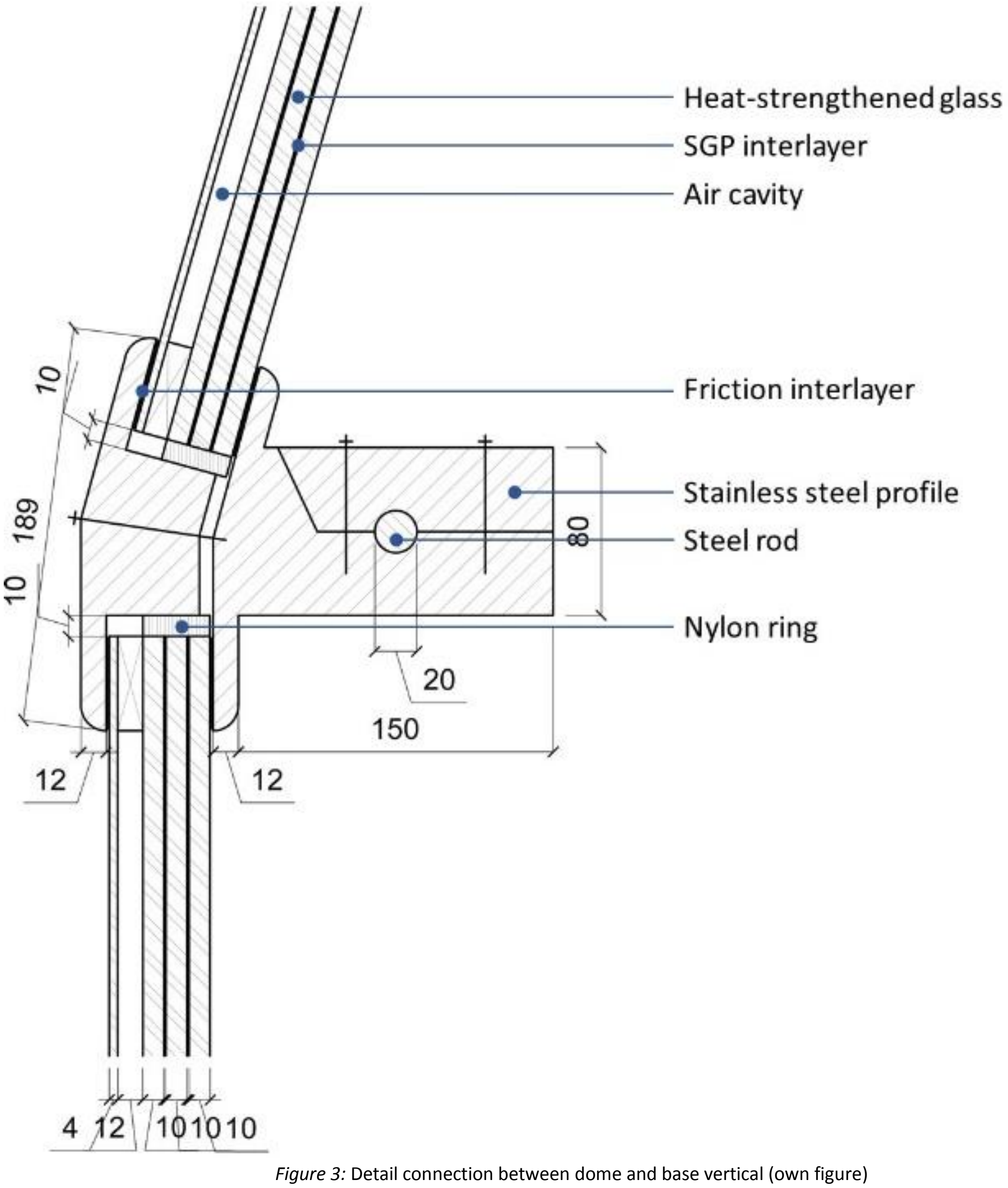


Figure 3: Detail connection between dome and base vertical (own figure)

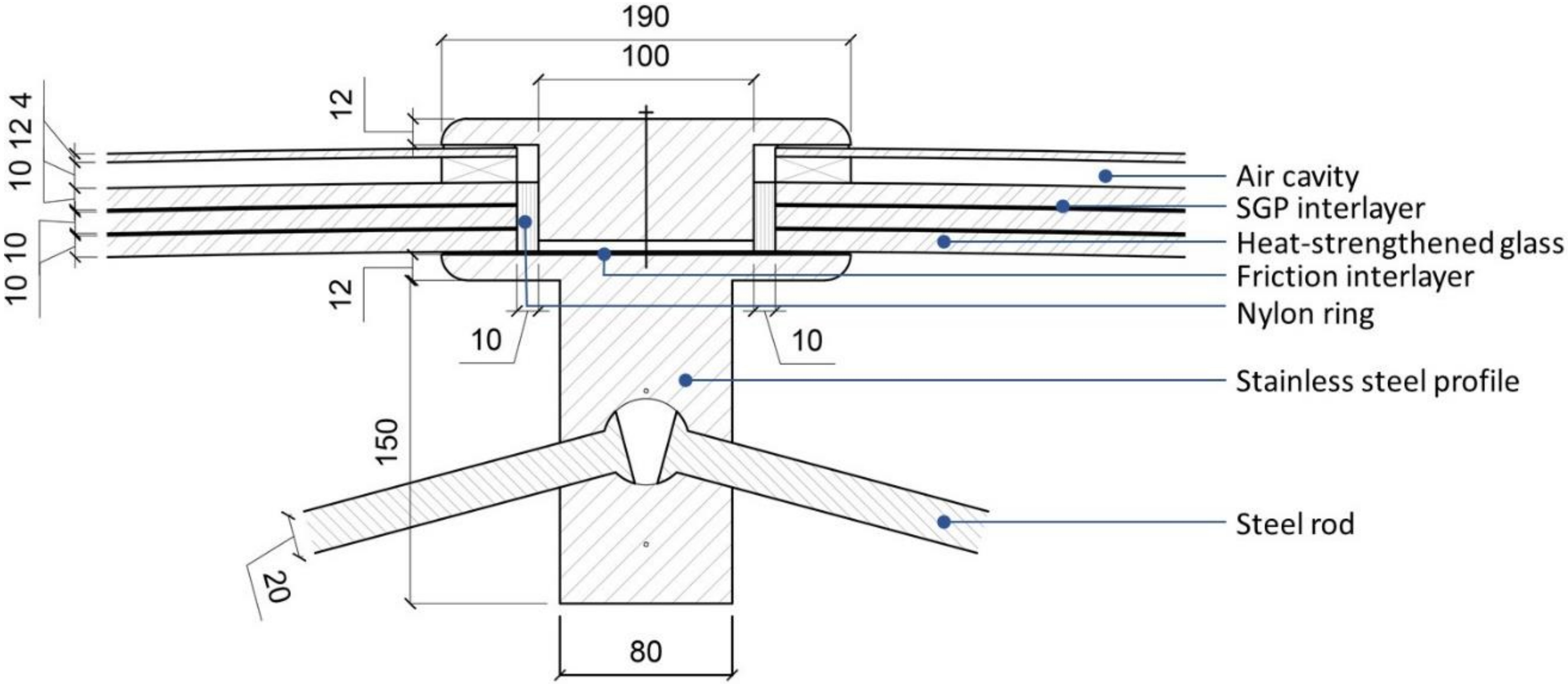


Figure 4: Detail connection between dome and base horizontal (own figure)

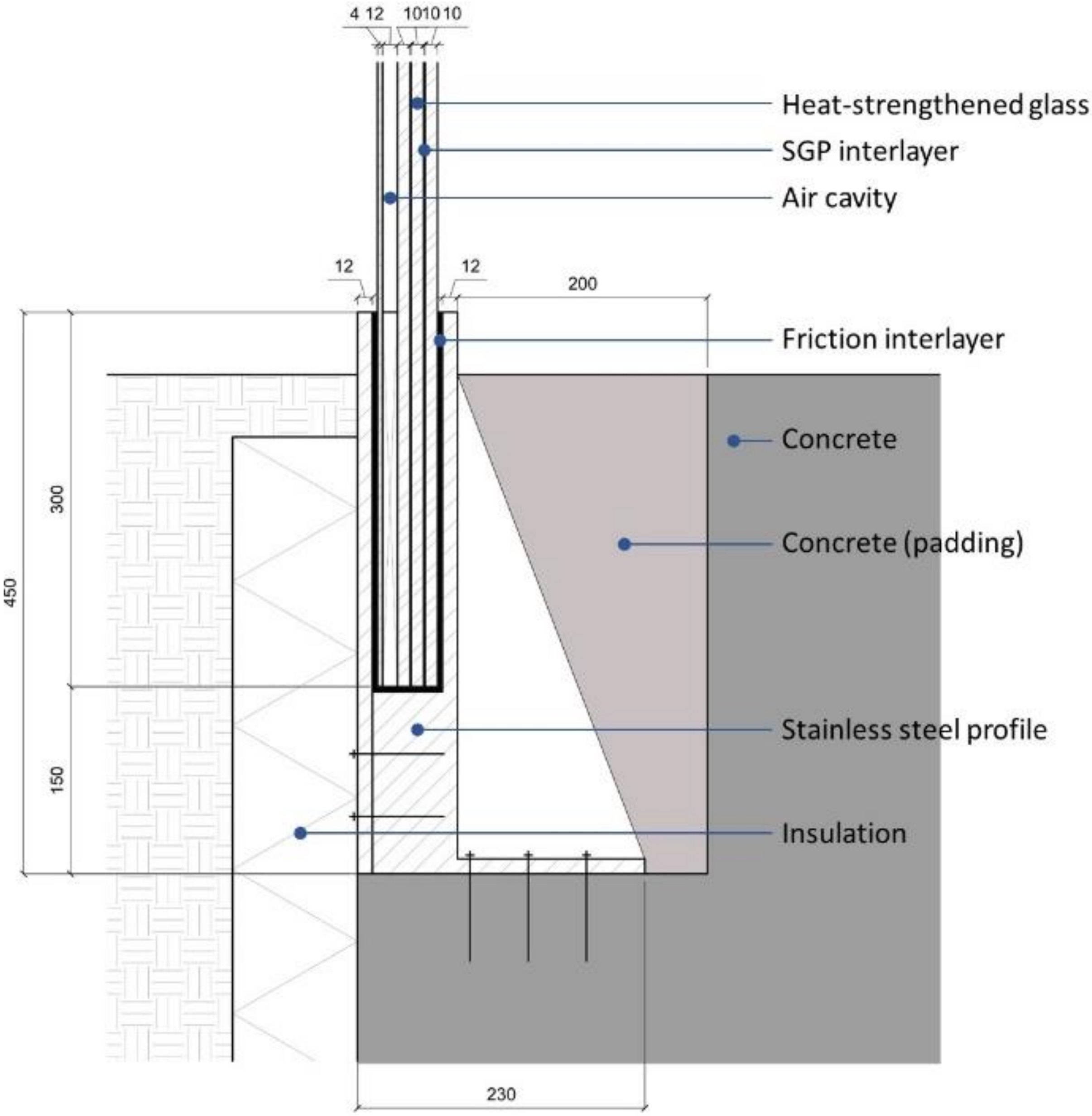


Figure 5: Detail connection to the ground floor vertical (own figure)

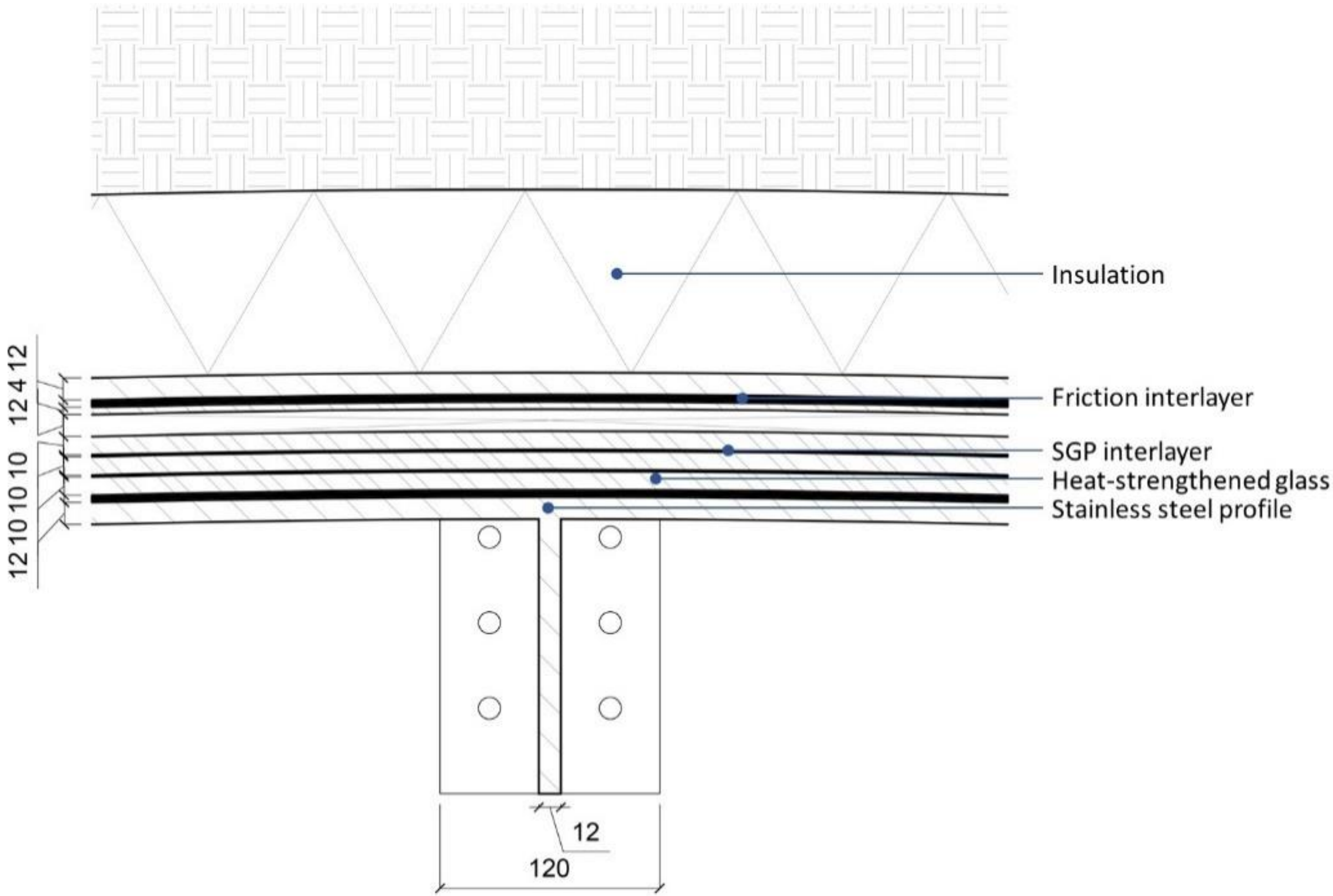


Figure 6: Detail connection to the ground floor horizontal (own figure)

Table 1: *Structural verification dome connection clamp connection 150 mm diameter direction 1* (own table)

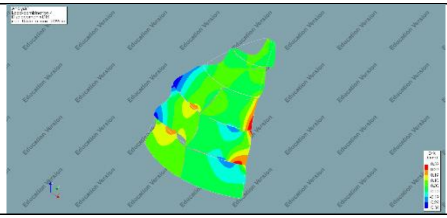
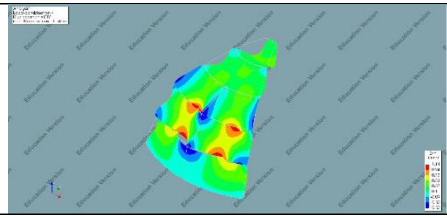
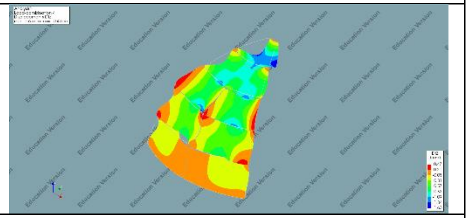
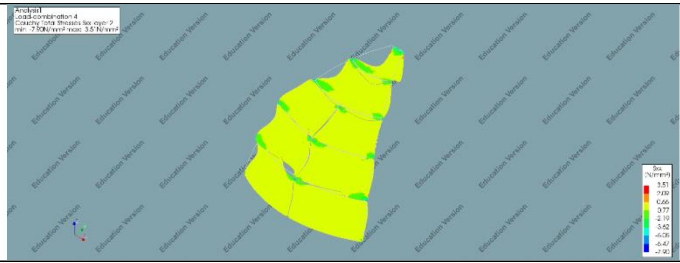
<table>
<tr><th colspan="7">Deflection:</th></tr>
<tr><td>Type deflection:</td><td colspan="2">DtX</td><td colspan="2">DtY</td><td colspan="2">DtZ</td></tr>
<tr><td>Result:</td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>Maximum deflection:</td><td colspan="2">0.39 mm</td><td colspan="2">1.14 mm</td><td colspan="2">1.60 mm</td></tr>
<tr><th colspan="7">Stress:</th></tr>
<tr><td>Type stress:</td><td colspan="3">Sxx</td><td colspan="3">Syy</td></tr>
<tr><td>Result:</td><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td>Maximum stress (tension):</td><td colspan="3">3.51 N/mm^2</td><td colspan="3">4.52 N/mm^2</td></tr>
<tr><td>Maximum stress (compression):</td><td colspan="3">7.90 N/mm^2</td><td colspan="3">5.78 N/mm^2</td></tr>
</table>

Table 2: *Structural verification dome connection clamp connection 150 mm diameter direction 2* (own table)

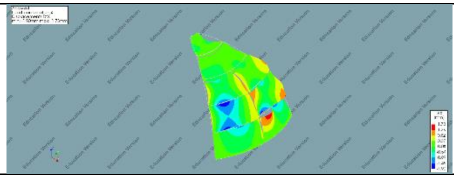
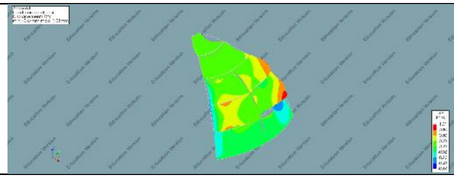
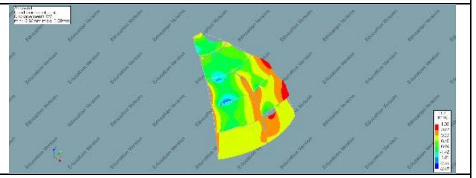
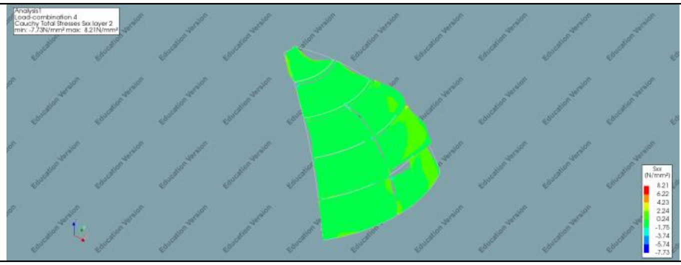
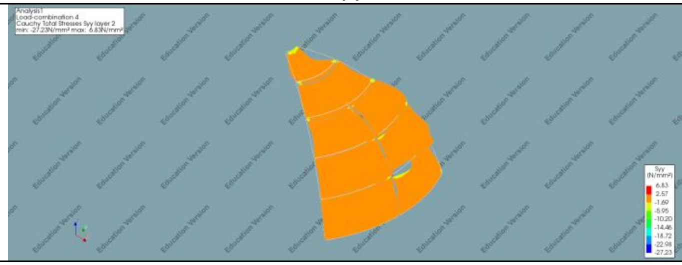
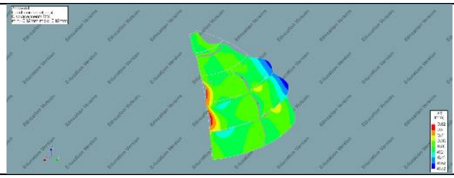
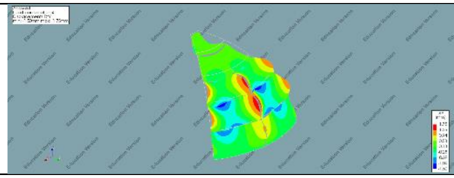
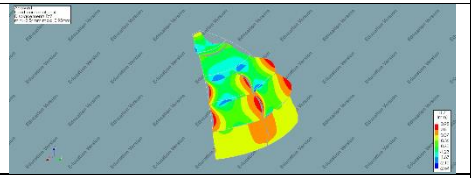
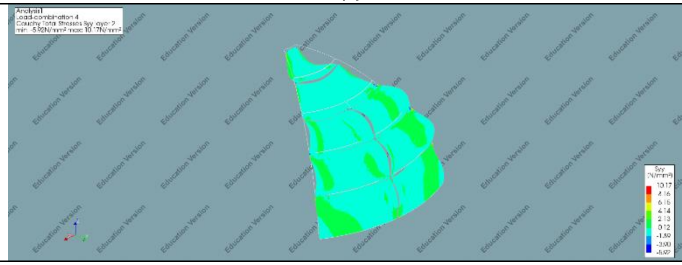
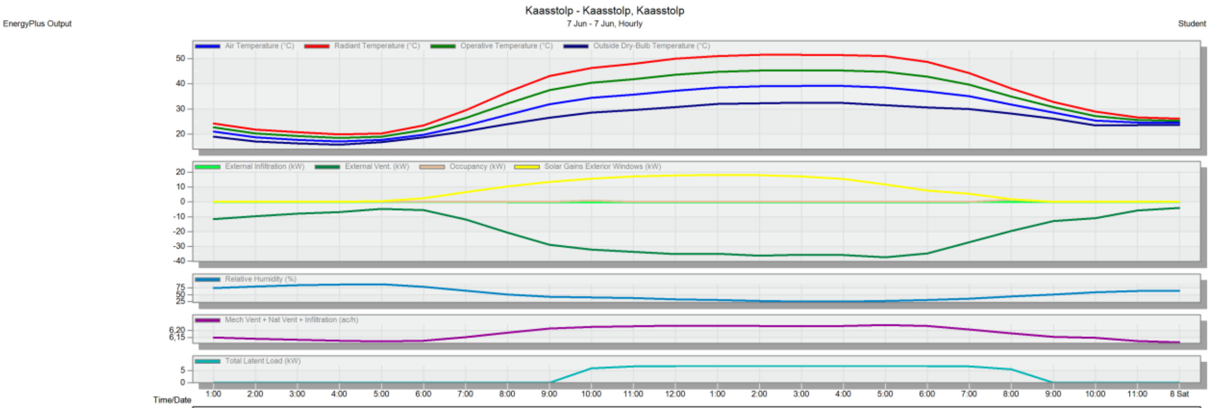
Deflection:			
Type deflection:	DtX	DtY	DtZ
Result:			
Maximum deflection:	1.90 mm	1.01 mm	2.88 mm
Stress:			
Type stress:	Sxx	Syy	
Result:			
Maximum stress (tension):	8.21 N/mm^2	6.83 N/mm^2	
Maximum stress (compression):	7.73 N/mm^2	27.23 N/mm^2	

Table 3: *Structural verification dome connection clamp connection 150 mm diameter direction 3* (own table)

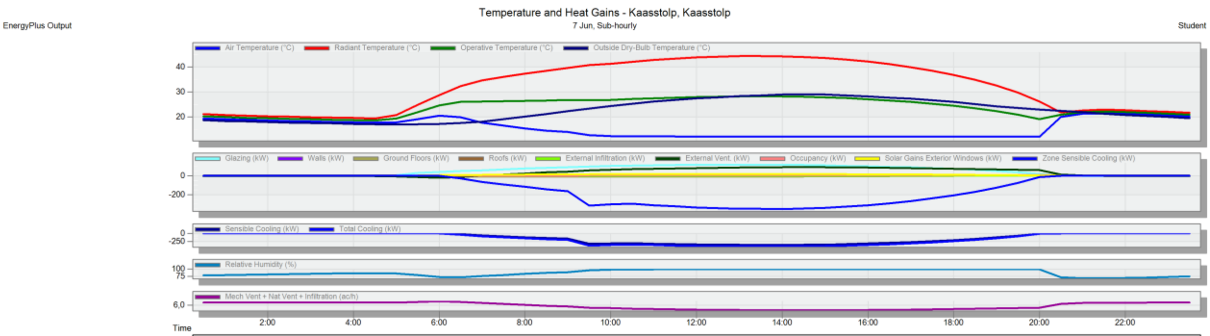
<table>
<tr><td colspan="7">Deflection:</td></tr>
<tr><td>Type deflection:</td><td colspan="2">DtX</td><td colspan="2">DtY</td><td colspan="2">DtZ</td></tr>
<tr><td>Result:</td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>Maximum deflection:</td><td colspan="2">0.82 mm</td><td colspan="2">1.75 mm</td><td colspan="2">2.54 mm</td></tr>
<tr><td colspan="7">Stress:</td></tr>
<tr><td>Type stress:</td><td colspan="3">Sxx</td><td colspan="3">Syy</td></tr>
<tr><td>Result:</td><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td>Maximum stress (tension):</td><td colspan="3">5.17 N/mm^2</td><td colspan="3">10.17 N/mm^2</td></tr>
<tr><td>Maximum stress (compression):</td><td colspan="3">8.99 N/mm^2</td><td colspan="3">5.92 N/mm^2</td></tr>
</table>



Time/Date	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00
Air Temperature (°C)	21,01	18,78	17,65	17,03	17,65	19,74	23,27	27,64	31,83	34,45	35,73	37,21
Radiant Temperature (°C)	24,25	21,85	20,78	19,87	20,28	23,47	29,45	36,73	43,17	46,31	47,97	49,98
Operative Temperature (°C)	22,63	20,31	19,22	18,45	18,96	21,60	26,36	32,18	37,50	40,38	41,85	43,60
Outside Dry-Bulb Temperature (°C)	18,98	17,10	16,25	15,85	16,85	18,77	21,17	23,90	26,55	28,55	29,52	30,67
External Infiltration (kW)	-0,10	-0,08	-0,07	-0,06	-0,04	-0,05	-0,10	-0,17	-0,24	-0,27	-0,28	-0,29
External Vent. (kW)	-11,52	-9,59	-8,01	-6,80	-4,59	-5,48	-11,76	-20,70	-29,00	-32,17	-33,74	-35,35
Occupancy (kW)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,97	0,19	0,00
Solar Gains Exterior Windows (kW)	0,00	0,00	0,00	0,00	0,47	2,52	6,49	10,40	13,56	15,79	17,23	17,96
Relative Humidity (%)	73,57	79,64	84,63	87,42	87,88	79,24	64,59	50,84	42,53	40,27	38,38	33,77
Mech Vent + Nat Vent + Infiltration (ac/h)	6,15	6,14	6,13	6,13	6,12	6,13	6,15	6,18	6,22	6,23	6,23	6,24
Total Latent Load (kW)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	5,95	6,73	6,92

Time/Date	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	8 Sat
Air Temperature (°C)	38,47	39,00	39,21	39,11	38,49	36,99	35,04	31,78	28,53	25,43	24,54	24,43
Radiant Temperature (°C)	51,04	51,61	51,57	51,41	51,06	48,67	44,29	38,14	32,84	28,95	26,69	26,16
Operative Temperature (°C)	44,75	45,31	45,39	45,26	44,78	42,83	39,67	34,96	30,68	27,19	25,61	25,29
Outside Dry-Bulb Temperature (°C)	31,98	32,22	32,58	32,40	31,55	30,55	30,00	28,17	26,17	23,45	23,52	23,73
External Infiltration (kW)	-0,29	-0,30	-0,29	-0,30	-0,31	-0,29	-0,23	-0,16	-0,11	-0,09	-0,05	-0,03
External Vent. (kW)	-34,95	-36,44	-35,66	-36,00	-37,36	-34,74	-27,29	-19,67	-12,94	-10,99	-5,68	-3,94
Occupancy (kW)	0,00	0,00	0,00	0,00	0,00	0,00	0,09	1,29	0,00	0,00	0,00	0,00
Solar Gains Exterior Windows (kW)	18,23	18,12	17,18	15,40	11,85	7,70	5,42	1,90	0,12	0,00	0,00	0,00
Relative Humidity (%)	30,54	27,49	25,50	25,86	27,11	31,22	35,87	44,07	51,27	59,46	63,79	64,83
Mech Vent + Nat Vent + Infiltration (ac/h)	6,23	6,23	6,23	6,23	6,24	6,24	6,21	6,18	6,16	6,15	6,12	6,11
Total Latent Load (kW)	6,92	6,92	6,92	6,92	6,92	6,92	6,83	5,63	0,00	0,00	0,00	0,00

Figure 7: Temperatures and gains, all passive strategies (own figure)



Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Air Temperature (°C)	18,51	17,78	20,50	15,37	12,30	12,04	12,01	12,00	12,00	12,00	21,19
Radiant Temperature (°C)	20,27	19,52	28,71	37,33	41,31	43,79	44,28	42,14	36,82	26,08	22,65
Operative Temperature (°C)	19,39	18,65	24,61	26,35	26,81	27,91	28,14	27,07	24,41	19,04	21,92
Outside Dry-Bulb Temperature (°C)	17,86	17,14	17,14	20,02	24,34	27,34	28,90	28,18	26,02	22,90	20,74
Glazing (kW)	-2,49	-2,39	40,60	77,07	105,11	116,82	116,70	103,06	74,67	20,98	-2,14
Walls (kW)	-0,05	-0,06	-0,07	0,12	0,21	0,22	0,25	0,30	0,31	0,21	-0,04
Ground Floors (kW)	4,85	5,04	-5,30	-9,20	-8,74	-9,34	-8,41	-5,60	-0,75	7,83	3,71
Roofs (kW)	-0,17	-0,17	-0,22	0,18	0,57	0,78	0,83	0,71	0,49	0,22	-0,14
External Infiltration (kW)	-0,03	-0,03	-0,16	0,21	0,55	0,69	0,75	0,72	0,63	0,50	-0,02
External Vent. (kW)	-3,74	-3,66	-18,97	25,82	66,01	83,08	91,25	87,59	76,44	60,01	-2,58
Occupancy (kW)	0,00	0,00	0,00	0,00	6,92	6,92	6,92	6,92	6,92	6,92	0,00
Solar Gains Exterior Windows (kW)	0,00	0,00	6,48	12,97	16,48	17,93	17,65	15,55	11,17	2,90	0,00
Zone Sensible Cooling (kW)	0,00	0,00	0,00	-117,02	-304,11	-335,61	-352,44	-311,27	-207,83	-13,32	0,00
Sensible Cooling (kW)	0,00	0,00	0,00	-117,03	-304,11	-335,61	-352,44	-311,27	-207,83	-13,32	0,00
Total Cooling (kW)	0,00	0,00	0,00	-148,17	-354,99	-382,87	-398,42	-353,12	-240,59	-16,34	0,00
Relative Humidity (%)	81,58	85,44	72,14	83,39	98,27	99,79	99,97	99,99	100,00	99,98	68,94
Mech Vent + Nat Vent + Infiltration (ac/h)	6,11	6,11	6,18	6,01	5,86	5,79	5,76	5,78	5,82	5,88	6,11

Figure 8: Temperatures and gains, mechanical cooling (own figure)