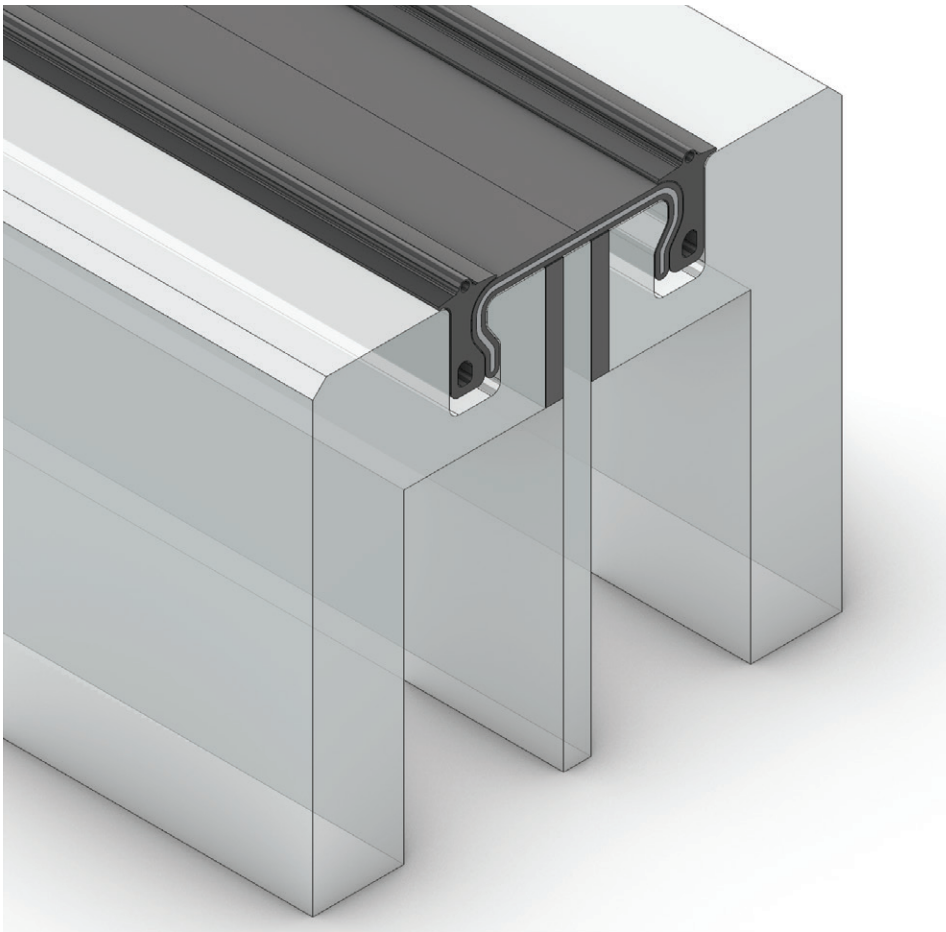

Re-LOOP TRANSPARENCY

Exploring the potential of combining transparency and circularity
in an insulated glass unit

Master Thesis

MSc Architecture, Urbanism and Building Sciences

Track
Building Technology

Studio
Sustainable Design Graduation Studio

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The completion of this thesis marks the end of a remarkable two-year journey as a Master's student in the Building Technology master track of TU Delft. The last eight months, during which my main focus was the development of this thesis, followed a procedure that can be described as anything but linear. Through this course, which has been characterised by continuous process of trial and error, led to valuable lessons being learned and great knowledge being gained.

Personally, the most important gain was the skills acquired in terms of dealing with the design challenges and the challenges implicated in the personal design journey of someone who is aspiring to make a contribution, however small, to the novel field of sustainable technologies in the demanding academic context of TU Delft.

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1. Summary

Keywords:
Reversible Insulated Glass Units, Demountable Glass Facade, Reversible Glass Connections, Circular Glass Facade

Glass is one of the oldest building materials used in the building envelope. Its attractiveness to architects, designers and users is mainly due to its fascinating ability to combine two otherwise contradictory functions; to separate and protect the interior from the exterior environment while at the same time allow for openness by letting daylight penetrate the space.

Apart from the apparent and basic function of transparency, glass, if properly designed, can fulfill almost any role in a building structure, from insulating a facade, to taking building loads besides its own weight and the imposed wind forces. Especially in terms of a building's thermal performance, the assembly of single glass panes into insulated units is a colossal advancement for the building sector towards more sustainable structures since it allows the creation of fully glazed facades with minimised thermal losses.

However, the use of insulated glass units while improves greatly the energy conservation of glass buildings, it neglects to account for the impact of this assembly procedure on the waste streams the materials used create once their service life is over. Currently, there is no provision for extending the life-time of IGUs by the means of reuse, refurbishment or recycling and consequently they end up being discarded in landfills after a limited time of use.

For this reason, it is crucial to design an alternative IGU that abides by the laws of circularity, meaning the use of design approaches with an end-of-life plan for new products used as construction elements. Such a circular approach could greatly benefit the transition from a linear to a circular economy which is indispensable for the building sector since it accounts for a large amount of construction and demolition waste that end in landfills every year. The pollution from these wastes could be significantly reduced if the products applied were initially designed to be used in a circular way instead of having a single-life character.

The current master's thesis focuses on the exploration, through detailed design, of the different ways in which an insulated glass unit can become more circular without compromising its transparency. The term circularity here refers to a design that tackles the end of life of the unit by facilitating its remanufacture in case its thermal performance starts decreasing; the reuse of parts of it or of the whole unit, and the recycling of the glass panes when neither reuse nor remanufacture are an option. Moreover, the aim is to create an IGU that is as transparent a possible by minimising the optical result of the current IGU edge seal connections.

In order to create a circular IGU, firstly, contaminating factors on the glass surfaces that could hinder their recylcability should be avoided. Secondly, a reversible way of connecting the different glass panes that comprise the IGU is opted for. Currently used IGUs have edge seals that consist of an element called a spacer bar and sealing elements that ensure the structural stability of the unit and prevent the air and moisture diffusion to the cavity. The element that connects the glass with the spacer bar in the current IGUs is a strong structural adhesive of black colour that cannot be removed without contaminating the glass. This is precisely the element that this thesis aims at replacing through an alternative connection design that enables the reversibility of the unit and the reduction of the optical impact of the edge seal.

The design exploration phase led to a final design that achieves the initial goal using an innovative alternative connection that replaces the spacer bar and secondary seal of a typical IGU with two cast glass elements each fused to the edge of the float glass panes. The connection of these cast glass elements occurs with the use of a simple mechanical clamping element, a metal spring clip that can be easily applied and just as easily removed. The small dimensions of this clip and its application internally between the float glass panes ensures the reversibility of the edge seal as well as its improved optical result.

The final design remains in a research stage proposal and further testing would be necessary regarding its thermal performance, its structural rigidity and the assurance of its good weather sealing. However, this research through design exploration concluded to a feasible, in theory, design that achieves the initial goal.

2. Research Framework

2.1 Problem Statement

2.2 Design Vision

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2.1 Problem Statement

The advancements in the recent decades in the technology of glass structures have resulted in a vast use of glass in the built environment. The main reason for the great appeal glass has to architects and users is its inherent transparency that can be successfully combined with other compelling functional roles that until recently seemed impossible from such a diaphanous and brittle material. Out of these roles, some of the most important ones are the ability of glass to be thermally insulated and to bear loads while continuing to maintain high transparency levels.

Especially in terms of glass' thermal performance, the assembly of single glass panes into double and triple glazed insulated units is a tremendous breakthrough for the glass industry since it enables the design and construction of fully glazed facades with minimised thermal losses. Nevertheless, this assembly of glass into insulated glass units (IGUs) still requires some matters of attention that could be further improved regarding its sustainable use and its aesthetic properties.

The only currently known way of bonding two float glass panes into an insulated unit with a cavity between is with the employment of structural silicone adhesives. This bonding method creates a visible black edge in the perimeter of the unit resulting in reduced transparency levels of the unit compared to a single glass pane.

In terms of sustainability, glass is a material that is very durable in time and has the ability to be 100% recyclable if certain contaminating factors are avoided, making it a potentially very sustainable construction material. However, the assembly of glass into IGUs while minimises the problem of energy consumption in the building envelope, at the same time, hinders the potential of the IGU to be refurbished and of the glass elements to be recycled at the end of the unit's life. The use of edge seals that adopt structural silicone adhesives makes the glass panes separation very difficult and even when a separation is achieved the glass surfaces are left with contaminating elements that prohibit their recycling back to float glass. Furthermore, these seals are the weakest spots in the IGU in terms of lifetime expectancy. While glass due to its durability can be used for more than 100 years, these edge seals start failing after approximately 25 years, leading to the reduced thermal performance of the IGU. The lack of provision for the reversibility of these seals for the refurbishment of the IGU consequently reduces significantly the lifetime of the whole unit that ends up being used as a single life component that is discarded in landfills.

The building industry is currently finding itself in an attempt to embrace and promote more circular approaches in terms of waste streams and material usage as a way to help in the combat against greenhouse gas emissions (GHG) that is deeply affected by the excessive use of energy to continuously produce new products and by the pollution due to construction and demolition waste. In that direction, a more circular approach needs to be implemented in the design of insulated glass units in order to firstly, prolong their lifetime by enabling their re-manufacturing once their edge seals are outdated; and secondly, to enable the recycling of glass if remanufacturing and reuse of the unit is no longer an option.

The above mentioned matters of attention regarding insulated glass units lead to the formulation of a problem statement that concerns the question of whether it is possible to create an alternative IGU that tackles the current challenges of circularity in terms of refurbishment and recycling while simultaneously improving the visible result of the necessary edge seals of the unit.

Figure 1. Insulated Glass Units. From https://glassupply.com/insulated-glass-units/

Figure 2. Window glass recycling-momentum recycling. From https://colorado.momentumrecycling.com/colorado-window-recycling/

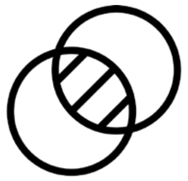
2.2 Design Assignment

The ongoing thesis aims at exploring the possibilities of developing a circular design with maximised transparency both at the level of an insulated glass unit as well as in its application in a fully glazed facade.

Definition of Circularity

The circularity in this thesis is described by a design that can prolong the lifetime of the product and lead to fewer landfills, aiming for the reuse, refurbishment and recycling of the whole unit or its individual components after the lifetime of the original use has been completed.

Definition of Transparency



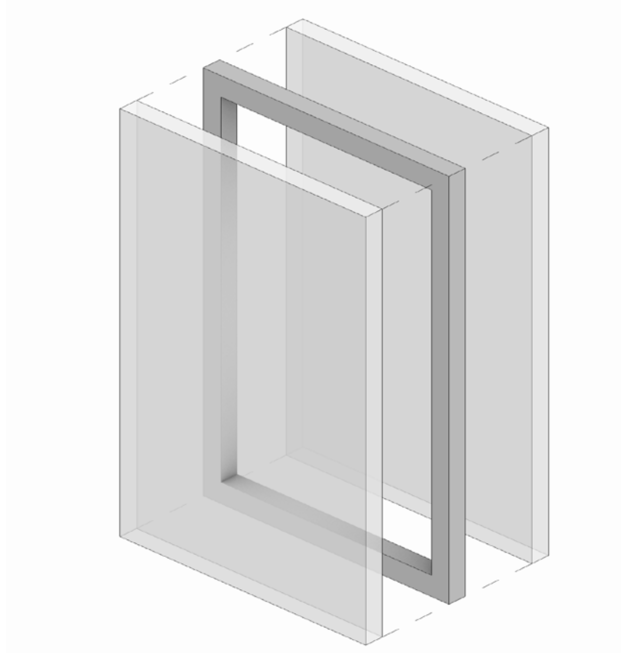
The term transparency should also be clarified here as it is a non-tangible term that is difficult to be quantitatively assessed. Therefore, as it is impossible for any kind of structure to be completely transparent this thesis aims at a connection design that is as optically unobtrusive as possible, meaning minimised and optically discrete connection elements in terms of dimensions even if the materials used are not transparent themselves.

Research Focus

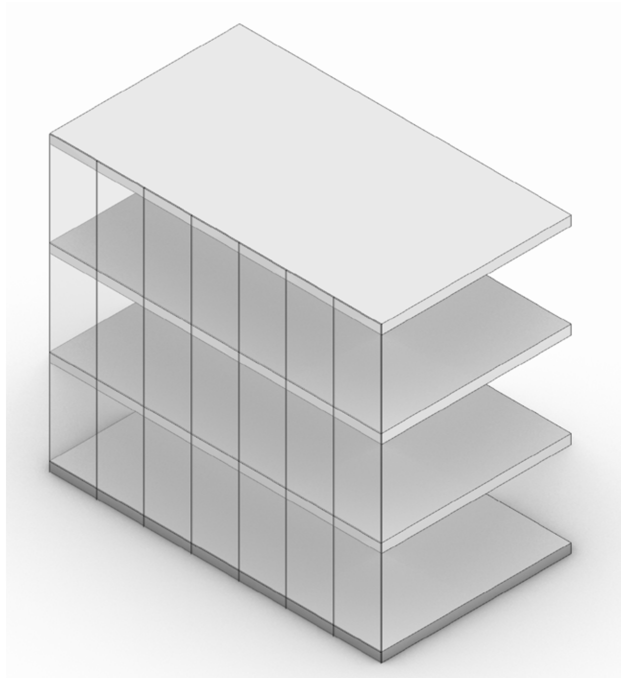
The primary focus of the design research is the connection between the different glass panes that make up an IGU in a way that it can be reversible and enable a circular use of the individual components of the whole product while ensuring a high transparency level. Secondly, the application of these insulated glass units in a fully glazed facade level is opted for, with maximised transparency and reversibility as the main design guidelines.

The design approach is principally based on research during the whole span of the project. Firstly as research on existing literature on the topic of sustainable glass structures and connections. Secondly, the research is continued during the design phase in a methodical way of trial and error. The initial part of the design phase consists of developing different design concepts and assessing them based on the design criteria set during the literature review. Moreover, literature research is continuously conducted regarding suitable materials and possible mechanisms that can work in the different designs. Apart from research, the main focus of the design approach is based on the constructibility of the connections through detailing.

1 Reversible Connections of Maximum Transparency in an Insulated Glass Unit (IGU)



2 Application in a Fully Glazed Facade



2.3 Research Question

According to the problem stated above, the main objective of the research is to contribute to the innovation of sustainable glass structures by developing a new reversible inuslated glass unit system without compromising its transparency and the application of it in an also reversible fully glazed facade.

This will be done by investigating the potential and limitations of applying reversible connections, not only for connecting an IGU to its adjustment structure but also for connecting the different elements of an IGU together, with the goal of maximizing transparency both within the IGU and in its connection system.

Main Research Question

To what extent can transparency and circularity be combined in an insulated glass unit (IGU) that can be applied in fully glazed facades?

Research Subquestions

1. What are the main design criteria in the development of a circular IGU of maximised transparency?

(a) in terms of the whole unit

and

(b) in terms of its edge seal connection?

2. What are the potentials and limitations of implementing a circular design of maximised transparency:

(a) in an insulated glass unit (IGU)

and

(b) during its application in fully glazed facades?

2.4 Relevance

Relevance to Graduation Studio

The building technology sustainable design graduation studio aims for innovative and sustainable design technologies in the built environment. The use of glass in the built environment has been known since the period of the roman empire. Glass is a material that can be used very sustainably, however, the current use of glass in building industry applications still faces many obstacles regarding sustainability. These obstacles are mainly associated with a lack of design options that tackle the end-of-life of insulated glass products allowing its reuse, refurbishment and recycling. TU Delft has been leading the way towards valuable research on the alternative ways of using glass more sustainably, including taking advantage of its recycling potential, while improving its structural capacity, thermal performance and architectural appeal. The current thesis aims to further contribute to this quest for innovation in sustainable glass structures by focusing on finding circular and optically discrete ways to create insulated glass units that are necessary for the minimisation of thermal losses in contemporary buildings.

Scientific and Social Relevance

The ‘take-make-waste’ model of the current linear economy of the world has a vastly negative impact on natural resources depletion and environmental pollution due to increased waste volume and emission of greenhouse gases that are causing the climate crisis. The Dutch government is aiming in transitioning to a fully circular economy by 2050. Governments, industries and civil society organisations must join together to facilitate a circular economy in this attempt to shift. According to the European Commission, construction and demolition waste consist of approximately 25-30% of the total waste generated in the EU in terms of mass and volume, resulting in one of the biggest waste streams produced in the EU. A big part of this waste includes materials that can be reused or recycled. Glass is a material that if used correctly can be very circular since it has a big lifetime due to its durability and it can also be recycled if not contaminated by post-production processes.

However, the construction industry currently uses insulated glass units that are permanently bonded using structural sealants that contaminate the glass surfaces, thus, hindering its potential for recycling or reuse at the end of the unit’s life. Moreover, these sealants have a very limited life span compared to the glass itself and since there is no provision for replacing them and for refurbishing or recycling of parts of the insulated glass units they end up being single-use products with a limited lifespan that end up in the landfills.

The aim of this thesis is to contribute to a more circular design in insulated glass structures that exhibit the necessary thermal insulating properties while maintaining high levels of the desired transparency. The circularity is mainly tackled in the form of reversible connections that enable the reversibility of the whole structure and facilitate either the refurbishment of the unit or the reuse or recycling of its individual parts.

2.5 Research Methodology

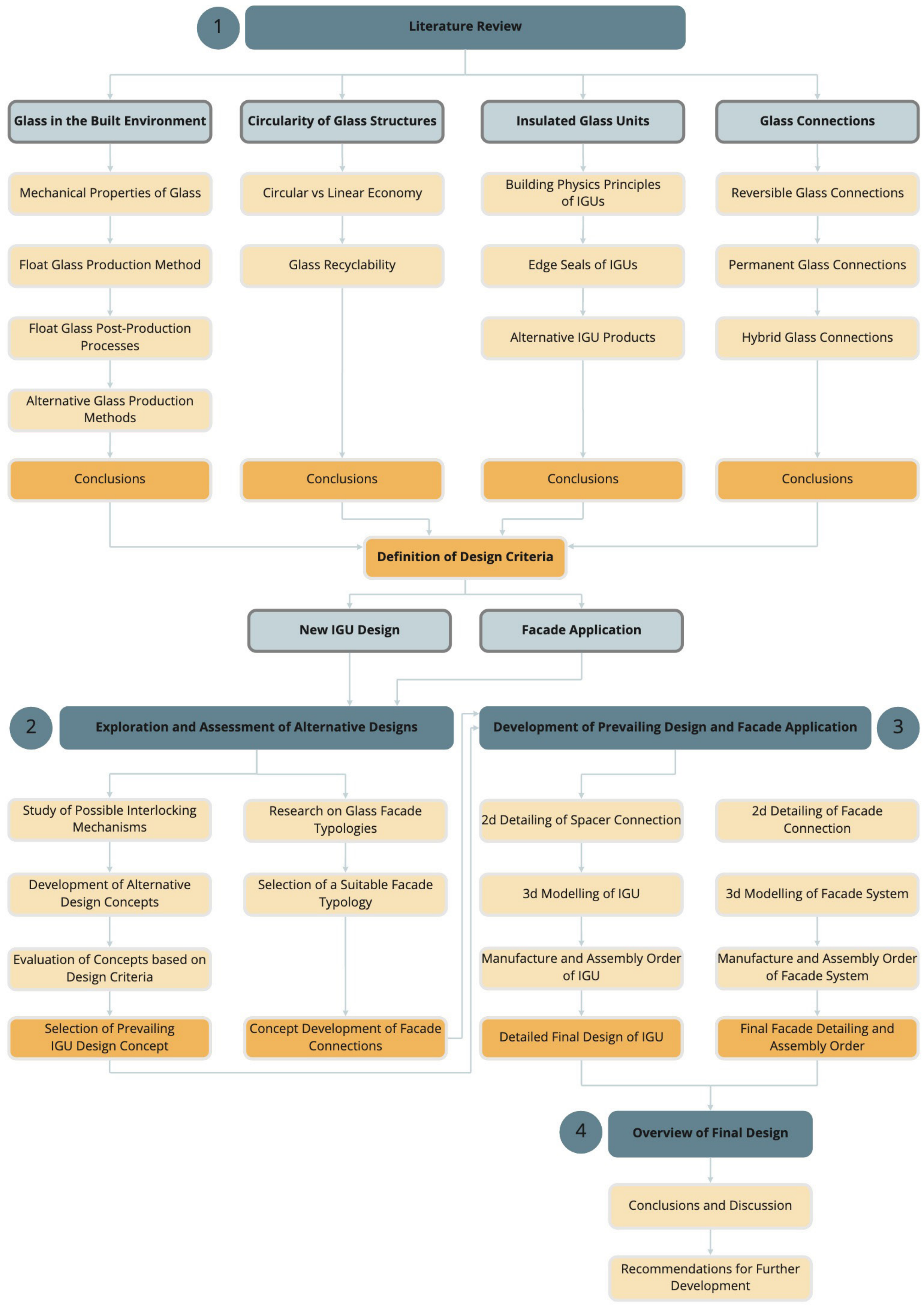
The process of development of this thesis is divided into four phases:
Phase 1: Literature Review
Phase 2: Exploration and Assessment of Alternative Designs
Phase 3: Detailed Development of Prevailing Design
Phase 4: Conclusions and Reflections

Phase 1 consists of a thorough literature review of books, papers, reports and websites relevant to the research question leading to a better understanding of the design problem and the definition of the design criteria needed for the next step. More specifically, the research begun from a review of glass as a construction material, focusing on its properties, the currently used glass structure types, different glass recipes and post-production processes. A review of the factors that facilitate and limit the circular use of glass in the built environment followed. The current state-of-the-art of insulated glass units technology was studied in terms of their thermal performance and their edge seals, focusing on the necessary functions that need to be fulfilled, and the effect the effect each of them has on the circular use of glass. Finally, typically used connections in glass structures were also reviewed leading to their assessment based on their load-transfer abilities, their potential for reversibility and their effect on the transparency of the structure. At the end of the literature review, the conclusions led to the development of specific design criteria that need to be integrated into the design phase and some initial design concepts that could answer the research question.

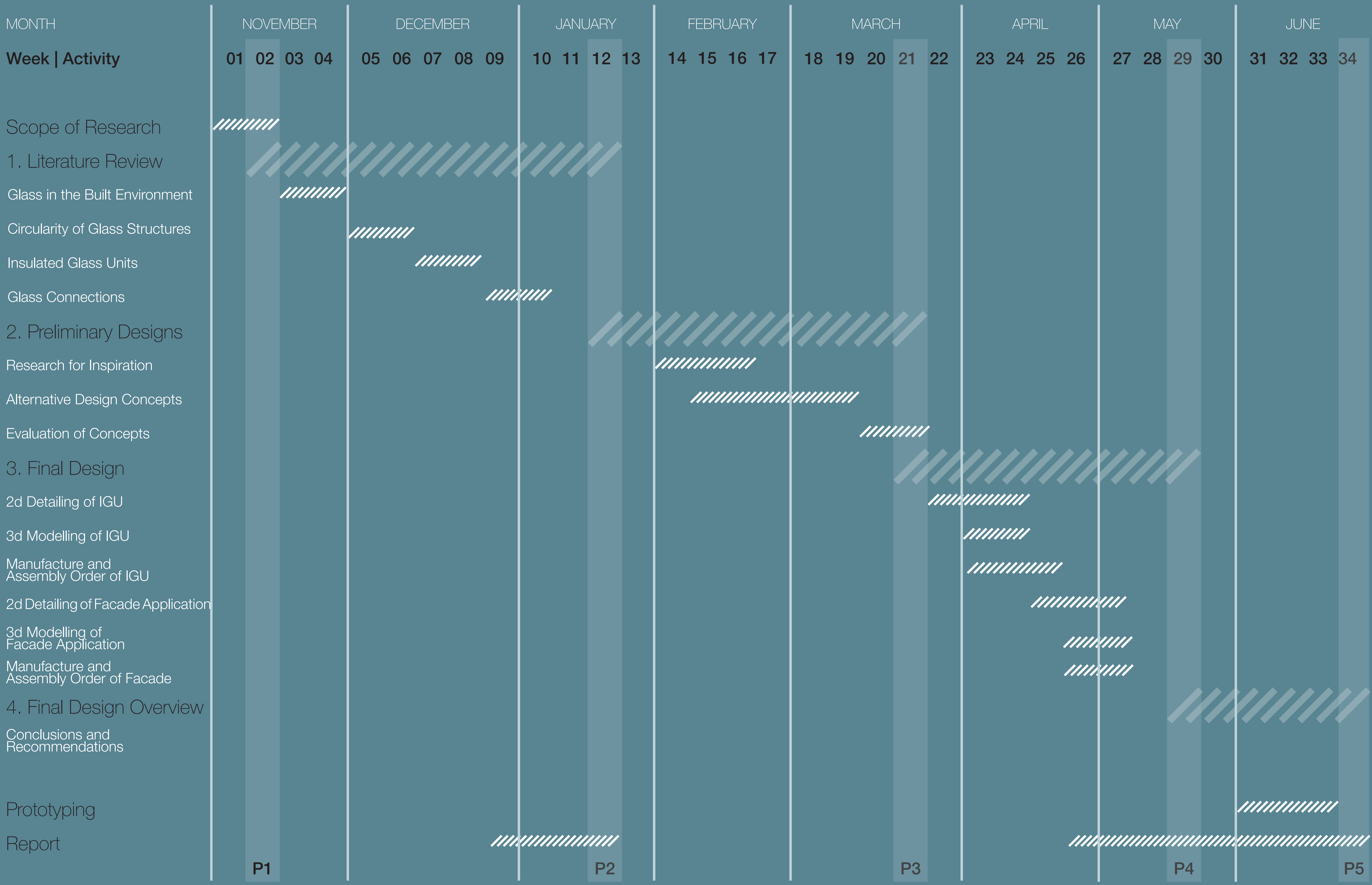
Phase 2 consists of a research by design procedure during which a meticulous exploration process of alternative design options focusing mainly on the new edge seal was conducted. During this phase firstly, more research was conducted into existing applications and mechanisms in different fields of engineering in order to extract inspiration and engage in an out-of-the-box thinking approach to the design assignment. This process led to the development of eight different possible design solutions for the new edge seal connection of the IGU. These solutions were subsequently evaluated according to the set design criteria with the help of an assessment matrix. At the end of the assessment procedure, two design concepts prevailed. They were further developed in more detail until one of them was chosen as the final design that could answer the design assignment more aptly. Since the focus of this thesis was set out to be the constructibility and detailing, the research and design tools used during this exploratory phase are sketching, 3d modeling and research on the materiality. Simultaneous with the development of the edge seal, thorough research on the existing glass facade typologies was made. This led to the identification of some key points regarding the potentials and limitations of maximising the transparency of the facade while ensuring its circular character that was taken into consideration for the design of the edge seal.

The focus of phase 3 was the finalisation of the design of the IGU edge seal connection and the application of the unit in a facade typology leading to the detailing of the connection between the different units once applied in a fully glazed facade. Through research on the materiality of the edge seal connection, the final 2d details were developed followed by a 3d model of the whole unit and its assembly order. Afterwards, the application on a curtain wall facade scenario was conducted with the parallel finalisation of the facade joint connection between the different glass panels. Facade detailing in 2d and 3d modeling and assembly order also occurred in this stage for the final facade application.

The final step for the finalisation of this thesis and the completion of the design assignment occurs in phase 4 where an overview of the final design as well as the whole research by design process is conducted. Conclusions concerning the whole process are made and recommendations for further research are given.



2.6 Time Planning



03. Literature Review

Glass in the Building Envelope

The following chapter constitutes the findings of a thorough research on the topic of glass used in the building envelope. The aim of the research is the understanding of the current potentials and limitations of using insulated glass in the building envelopes in a more circular way while at the same time maximising their transparency in the unit itself as well as in a facade application level.

The research is divided into six main chapters. It begins with a broader review of the properties of glass as a construction material and the current production methods of glass for building envelope usage focusing on the reasons that facilitate or impede its circular use. The research is further expanded to include the technology behind the creation of insulated glass units and the properties they must possess as well as the factors that are interfere with their circular use. Typical connections used in glass structures are also studied and are assessed in terms of their load transfer abilities, their potential for reversibility and their effect on the transparency of the structure. At the end of the research, conclusions are drawn leading to the formulation of the design criteria for the new IGU regarding the whole units as well as the connection between the different glass panes.

3.1 Glass as a Construction Material

3.2 Circularity in Glass Structures

3.3 Insulated Glass Units - Thermal Performance

3.4 Insulated Glass Units - Edge Seals

3.5 Connections in Glass Structures

3.6 Literature Review Overview and Conclusions

3.1 Glass as a Construction Material

3.1.1 Glass Manufacture

Glass is a crystalline amorphous solid and is also described as a solidified liquid as it possesses qualities of both. The molecules that it consists of are in random order and therefore cannot form a crystal lattice. The result is glass's characteristic transparency. Compared to other crystals, glass is characterised by amorphous isotropy since its properties are not dependent on the direction they are measured.

Glass is manufactured by a mixture of raw materials in a solid state that is heated at a high enough temperature for the mixture to become viscous. Afterwards, the mixture is cooled down rapidly so that no crystallisation can occur. During the cooling process, the atoms are locked in a random arrangement that is similar to that of a liquid state and therefore they cannot form a crystalline state that solids possess.

The raw materials that are used to form the mixture to be heated are dependent on the glass type. The main components are the following. The former is the main ingredient that is heated in very high temperatures to ensure the viscosity of the mixture. The most usually used former is silicon dioxide, $SiO2$, which is the main component of silica sand. Because of the very high temperatures needed to heat the former in order for it to become viscous, a flux, such as soda ash and potash needs to be added to the mixture in order for the melting temperature to be lowered. Moreover, a stabiliser such as calcium oxide from limestone is added to avoid the glass from dissolving or forming unwanted crystal impurities. More additives in an amount of less than one per cent of the whole mixture can be included to alter the optical properties of the glass. The dry ingredients are mixed together in a batch. A furnace melts the batch to form a liquid compound. Finally, broken glass pieces, called cullet, are added to the mixture to aid the melting procedure. (Mills, n.d.)

The final step after the creation of the glass mixture concerns pouring the mixture into shape and letting it cool down. The cooling process of glass is called annealing. It is important that annealing happens gradually and evenly throughout the glass component in order to avoid stress concentrations which can lead to unwanted breakage.

Different types of glass are produced with small alterations in the chemical composition of the used mixture. The most commonly used glass in the building envelopes is soda-lime glass. Soda-lime glass is alternatively known as window glass since it is the most common type of glass used in the windows of buildings. It is also vastly used in the packaging industry. Its composition is 70% silica and the remaining amount is divided between soda as flux and lime as the stabiliser. Soda-lime glass is very popular because it is the least expensive glass type. In addition, it is chemically stable and easily workable making it a suitable choice for fabrication and cutting. On the other hand, it is not as scratch resistant as other glass types and often it is needed to be chemically strengthened for increased strength or tempered for increased strength and thermal shock resistance. (Mills, n.d.)

3.1.2 Mechanical Properties of Glass

Different types of glass recipes result in variations in chemical compositions, which accordingly result in different properties for each type. The most crucial aspect to consider when designing with glass is that it is a brittle material showing only elastic deformation which means that it fractures without warning. Moreover, glass shows high compressive strength which makes it a very appealing construction material that combines strength and transparency.

Tensile and compressive strength

In order to understand glass' load-bearing capabilities, it is important to mention some characteristics that affect them and are associated with its micro-structure. Due to the strong atomic bonding forces present in its structure, glass with a flawless micro-structure and a very smooth surface can exhibit excellent mechanical strength. (Schittich et al. 2007, p.90) However, this is almost never the case in realistic scenarios. The micro-structure of glass is full of microscopic irregularities and defects, therefore glass is not entirely solid. Moreover, damage on the surface and edges of a glass component, including scratches and notches that can be the result of abrasion or other mechanical sources or load transfer, can occur according to Wurm (2007, p.32).

All the aforementioned defects play a crucial role in determining the tensile strength of a glass element. It is important to highlight that the tensile or bending strength of glass is never a constant value but varies according to the surface and micro-structure quality. Moreover, glass can undergo treatments that minimise its flaws and increase its strength.

Notches, small cracks, scratches and generally anything that disrupts the compactness and smoothness of glass leads to very high tensile stress concentrations when the element is subjected to mechanical forces. The crucial part here is that because of the brittle nature of the glass as a material these stress peaks cannot be neutralised by plastic deformation in contrast to other non-brittle materials. Therefore, if the tensile stresses surpass a critical value the element will fracture as the cracks will propagate quickly from one edge of the glass to the other. This results in only a small percentage of the material's tensile strength being actually used. According to Wurm (2007, p.32) the average tensile strength of soda-lime glass is 45 MPa.

On the other hand, the average value of the compressive strength of glass is almost ten times that of its average tensile strength. This is due to the fact that when a glass element is subjected to compression the defects and irregularities are also compressed and closed down and therefore do not affect negatively its compressive strength. Wurm (2007, p.32) mentioned an average compressive strength of 500 MPa, although under permanent load this value drops Ito approximately 170 MPa.

	Steel S 235	**Softwood S 10**	**Concrete C20/25**	**Glass Soda-lime glass**
Refractive index η	–	–	–	1.5
Density ρ [kN/m³]	78.5	6	22	25
Modulus of elasticity E [kN/cm²]	21 000	1 100	2 900	7 000 (like aluminium)
Tensile strength $f_{t.k}$ [kN/cm²]	24 (yield strength)	1.4	0.22	4.5
Compressive strength $f_{c.k}$ [kN/cm²]	23.5	II 1.7–2.6 ⊥ 0.4 –0.6	2	approx. 50
Limiting tensile stress σ_{Rd}	21.8	0.9	(~0.1)	1.2/1.8
Thermal conductivity [W/m x K]	75	II 0.5 ⊥0.2	1.6	1
Thermal shock resistance ΔT [1/K]	–	–	–	40
Coefficient of thermal expansion α_T [1/K]	12×10^{-6}	II 5×10^{-6} ⊥ 35×10^{-6}	10×10^{-6}	9×10^{-6} 60 K ≈ 0.5 mm/m

Table 1. Soda-lime glass properties compared to other construction materials. Originally From Glass Structures: Design and Construction of Self-supporting Skins. (1st ed., p.36), by Wurm, J., & Peat, R. (2007).

Young's modulus

Glass possesses a modulus of elasticity of about 700 GPa, which compared to other typical construction materials is one-third of the value of steel and five times higher than that of hardwood according to Wurm (2007, p.32). The deformation of glass happens in a linear-elastically manner under load up to the point when its tensile strength is exceeded leading to sudden breakage. Until the point of fracture, the strain (e) is proportional to stress (s), as shown in figure 3. As a way to prevent stress concentrations, direct contact of two glass elements or between glass and hard materials like metal should be avoided at all times.

Thermal shock resistance

The lack of plastic deformation of glass makes it susceptible to stresses resulting from temperature shock, meaning expansions and contractions arising from temperature differences which are expressed by the thermal expansion coefficient. Soda-lime glass has a thermal expansion coefficient of about 9×10^{-6} 1/K, which is three-quarters that of structural steel in accordance with Wurm (2007, p.32) This coefficient is of the utmost importance when designing the connections of glass elements with other materials in construction. A material with a similar thermal expansion coefficient to that of glass but with an increased cost related to other materials is Titanium.

Thermal shock resistance depicts the maximum difference of temperature that a glass element can withstand before fracture. This value is 40 Kelvin for soda-lime glass which is quite low as stated by Wurm (2007, p.32). Tempering or heat-strengthening the glass improves the values of its thermal shock resistance.

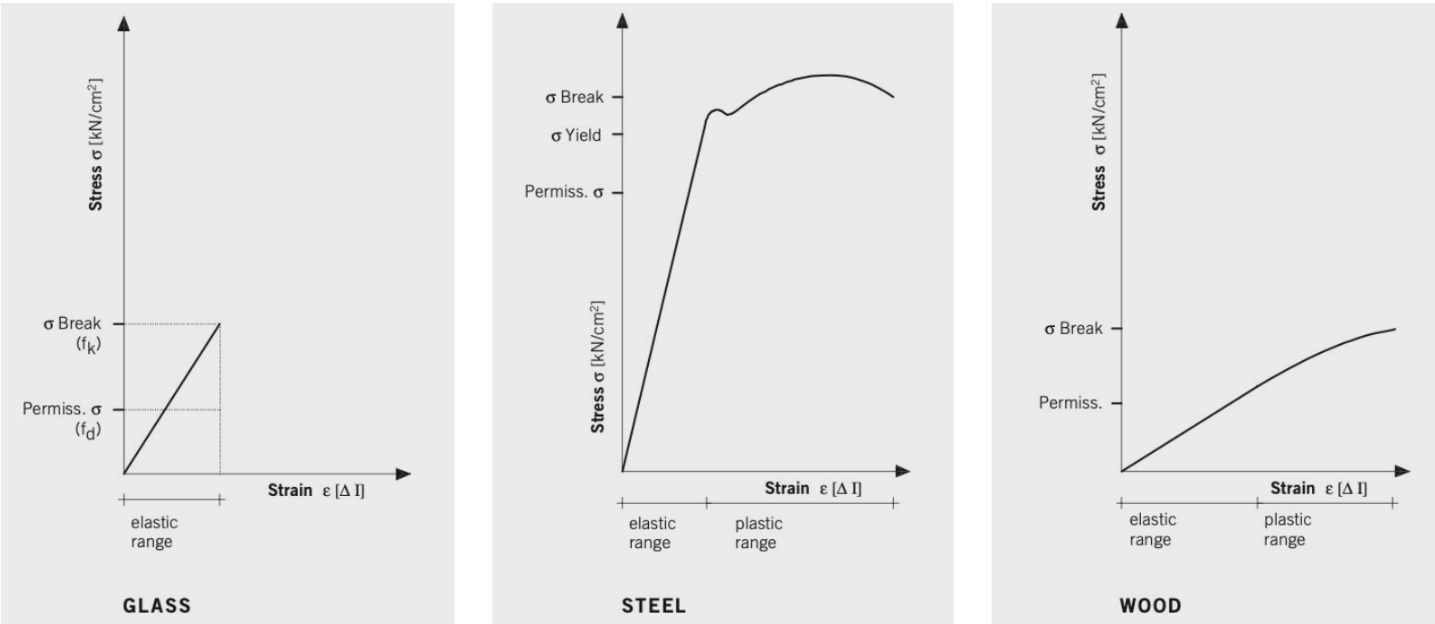


Figure 3. Qualitative comparison of stress-strain curve for glass, steel and wood. From Glass Structures: Design and Construction of Self-supporting Skins. (1st ed., p.38), by Wurm, J., & Peat, R. (2007).

To conclude, glass is a material that although its use in the building envelope has been known since ancient years, its structural capabilities have only recently been discovered. The high compressive strength renders it an ideal construction material where transparency is desired. However, the intrinsic brittleness of glass and its lack of plastic deformation are some key points that require attention when designing glass structures.

3.1.3 Float Glass Production Method

The most prevailing form of glass used in the built environment and more specifically in the building envelopes nowadays is flat glass panes. Flat glass can be produced by three methods, float glass, rolled glass and drawn glass. Over the three, float glass is the technique that is by far most commonly used accounting for approximately 90% of the flat glass production according to Wurm (2007, p. 45).

The manufacturing method of producing float glass today has its origins in the technique conceived by Alastair Pilkington more than half a century ago, in 1959. Soda-lime is the most commonly used recipe in the float glass process. The first step of the procedure consists of melting the raw materials at a furnace at a temperature of 1300-1600 C. The temperature and the exact materials depend on the glass type to be produced. Subsequently, the melted mixture floats on a molten bath of tin at a lower temperature of around 1100 C so that the glass is spread producing a continuous flat surface. The greatly homogeneous thickness of the final product can be manipulated by altering the rate of drawing the glass out of the tin bath. The final step of this procedure is the solidification of glass which happens by gradual cooling of the glass in an annealing lehr of 600C temperature as stated in Wurm (2007, p. 46)

Colours can be added and different light transmittance values can be achieved during the production process. Moreover, the natural green shade of glass can be eliminated by reducing the concentration of iron in the glass recipe. These types of glasses are called low-iron or clear-white glass and are very popular for use in the building envelope.

The current advances and limitations in the float glass industry allow for glass to be manufactured in thicknesses from 2, 3, 4, 5, 6, 8, 10, 12, 15, 19 and 25 mm, with 4 to 15 mm being the most commonly used in building envelopes. The higher glass thicknesses are not so commonly used due to the increased annealing and post-production processing time.

As far as the size of float glass panes is concerned, the width of float glass is a fixed dimension of 3.21 m. The length of the standard float glass, also called a jumbo plate, is 6 m. Current technology allows for bigger lengths as well up to 24 m, but the cost of fabrication is highly increased in these cases. These standard dimensions are governed not only by the actual float production line, but also from the handling and transportation equipment limitations.

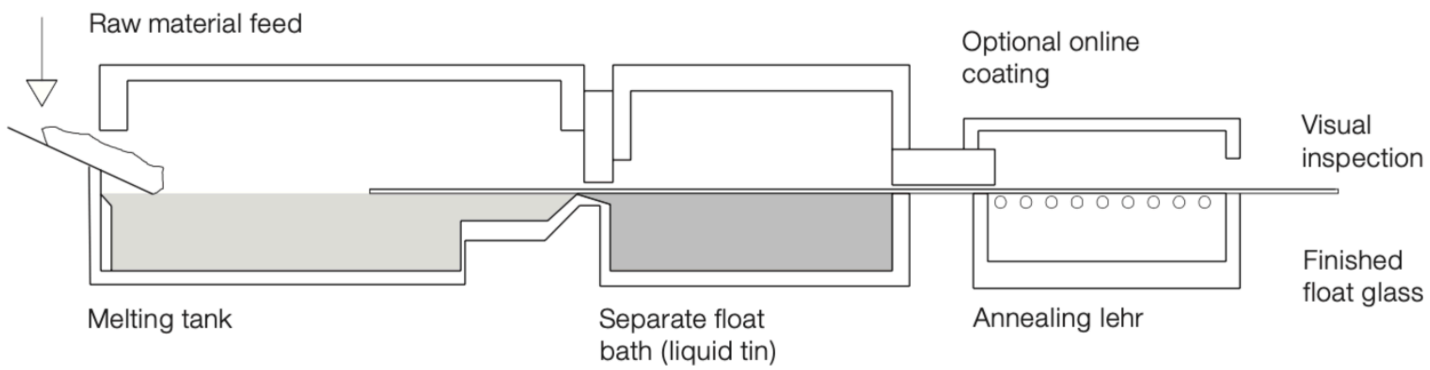


Figure 4. Float and Rolled Glass Processes. From "Glass Construction Manual" (2nd ed., p 61), by Schittich, Staib, Balkow, Schuler, & Sobek. (2007).

3.1.4 Float Glass Post-Production Processing

The reason behind float glass' exceeded use is its high geometrical accuracy and excellent transparency which render it the most suitable glass to be used in the built environment. Nevertheless, further processing of float glass is needed in all cases in order for it to be used in the building envelopes.

Cutting and Shaping

The strength of the glass is directly dependent on the shape and quality of the treated edges and surfaces. Float glass comes out of the annealing lehr in the form of a continuous ribbon. It is then only logical that it needs to be cut in the desired sizes. In order to achieve the high precision that is needed cutting is usually done with CNC machines, using a diamond-tipped cutting arm that has a cutting accuracy of up to 0.1 millimetres according to Wurm (2007, p.53).

Apart from cutting the glass to the appropriate sizes, it is very common for holes to be made that are necessary for the assembly of the component and its connection to the building structure. Usual hole shapes are cylindrical, countersunk or undercut holes that can be made in the diamond drilling process by local grinding. The water jet process can also be used in case more complex geometries need to be accomplished. Holes are always drilled from both sides to avoid cracks and breakage. The tolerance for alignment of the holes is half a millimetre maximum as stated in Wurm (2007, p.53).

Edge Working

Grinding and polishing the cut glass edges is the next step in the shaping process. The edges of cut float glass have small defects and micro-cracks that need to be smoothened by edge working. The importance of edge working is that it increases the strength of the glass pane by reducing the risk of cracks and breakage that are is probable with sharp edges.

Metal tools with a bonded coating of carborundum or diamond particles are used for this process as reported by Wurm (2007, p. 50). Several stages that consist of decreasing the grain size each time are involved in this procedure. The process stops when the optical and mechanical properties are accomplished. A variety of shapes for edge working is possible. The simplest is the normal cut edge which is only used in cases that the glass does not run the risk of being hit. Edge mitres up to 45°, bevelled, round or half-round edges, stepped rebates, grooves are also possible.

Cutting glass, drilling holes and edge working are procedures that do not affect the recyclability of glass.

Tempering

Float glass that comes straight out of the annealing lehr is called annealed glass. The annealed structural glass shows a perfectly elastic behaviour up until it fractures into large shards without any prior warning. The fracture may be a result of bending stresses, thermal stresses or temperature differences caused by thermal shock. Glass tempering is the term used to describe the procedure with which the glass can be strengthened by increasing its tensile strength. Heat or chemical treatment are the two ways to achieve glass tempering.

In accordance with Wurm (2007, p.55) , during heat tempering, the glass pane is heated to its transformation point which is around 640 °C. After the whole glass mass has reached the desired temperature cold air is blasted on it so that it can cool rapidly. During this rapid cooling which is called quenching the outer glass surfaces are cooled down while the inside of the glass mass remains hot. The result of this temperature difference is that at the inner part of the glass tensile forces are developed while the outer part is subjected to compression, closing any defects that are crucial for the overall tensile strength. This pre-stressing of the glass results in a higher overall tensile stress resistance.

Thermal tempering is divided into two categories: heat-strengthened and fully tempered. The principle behind both procedures is the same. The only difference is the rate of cooling down the glass. In the fully tempered case, the quenching occurs more rapidly than in the heat-strengthened case, leading to an even bigger tensile strength around 120 MPa, while heat-strengthened accounts for tensile strength of around 40 MPa according to Schittich et al. (2007 p.65)

A crucial aspect of both these types of glass tempering is the altered fracture pattern in comparison to annealed glass which is influenced by the tensile stresses developed inside the glass. Fully tempered glass is also known as safety glass due to the fact that it fractures in small pieces making it a safer option for injury prevention. On the other hand, heat-strengthened glass has a pattern of breakage more similar to that of annealed glass, meaning that it breaks into relatively big pieces that lead to reduced safety but also help glass maintain its shape and thus its load-bearing capacity, something that cannot be done in the case of the fully tempered glass's fracture pattern in smaller pieces. The difference in the fracture patterns an be seen in Figure 6.

Glass tempering via chemical treatment occurs by dipping the glass panes into electrolysis baths at 300 C. The small sodium ions on the surface of the glass are exchanged for the 30% larger potassium ions leading to compressive stresses. This results in a different residual stress profile. Chemically toughened glass has a similar breaking pattern to heat-strengthened glass. The use of chemical tempering is not common and is mainly limited to complicated geometries when thermal treatment cannot be applied. Moreover, its use in the building industry is restricted, because it leaves little room for imperfections. Scratches penetrate the compression zone and result in a fracture according to Haldimann et al. (2008, p.12)

It is very important to mention here that glass that has been toughened via tempering methods has lost its ability to be further processed in terms of drilling holes or edge working. All these procedures must be carried out beforehand. Regarding glass recycling, tempering has no negative impact on the ability of glass to be recycled.

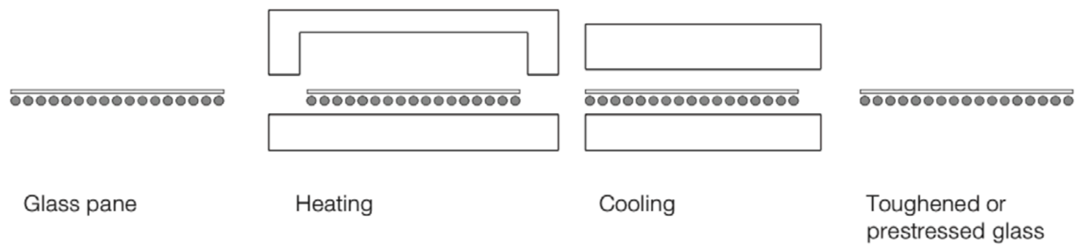


Figure 5. Tempering process. From "Glass Construction Manual" (2nd ed., p 66), by Schittich, Staib, Balkow, Schuler, & Sobek. (2007).

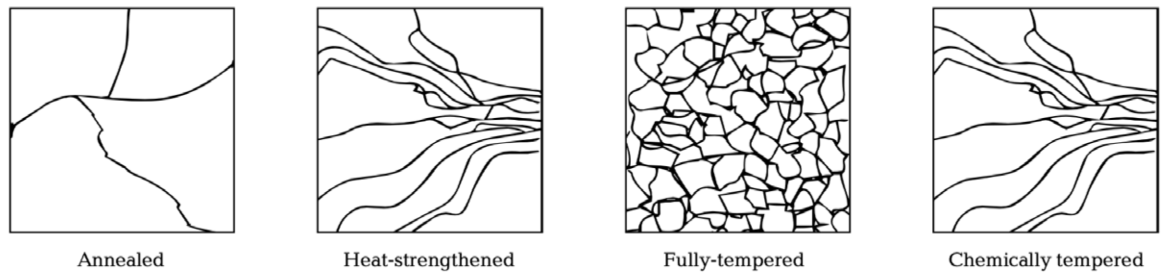


Figure 6. Tempering Effect on Fracture pattern. From "Glass Construction Manual" (2nd ed., p 66), by Schittich, Staib, Balkow, Schuler & Sobek. (2007).

Lamination

Glass lamination is a procedure during which at least two panes of float glass are permanently bonded together with the use of an interlayer. The most common interlayer materials currently used in glass lamination are polyvinyl butyral (PVB), cast-in-place resin (CIP), ethylene vinyl acetate (EVA) and SentryGlas Plus (SGP) from Dupont as stated by Wurm (2007, p. 64). The glass pieces used can be of various thicknesses and differently strengthened glass types can be combined as long as the final mechanical and optical properties of the composite glass are fulfilled.

The most common laminating technique consists of assembling the soon to be combined glass sheets with an extruded sheet of an interlayer between them and passing them through an oven at a temperature of around 70 C. From there the composite is further passed through rollers and the heat and the pressure of up to 14 bar ensure that there are no air inclusions between the glass and the interlayer. Finally, the laminated piece is moved to an autoclave where it is heated to approximately 140°C under a pressure of about 800kN/m2 (120psi) in a vacuum bag according to O'Regan et al. (2014 p.10)

The main benefits of lamination are associated with enhanced structural and safety performance of the glass. The lamination process constitutes an important improvement of the post-fracture behaviour of the glass. If one of the laminated sheets fails then the fragments remain bonded and a certain load-bearing capacity is preserved. Moreover, it is usual for three glass sheets to be laminated so that in case of failure of one of them the other two can compensate for its failure. The post-breakage behaviour of the laminated element is also highly dependent on the interlayer material used.

Among float glass post-production processes lamination has the biggest negative impact regarding recyclability and it is one of the main reasons why float glass is so seldom recycled in a closed-loop manner due to challenging techniques required to separate the glass and the lamination removing the contamination from the interlayer. More information can be found on chapter 3.2.5 "Factors that limit glass recycling"

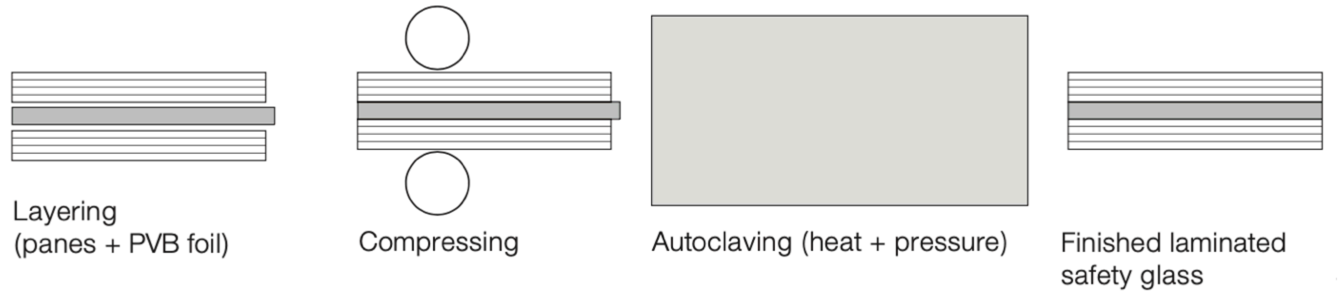


Figure 7. Glass lamination process. From "Glass Construction Manual" (2nd ed., p 69), by Schittich, Staib, Balkow, Schuler, & Sobek. (2007). (2007).

Fritting

Ceramic frits are often printed on glass surfaces for reasons of architectural appeal, for increased privacy or for shading purposes. These frits include ceramic compounds that require very high melting temperatures so their use could lead to minor flaws introduction resulting in lower mechanical properties. Therefore, these kinds of coatings are not currently considered suitable for glass recycling purposes.

Coatings

The application of coatings on the glass surface serves to increase the thermal performance of insulated glass units and to help control the solar gains of a building through the glass. The application of coatings can occur either during the float line process or afterwards. They are usually made of very thin metal layers projected on the glass surface. More in-depth analysis of the types of coatings used and their properties can be found in chapter 3.2.3 under the paragraph "Coatings".

Regarding their effect on recyclability, the high temperatures in which the float glass remelting occurs can burn off soft and hard coatings quite easily, but their presence might have negative impact on the optical qualities of the recycled glass.

IGU assembly

Float glass either in a single layer or in a laminated composite while may have a high load-bearing capacity, lacks satisfying thermal insulating properties. In order for float glass to be used in the building envelope with satisfying thermal resistance, it needs to be further assembled into an Insulated glass unit. This procedure and its properties will be analysed further in chapter 3.3 "Insulated Glass Units".

3.1.5 Casting as an Alternative Glass Production Method

Casting is a glass production method that is not commonly used for glass used in the built environment mainly because of the extreme popularity and wide use of the float glass structures. However, recent research on the subject and a few built examples have proven the great potential that lies in the use of cast glass to create structures with load-bearing abilities that break out of the restricted design shapes enforced by the two-dimensional nature of float glass.

Casting Process

The cast glass manufacture principle lies in the use of moulds of desired shapes where the molten glass is poured into. There are two categories of casting, primary and secondary casting, depending on the initial state of the glass to be used in the process. A molten mixture of raw ingredients is used in primary casting, while secondary casting consists of reheating already existing glass pieces. The advantage of secondary casting is the use of lower operating temperatures.

Primary casting is further divided into hot-forming and kiln-casting. In hot-forming molten glass mixture coming straight from the furnace is poured into a mould and is then cooled down in a second annealing furnace according to Oikonomopoulou et al. (2018). On the other hand, in kiln-casting one kiln containing the glass pieces to be melted is placed on top of each mould inside the furnace so that the mixture melting inside the kiln can be poured directly into the mould.

Both methods share a similar annealing process. As stated by Oikonomopoulou et al. (2017), the glass is rapidly cooled to a few degrees below its softening point so that crystallisation of the glass molecules is avoided. The right annealing process of cast glass is crucial for the prevention of stress concentrations that can result to fracture. During this process, the degree of resulting internal stresses is highly dependent on the temperature difference between the warmest and coolest parts of the glass, its coefficient of expansion and the thickness of the section (Shand, Armistead 1958). Moreover, Oikonomopoulou et al. (2018) suggest that round or ellipsoid shapes and equal distribution of mass should be chosen instead of sharp, pointy edges where non-homogeneous shrinkage can lead to internal residual stress concentration.

Mould Types

The selection of a suitable mould is crucial in glass casting. It is highly dependent on the volume of production and affects greatly the level of accuracy that is aimed for. Additionally, cost and time are two more factors to be taken into account. Hence, for small production, the cheaper disposable mould is usually preferred although in this case the level of surface accuracy might be compromised. On the other hand, for larger batch production permanent moulds, made from steel or graphite, are preferred. Permanent moulds have the advantage of higher accuracy obtained and less post-processing required in contrast to single-use moulds.

Size and Shape

Glass casting into moulds enabled the creation of solid three-dimensional glass components of considerably larger cross-sections and of virtually any shape. Their large cross-sections make it possible for these elements to form self-supporting structures that do not suffer from buckling and no do need any additional supporting components in agreement with Oikonomopoulou et al. (2015a). The current limitation of cast glass structures is imposed by the time-consuming annealing time due to its increased cross-section compared to float glass. For this reason, the few architectural applications of cast glass have restricted their size to that of a standard construction brick.

Advantages of Cast Glass in Terms of Circularity

Glass casting provides a new potential in the field of glass recycling due to its increased flexibility in the production method. The reason is that cast glass components have a significantly bigger cross-section than float glass panes, thus, their mesostructure allows a bigger amount of flaws than float glass without the necessary reduction of its mechanical or aesthetical properties according to Bristogianni et al. (2018b)

This flexibility enables the tolerance for lower quality cullet compared to the float glass industry. Moreover, cast glass can accept full cullet recycling in contrast to float glass, where only a low cullet-to-raw materials ratio is allowed. Furthermore, while the float line industry uses a specific recipe for production with the above-mentioned restrictions in terms of quality and percentage of material input, the casting method is more flexible in terms of recipes used and even allows for different glass types to be mixed and remelted together without causing contamination of the production. Hence, even class B waste glass coming from the float line can be recycled into cast glass structural elements. This way, casting enables for the first time closed-loop recycling of glass that would normally get down-cycled or discarded due to contamination or to the mix of different glass compositions as stated by Oikonomopoulou (2019).

Limitations of Cast Glass for use in the Building Envelope

Although using cast glass shows great potentials in terms of the recyclability of glass thus enabling more circular structures there are some limitations regarding its use in the building envelope that need to be mentioned. Firstly, in terms of transparency, cast glass cannot reach the smooth surface quality of float glass and the bigger its cross-section the higher the optical distortion. Moreover, the use of class B cullet although can produce very strong glass blocks has reduced optical quality because of the increased imperfections in the recipes. Furthermore, in terms of post production processing, cast glass cannot be heat treated for safer breakage like float glass which poses an issue in terms of safety of the structure especially if applied in high rise buildings.

Figure 8 and Figure 9. Primary casting (hot forming) and secondary casting (kiln-casting). From (Oikonomopoulou et al., 2018) https://doi.org/10.1016/j.jobe.2018.07.014.

3.1.6 Overview and Conclusions

In this chapter, the use of glass as a construction material was viewed. Glass is a unique material whose transparency makes it ideal to be used in building envelopes and the increasing advancements in the glass technology have enabled the creation of more and more transparent facades by implementing larger glass surfaces.

When designing with glass special attention should be given to its brittle character and lack of plastic deformation that can result in fracture without prior warning. Moreover, regarding its mechanical properties, glass possesses high compressive strength which allows it undertake structural loads as well. Nevertheless, special attention should be given to its considerably lower tensile strength which is greatly influenced by surface irregularities. Therefore, great attention should be given to the quality of the glass surface and edges and hole drilling should be avoided since it introduces stress concentrations.

Float glass made out of soda-lime glass recipe is the main glass type used in current glass structures. This production method generates fully transparent and smooth glass panes. Moreover, post-production procedures that the float glass pane undergoes such as heat strengthening and lamination can ensure its safe use in the building envelope. Finally, float glass panes assembled into an insulated glass unit can also result in building facades that apart from excellent optical qualities possess great thermal insulating properties as well. However, the potential of glass to be used in accordance with the principles of the circular economy is affected by its post-production additional processing to enhance its strength and thermal performance.

Apart from float glass manufacturing, glass casting is an alternative production method that can take greater advantage of the potential of glass to be recycled and can generate glass panes with greater shape freedom. On the other hand, cast glass lacks in comparison to float glass in terms of safe breakage and does not possess the smooth and completely transparent surface that float glass does.

3.2 Circularity in Glass Structures

3.2.1 Linear vs Circular Economy

According to European Commission (2018), the long-term plan for the EU is to be climate-neutral by 2050, meaning having an economy with net-zero greenhouse gas (GHG) emissions. For GHGs to be reduced, decarbonisation of the primary energy used in the prevailing industries is of the utmost importance. One way to achieve this is by employing alternative energies such as solar and wind but also by focusing on more efficient usage of energy. However, a change in the manufacturing process and the usage of products is equally crucial.

While 55% of the global GHG emissions are the result of the supply and consumption of energy in the building and transport industry, the other 45% is the outcome of product fabrication processes and their end-of-life management according to Ellen MacArthur Foundation (2021).

The way currently developed economies work is based on a linear approach of 'take-make-waste' as described by the Ellen MacArthur Foundation (2021). The linear economy is based on extracting materials and transforming them into products using large amounts of primary energy. Common practice is that after the product has accomplished its purpose, even if it is still functioning in parts or as a whole, it is discarded to landfill. This approach is highly extractive of the reserves of the natural resource and leads to the production of greenhouse gases (GHGs) that are the main culprit of the current climate change. It additionally creates increased pressures on landfills leading to widespread ecosystem pollution.

The linear economy model has vast impacts on the financial aspects as well. So far it could be sustained because of the abundance of cheap raw materials. Nevertheless, with the ever-growing world population, natural resources will become more scarce leading to increased costs of materials.

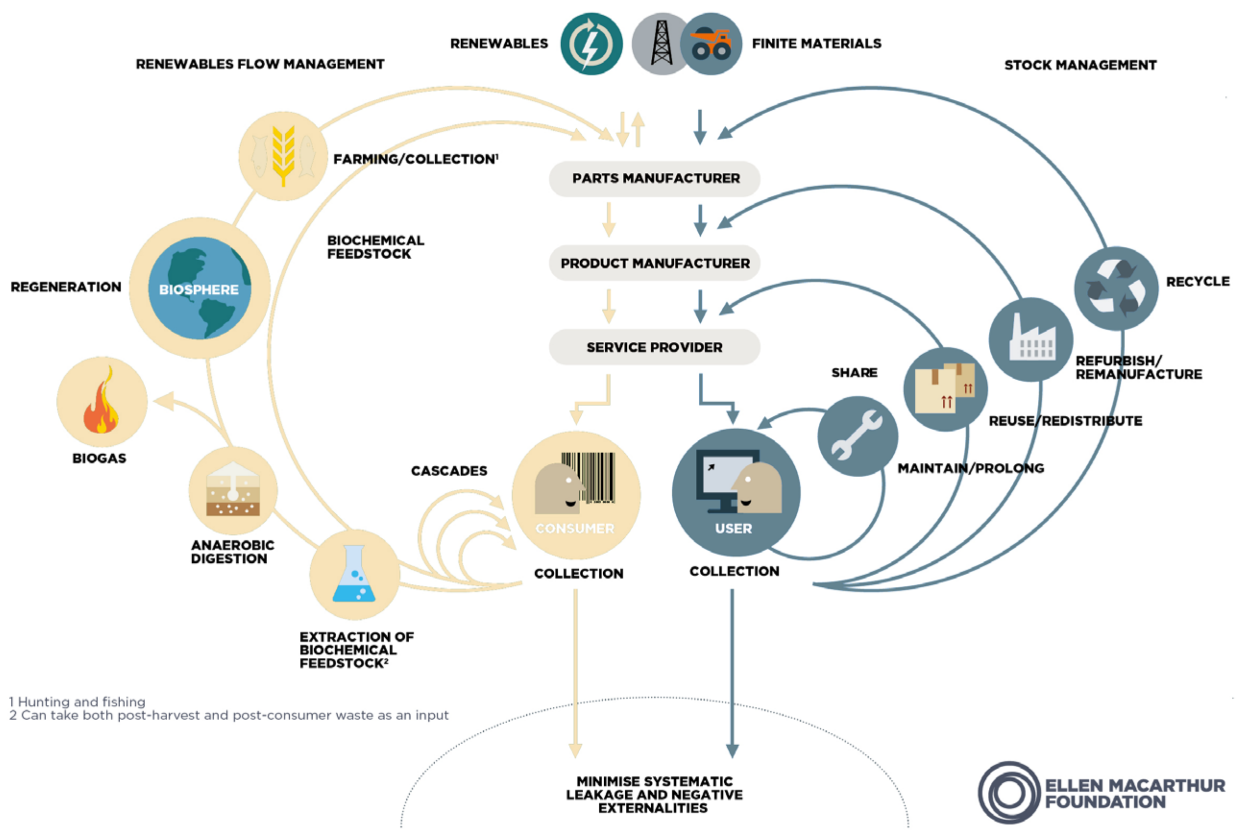


Figure 10. The circular economy diagram. From "Circular economy diagram", by Ellen MacArthur Foundation, 2019, https://ellenmacarthurfoundation.org/circular-economy-diagram

For all the above-mentioned reasons it is becoming more crucial than ever to procure a long-term alternative model of sourcing and using the natural resources available. The circular economy approach provides a new point of view concerning material usage, product manufacturing, and waste management added to the necessary shift to renewable sources and more efficient energy usage to accomplish the goals for the energy transition.

The circular economy promotes a radical change in the foundations of the global economy. It has its roots in concepts dating back to the 1970s, however, the model has gained attention recently thanks to the Ellen MacArthur Foundation promoting the global transition to the circular economy.

The Foundation has developed a visualised way to better understand the principles of the circular economy using the 'butterfly' diagram. (Figure 27) According to this diagram, the material flows are divided into two interacting loops: the biological and the technical resource cycles.

The biological cycle implements the use of renewable and bio-based resources so that they can be returned to the biosphere after their end of life. Examples of that are composting or anaerobic digestion.

The technical cycle focuses on the use of technically developed products in a way that enables a more prolonged lifespan and the ability to reuse, remanufacture and recycle once their original purpose has been fulfilled. This way waste is minimised by avoiding single-use components that end in landfills.

3.2.2 Circular economy in the built environment

The engineering and construction industry of the built environment consisting of buildings, infrastructure, energy, water, and waste systems is a major field that contributes negatively to the rapid consumption of natural resources. The current rate of natural resources consumption is double their extraction rate. The foreseen world's population growth in the near future will increase this rate as more infrastructures such as housing facilities will need to be constructed. By shifting to a circular economy model the negative impact of this growth in the built environment can be minimised.

Design is the key aspect to escape from the current linear economy model. Buildings and their individual components should be designed for a whole life-cycle and not simply an end-use in accordance with ARUP (2016).

According to Ellen MacArthur Foundation (2021), the circular built environment should be governed by three design-driven principles:
1. Eliminate waste and pollution to reduce GHG emissions across the value chain
2. Circulate products and materials to retain their embodied energy
3. Regenerate nature to sequester carbon in soil and products

1. Eliminate waste and pollution

The first step of a circular building design is the reduction of material usage in order to eliminate the extraction of natural resources and the resulting pollution from their future waste at their end-of-life. Material optimisation techniques and alternative materials that use renewable energies or less carbon during their production can be used for this goal.

2. Circulate products and materials

A circular building design aims at longer usage and circulation of products and materials in order to minimise and preserve their embodied energy. This aim can be successfully achieved by designing adaptable products apt for disassembly, reuse, re-manufacturing, refurbishment or recycling when the previous options are not feasible.

2.a Reusing products and components

The method of reusing whole building components or parts of them that are still in functional condition helps maintain the embodied energy that was used to create these products. The more the lifespan of a product is elongated the more the amount of energy and natural resources initially used during its production is balanced out by its prolonged lifetime compared to creating a new product.

2.b Recycling materials

While reusing products and materials is for sure the best way to avoid new GHG emissions, recycling materials is also a process that contributes to the circular economy goals. Although energy is necessary for the recycling process it still requires much less primary energy than the production from virgin materials. With recycling the extraction of more natural resources to create a new product is prevented. Moreover, the polluting processes that accompany the end of life of a product, such as incineration and landfill, are avoided.

3. Regenerate Nature

The circular economy promotes also a regenerative design using renewable and bio-based materials such as wood that can replenish the amount of carbon dioxide depleted during their manufacture and usage by being returned to their natural systems after their use.

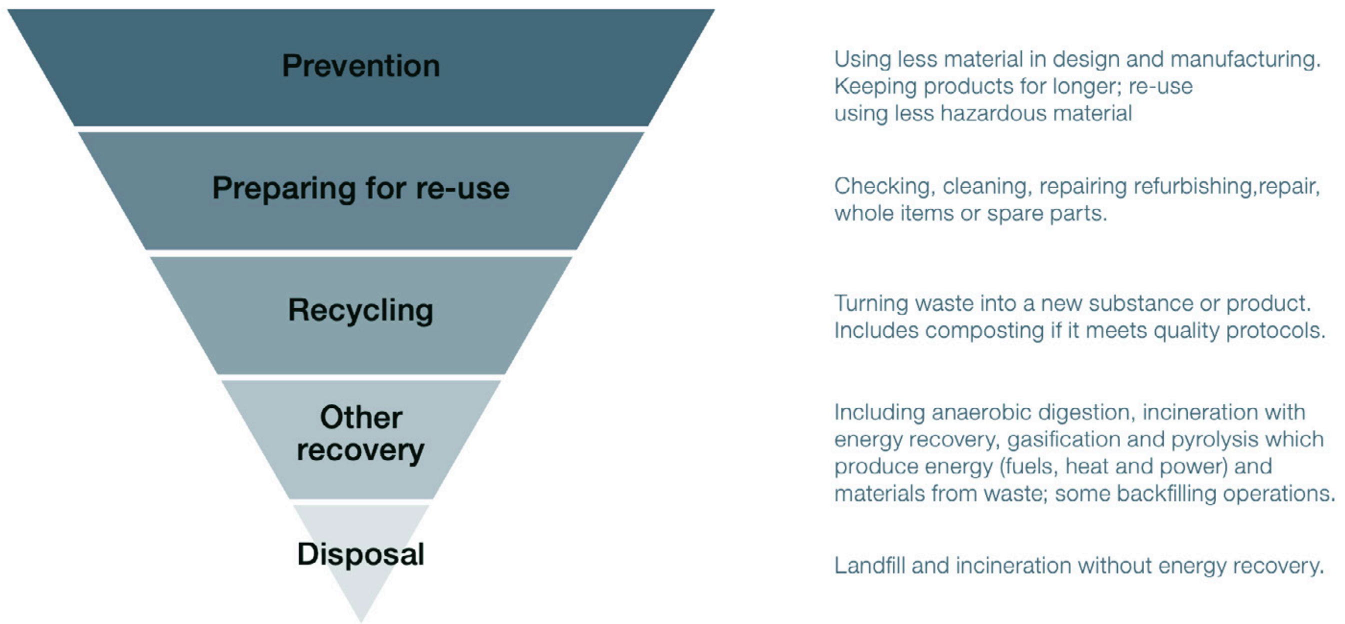


Figure 11. The Uk waste hierarchy. From "Re-thinking the life-cycle of architectural glass", by DeBrincat & Babic, 2018, https://www.arup.com/perspectives/publications/research/section/re-thinking-the-life-cycle-of-architectural-glass

3.2.3 The environmental benefits of recycling glass

Glass is a sustainable material that can, theoretically, be infinitely recycled without compromising its quality and its mechanical and optical properties. The recycling procedure consists of remelting pieces of waste glass, called cullet, and mixing them with raw materials. The use of cullet in the prevailing float glass industry provides significant environmental benefits and can contribute to the shift towards a more circular economy.

More specifically, with the introduction of one tone of cullet into the float glass production, a reduction of 1.2 tonnes of raw material use is achieved. This is particularly beneficial for the reduction of natural resources depletion. Moreover, the use of cullet requires less energy for the melting of glass compared to that needed to melt raw materials. For every 10% cullet used there is a 3% reduction of used energy, or alternatively, 300 kWh of energy is saved for every one tonne of cullet. Furthermore, for every tonne of cullet included the CO_2 emissions are reduced by 250-300kg. (DeBrincat & Babic, 2018) Finally, we cannot ignore the significance of glass recycling towards the reduction of the waste that goes to landfills and pollutes the environment.

3.2.4 The current state of recycling in the float glass industry

Two types of recycling currently exist, closed-loop and open-loop recycling. In closed-loop recycling, all the materials resulting from the recycled product are returned into the loop of the same manufacturing process. The key to success in this type of recycling is that the products are being constructed with a recycling end-of-life plan. Closed-loop recycling is achieved in a high percentage for the soda-lime glass used in beverage packaging like glass bottles.

On the other hand, in the open-loop recycling, often referred to as down-cycling procedure, the materials generated from the recycled product are not returned into the same cycle but are transformed into new raw materials or waste products that can be used in other industrial sectors.

In spite of its potential for recycling, the glass used in the building sector is seldom brought back into the loop. The construction industry is dominated mainly by float glass whose recyclability is currently very limited due to very strict requirements regarding the quality of cullet that can be used. Currently, the percentage of cullet that is being used in closed-loop recycling is only 9% in the Netherlands, which is one of the leading countries in glass recycling, and it comes almost exclusively from discarded pre-consumer internal cullet, meaning glass that was discarded from the float glass line itself before being used in the built environment. Therefore, float glass remains a linear economy whose products end at landfills after their usage or are down-cycled into glass bottles or glass wool insulation.

The contamination of post-consumer cullet, meaning cullet that has been used in the built environment, is the main reason why float glass closed-loop recycling is so challenging to be achieved. Among the most common cullet contaminants are adhesives, coatings, ceramic fritting and laminating layers, typically found in IGUs, whose removal is still technically challenging for the float glass industry.

According to a classification made by ARUP (2016), there are three categories of cullet qualities regarding float glass recycling as can be seen in Figure 27.

Class C

This class contains high contaminated glass with ceramic fritting or printed glass, spacers bars and glass mixed with other construction materials. This category is highly unsuitable for remelting and can only be used for road paint or for the creation of aggregates.

Class B

This category is alternatively called mixed cullet and allows for a small amount of contamination. Coated or laminated glass whose lamination could not be removed is usually used in this case. This type of cullet is usually down-cycled into container glass and glass wool insulation.

Class A

Class A consists of pure glass clear from any contamination. It is the only class of cullet currently accepted by float glass manufacturers due to their extremely high requirements for purity to achieve the desired optical qualities. This kind of cullet almost exclusively comes from internal glass not used during the processing and glass manufacturing before leaving the float glass factory. The bet of the building industry on glass recyclability is to find ways to facilitate the collection of post-consumer Grade A cullet from the existing building stock.

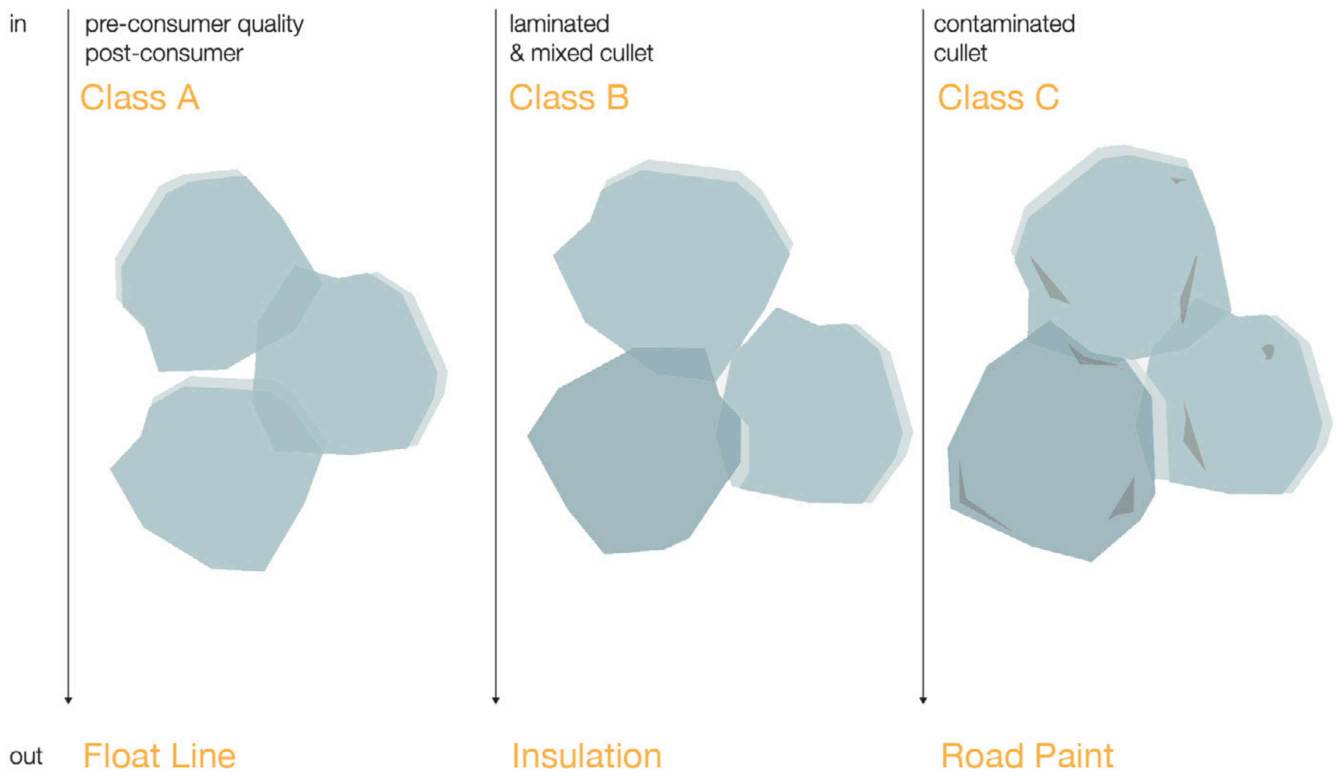


Figure 12. Cullet classes. From "Re-thinking the life-cycle of architectural glass", by DeBrincat & Babic, 2018, https://www.arup.com/perspectives/publications/research/section/re-thinking-the-life-cycle-of-architectural-glass

3.2.5 Factors that limit glass recycling

Lamination

Among float glass post-production processes lamination has the biggest negative impact regarding recyclability and it is one of the main reasons why float glass is so seldom recycled in a closed-loop manner. The challenge lies in the specialised techniques required to segregate the glass and the lamination removing the contamination from the interlayer. The current advancements in technology have made possible the use of a pulverizing and separating machinery (DeBrincat & Babic, 2018) that crushes and grinds the glass into small fragments. Nevertheless, the size of these fragments does not meet the "cullet A" standard of the float glass industry. Hence, laminated glass cannot be brought back into the loop and usually ends up being down-cycled into glass containers whose recycling process is more flexible in such tolerances.

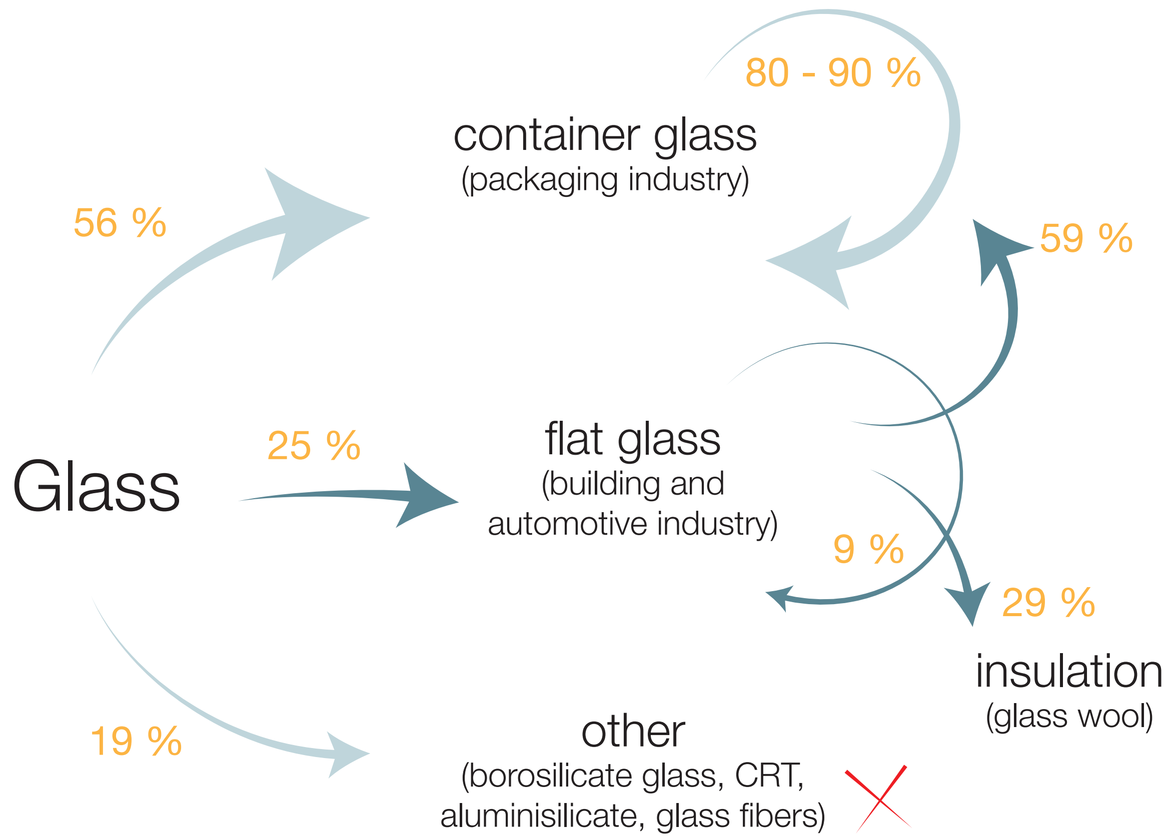


Figure 13. Diagram of the current glass recycling scheme in the Netherlands compared to the Re3 Glass proposal. From (Oikonmopoulou, 2019), https://doi.org/10.7480/abe.2019.9.4088

Coatings

The application of coatings on the glass surface serves to increase the thermal performance of insulated glass units and to help control the solar gains of a building through the glass. The coatings are applied either during the float line process or afterwards and are usually made of very thin metal layers projected on the glass surface.

Regarding their effect on recyclability, the high temperatures in which the float glass remelting occurs can burn off soft and hard coatings, therefore, in theory, their use is not endangering the recycling process. However, the cullet containing large amounts of coated glass cannot be considered of Grade A quality since the effect of a burnt coating being brought back into the recycling loop can result in glass panes of slightly altered colours which hinders their use in building envelope uses where the desired optical quality is the highest. Therefore, the coatings remain a contaminating factor for the float glass recycling industry not because of their effect on the mechanical properties of glass but because of their impact on the optical qualities of the final product and for this reason it ends up being down-cycled.

Moreover, in the case of recycling float glass into cast glass coatings affect this procedure depending on the types of coating and the ratio of coated glass cullet to clear glass according to Van Der Velden (2020). The temperature at which the coating melt determines whether or not they are suitable for cast glass recycling. Hard coatings, in particular, that contain nickel sulphide inclusions as well as heat-resistant coatings may cause problems because they are not easily burnt off in lower remelting temperatures.

Fritting

Ceramic frits are often printed on glass surfaces for reasons of architectural appeal, for increased privacy or for shading purposes. These frits include ceramic compounds that require very high melting temperatures so their use could lead to minor flaws introduction resulting in lower mechanical properties. Therefore, these kinds of coatings are not currently considered suitable for glass recycling purposes.

IGU Assembly

The way float glass is currently assembled in insulated units highly impacts its potential for reuse and recycling. For reasons of thermal performance, building envelopes use insulated glass units that are created by adhesively bonding together two or more panes of glass using a metal spacer to separate them. The unit is then hermetically sealed around its edges to ensure good thermal performance during its service life.

The specific bonding and sealing method pose two great problems that impede glass from being used circularly in the form of IGUs. Firstly, while the glass itself has a big lifespan and could last in a building for an average time of 100 years (Ebberts, 2010), the lifespan of the sealants is a lot smaller, reducing the overall lifespan of the whole IGU to approximately 25-30 years. Moreover, the adhesive connection of the different components of the IGU does not allow for the reuse of parts of the unit that are still functional. Finally, this permanent bonding of glass, spacers and sealants makes their separation difficult and very labour-intensive. Therefore, the post-consumer glass found in IGUs is almost never kept free from contamination during their deconstruction and collection process of demolition waste, thus impeding its recyclability.

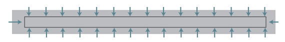
Post-production Glass Process	Impact on glass recyclability	Notes
 Cutting	No Contamination	–
 Hole Drilling	No Contamination	–
 Edge Working	No Contamination	–
 Heat Strengthening	No Contamination	–
 Lamination	Heavy Contamination	Current de-laminating process does not allow for closed-loop recycling
 Coatings	Light Contamination	Can be burnt off but reduces optical quality
 Fritting	Heavy Contamination	Cannot be burnt off
 Structural Silicone (IGU)	Heavy Contamination	Even careful removal of silicone leaves contamination traces

Table 01. Table showing the impact of each float glass processing on recyclability.

It is important to mention here that a strict classification of the post-production of float glass processes that can be allowed in the glass recycling is very hard and it is also highly dependent on the current industry restrictions and on each company's policy. Moreover, since technology is continuously evolving in this matter, new solutions could be possible every day to facilitate float glass recycling that produces glass panes with excellent optical qualities. The specific table and findings in this literature review reflect the current float glass industry potentials and limitations.

Table 01 consists of a summary of the above-mentioned glass processes regarding their impact on float glass closed-loop recycling. It is evident that like mentioned before, lamination, the assembly of glass into IGUs are the biggest challenges in the field of closed-loop float glass recycling because of the great amount of contaminating factors found in the cullet. Glass fritting has a similar impact on closed-loop recylae as lamination and IGU assembly although its application is significantly less common. The use of cullet with such heavy contamination has an impact on the mechanical properties of glass making them unsuitable for use in the building structures. The application of coatings is also a process that hinder glass recylcability but its effect is mainly on the optical qualities of the final product while their mechanical properties might remain intact.

3.2.6 Conclusions

Currently developed economies are based on a linear approach of 'take-make-waste' as described by the Ellen MacArthur Foundation (2021), which is highly extractive of natural resources and is accountable for the high energy consumption and environmental pollution. The circular economy approach provides an alternative point of view concerning material usage, product manufacturing, and waste management. This change is indispensable for the transition to an economy with net-zero greenhouse gas (GHG) emissions by 2050 which is the goal of the EU.

The circular economy focuses on innovative design approaches that:
1. Eliminate waste and pollution to reduce GHG emissions across the value chain,
2. Circulate products and materials to retain their embodied energy by
   a. Reusing products and components and
   b. Recycling materials, and
3. Regenerate nature to sequester carbon in soil and products

The engineering and construction industry of the built environment that consists of buildings, infrastructure, energy, water, and waste systems is a major field that contributes negatively to the rapid consumption of natural resources. For this reason the circular economy approach proposes to tackle this aspect through innovative design.

Focusing more specifically in the glass industry, float glass used in the building envelopes has the potential to be collected and remelted together with raw materials to create new glass. The integration of cullet in from the glass manufacturing industry can save significant amounts of energy. Nevertheless, the recyclability of float glass in reality is currently very limited due to the presence of contaminating factors that are not accepted by the float glass industry quality standards because of the impact they have on the mechanical and optical properties of the final recycled glass product. Thus, there is a lot of glass waste whose potential for reuse and recycle is not fulfilled and is discarded in landfills. Therefore, in order for post-consumer glass to be used in a more circular manner its collection at the end of its life should be in a controlled and careful manner to avoid contamination.

A significant step towards that direction would be a change in the industry itself, by giving the contractors the necessary incentives to sort of materials on-site and recycle them instead of depositing them in landfills. Moreover, the need for new circular designs of alternative IGUs that avoid contaminating factors and can be easily demountable could prolong the lifespan of the glass used in the built environment by avoiding the current obstacles at end of life of these units so that they can be easily dismantled, with optimal separation of materials, avoiding contamination.

In order to facilitate a more circular IGU design it is important that the glass is kept as pure as possible. Contaminating factors such as lamination, structural silicone adhesives from the IGU assembly, glass fritting and coating application should be avoided to the extent that they don't hinder the IGU's structural, thermal and safety requirements. In the case that this is not feasible, a design that enables the segretgation of the contaminating factors form the pure glass elements is the next best approach. Key for the success for recycling building glass is, therefore, a design that enables a relatively easy disassembly of the units, avoiding a laborious procedure and leaving the glass free of contamination.

3.3 Insulated Glass Units - Thermal Performance

3.3.1 The built-up of an Insulated Glass Unit (IGU)

Insulated glass units are the most commonly used construction elements nowadays where the combination of thermal performance and transparency is desired in building envelopes. They consist of two or more layers of glass separated by a spacer bar, to create a cavity that ensures the insulation of the component, and are linearly sealed together at their edges with an adhesive to ensure the cavity is permanently sealed in an air and water-tight manner. The cavities can also be filled with air or inert gas and coatings can be additionally applied to one of the glass surfaces for increased thermal performance.

A variety of glass types can be converted into insulated units including by using two glass panes with an in-between cavity. These glass types can be curved glass, fire-resistant glass, rolled or cast glass. However, the majority of insulated units use flat glass panels manufactured by the float process and they are typically used in thicknesses varying from 3 to 12 mm. Thicker glass can also be used where special conditions need to be met. Apart from annealed glass laminated or tempered glass may also be used as part of the insulating system if increased safety is required. Laminated glass and laminated safety glass are also used to increase the safety and the sound insulation of the facade. The quality and thickness of the glass panes depend on the desired structural and thermal performance. Wurm (2007, p.75)

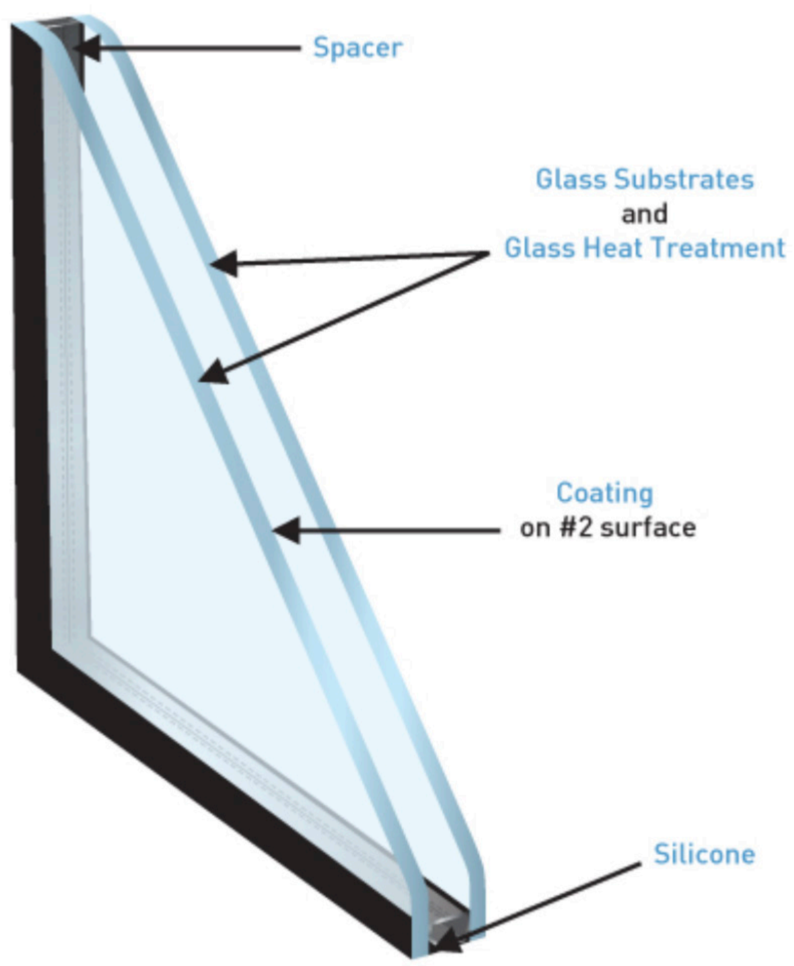


Figure 14: The built-up of a standard IGU. From GlassTech Thermopan, https://www.glasstech-termopan.com/products-projects/products/insulated-glass/

3.3.2 Energy Flow Mechanisms

The insulating value of an IGU is dependent on the type and thickness of the glass sheet, the size of the glazing cavity, the material used in the spacer, the type of edge seal, the presence of inert gas in the cavity and finally the application of coatings as well as their type and position. The following chapter will focus on the principles of building physics that determine the thermal performance of an insulated glass unit.

The principle behind the increased thermal resistance of double glazing in comparison to a single glazing element is the presence of an air cavity that separates the two different glass components. With the addition of the second pane, the thermal resistance can be doubled. Additionally, more than two glass panes can be used in an insulated glass unit in order to further increase its thermal resistance but the insulation will be improved at a decreasing rate. However, each additional layer of glass adds to the insulating value of the assembly but at the same time, the visible light transmission and the solar heat gain coefficient are reduced.

The building physics principles behind the thermal resistance of an insulated glass unit are similar to those of a standard cavity construction. The overall energy that flows through a glazing component is the result of the following functions:

a. Temperature Driven Heat Transfer
b. Solar Gain
c. Infiltration

3.3.2.1 Temperature Driven Heat Transfer

Heat flows through a construction element when there is a difference in temperature. Heat always flows from the high-temperature location to the low-temperature one. The temperature differences between the interior and the exterior space of a building lead to heat being gained or lost from the glazing element due to the following three modes of heat transfer present:

3.3.2.1.a Conduction

Conduction is the process by which heat is directly transmitted through the material of a substance when there is a difference in temperature.

The heat conduction coefficient (λ) shows how much heat flows through a layer of material of 1 meter thick and with a surface area of 1 m2, where the difference in temperature is 1 K (1 °C). The unit of λ is W/mK. Van der Linden (2013, p.5)

The heat conduction coefficient differs for each material. The larger λ is, the easier it is for a material to conduct heat. The heat conduction coefficient of glass is around 1 W/mK, while the heat conduction coefficient of standard insulation material (rockwool, EPS) is 0.035 W/mK.

The heat resistance (r) of a layer of material of a particular thickness (d) is found by the division of the thickness (d) of the material by the heat conduction coefficient (λ). Therefore $r=d/\lambda$.

3.3.2.1.b Convection

Convection is the transfer of heat by the movement of gases or liquids through air layers on the exterior and interior of an insulated unit's surfaces as well as between inside its cavity. The amount of heat transferred via convection depends on the speed of the flow of the transport medium (air or wind speed) as well as the difference in temperature between the object and the medium that is flowing past it.

The cavities in IGUs are not being ventilated, meaning that no external airflow is inserted through them. However, the air in the cavity is not always still; convective flow is developed under the following mechanism. When one of the glass panes of the IGU is heated the air next to it inside the cavity gets warm and due to that, it rises. When the warm air reaches the cooler glass pane it cools down and falls due to the fact that it becomes heavier. This air circulation inside the cavity creates a rotating convective flow that transfers heat from the inner to the outer cavity leaf. Van der Linden (2013, p.7)

3.3.2.1.c Radiation

Radiation describes the movement of heat through space from one place to another by electromagnetic radiation waves or rays. It does not require a form of matter to be transferred. Every surface radiates a certain amount of heat. This amount is determined by the temperature of the surface. The emission coefficient (ε) is a function of the wavelength λ and the temperature. A "black body radiator" is a surface that emits the maximum amount of radiation connected to its temperature. Its emission coefficient equals to ε=1. Radiation occurs inside the cavity of an IGU due to a temperature difference of the inner surfaces of glass leaves.

To conclude, the heat resistance of a cavity due to temperature-driven heat transfer is dependent on all three heat floes, conduction, convection and radiation.

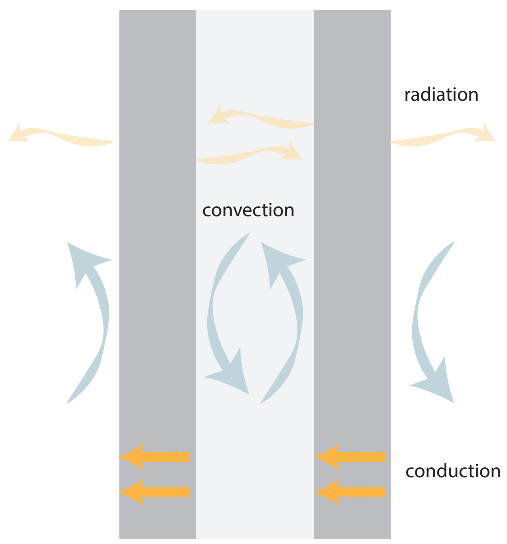


Figure 15. Heat transfer in cavity constructions. Based on Building Physics. (1st ed, p.7), by Van der Linden, A.C., (2013).

The temperature-driven heat flow occurring in an IGU is divided into convection and conduction in the air cavity and radiation exchange between the glass surfaces. The heat transfer through conduction and convection inside a cavity is highly affected by the cavity width. In narrow cavities, conductive flows are very high due to the fact that the layer of air inside the cavity is very thin to successfully resist conduction. On the contrary, in narrow cavities convention flows are developed with much more difficulty than in wider ones. The contrary occurs in wide cavities. Finally, the radiative heat flow is not affected by the width of the cavity but only by the temperatures on the surfaces of the glass panels on the sides of the cavity. The effect of the cavity width on conduction and convection is very conflicting so optimum cavity sizes should be no less than 8 mm wide for a good balance between the two heat flows to be found according to Van der Linden (2013, p.7)

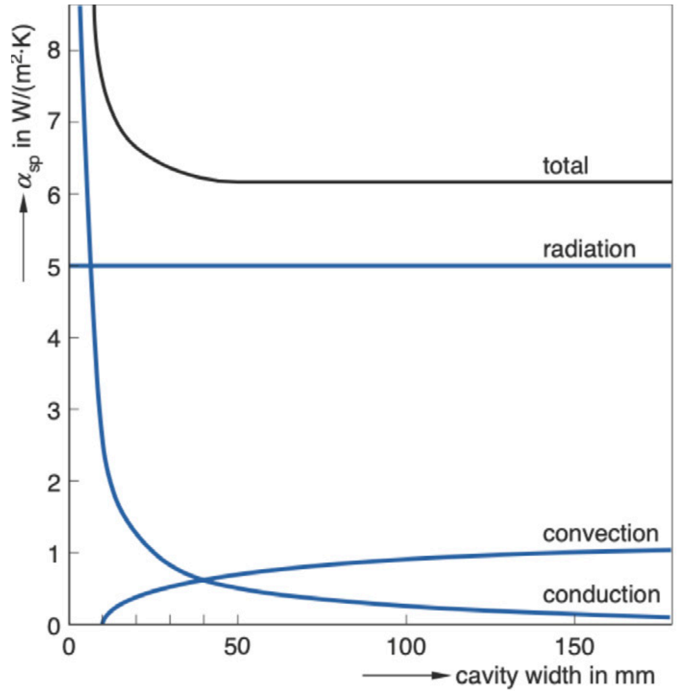


Figure 16. Heat transfer through vertical air cavities through conduction, radiation and convection as a function of the cavity width. From Building Physics. (1st ed, p.7), by Van der Linden, A.C., (2013).

Total heat transfer coefficient U-value

The insulating value of a glazing component is quantified by its U-value. This factor indicates the rate of heat flow through the fenestration product in W/m2K, including the conductive, convective, and radiative heat transfer for specific environmental conditions. Hence, it represents the heat flow per hour, in Watts through each square meter of glazing product for a 1°C temperature difference between the indoor and outdoor air temperature. Van der Linden (2013, p.10)

The U-value should be as low as possible for a certain material to show good insulating properties. It depends on the thermal properties of the materials in the component and the weather conditions, as the wind speed and the temperature difference.

The total thermal resistance, R-value, of a glazing component is calculated by the reciprocal of the total U-factor. Therefore, R=1/U.

The U-value of a single glass pane of 10 mm thickness is 5.6 W/m2K and of a typical double glazing unit of two panes of 10 mm thickness each is 2.8 W/m2K.

3.3.2.2 Solar Heat Gain

The second factor that greatly affects the energy performance of an insulated glazing component is its ability to absorb solar heat gains through the glass elements. Solar heat gain is the glass's absorption of energy from the direct and diffuse radiation that comes directly from the sun and the sky or is reflected from the ground and other surfaces. The solar heat gains of a glass element determine in the most part the necessary cooling load of a building since the intensity of the heat gain can be so big that it exceeds the heat transfer from any other sources like the temperature-driven heat gains or losses.

There are three characteristic functions of solar radiation that influence the solar heat gains of a glass component. These are the transmission, the reflection and the absorption of solar energy through the glass.

3.3.2.2.a Transmittance (t)

The term transmittance refers to the percentage of solar radiation that is able to pass through the glass. The transmittance depends on the type of glass used, the number of layers of glass used and the presence of coatings. Moreover, it can be modified to fit the building's energy needs by altering the properties of the material itself creating tinted glass, and by the application of coatings on the glass surfaces.

Solar transmittance is further divided into "visible light transmittance," "UV transmittance," or "total solar energy transmittance" according to the type of solar energy passing through. The transmission of visible light determines how effective a type of glass is in providing daylight and a clear view through the glazing product. Visible transmittance is the amount of light in the visible portion of the spectrum that passes through a glazing material and does not have a direct effect on the heat gains. It ranges from 90 to 10 % with the higher values corresponding to clearer glass and lower values to tinted or coated glass.

The early uses of methods to reduce solar gains unavoidably reduced the visible transmittance as well. However, advances in that field have led to the use of spectrally selective tinted glasses and coatings that do not compromise visible transmittance.

3.3.2.2.b Reflectance (r)

The second function of a glass surface in relevance to solar radiation is its ability to be reflected. The percentage of the solar energy that will be reflected off a glass surface depends on the quality characteristics of the surface, the presence or absence of coatings and the angle of incidence of light on the surface. The application of metallic coatings on the glass surface can enhance its reflectivity.

3.3.2.2.c Absorbance (a)

The remaining solar energy that has not been transmitted through the glass or has not been reflected off its surfaces will be absorbed. After the absorption of solar energy from the glass, this energy will be turned into heat, leading up to a raise in the temperature of the glass element. The absorbance of clear glass is very low, on the contrary. The levels of absorbance of glass can be increased with the addition of chemicals suitable for absorbing solar energy. The glass has a darker colour when it is altered to absorb visible light while for the absorption of ultraviolet or near-infrared radiation, there is no visible change in the glass' colour.

g-value

The total solar energy that is gained through the glass is characterised by the g-value. It is defined as the difference in heat flow through the glass with and without solar radiation, divided by the glass area multiplied by the load of the incident solar radiation. The g-value is between 0 and 1, with 0 describing a situation where no solar energy enters the room through the glass and 1 where all solar energy that falls on the glass surface enters the room.

Finally, the total solar energy that enters inside a building via an IGU is the result of the glass' g-value multiplied by the glass' surface and the solar load.

$Q_{solar} = g * A_{window} * q_{sun}$

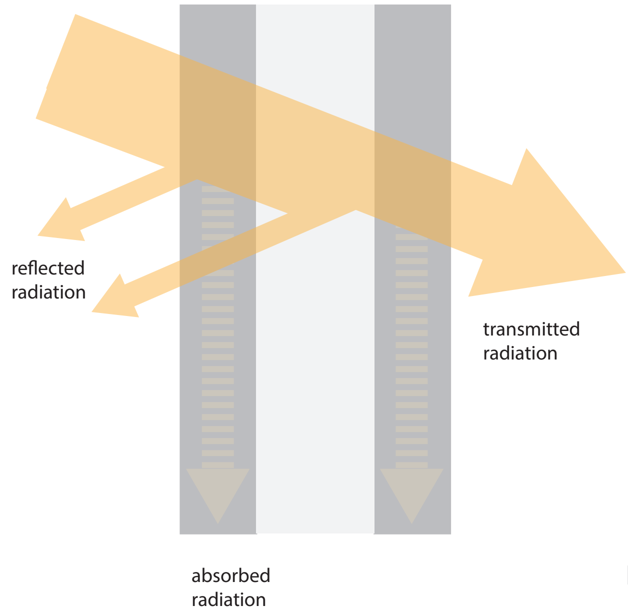


Figure 17. The behaviour of heat transfer in Low-E coated windows.

3.3.2.3 Infiltration

The infiltration that takes place in a glazing component happens via gaps and cracks that allow air to pass through. Infiltration greatly reduces the insulating value of the component and is associated with poor construction and maintenance aspects. The effect of infiltration in heat loss or gain is measured in terms of the amount of air (cubic feet or meters per minute) that passes through a unit area of glazing product (square foot or meter) under given pressure conditions. The intensity of this effect fluctuates according to the prevailing wind and temperature conditions.

3.3.3 Ways of further improving the thermal resistance of IGUs

Additional Cavity

The addition of an extra glass pane in the standard double glazed insulating unit further reduces its u-value by minimising the radiative heat transport that occurs between the different glass panes. The existence of a third pane decreases the temperature difference between the inner and outer glass panes that act as radiators. This is due to the fact that the radiative heat transfer now occurs between the inner warmer pane and the middle pane that has a higher temperature than the outer pane that is in direct contact with the exterior environment.

However promising this method may be for the enhanced thermal insulation of the unit, some disadvantages must be noted. Firstly, the solar radiation can result in overheating of the middle glass pane and in order for a fracture to be avoided due to thermal expansion this pane should be made of toughened glass. Moreover, the use of an additional glass sheet increases the weight and the width of the whole component thus increasing its cost. Finally, each additional glass pane used results in a reduction of the visible light transmission and the solar heat gain coefficient affecting the unit's capacity for solar heat gains and daylight.

Coatings

The application of low emissivity coatings on one or more of the surfaces of the glass panes of an IGU is a way to further reduce its u-value and therefore improve its thermal resistance. The presence of such coatings impacts the radiative heat exchange between the different glass surfaces of the IGU.

When coatings are applied to a glass surface of an insulated glass unit they affect the surface's emissivity value, and therefore, impact the heat transfer through radiation which leads to a change in the total thermal resistance values of the cavity resulting in a lower u-value. The application of coatings on the surface of a glass is also a very efficient way to control the solar heat gains of the IGU additionally to improving its thermal resistance.

The principle behind the development and use of coatings is based on the fact that the solar spectrum consists of electromagnetic radiation of different wavelengths, not all of which are visible. First comes the short-wave invisible ultraviolet then, the visible spectrum, and lastly the longer, invisible near-infrared waves. The visible light is only a small portion of the whole electromagnetic spectrum, the remainder is largely infrared with a small amount of ultraviolet.

With the use of coatings it is, therefore, possible to selectively admit or reject different portions of the solar spectrum. When using coatings on a glazed surface the climate in which the product is addressed should be taken into account. Cold climates for example need a maximisation of solar heat gains during the winter season while hotter climates do the opposite. Moreover, the conflicting needs of the same climate conditions in the different seasons should be taken into account in order to find the most suitable option.

Low-E coatings are divided into two categories according to their manufacturing procedure: online and offline coatings.

a. Online coatings (pyrolytic coating)

Online coatings, or pyrolytic coatings, are applied during the manufacturing process of float glass. Their application technique consists of the spread of a metal oxide on the glass surface while the glass remains in high temperatures so that a firm bonding of the coating to the glass can be achieved. The metal oxide reflects the solar radiation and lowers the emissivity of the glass surface. Typical emittance values for these coatings are between $\varepsilon = 0.20$ and $\varepsilon = 0.10$. An alternative name for these coatings is “hard” coatings due to their high durability. They can be exposed to outside air and cleaned without a decrease in their efficiency, which allows for more flexibility in their use. Online coatings cannot be used with cast glass though.

b. Offline coatings (Magnetron sputtering)

Offline coatings, or sputtered coatings, are applied after the production and cutting of the float glass. The procedure consists of the application of very thin layers of metal oxide, such as silver, being deposited on glass in a vacuum chamber. These kinds of coatings are more susceptible to wear and tear if exposed to environmental conditions and thus, they must be protected from humidity and direct contact. This is why they are also called “soft coatings” and they are usually placed inside a cavity of an IGU. A procedure called edge deletion must occur when using these coatings. This means the removal of a narrow strip of coating around the edges of the glass pane that will further be assembled into an IGU in order to avoid its corrosion by moisture during its service life. The emissivity of these coatings is between $\varepsilon = 0.10$ to $\varepsilon = 0.02$, lower than online coatings. While the emissivity of uncoated glass is $\varepsilon = 0.84$.

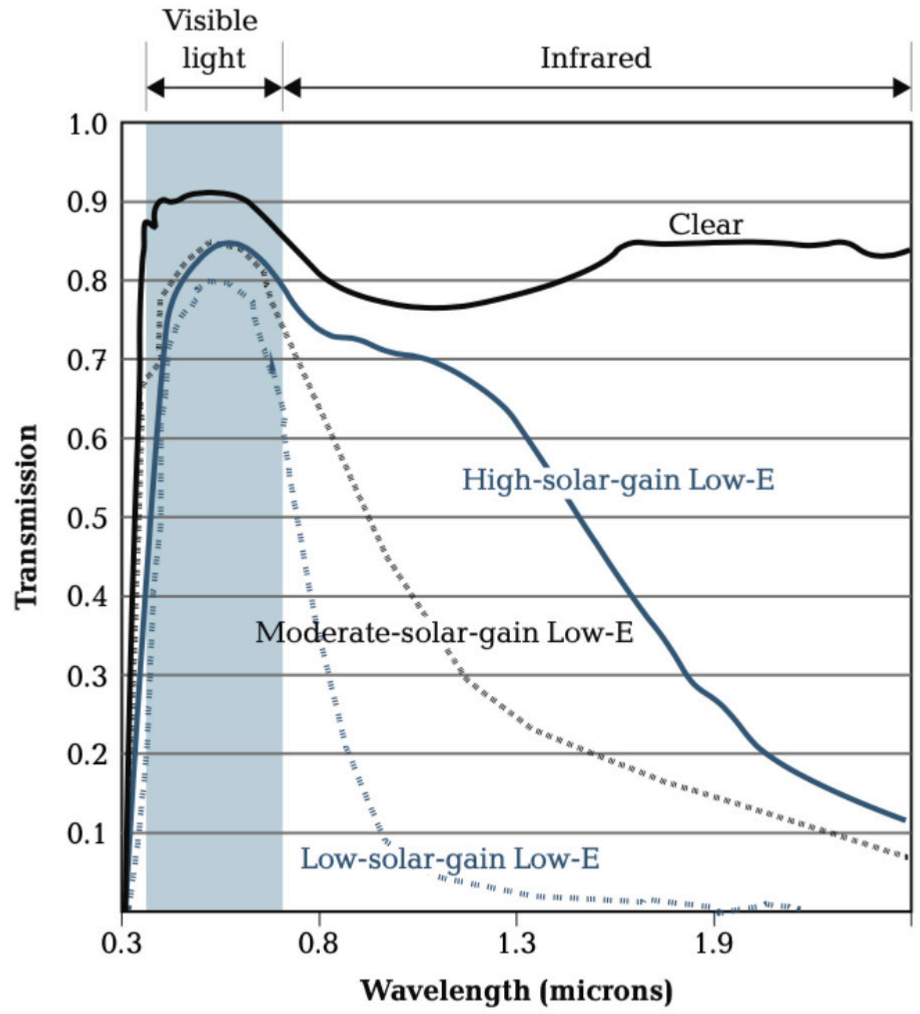


Figure 18. The behaviour of heat transfer in Low-E coated windows.

Gas Fills

The use of less conductive inert gases to fill the IGU's cavity reduces the thermal losses through conductive and convective flows due to their large atoms behaviour. Moreover, narrower cavities can be used since the effect of conduction is minimised by the use of gas. The inert gases typically used are argon and krypton. Both are nontoxic, nonreactive, clear, and odourless. Argon is less efficient than krypton but is also more easily extracted and therefore less expensive. Each gas has a different optimum cavity size. IGUs filled with argon perform best with a cavity size of 12mm wide while krypton filled units can take advantage of narrower cavities, particularly useful in case of renovation projects where width is an issue.

The efficiency of inert gases is particularly increased in combination with the use of low-E coatings. The presence of coating significantly reduces heat losses from the radiative heat transfer between the glass surfaces so the gas fill can influence more successfully the effect of the convective and conductive heat flows inside the cavity.

However promising the use of inert gases may be for the thermal performance of the unit it is also accompanied by manufacturing challenges that have to do with the successful filling and sealing of the cavity. The current technology of filling an IGU with inner gas consists of inserting the gas into the cavity using a pipe through a hole at the edge of the unit. The typical gas fill achieved currently is no more than 90% due to the fact while entering the cavity the gas is mixed with air so a 100% gas fill is not possible.

Vacuum Glazing

Vacuum glazing describes the creation of a completely airtight seal around the edges of the IGU. In a vacuumed cavity convection and conduction are minimised to zero. However, the presence of even a small negative pressure inside the cavity makes the glass panes deform and even break. For this reason, additional supports inside the cavity are needed to link the different ones structurally. These supports resemble very small spacers and therefore act as many small thermal bridges between the two glasses. Another way to overcome the negative pressure issue of the cavity is by applying a translucent, pressure-resistant insulating material such as aerogel although this would compromise the transparency of the unit.

Convective barriers

An alternative way to reduce the convection inside the cavity of an IGU is by applying a mechanical barrier that divides the cavity into two narrower ones thus reducing the convective flows while the thermal conductivity stays stable. These barriers can be either vertical or horizontal but for the sake of transparency vertical ones are preferred. The materials that can be used are thinner glass or plastic and they can also carry low-e coatings. The advantages of this technique compared to additional glazing panes is the reduced weight and width as well as the absence of risk of overheating of the middle pane.

The above mentioned means of creating insulated glass units with satisfactory thermal performance result in a quantifiable insulated value of the glass part of the IGU which is called its u-value [W/m2K]. The u-value of a single glazing is around 5.6 W/m2K. The use of a second pane reduces it to 2.8 W/m2K and the use of a low-e coating further reduces it to 1.8 W/m2K. The cavity fill with argon gas can result in a u-value of near 1.2 W/m2K and the use of a thin convective barrier inside the cavity can result in a u-value of 0.8 W/m2K. The thicknesses of the glass panes as well as the width of the cavity or cavities play an important role in the definition of the final u-value. Finally, it is important to highlight that the aforementioned u-values concern only the center of glazing area.

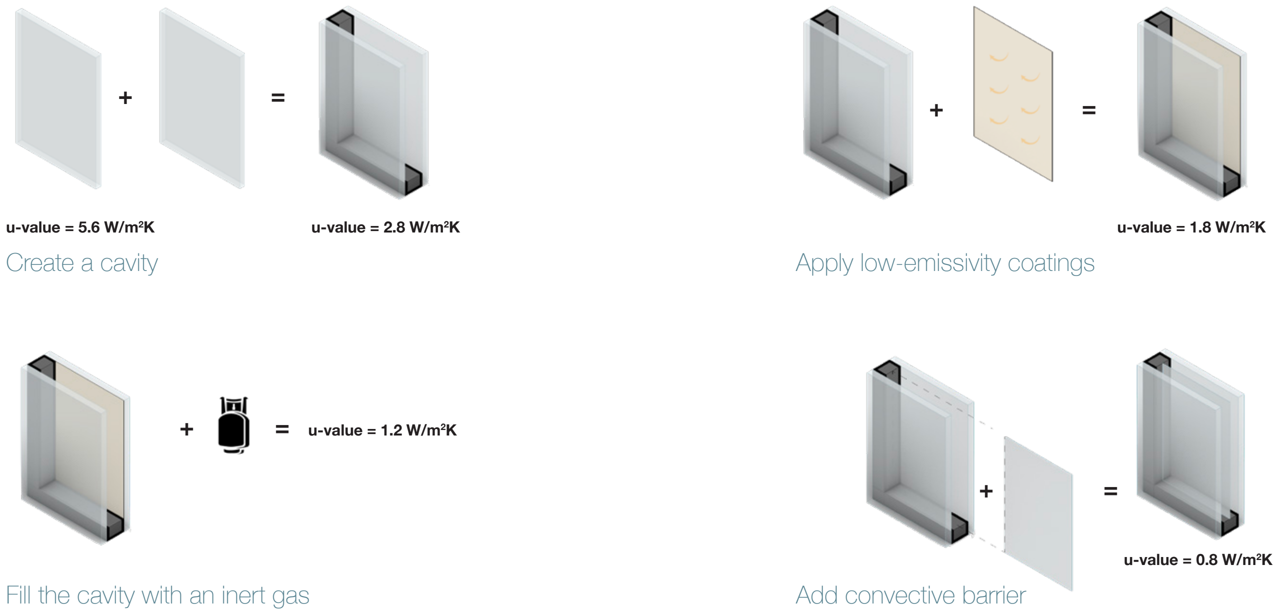


Figure 19. The u-value of typical IGUs.

3.3.4 Total Product U-value

The U-factor of a total IGU assembly is a combination of the insulating values of the glass part, the edge effects the result from the peripheral bonding of the IGU and the insulating value of the frame.

Centre-of-Glazing U-value

The U-value of the glazed part of the insulated unit is affected primarily by the total number of glazing layers, the dimension of the cavity separating these layers, the presence and type of gas that fills the cavity, and the presence and properties of coatings on the various surfaces. The U-factor for the glazed part alone is referred to as the centre-of-glass U-value.

Edge Effects

The spacers around the edges of an insulating glass unit have a very significant effect on the overall u-value of the component. Depending on the material used the heat flow through the spacer is usually much higher than in the centre of the glazing. This is accountable for increased heat loss along the outer edge of the IGU. The magnitude of the impact of these “edge effects” is dependent on the insulating value of the glazed part. The higher the thermal resistance of the glass the more significant for the overall performance of the unit is the impact of the edges.

Frames

The heat loss via the frame of an IGU can be quite significant as well depending on the size and material used. The larger the frame and the more conductive the material used, the bigger the thermal losses. However, the calculation of the impact of the frame on the total u-value is quite difficult since frames are rarely solid elements of the same thickness all around. Hollow and composite frames are often used and apart from their conductive value, the convective flow next to the glass as well as the radiative heat exchange between the different surfaces must be taken is not account.

Overall U-value

Since in an IGU there are different u-values for each part of the unit an overall u-value must be calculated for the whole unit.

The calculation formula for the total U-value, Uw, is defined as:

$$U_w = \frac{\sum A_{glass} U_{glass} + \sum A_{frame} U_{frame} + \sum l_{glass} \Psi_{glass}}{\sum A_{glass} + \sum A_{frame}}$$

With Ψglass the linear heat transfer coefficient relates the additional heat loss to the length of the linear feature (in this case the perimeter of the panel).

3.3.5 Alternative Glass Products with Insulating Properties

Profiled glass

The profiled glass currently produced is a U-shaped glass fabricated by the casting method. The production technique consists of passing the melted glass mixture of the raw ingredients through a mould in order for the edges to be bent upwards at 90° giving a channel-shaped final result of restricted width but of great lengths.

The particular geometry of the profiled glass allows for an installation without any transoms, simply by combining in the right way the different pieces. There are three popular installation systems. The single-leaf system, the single-leaf “sheet piling” system and the double-leaf system according to Schittich et al. (2007, p.63)

Profiled glass can consists an interesting alternative insulated glass when installed as a double-leaf system since there is an air cavity between the two different glass pieces. The difference between this system with the standard insulated glass units is the absence of air seal and dehumidification of the cavity, instead, a vapour pressure equalisation is used to avoid condensation by providing an opening to the drier outside air.

In terms of transparency, the specific manufacturing method produces slightly translucent glass surfaces meaning compromised transparency compared to a typical float glass IGU. In terms of circularity, the “double leaf” installation allows the reversibility of the structure but special attention must be given to the seals used between the glass panes during the installation and whether these contaminate the glass or not.

Figure 20 and 21. Single leaf profiled glass installation From “Glass Construction Manual” (2nd ed., p 63), by Schittich, Staib, Balkow, Schuler, & Sobek. (2007).

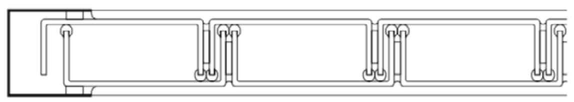


Figure 22. Double leaf profiled glass installation From “Glass Construction Manual” (2nd ed., p 63), by Schittich, Staib, Balkow, Schuler, & Sobek. (2007).

Hollow Glass Blocks

Hollow grass blocks or alternatively known as glass bricks are all-glass elements with an integrated cavity because of which they possess good insulating values. Their manufacture consists of pouring the melt glass mixture of the raw materials, which have been heated in a furnace of 1500 C, into shell-shaped moulds. In order for the glass mixture to be spread into the mould, a plunger is used to push it down. Each shell consists of half of a block and their outer surfaces can be smooth or can have a textured pattern. Once the halves are cooled down to 600 C, two halves are placed facing each other so an airtight seal can occur between them. Their edges are reheated to their melting temperature and the two elements are pressed together so that the two different glass pieces can be fused together into one whole element. The next step is the transportation of the fused blocks in an annealing lehr where they can cool down slowly in order for breakage to be prevented.

In terms of circularity, the lack of coating application and the fusion lack of use of additional materials at their edge seal makes them a circular choice. However, hollow glass blocks do not reach the thermal resistance of an IGU made of float glass without a coating applied to them. Moreover, in terms of transparency, their manufacturing method does not produce smooth surfaces like float glass although the use of glass fusion allows an all-glass result.

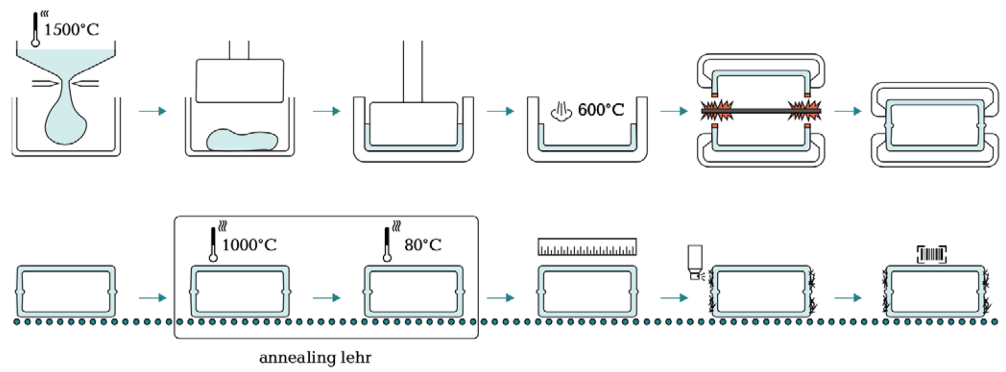


Figure 23. Production of hollow glass blocks. From Van Der Velden (2020).

Insulated Units with Cast Glass Components

Recent research conducted in TU Delft by Van Der Velden (2020) and Nathani (2021), provided new insights into ways insulated glass units can be created using alternative glass production methods such as cast glass. Such an approach also expands the IGU use in load-bearing structures. The focus of both the above-mentioned thesis was specifically on cast glass due to its potential for recyclability compared to structural float glass. Nathani (2021) developed four different promising design concepts some of which were based on the conclusions from the previous research of Van Der Velden (2020). Therefore, these are mentioned below.

Concept 1. Hollow glass block with thicker cross-sections

This design concept is based on the typical hollow glass blocks with the deference of the fact that cast glass of thicker cross-section is used to be able to carry the structural loads, something that is not possible in the case of the typical hollow blocks. Single and double cavity are examined and double cavity with coating application is found to best performing in terms of thermal resistance. The presence of a second cavity might reduce the overall transparency of the unit causing some optical distortion. In terms of circularity, the lack of a provision for the separation of the coated part from the contamination-free glass reduces the potential of the specific design for circularity.

Concept 2. Hollow glass block with thicker cross-sections and a coated convective barrier

This design is an alteration of the first one with the difference that a coated thin glass layer is added inside the cavity dividing it into two separate ones. This intermediate glass layer acts as a convective barrier. This design shows promising results in terms of thermal performance without compromising the transparency of the unit. Moreover, a suitable reversible connection would ensure the circular character of this concept as well.

Concept 3. Combination of a solid and a hollow block

This concept is a combination of a solid cast glass block that plays the load-bearing role and a coated half hollow block which is added for the creation of a cavity and does not carry any structural loads. This combination result in a satisfying thermal performance. Moreover, this design practically consists of a recyclable and a non-recyclable part and the development of reversible connection for these two glass elements can lead to a circular choice.

Concept 4. Multiple air cavities

This design concept is based on the creation of multiple air pockets that highly increase the thermal resistance of the block while providing an even load distribution. This design shows great thermal resistance and can be manufactured as one component made with cast glass using a mould. Recyclability is a great advantage here since the absence of contaminants makes it easily recyclable. However, in terms of transparency the presence of multiple cavities means that the number of refracting surfaces is increased which lead to high optical distortion and reduced transparency.

The aforementioned design concepts by Nathani (2021), provide useful insight on alternative was insulated glass units can be created. Furthermore, this research introduces the concept of combining the load bearing capacities of structural glass into insulated glass blocks. For the scope of this thesis these concepts are assessed for their effect on the transparency and the circularity of the units. Concepts 2 and 3 show the most promising results in these two aspects since they can be made by separate glass pieces that with a suitable reversible connection can be separated and the unit could be refurbished is at some point its thermal performance is reduced, or the glass panes can be recycled or down-cycled depending on the contamination presence on their surfaces. Moreover, these two concepts the minimum amount of glass panes thus resulting in an enhanced transparency of the overall unit.

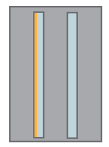
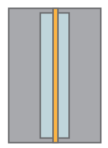
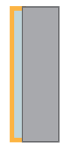
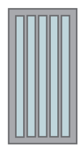
Concept No	Load Transfer	Thermal Insulation	Circularity	Transparency	Notes
1 	++++	++++	+	++	Difficult separation of contaminated part, Non-satisfying optical quality
2 	++++	+++	++++	+++	Must be created in two pieces, Satisfying optical quality
3 	++++	+++	++++	+++	Must be created in two pieces, Satisfying optical quality
4 	++++	+++	++++	++	Can be created in one piece Not satisfying optical quality

Table 02. Assessment of Nathani (2021) concepts

3.3.6 Overview and Conclusions

This chapter reviewed the ways in which an insulated glass unit can be created and the building physics rules that affect its thermal insulation properties. Moreover, the different glass types used in IGUs were reviewed.

A single glass leaf if used in the building envelope does not provide with a satisfying thermal resistance and accounts for great thermal losses and increased energy usage. Therefore, the combination of two glass panes into one unit using air as insulating means inside their in-between cavity is the first and basic step towards the improvement of the thermal performance of glass used in the building facades.

The increasing need for further improving the thermal resistance of IGUs has led to the development of additional ways to further improve their insulating value. The most commonly used ways are the application of a low emissivity coating on one of the glass surfaces that reduces the radiative heat transfer between the different glass panes. Furthermore, a less conductive inert gas such as argon or krypton can be used to fill the cavity by reducing the heat losses through conductive and convective flows. Argon is more commonly used because of its lower price though it is less efficient than krypton.

If the thermal performance of an IGU is not satisfactory then a third glass pane can be added creating a triple glazed insulating unit with two cavities. Since using a third glass pane of similar thickness to the two main ones can result in increased cost and weight of the unit alternative elements can be used. These are called convective barriers and consist of elements that provide a mechanical barrier to the convective floe inside the cavity by dividing it into two separate ones. These barriers can be thinner glass panes or even plastic and can also be coated. Finally, vacuum glazing the cavity and creating a completely airtight seal in the IGU edges is a way to significantly improve the thermal resistance of the unit although there are construction difficulties associated with this process. The total unit u-value is further affected by the effect of the edge seals and the frames used during its application in the building envelope. More in depth information on the edge seals is provided in the following chapter.

As previously mentioned, the basic principle behind the creation of insulated glass units is the combination of two glass panes with an air cavity between them. Different types of glass can be used and with different possible combinations. The prevailing type of glass used in the majority of IGUs used in the built environment is float glass. The float glass panes are separated with the help of a spacer bar and are bonded together and sealed with structural silicone. This type of IGU exhibits the best surface quality in terms of transparency and has discrete black visible edges form the silicone seal. The sealing method however, results in a non-reversible design that does not enable the circular character of the unit. Finally, IGUs made of float glass can be manufactured in a great variety of sizes from very small to very big glass panes, their dimensional limitations are the same for single leaf float glass panes.

The second most common glass product with insulating properties used in the building envelopes is the hollow glass blocks. These blocks are quite different from float glass IGUs regarding their manufacturing process, final optical result and use. Hollow glass blocks are manufactured in small squared blocks, typical dimensions are 200 *200 mm. Moreover, the surface quality of these blocks is not as smooth as that of float glass and there is always some optical distortion. In terms of their bonding hollow glass blocks are manufacture in two halves that are later fused together resulting in an all-glass unit. This unit can be recycled if contaminating factors such as coatings are avoided. However, the lack of coating application cannot provide a thermal performance of the desired values.

Profiled glass in “double leaf” installation is another insulating glass alternative. This product exhibits translucent surfaces resulting in reduced transparency. Its installation method allows for reversibility although in terms of glass recyclability the sealants used during the installation process need to be assessed in terms of contaminating factors.

Finally, recent research in TU Delft has led to the proposal of alternative insulated glass products using cast glass elements in different combinations. The innovation in this case is the increased load-bearing capacity of these products due to the use of thicker cast glass cross-sections. Moreover, the use of cast glass can result in greatest shape freedom. In terms of circularity cast glass is an alternative glass type that can be recycled more easily that float glass, although its surface transparency is not as smooth as that of float glass. Finally, the circular character of these products highly depends on the connection used to bond together the different glass panes. A reversible connection can result in a very circular design.

3.4 Insulated Glass Units - Edge Seals

The typical IGU consists of two float glass panes, that can mechanically interact via a hermetically-sealed cavity between them. The principal role of the edge seal is to connect the different glass panes and ensure that they are kept separated at equal distances while acting as a barrier to prevent infiltration of water vapour or exfiltration of the air or inert gas that fills the cavity between the panes. The edge seals are responsible for the structural integrity by being rigid enough to keep the glass panes together while allowing some flexibility to accommodate movements that occur during the life-time of the unit. Moreover, the edge seals affect on the thermal performance of the unit by affecting the total u-value. Finally, the edge seals have an impact on the aesthetic result of the IGU due to the visible black silicone elements.

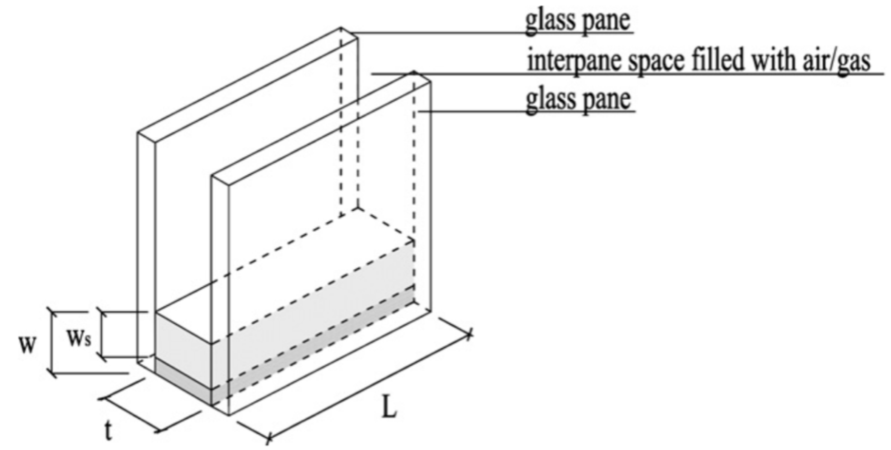


Figure 24. Edge Seal of a Double IGU. From (Van Den Bergh, et al., 2013) .

3.4.1 IGU Edge Seals Components

There are four main elements that make up the edge seal of an IGU. These are the spacer bar, the primary and secondary sealants and the desiccant. In terms of dimensions, the total width (w) of the edge seal varies from 4 to 8 mm while the total thickness (t) is determined by the cavity size and is typically between 12 and 14 mm according to (Van Den Bergh, et al., 2013) as seen in Figure 24.

3.4.1.a Spacer Bars

During the first years of the launch of insulated glass units in the market, the way to bond them together was by the technique of fusing together the edges of glasses so that a permanent seal could be created ensuring the system's stability. This bonding method however introduced great thermal bridges.

The ever-increasing need for improvements in the thermal resistance of the IGU systems led to the use of spacers, as a means of separating and permanently sealing the glasses together, instead of the older glass to glass fusing. In this system, the glass sheets are bonded to a continuous spacer around their perimeter so that a cavity can be created which is essential for the insulation of the component. Spacers also integrate a desiccant that absorbs the moisture of the cavity so that fogging of the glasses can be avoided.

The role of the spacer bar is firstly to provide rigid support in compression in order for the distance of the glass panes to be kept the same so that there is no change in the cavity width. The typical width of spacer bars (w_s) varies between 4 mm and 8 mm and the most common thicknesses are between 12 mm and 14 mm depending on the cavity size in accordance with (Van Den Bergh, et al., 2013).

The performance of the whole IGU system is greatly influenced by the choice of spacer materials. The types of spacer bars that are currently available in the market are divided into three main categories; (a) metal spacers, (b) thermally improved metal spacers and (c) non-metal spacers.

The metal spacers include aluminium, galvanized steel and stainless steel. They are very rigid but the big thermal conductivity of metals introduces thermal bridges at the edges of the unit.

Thermally improved metal spacers include U-shaped steel profiles or hybrid spacers made of stainless steel profiles combined with a highly insulating plastic top that breaks the thermal bridge at the top edge of the spacer bar. Finally, thermally broken aluminium can also be used by integrating a thermal barrier in the middle of the aluminium spacer to create a warm-edge effect. These types of spacers also have great rigidity but their impact on the thermal bridges is significantly reduced.

The non-metal spacers implement a non-metallic main structural component. A metallized foil is often integrated to ensure the seal's water vapour and gas impermeability. These kinds of spacers can be used in the form of a composite constructed from several components such as highly insulating composite plastics or a flexible stabilizer, a moisture barrier membrane, a desiccated top coating, and a stiffening layer. Structural foam is an alternative option made from desiccated silicone foam or ethylene-propylene-diene-monomer (EPDM) foam with an integrated moisture barrier. Finally, thermoplastic spacers are nowadays widely used. They are extruded directly between the glass panes, creating a homogeneous and continuous edge seal and are made from PIB with integrated desiccant with no need for additional metallized foil. Non-metal spacers are the best-performing spacers currently available in the market in terms of thermal performance. Furthermore, they are significantly more flexible than the spacers that integrate a metal component. Their wide use during the last year has proven that the rigidity of the spacer bar is not necessary and that flexible spacers can work even better in terms of the structural integrity of the unit since they can accommodate bigger movements, thus avoiding stress concentration on the glass panes in contrast to the rigid metal spacers.

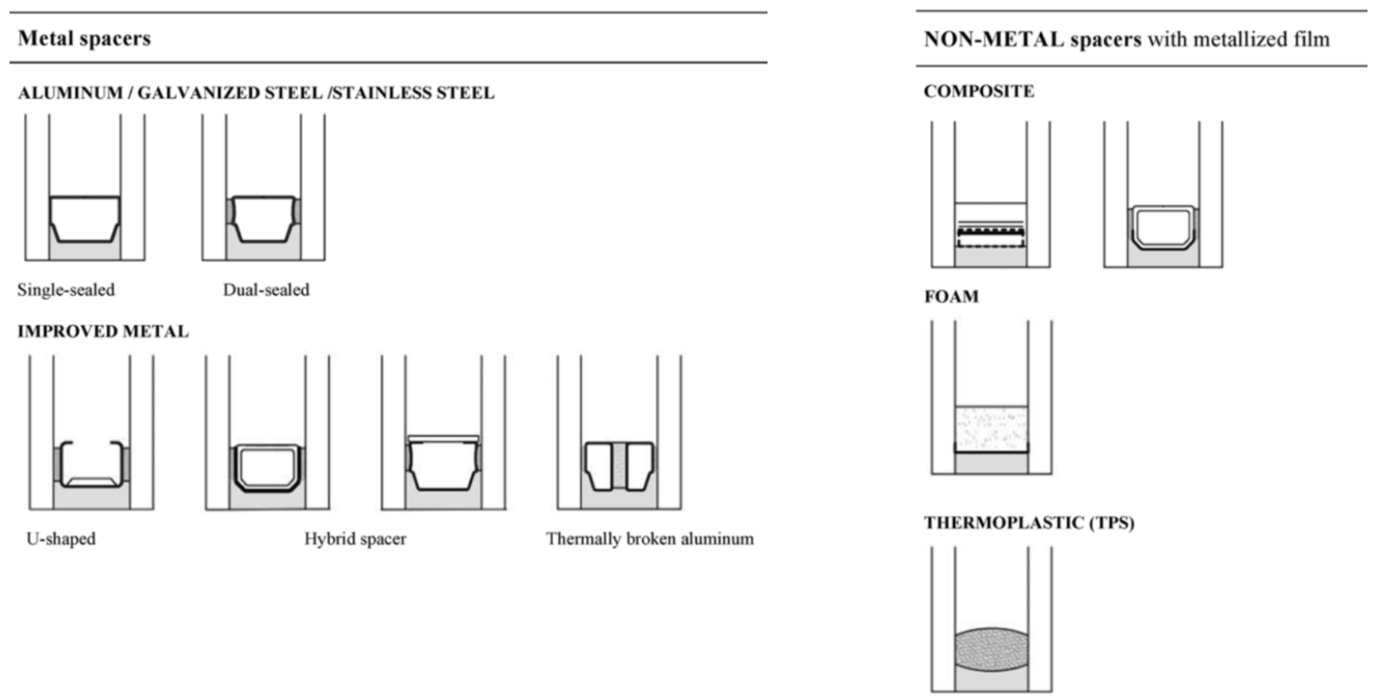


Figure 25. Categorization and schematic representation of spacer systems . From (Van Den Bergh, et al., 2013) .

3.4.1.b Sealants

The sealants used in an edge seal structurally bonds the glass panes and spacer bar together while providing a high level of moisture vapour and gas diffusion resistance and allowing some flexibility to accommodate glass movements. Older IGUs were single-sealed and possessed only a secondary seal but current high-performing IGUs are dual-sealed and these functions are performed separately by the primary and the secondary sealants.

Primary seal (PIB)

The primary seal is applied between the spacer bar and the glass panes bonding the glass panels to the intermediate spacer bar and its main purpose is to create a gas and moisture barrier from the exterior to the interior of the cavity. According to ISO 20492 and EN 1279 standards, it must have high moisture vapour transmission resistance characterized by the moisture vapour transmission rate (MVTR) or average moisture penetration index, I_{av}. Current standards allow a gas leakage rate Li (i.e., the volume of gas 'i' leaking from a gas-filled unit) of less than 1% per year as stated by (Van Den Bergh, et al., 2013).

Apart from the primary seal, a metallic element is necessary as well to act as a vapour and gas barrier. Metal can be found either in the spacer bar or in the form of a metal foil integrated into the spacer design. The typical thickness of a primary sealant is between 0.2 to 0.6 mm and the moisture diffusion from the seal is less when the primary seal is wider and thinner.

As far as the materials are concerned, synthetic rubbers, typically polyisobutylene (PIB) are used. PIB is a thermoplastic and it is important to mention that its strength decreases rapidly as temperature increases. For this reason, it must be subjected to UV and oxidative stability tests, and it must additionally be tested for compatibility with any polymeric glazing components that will be used in the IGU such as secondary sealants. In terms of reversibility, this also means that it can be easily removed by heating it up.

Finally, the primary PIB seal accounts for a very limited mechanical bond between the spacer bar and the glass panels, therefore, it is fully disregarded as a load-bearing component of the edge seal.

Typical IGUs use PIB of black colour but transparent PIB can also be found on the market for application on edge seals where greater transparency is desired.

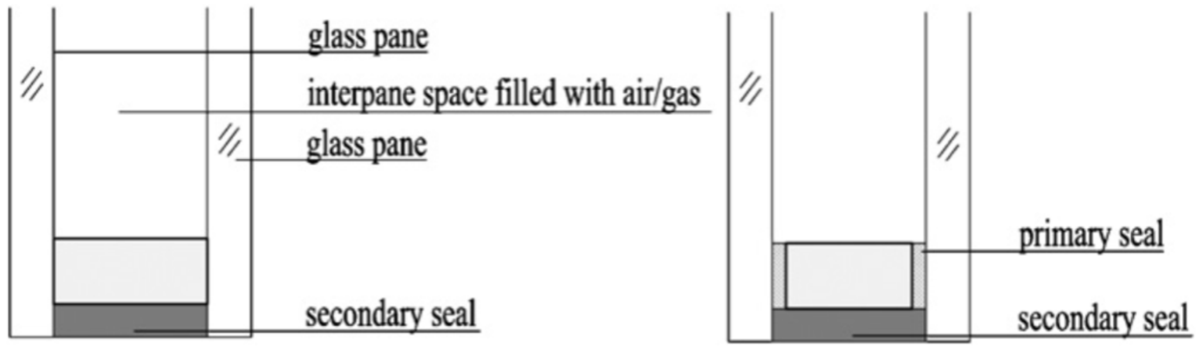


Figure 26. Single-Sealed and Double-Sealed IGU. From (Van Den Bergh, et al., 2013) .

Secondary Seal

The secondary sealant does not contribute significantly to the impermeability of the edge seal due to the fact that the water vapour permeability of PIB is far lower than that of the secondary seal, regardless of the material of the secondary sealant.

The secondary sealant plays the main structural role of the edge seal. It is applied around the perimeter of the glass and functions as the adhesive element that bonds the glass panes and spacer bar together. If the spacer bar takes the compressive forces, the secondary seal accounts for the tensile ones having moderate stiffness and resistance in tension according to (Van Den Bergh, et al., 2013). A typically used secondary sealant by DOWSILTM 3363, a two-part silicone sealant by Dow Corning (www.dow.com), has a stiffness of Es = 4.8 MPa and a tensile strength of fu,s = 1.5 MPa.

Moreover, the secondary sealant needs to have certain flexibility in order to accommodate glass movements that occur under a variety of continuous mechanical stresses. These stresses can be due to pressure differences between the interpane space and the outside atmosphere during manufacturing, transportation, and installation; stresses during the service life from environmental conditions such as solar radiation, temperature differences, wind loads, and barometric pressure as seen in Figure 27. Apart from the aforementioned functions, the secondary sealant also acts as an additional protective layer of the primary sealant from vapour and air diffusion.

The thickness of the secondary seal width is around 4mm with a minimum of 3mm of secondary sealant being required to cover the primary sealant and protect it from contact with moisture. The materials most widely used are Polyurethane (PU), silicone (Si) and polysulfide (PS), while hot-melt butyl or epoxy-based sealants acn also be applied.

As already mentioned, the use of the secondary sealants is what prevents the reversibility of an insulated glass unit. The materials used in the seal create a very strong bond with the glass panes and the spacer bar that does now allow for easy separation and even when a separation is achieved, the contaminating factors left on the glass surfaces make them non-recyclable. Finally, the black colour of these seals in combination with the spacer bar, affects the transparency of the edge seal.

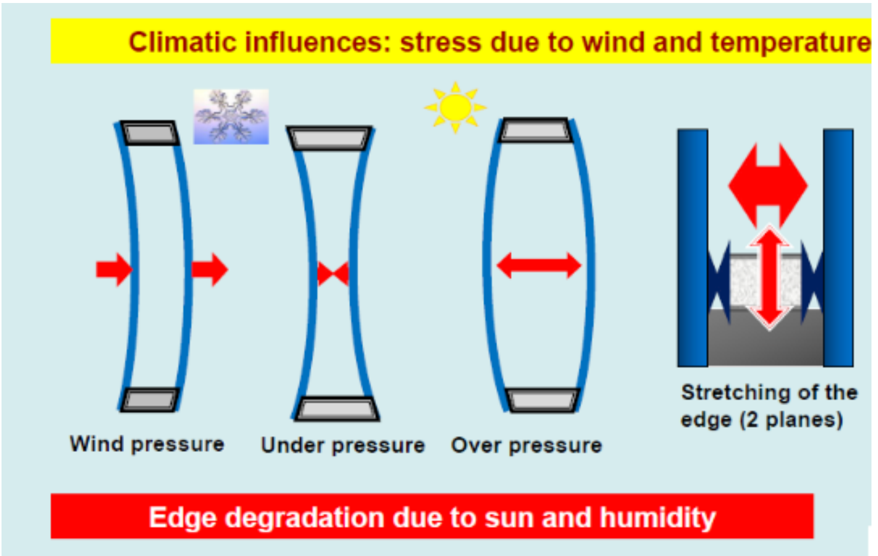


Figure 27. IGU distortions due to climatic influences. From Kilthau, F. (2006). The Role of Desiccant in Insulating Glass [Power Point slides]. Grace. http://www.fenzi-na.com/pdfs/IGMA%20Vegas%20September%2006%20Role%20of%20IG%20Desiccants.pdf

3.4.1.c Desiccant

During the assembly and weather-sealing of the IGU with the primary PIB sealant and the secondary sealant, some moisture is trapped inside the unit. The role of the desiccant in an IGU assembly is to absorb the moisture that has been captured inside during the assembly of the unit. Additionally, the desiccant is responsible for the absorption of any water vapour that might be diffused via the edge seal during the lifetime of the IGU. The presence of the desiccant is, therefore, crucial for the prolonging of the unit's service life by adsorbing any moisture and organic vapour that can be detrimental to the thermal performance of the IGU until the desiccant is saturated.

Nevertheless, the capacity of desiccant is limited and once it is saturated it cannot absorb any more moisture. This is why it is mainly used for the uptake of the already trapped-in moisture during the assembly phase and not as a moisture barrier during the service life of the unit.

Most commonly used desiccants are molecular sieves which are highly porous crystals with uniform pore sizes of 3, 4, 5, and 10 Angstroms (Å). Silica gel is an alternative option consisting of a highly porous granular-shaped desiccant with pore sizes ranging from 20 to 200A˚. Finally, a blend of 3-Å molecular sieve and silica gel can be used to prevent both condensation and chemical fogging by adsorbing water vapour as well as off-gassed organics while also limiting the adsorption of argon or nitrogen gas as stated by (Van Den Bergh, et al., 2013).

According to Kilthau (2006), in the most traditional IGUs, a metal spacer box is filled with granular-shaped desiccant. However, with the use of alternative, better-performing spacers, alternative desiccant applications are also found. These can be U-channel systems where the spacer is folded into a channel that contains a desiccated polymeric matrix. A desiccant matrix, unlike the loose-fill desiccants used in the spacer boxes, is a continuous element that adheres to a U-type spacer in an open channel. This type of system is used in high-speed automated IGU manufacturing. Foam spacer systems are another desiccant alternative which consists of a desiccated foam with an integrated moisture barrier film and an acrylic PSA along the sides to ensure its adhesion to the glass panes. Finally, the thermoplastic spacer is a PIB-based spacer that replaces primary sealant and desiccant and can be extruded directly from a drum to the glass surface. The different ways in which a desiccant can be integrated in the spacer bar are seen in Figure 28.

The indispensable integration of a desiccant in an IGU assembly is a factor that does not affect the circular character of the unit but greatly impacts its edge seal transparency since it consists of a visible element that cannot be avoided.

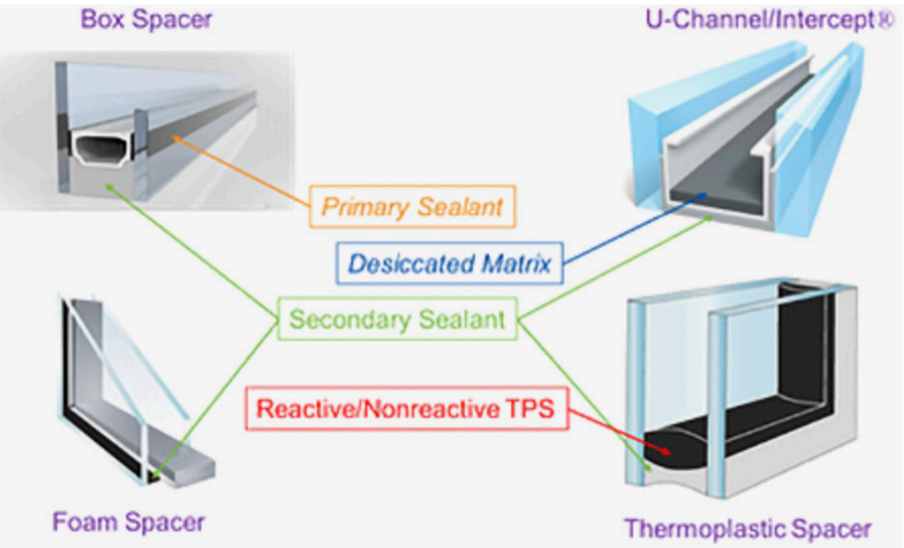


Figure 28: Different desiccant integration options. From https://aladdininsulation.com/2015/02/1068/

3.4.2 Structural Integrity

In terms of structural performance, IGUs can be considered as a form of composite (double glass) systems whose structural integrity is strictly related to the existence of linear, flexible connections along the edges in accordance with (Bedon & Amadio, 2020).

Regarding the mechanical properties of the edge seals, the compressive forces applied to the IGU are taken by the spacer bar, while the secondary sealant is responsible for the tensile ones. The different commercially available spacer bars have very different compressive strength and stiffness values. Spacer bars that use metal as the structural component are very rigid. On the other hand, the less conductive thermoplastic or structural foam spacers have considerably low stiffness and compressive strength for this matter, they can tolerate larger movements without critical stress concentrations on the glass surfaces. Therefore, it is hard to conclude an absolute number regarding the necessary compressive strength and stiffness to translate it into the new connection design. However, all edge seals currently used have in common the tensile strength that derives from the secondary seal. In order to derive some quantifiable design criteria for the aim of this thesis the minimum necessary tensile strength and flexibility of the new edge seal will be based on the values of the secondary sealant. Therfore a stiffness of Es = 4.8 MPa and a tensile strength of fu,s = 1.5 MPa are set based on the typically used secondary sealant DOWSILTM 3363, by Dow Corning.

3.4.3 Thermal Performance

In terms of thermal performance, the impact of the edge seal on the overall thermal performance of the IGU is observed in the edge-of-glass region which is the perimeter of the glass between the edge and the point where the glass surface temperature is the same as the temperature at the center of the glass. The width of this region varies from 63 to 102 mm according to (Van Den Bergh, et al., 2013). The more conductive the edge seal is the lower the temperatures at the edge-of-glass region, which consequently increases the potential for condensation that can be detrimental to the thermal performance of the IGU. Moreover, the effect of the edge seal on the total u-value can be significant especially in higher-performing IGUs.

Spacer bars are mainly responsible for the effect on the edge seal on the total u-value of the unit. There is a logarithmic relationship between the overall U-value and thermal conductivity of the spacer bar. The edge-of-glass u-value is improved when spacers with low thermal conductivity are used. Variations in thermal conductivity greater than 2.0 W/(m K) do not significantly affect the total product U-value. Moreover, the thermal conductivity has a larger the smaller the window size is. All metal spacers have an effective thermal conductivity greater than 2.0W/mK. The best performing spacers available today have an effective conductivity of around 0.25 W/(m K) as stated by (Van Den Bergh, et al., 2013).

Other parameters that affect the thermal conductivity of the edge seal apart from the spacer bar material are the overall spacer system width, the choice of sealant material and the thickness of the primary sealant.

(Elmahdy et al.) have proved that replacing highly conductive aluminium spacers with a less conductive one can reduce the total u-value by 6% in the standard double-glazed wood-frame window that does not have low-emissivity coating and by 12 % in high-performance IGUs.

The edge seal's thermal performance can be improved by increasing the length of the path of the heat transfer. This can be achieved in the following ways:

- reducing the width of the edge seal (w)
- increasing thickness of the edge seal (t)
- reducing the thermal conductivity of the edge seal (λ)

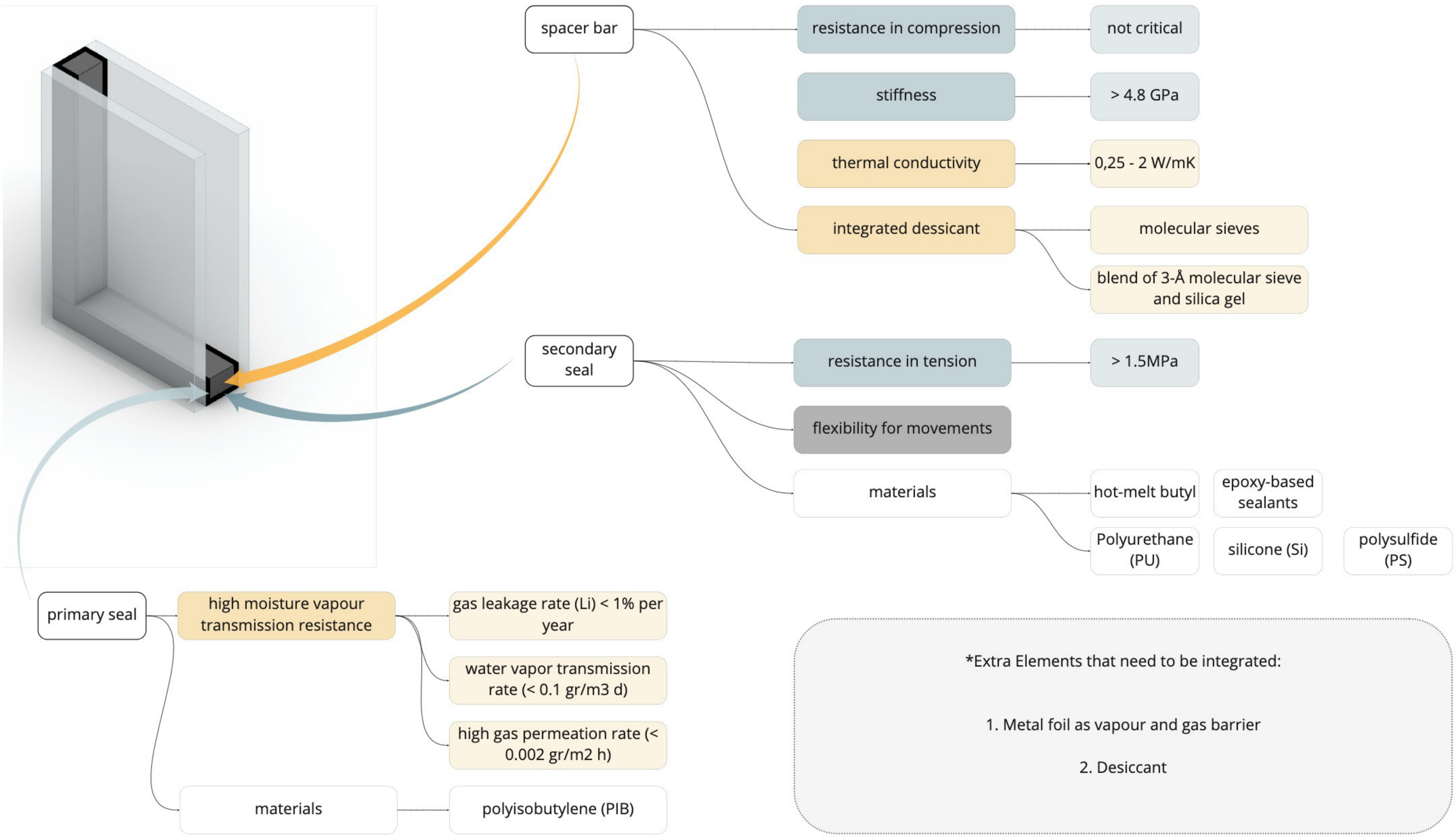


Figure 29: Diagram of the typical edge seal properties

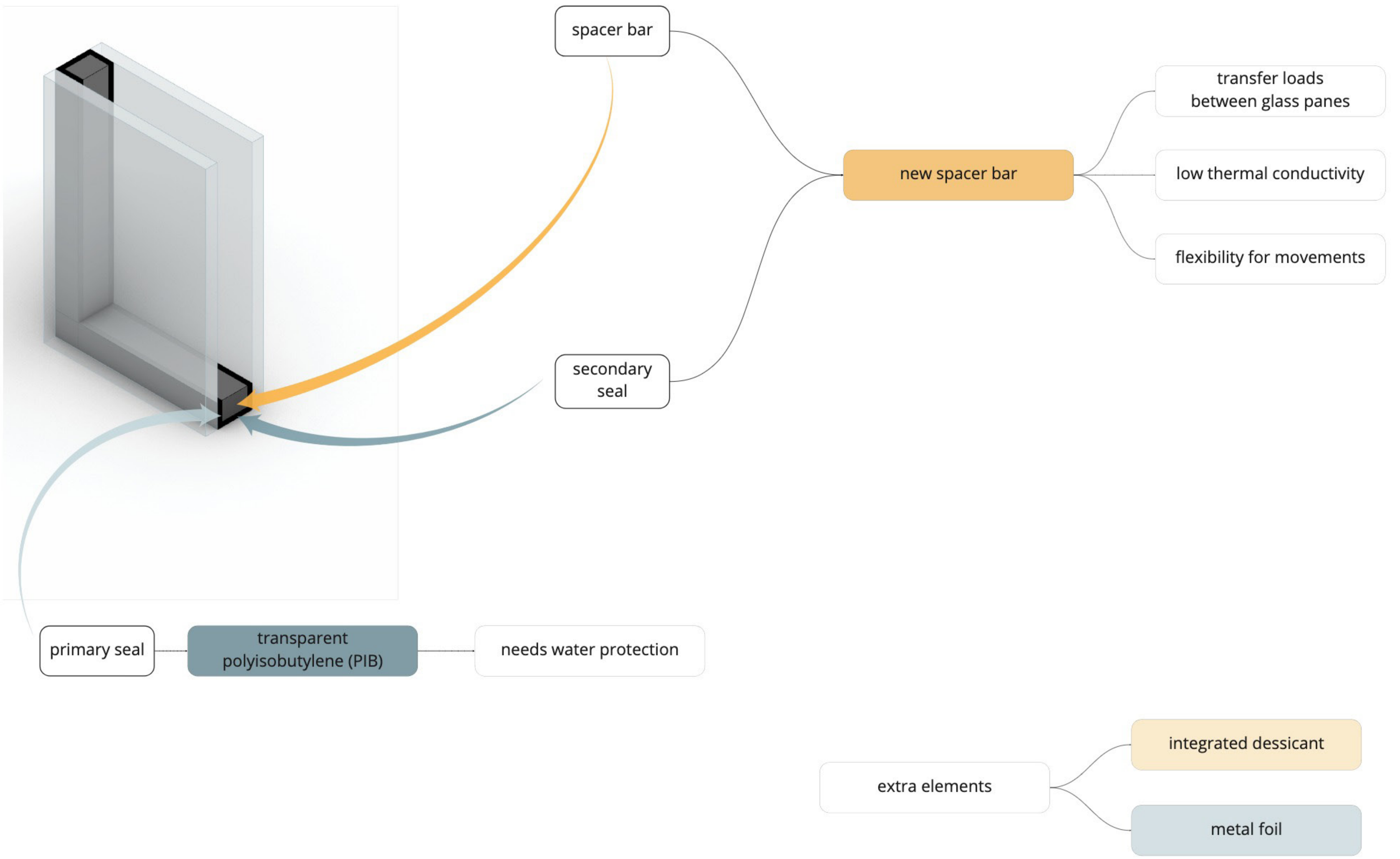


Figure 30: Diagram of the new edge seal properties

3.4.4 Overview and Conclusions

The review of the edge seals of the insulated glass units currently used aims at understanding the main functions an IGU edge seal needs to fulfill and drawing some conclusions on how these aspects can be translated into the new design.

Traditional IGU edge seal design consists of a dual-seal edge system that is applied around a desiccant-filled box spacer. The spacer bar can be made of metal or thermally broken metal elements and can alternatively be made of composites with a metal and a non-metal part, thermoplastics or structural foams. The latter category of non-metal spacers is mainly preferred for their reduced thermal conductivity and are, therefore, improving thermal performance of the whole IGU system. The primary sealant is composed of polyisobutylene (PIB) and is responsible for the impermeability of the seal to vapour and moisture as well as cavity gas leakages. The secondary seal is an additional layer of protection to the primary seal and its main responsibility is the structural rigidity of the unit while allowing for movements resulting from thermal expansions and weather conditions. Finally, a crucial part of the IGU assembly is the need for a desiccant integration to absorb the moisture that was trapped in the unit during its assembly phase. The desiccant depends on the spacer type that is used and is usually integrated into it.

In terms of circularity, the permanent bond between the secondary sealant and the spacer bar is what makes the unit non-reversible while the PIB primary sealant can be easily removed by applying high temperature. Therefore, the new connection needs to avoid completely the use of a secondary sealant and a combination of the structural properties of the spacer bar and the secondary sealant needs to be integrated into alternative elements. The PIB can be kept since it is necessary for the prevention of moisture and vapour penetration and can be reversible. Finally, a desiccant needs to be integrated into the design using one of the existing alternative ways it is currently used.

Regarding the desired transparency of the new edge seal, the new connection that substitutes the structural role of the spacer bar and the secondary sealant aims to be as discrete as possible in terms of dimensions and as transparent or translucent as possible regarding the materials used. For this reason during the design phase transparent or translucent materials will be considered and preferred. Moreover, for the moisture barrier, transparent PIB instead of the typical black ones can be used without hindering the optical quality of the edge seal. Finally, the essential presence of an integrated desiccant is a factor that might unavoidably reduce the desired transparency of the seal since there are currently no transparent or translucent desiccant integration options.

To conclude, the new edge seal connection needs to ensure the structural stability of the unit while allowing for some flexibility to accommodate movements. The compressive strength that is currently undertaken by the spacer bar cannot be quantifiable since there are big variations in the values of the commercially available spacer bars. The tensile strength of the edge seal that results from the secondary seal is quantified in approximate $f_{u,s}$ = 1.5 MPa and the stiffness around E_s = 4.8 MPa. Furthermore, the new connection needs to act as a moisture and vapour barrier warrantied by the presence of a PIB layer. Moreover, it needs to have a low thermal conductivity of no more than 0.25 W/(m K) and it needs to be durable to UV radiation and corrosion from water.

Figure 29 consists of a diagram of the properties of typical edge seals that need to be translated into the new connection design. Figure 30 depicts a mapping of insulated glass unit edge seals regarding their reversibility and their transparency. It is evident again that there are currently no reversible IGU systems on the market. Moreover, focusing on the individual parts of a typical IGU system made out of float glass we can observe that the elements that impact their reversibility and transparency are the spacer bar and the secondary sealant. In an attempt to create a reversible IGU edge seal with minimised optical effect of the edge seal components it is evident that attention must be placed in the materiality of the new connection system as well as in its geometry.

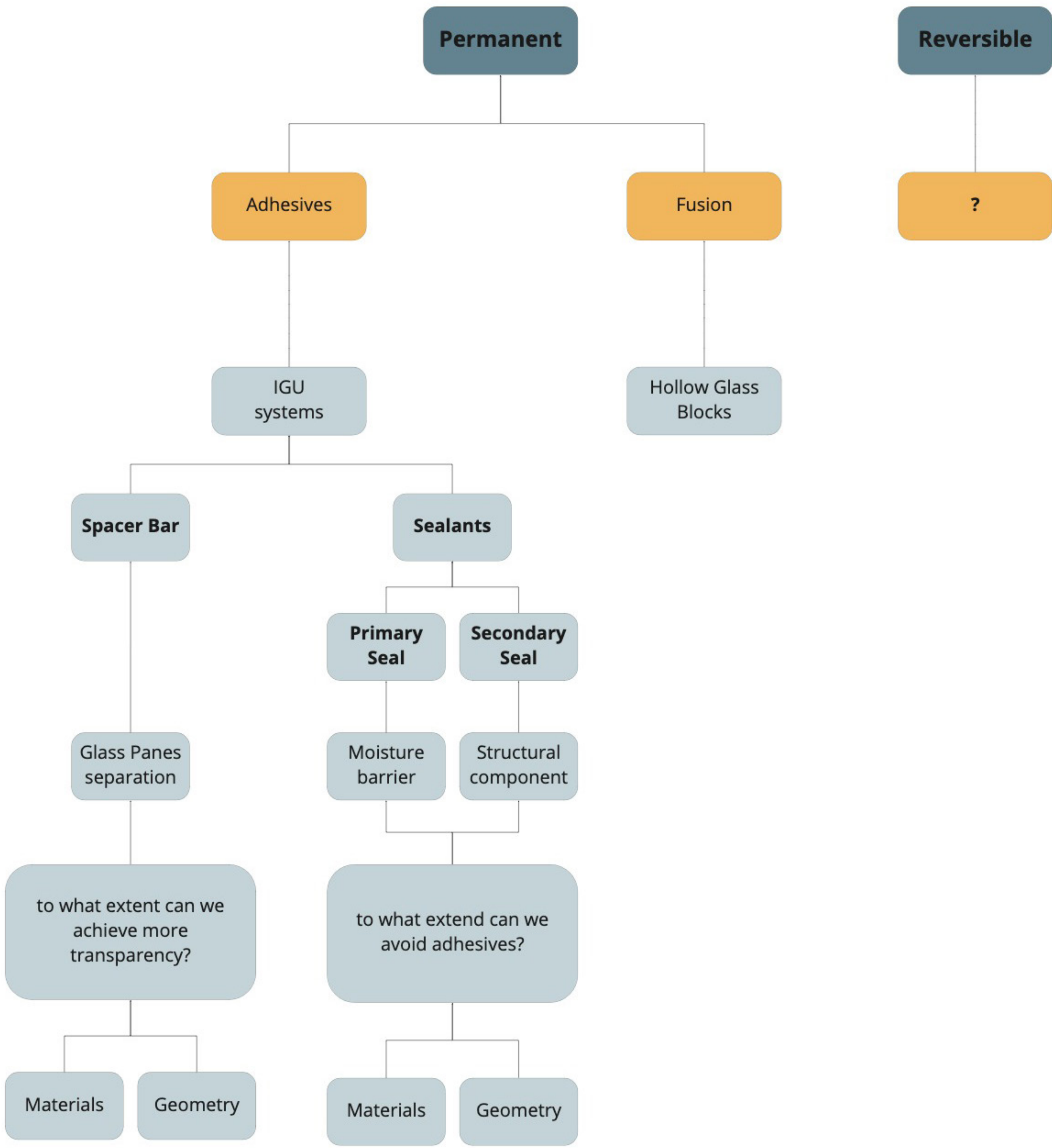


Figure 31: Diagram of the current edge seals properties regarding reversibility and transparency

3.5 Connections in Glass Structures

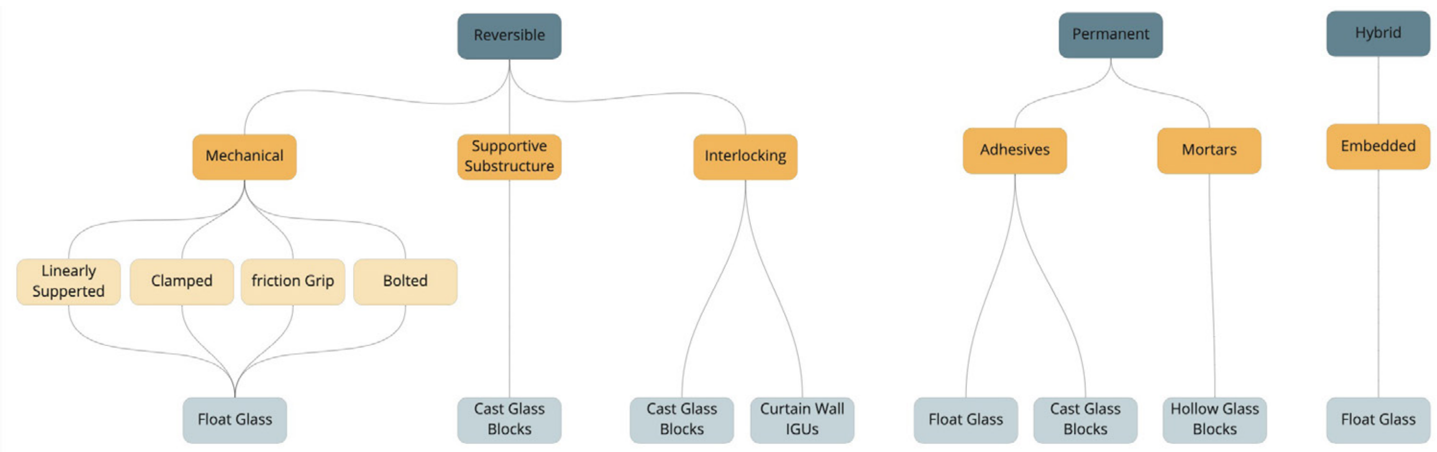


Figure 32. Categorisation of connections in glass structures according to their potential for reversibility

The connections of the structural elements have a great effect on the cost, efficiency, robustness and sustainable character of the whole construction. Particularly when building with structural glass, the importance of finding suitable connection types can be more crucial than with any other conventional building material. This is due to the intrinsic qualities of glass. Glass is a brittle material and because of that, it cannot plastically redistribute possible stress peaks imposed by external forces.

Connections in glass systems need to facilitate the transfer of forces from one element to another in a safe and gradual way as well as compensate for construction tolerances and accommodate building movements due to thermal expansions and deformations under loads. Moreover, connections in glass structures have a great impact on the overall aesthetic result in terms of transparency of the structure and on its ability to be circular in terms of ease of demountability and reusability.

In this chapter currently used connection types in glass structures have been divided into permanent, reversible and hybrid connections. These connections and their subcategories will be analysed and assessed in terms of transparency, circularity, ease of assembly, and load-transfer ability.

3.5.1 Reversible Connections

Reversible connections are classified according to the mechanism of load transfer into mechanical connections, interlocking connections and connections that use a supportive substructure. Mechanical connections are widely used in float glass panels. The potential of interlocking connections are widely used in insulated unitised curtain walls and their potential is still being researched in the field of cast glass load-bearing blocks. Finally supportive substructures have been used in cast glass blocks.

When applying mechanical connections in a glass component it is essential for smooth stress distribution in the brittle glass to avoid direct contact of glass with glass and of glass with other hard materials such as metal. Hence, in order to ensure an even load transition between the connections and the glass a suitable intermediate layer needs to be applied. The stiffness of the material is crucial, therefore, the material should possess a young's modulus smaller or similar to that of glass. Moreover, in order to satisfactorily transfer forces, the interlayer should have adequate strength which means that materials with high compressive strength are preferred. Finally, the interlayer has to be durable to withstand corrosion and thermal shock. Plastic, resins, neoprene, injection mortars, aluminium or fibrous gaskets have properties that make them satisfactory interlayer materials for glass structural connections.

Mechanical connections are further subdivided into linearly supported, clamped connections, friction grip connections and bolted connections.

Linearly supported connections

Continuous linear supports, where rectangular glass panes are supported along two or four edges, are a very simple and widely used manner of supporting glass elements. Their use is very suitable in framed constructions for connecting the glass to the aluminium, steel, plastic or timber frame. The self-weight of the glass is carried via the use of plastic setting blocks or neoprene layers. The out-of-plane loads, usually the result of wind pressure, are transferred to the frame through gaskets or structural sealants. This type of glass connection is usually encountered in the cases of the typical insulated windows and in curtain wall systems.

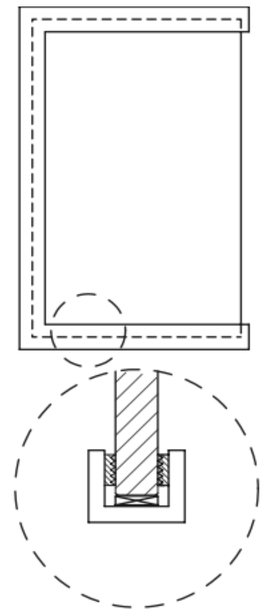


Figure 33. Linearly supported glass connection. From "Structural Use of Glass" (p.143), by Haldimann, M., Luible, A., & Overend, M. (2008).

Clamped connections

Clamped connections are accomplished using metal components that mechanically clamp the edges of a glass panel. The clamps are then fixed to substructure support. An interlayer of such as neoprene, EPDM rubber or similar material is placed between the metal parts so that the forces can be evenly transmitted. Additionally, a setting block is inserted where the glass pane sits and carries the in-plane loads ensuring a smooth transfer of the vertical loads according to O'Regan et al. (2014 p.15)

The small size of these connections has minimised their visual impact as well as the contact surface between the glass and the metal. In these minimised regions local stresses arise that need to be considered in the design phase. (Bedon & Santarsiero, 2018) This type of connection is typically used in low-stress glass connections or in small glass elements such as building balustrades.

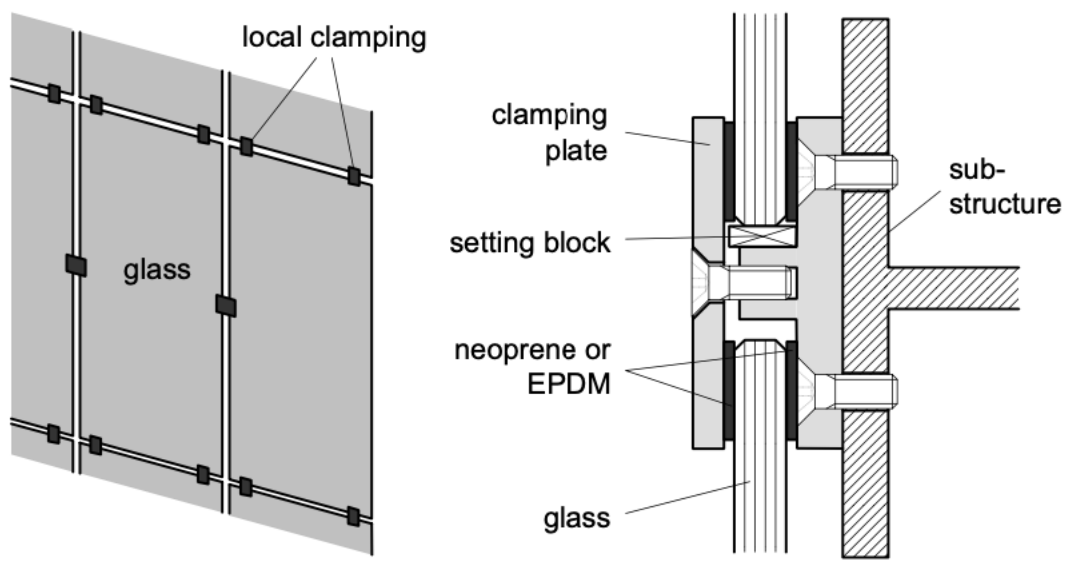


Figure 34. Low-friction clamped connection. From "Structural Use of Glass" (p.146), by Haldimann, M., Luible, A., & Overend, M. (2008).

Friction-grip connections

Friction grip connections are a subcategory of clamped connections that are able to transfer in-plane forces as well by the means of very tight camped fixings that develop friction-free connections. The connections are made up of clamped together steel plates with a prestressed bolt passing through them. The hole that accommodates the bolt is oversized so any contact is prevented between bolt and glass. Gaskets are placed between the glass and the steel plates as an interlayer to avoid their direct contact. The selection of gasket is crucial as it needs to show adequate strength to carry the normal stresses and must also resist the resulting shear stresses from the in-plane loads. However, the gaskets should not be extremely hard or the glass will be damaged by their contact. It must also possess sufficient flexibility to accommodate manufacturing tolerances of the different components of the joint. Finally, creep should be very low to avoid normal forces in the bolts. Pure aluminium or fibre gasket of 1 mm thickness are usually used. The void around the hole is filled with an isolation material. The advantage of this type of joint is that stress distribution occurs on a bigger surface area so stress peaks are avoided. Typical uses of friction grip connections are visible in structure fins and facades. Haldimann et al. (2008 p.147)

Friction-based connections might encounter issues with the interlayer used in laminated glass because of the pressure of the clamp against the glass that can squeeze out the interlayer material. To prevent this from occurring a soft aluminium layer can be inserted into the interlayer in the position of the fixing.

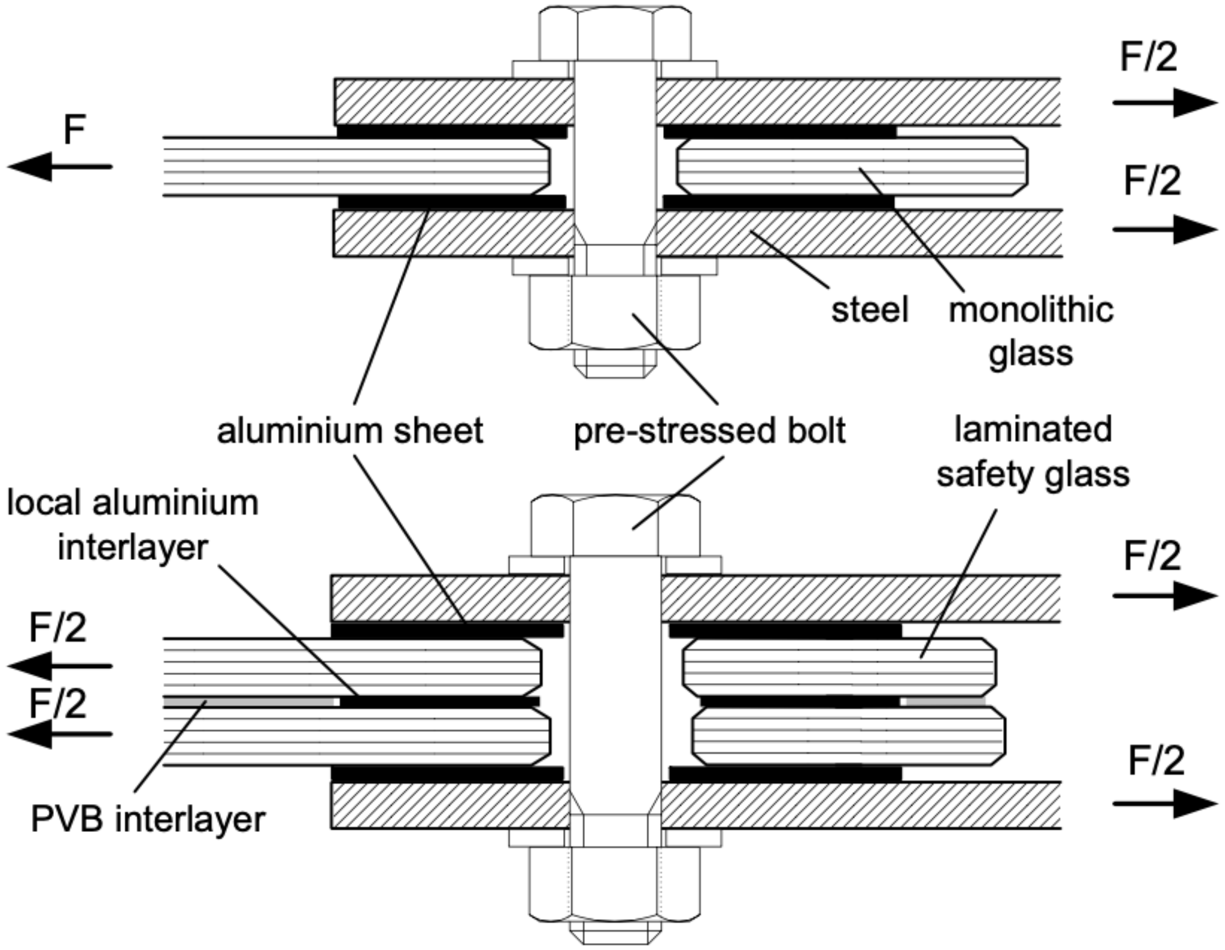


Figure 35. Low-friction clamped connection. From “Structural Use of Glass” (p.146), by Haldimann, M., Luible, A., & Overend, M. (2008).

Bolted connections

The use of bolted connections in glass elements is the result of the desire for glass connections with minimal visual impact for enhanced transparency of the structure. A wide variety of bolted joints have been developed over the last 20 years in the direction of maximised transparency while keeping the demountability of the structure.

In this type of connection, stainless steel bolts directly carry all the in-plane and out-of-plane loads of the glass. Aluminium bushings, POM or injected mortars are used to support the bolts and prevent the glass to bolt contact and reduce stress concentrations. Bolts were widely used in steel constructions before they were adopted by the glass field. A key aspect that needs to be taken into account when designing with bolted joints is that steel is a plastic material, therefore the stresses that are concentrated around the hole of the bolt are easily redistributed by local yielding. On the contrary, the brittle character of glass does not permit such yielding and stress concentrations, particularly the tensile ones, around the drilled glass holes that need to be taken into careful consideration in the design phase.

The intermediate materials play the role of accommodating these peak stresses with great success in the compressive forces but with very little success in the tensile ones because of the elongation of the holes. Therefore, these materials should possess sufficient strength and stiffness to transfer loads to and from the glass without causing fracture of the joint, while maintaining a certain softness to successfully redistribute stress concentrations. Finally, creep and UV resistance are also necessary. Aluminium, plastics like EPDM (ethylene propylene diene monomer), PEEK (polyether ether ketone), POM (polyoximethylen) or polyamide or injected resin or mortar are typically used. Haldimann et al. (2008 p.148)

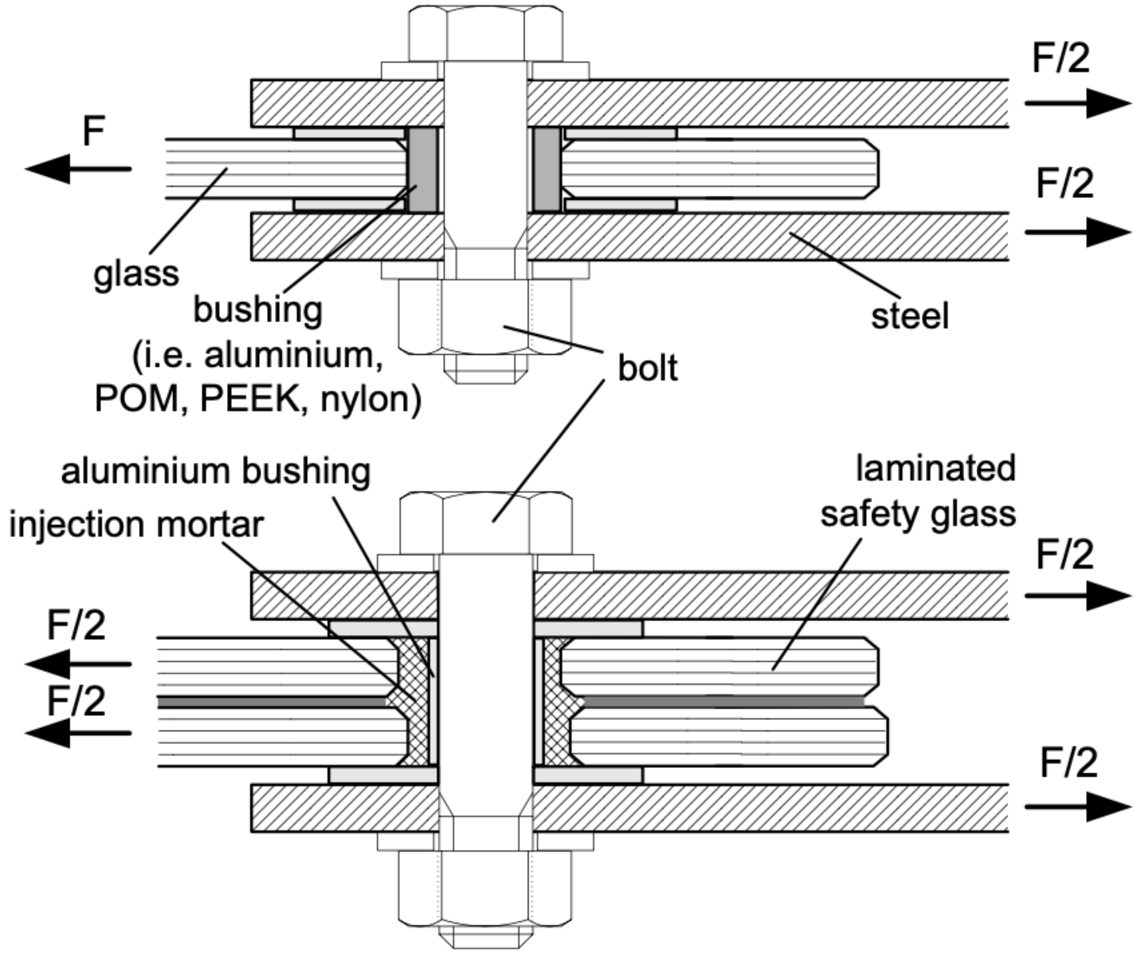


Figure 36. Bolted connection; top: monolithic glass, bottom: laminated safety glass. From “Structural Use of Glass” (p.151), by Haldimann, M., Luible, A., & Overend, M. (2008).

Supportive substructure

This connection method refers to a specific built example of the "Optical House", designed by architects Hiroshi Nakamura & NAP and manufactured by Equitone in 2012. The two-storey-high glass facade that functions as a transparent filter between the busy city life and the serene private garden of the, house is a state-of-the-art example of a facade made entirely of cast glass bricks with the implementation of a supportive substructure.

The connection has been used in combination with cast glass blocks and utilises a supportive, metal substructure to carry the tensile forces while at the same time achieving the aimed stiffness and resistance to buckling. This way the glass is free to accept all the compressive stresses. (Oikonomopoulou et al., 2018)

The supportive substructure as a bonding method in cast glass components is an innovative way that allows the use of cast glass bricks to be used in large surfaces as load-bearing structures. In terms of circularity, the principal advantage of this method is that no adhesives or mortar is used in the construction. This way the whole structure has the potential to be disassembled and reused in other future projects. The downsides of this method include the use of additional materials besides glass that compromise the transparency that is the main appeal in the use of a glass facade.

Figure 37. Assembly of the glass masonry wall. From "Designboom", by Nakamura, H. & NAP, 2013 (https://www.designboom.com/ architecture/hiroshi-nakamura-nap-optical- glass-house/)

Interlocking connections in cast glass units

The innovation behind this system lays in the interlocking bonding method of connecting cast glass components the size of a normal brick. Structurally speaking, the geometry of the interlocking components suppresses the lateral movements ensuring the lack of need of a substructure or frame. Moreover, this new system also proposes the use of a dry, interlayer such as polyurethane rubber (PU) or Polyvinyl Chloride (PVC) that is also colourless to be used between the glass components preventing stress concentrations caused by the immediate contact of two glass components. It also receives the stresses caused by imperfections during the casting procedure according to Oikonomopoulou et al. (2018)

According to experimental tests and research regarding the optimum shape of the glass components, organic shapes and geometries with curves that lack sharp edges lead to a prevention of residual stress concentrations making these shapes more compatible with the intrinsic characteristics of cast glass.

The advantages of this innovative system in terms of circularity lay in the complete ease of disassembly and reuse of the structure. The lack of any additional coating or adhesive materials results in a lack of contamination of the glass which makes it easily recyclable.

Figure 38. Physical prototypes of different interlocking geometries. From (Oikonomopoulou, 2019), https://doi.org/10.7480/abe.2019.9.4088

Interlocking connections in unitised curtain wall systems

Unitised curtain wall systems consist of pre-fabricated IGU panels that use dry, interlocking connections so that they can be assembled on site. These connections occur in the perimeter of each unit and are integrated into their transoms and mullions. The interlock of the frames is sealed by gaskets that also play the role of the first line of defense against water and air intrusion. The gaskets also allow for movement due to thermal expansions and from building deformations. Finally, the dry assembly of this connection type facilitates easy disassembly without damaging the components and enables the reuse of the whole unit if it remains in a functional state.

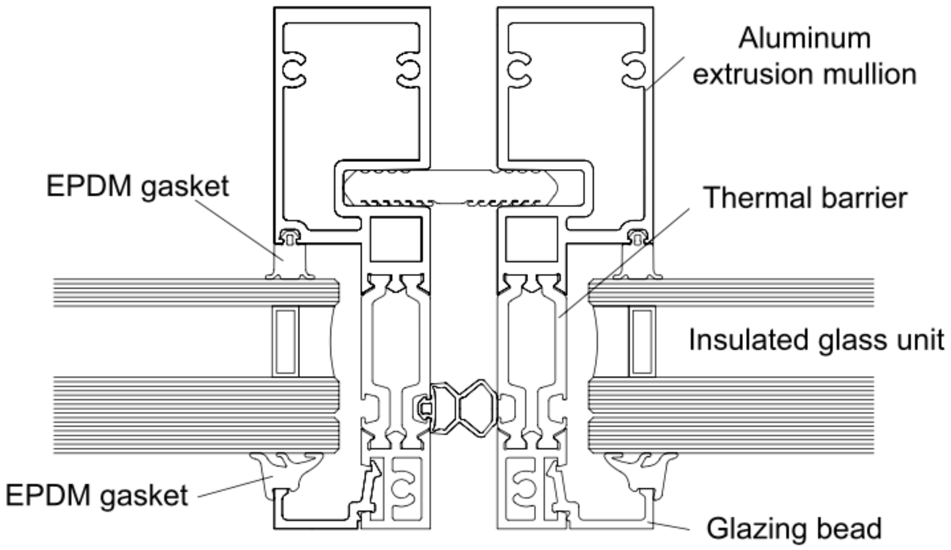


Figure 39. Curtain wall interlocking system. From "Structural Use of Glass" (p.151), by Haldimann, M., Luible, A., & Overend, M. (2008).

3.5.2 Permanent Connections

Adhesive connections

Permanent connections in glass systems include the use of adhesives and mortars. Adhesive connections are extensively used for connecting float glass panels and have also been used in certain real-life projects as a bonding method in cast glass blocks.

Adhesive connections describe the connection types in which adhesive polymer materials are used to bond glass to glass or glass to other building materials. Two types of adhesives exist. The first one is soft elastic adhesive connections used in low-stress glass connections, where the glass used does not have a load-bearing role in the structure. Structural silicone sealant is the most common adhesive used for low-stress glass connections. On the other hand, rigid adhesive connections, such as acrylic adhesives, epoxy adhesives and polyester resin, are used for the bonding of structural glass elements.

Adhesive connections can also be subdivided in terms of the surface they bond. They can be punctual, linear or 'surface-like'. In 'surface-like' adhesives the forces are transferred over a large surface. Corner beam-column or beam-beam connections usually require this type of connection. In linear adhesive connections, the transfer of forces occurs via a long linear surface. Structural silicone adhesive is typically applied in such a linear manner. Finally, in punctual adhesive connections, the loads are transmitted over a small area and therefore high mechanical resistance is necessary. Adhesive point-fixing and embedded laminated connections are characteristic examples of this type of bonding. (Bedon & Santarsiero, 2018)

The load-bearing capacity of adhesively bonded glass structures is greatly influenced by the duration and type of loading imposed on the structure. However, the load transfer of the connection depends on the area of the surface where the bond occurs, on the quality of the workmanship during the installation, as well as on the environmental conditions such as the UV light, the moisture levels and the temperature.

The advantage of this kind of connection when used in load-bearing glass structures is a relatively even transfer of incoming forces over the area where the glue is applied. Additionally, no preparation is needed in terms of drilling holes for the connections to occur. This aspect is beneficial to the ease of production as well as to the safety of the structure since stress concentrations that usually occur due to drilling for mechanical connections are avoided in this case. Moreover, transparency is enhanced with adhesive connections since no additional materials, such as metals, that are non-transparent are used. The thermal bridges are also minimised with these connections since no components of conductive materials pass through the glazing system. A great disadvantage of adhesive connections concerns the aspect of circularity. Except for structural silicone that can be easily be cut out, most adhesive materials once applied form a permanent bond with the glass and cannot be removed or replaced without harming the component. Moreover, glass contaminated with adhesives cannot be recycled and is therefore destined to end up in landfills.

Mortars are another type of permanent connection of glass elements and are extensively used to bond together non-load bearing hollow glass blocks into a wall. Similarly to adhesives, mortars are a non-reversible connection system making the replacement and reuse or recycling of the glass used not possible.

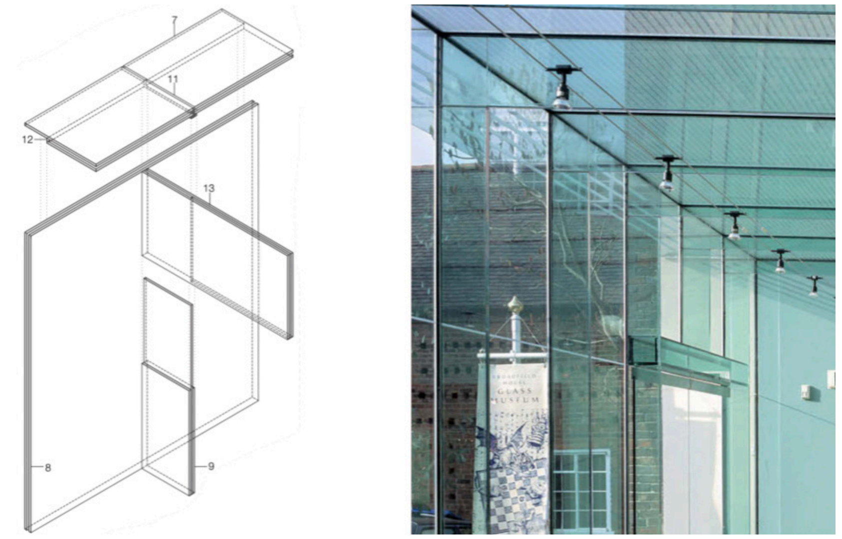


Figure 40. Adhesively bonded float glass fins. From "Glass Construction Manual" (2nd ed., p 309), by Schittich, Staib, Balkow, Schuler, & Sobek. (2007).

Figure 41. Adhesive connections in cast glass: Crystal Houses/MVRDV. From "ArchDaily," by Scagliola, D. & Brakkee, S., 2016 (https://www.archdaily.com/785923/crystal- houses-mvrdv).

3.5.3 Hybrid Connections

Embedded connections

Hybrid Connections for structural glass systems are connections that use both adhesives and mechanical bonding, such as the recent use of embedded laminated adhesive connections in float glass. These embedded connections utilise the same principle of creating laminated glass elements. A solid foil of transparent adhesive is placed between the glass sheet and the metal element that need to be bonded together. (Bedon & Santarsiero, 2018) Then, the elements to be bonded are placed in an autoclave, similar to the one used during the laminating procedure. The final component is a laminated glass pane with an embedded metal part that will, later on, be used on-site for the connection of the glass pane with other panes. In this type of connection, usually, the adhesive part of the joint is stiffer than the part responsible for the mechanical joint. This means that the largest part of the load is transferred via the adhesive and the mechanical element is used when the performance of the adhesive is exceeded.

The main advantage of this type of connection is the fact that the biggest part for the preparation of the connection has already happened at the factory and the component is ready to be transferred on site where metal to metal connections will occur. Embedded connections though very appealing for their ease of use, high achievable transparency and great mechanical strength, lack in the field of circularity as the lamination contaminates the glass making it non-recyclable and the separation of the metal from the glass is also quite difficult.

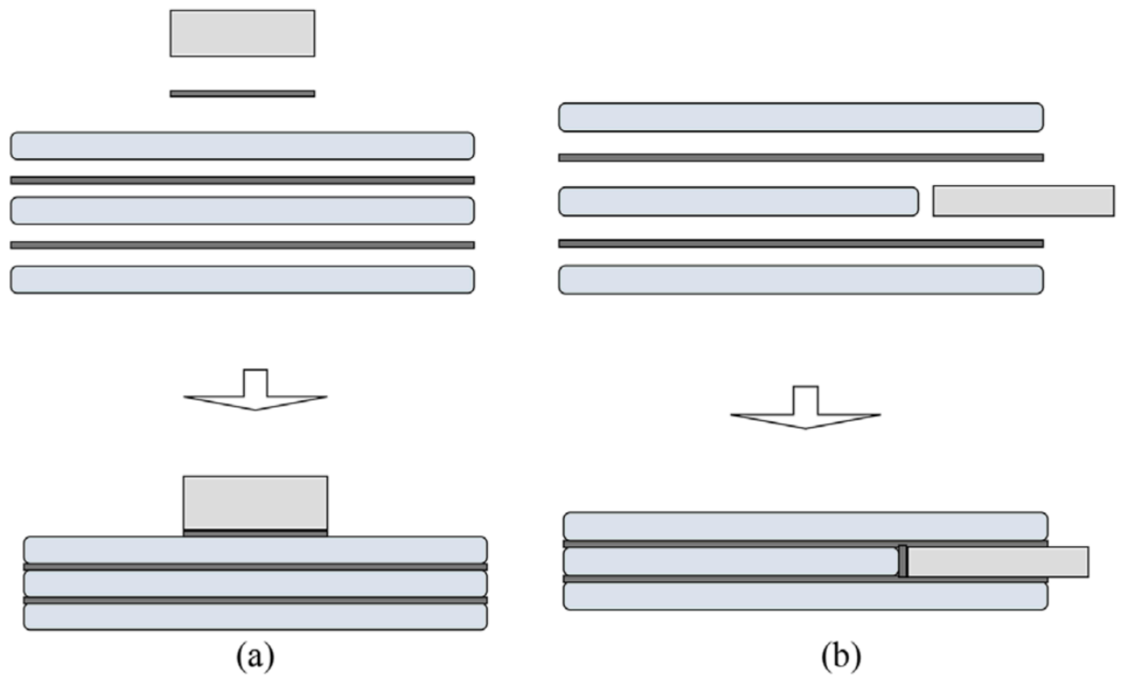


Figure 42. Embedded connections in laminated float glass. From Transparency in Structural Glass Systems Via Mechanical, Adhesive, and Laminated Connections - Existing Research and Developments.(Bedon & Santarsiero, 2018), https://doi.org/10.1002/adem.201700815

3.5.4 Overview and Conclusions

This chapter offered an overview of the different connection types used in glass structures and an assessment based on their potential for reversibility and their impact on the transparency of the composition. The glass used in these structures can be either an insulated glass unit or a non-insulated float glass pane that can also be laminated. Moreover, connections applied in cast glass structures are also reviewed since they provide inspiring alternatives in term of more reversible structures.

As already mentioned above, permanent adhesive connections are a very appealing option having the advantage of optical transparency and good and even load transfer without stress concentrations. On the other hand, their permanent character makes them non-circular. Hybrid connections also offer increased transparency and good load-bearing properties but lack in the field of circularity as well. Therefore these two types of connections are found ansuitable in the scope of this thesis. As far as reversible connections are concerned, the wide use of mechanical joints has proven their effectiveness when a balance between transparency and reversibility is required. On the downside, they require more careful design due to the introduction of stress concentrations resulting from hole drilling. Interlocking connections such as the ones used in cast glass blocks are a new but very promising glass connection type since they can provide satisfactory load transfer without using additional elements that either reduce the transparency of the structure or restrict its reusability and recyclability.

Finally, when using mechanical connections in a glass it is crucial to avoid peak stress concentrations in the glass elements because of their brittle character. In order for this to occur, direct contact of glass with glass and of glass with other hard materials such as metal must be avoided. For this reason, in order to ensure an even load transition between the connections and the glass a suitable interlayer is necessary to be integrated. The stiffness and compressive strength of the interlayer need to be carefully evaluated and a material with high durability and corrosion resistance should be preferred.

	Load transfer	Circularity	Transparency	Ease of production	Notes
mechanical	+++	++++	+++	++	peak stresses, hole drilling
interlocking	++++	++++	++++	++++	uniform load distribution
substructure	++++	++++	++	++	compromised transparency
adhesives	++++	+	++++	+++	non-reversible, glass contamination
mortars	+	+	+	+	non-reversible, need for additional substructure, compromised transparency
embedded	++++	++	++++	+++	reversible but make glass non-recyclable

Table 03. Assessment of glass connections according their impact on circularity and transparency

3.6 Literature Review Overview and Conclusions

Glass is a unique material that requires special attention when designing with it due to its brittle character. It exhibits great compressive strength while its tensile strength is significantly lower and depends on the quality of the glass surface and edges. Moreover, in order for glass panes to be used in large surfaces in the building envelopes it is necessary for them to possess certain insulating properties in order to minimise the building's thermal losses.

The creation of insulated glass units requires the combination of at least two glass panes into one unit with an insulating air cavity between them. Additional methods to further increase the insulating value of an IGU concern the application of low emissivity coatings on one of the glass surfaces, the use of inert gas fillings in the cavity and the addition of extra panes as convective layers inside the cavity.

One of the most crucial parts of an IGU that has a great impact on the overall thermal performance and structural integrity of the unit is the edge seal. The edge seal of a typical IGU consists of a spacer bar that enables the creation of the cavity, a primary sealant as a moisture barrier, a secondary sealant that bonds the whole unit together ensuring its structural stability. Finally, a desiccant must be integrated usually in the spacer bar to absorb the trapped-in moisture from the assembly procedure of the unit. These edge seals that create a permanent connection between the glass panes, apart from the very visible black elements that introduce in the perimeter of the unit, are one of the main reasons that impede the reversibility of the unit and constitute it a single life element.

Typical IGUs are created using glass panes made by the float glass process which is the prevailing glass manufacturing method in the current industry producing very thin flat glass panels with great transparency and smooth surface quality. Apart from its excellent optical qualities, float glass can undergo some additional processes after its production that improve its strength (heat strengthening), increase its safety and load-bearing capacity (lamination).

The post-production procedures of lamination and the use of adhesives used in a typical IGU assembly prevent glass to be recycled at the end of its life because of the high contamination degree that these elements introduce which endangers the mechanical qualities of the recycled glass. Moreover, coating application is another parameter that restricts glass recycling since the use of coated cullet can result in recycled glass of reduced optical qualities and for this reason it is avoided, even though its mechanical properties could remain intact.

In order to create a more circular IGU the aforementioned processes that hinder the potential of glass to be recycled should be avoided when the thermal and safety functions of the IGU are not jeopardised. Moreover, in the level of the edge seal, the main parameter that needs to be eliminated and replaced is the secondary sealant. For this reason an alternative reversible design of the edge seal connection that allows the easy separation of the different glass panes and enables the refurbishment of the unit if its thermal performance is reduced or the recycling of the contamination-free glass panes is crucial.

The restrictions in the thin and planar geometry of float glass makes the use of adhesives seem like the only possible connecting method if the edge seal, obstructing the use of reversible and optically discrete connections apart from bolted ones that require hole drilling which introduces stress concentrations in the glass elements.

Apart from float glass, cast glass manufacturing method is an alternative production technique that enables the generation of glass panes with great freedom of shapes breaking free from the restricting two-dimensionality of the float glass elements. This particular property of cast glass can be used to create reversible connections that do not demand the use of adhesives but can adopt mechanical or interlocking connection principles benefiting from the ability of glass to be cast in the desired geometries that can facilitate such a reversible connection. Moreover, glass casting allows the recycle of glass with higher contamination percentages than float glass without negative impact on the mechanical properties of glass although the optical quality of the recycled cast glass surfaces might be less than that of clear float glass. Finally, cast glass lack a treatment for safe breakage. Therefore, the use of cast glass as a more sustainable alternative that enables reversible connections because of its ability to be shaped in many geometries is something to be taken into account during the design phase without forgetting the limitations of cast glass regarding transparency and safety.

The literature review followed an analysis of the use of glass in the building envelope regarding its properties, the manufacturing methods and the processes that hinder its potential for circular use. Moreover, the technology of insulated glass units was studied in depth in terms of their building physics principles as well as their necessary edge seal properties. Finally, typical connections in glass structures were reviewed and assessed concerning their impact on the transparency of the structure and on the recylcability of glass.

The aim of the literature review was to gain a better understanding of the problem statement and to lead of the formulation of the design criteria regarding the creation of a new insulated glass unit that allows a more circular use of glass while having the maximum possible transparency. The following chapter focuses on a clear formulation and analysis of the design criteria that are necessary for the design phase.

4. Design Criteria

4.1 Design Criteria for the IGU as a whole

4.2 Design Criteria for the IGU Edge Seal Connection

The following chapter provides an overview of the design criteria that are necessary for the design exploration phase. The conclusions from the answer of the first research subquestion at the end of the literature review have provided answers to the following research subquestion:

"What are the main design criteria in the development of a circular IGU of maximised transparency?

(a) in terms of the whole unit

and

(b) in terms of its edge seal connection?"

The design criteria are divided into two categories. The first focuses on the IGU unit as a whole while the second on the connections of the edge seal between the different glass pane that make up the IGU.

4.1 Design Criteria for IGU

Regarding the design criteria that have derived form the answer to the research subquestion:

“What are the main design criteria in the development of a circular IGU of maximised transparency?

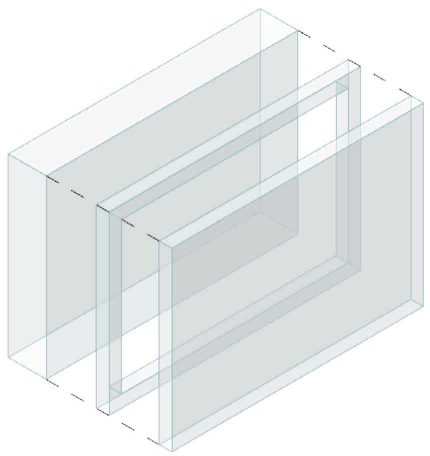
(a) in terms of the whole unit
and
(b) in terms of its edge seal connection?”

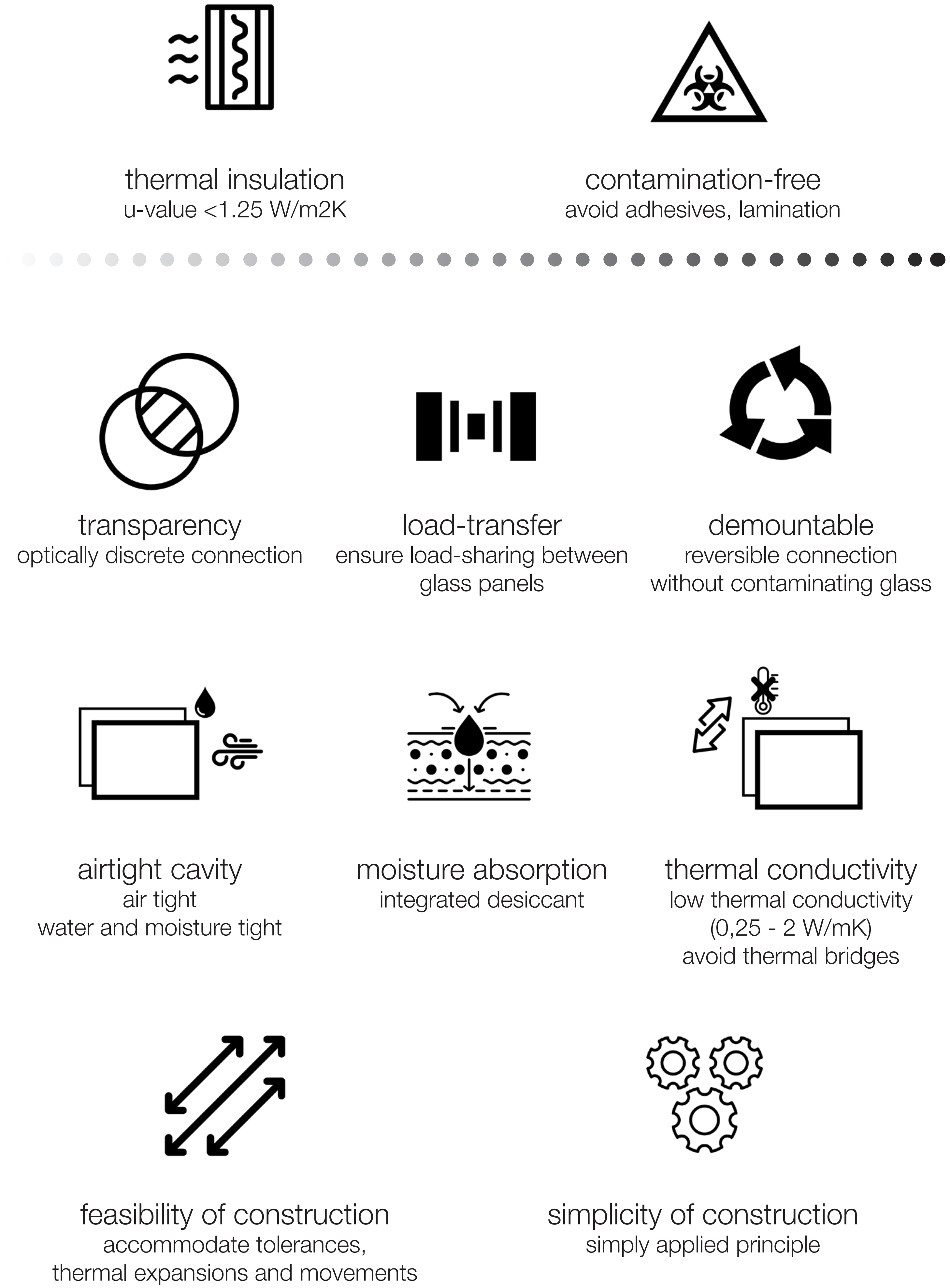
In terms of the whole IGU it is crucial that first and foremost good thermal insulating properties are ensured through the new design. A u-value of under 1.25 W/m2K is found acceptable for the scope of this thesis.

In terms of the guidelines of transparency ans circularity, the use of clear glass surfaces and the use of the least possible cavities is desired as more cavities lead to more optical distortion. Finally, regarding the circularity of the unit it is important that factors that contaminate its surfaces are avoided such as lamination and adhesives so that it can be demountable without leaving traces of contamination during the disassembly phase; hence a dry assembly system that avoids adhesives is opted for.

4.2 Design Criteria for IGU Edge Seal Connection

Regarding the edge seal connection between the different glass panels that make up an IGU the following design criteria are derived:
In order to maximise the transparency of unit the connection needs to be as optically discrete as possible in terms of dimensions and detailing. Moreover, in terms of circularity, as mentioned above, it needs to be fully demountable leaving behind no traces that can contaminate the glass and endanger its potential for recyclability.
Furthermore, an IGU is a complex product that needs to fulfill certain aspects in order to ensure a feasible construction and life use. Firstly, the connection needs to be able to transfer forces between the different glass panes. Moreover, it needs to allow for the accommodation of tolerances during the assembly and of movements that result from temperature and pressure differences during the product’s lifetime. Furthermore, the edge seal of the IGU needs to be completely air and water tight and it additionally needs to have a desiccant integration so that any moisture left during the assembly of the unit can be absorbed. Finally, an important aspect regarding the successfulness of the new design is the simplicity of the connecting principle. Currently used IGUs are manufactured in a quick, easy and efficient way and it is only logical that these properties are part of the new design as well.





Design Guidelines	Design Criteria		Prioritisation	Material oriented	Design oriented
Structural Capacity	compressive strength	not critial	+	M	D
Structural Capacity	tensile strength	> 1,5 Mpa	+++	M	
Structural Capacity	stiffness	> 4.8 GPa	+++	M	
Thermal Insulation	low thermal conductivity	0,25 - 2 W/mK	+++	M	D
Thermal Insulation	thermal expansion coefficient	close to 9 * 10^-6	++	M	D
Thermal Insulation	high moisture vapour transmission resistance	gas leakage rate (Li) < 1% per year water vapor transmission rate < 0.1 gr/m3 d gas permeation rate < 0.002 gr/m2 h	+++	M	D
Thermal Insulation	integrated dessicant		+++		D
Feasibility of Construction	flexibility for movements		+++	M	D
Feasibility of Construction	good durability	UV radiation water	+++	M	D
Transparency	high transparency		+++	M	D
Circularity	reversibility and recyclability		+++	M	D

The above table summarises the design criteria for the edge seal connection. A prioritisation of each criteria is made as well as a distinction between a material-oriented and a design-oriented approach for each one. As it is evident, most criteria are both design and material oriented.

Table 04. Table of categorisation of the design criteria for the edge seal connection

5. Investigation of Design Alternatives

IGU Edge Seal Connection

The following chapter consists of a thorough walkthrough of the investigation of different design alternatives towards the development of a circular IGU of maximised transparency.

5.1 Exploration of Possible Glass Combinations

5.2 Development of Preliminary Design Concepts

5.3 Evaluation of Different Design Concepts

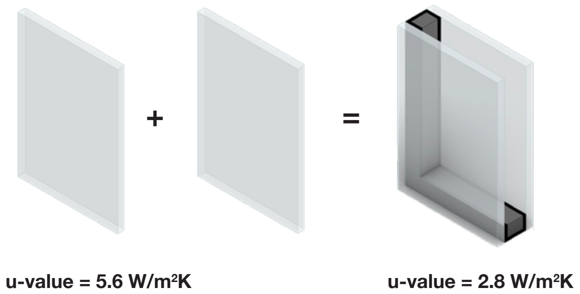
5.4 Prevailing Design Options

5.1 Exploration of Possible Glass Combinations

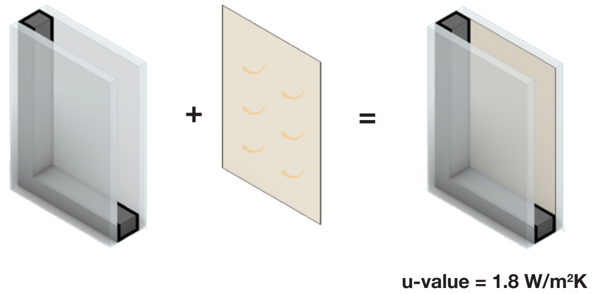
The following chapter illustrates the procedure of the design exploration that took place after the end of the literature review. From the literature review it was derived that in order to create an IGU at least two panes of glass with a cavity in between are needed. Moreover, a third thinner pane can be added to divide the cavity into two smaller ones functioning as a convective barrier. Additionally, coatings can be applied on one of the glass pane surfaces and the cavity can also be filled with an inert gas like argon. Finally, in order for the IGU to perform well thermally during its life time it is of the utmost importance that the cavity remains impermeable to air, water and moisture ingression. This is the role that is fulfilled by the edge seal connection that in the current IGUs consists of a spacer, made of either rigid or flexible materials, moisture barriers and a structural silicone seal that binds the unit together and ensures its structural stability as well as the protection of the cavity from weathering.

As previously mentioned during the literature review, the effect of the edge seal on the circularity of the whole IGU is crucial and the aim of this thesis is to create an alternative connection system that fulfills all the necessary roles of the typical edge seals while allowing for an easy disassembly, thus eliminating factors that contaminate the glass surfaces and prohibit its reuse and recycle.

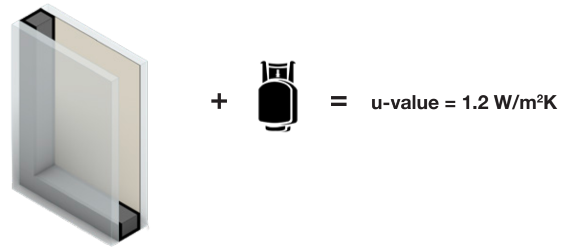
Typical ways of creating an IGU



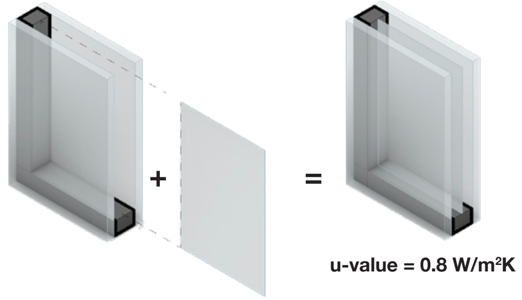
Create a cavity



Apply low-emissivity coatings

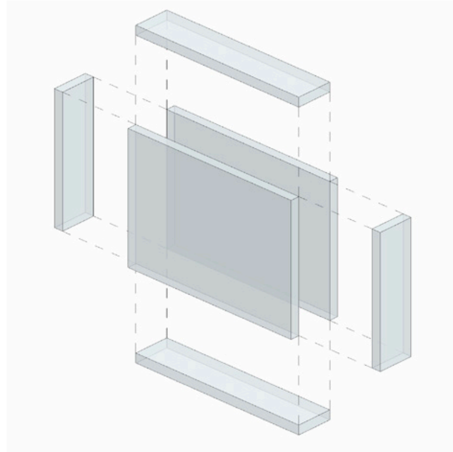


Fill the cavity with an inert gas



Add convective barrier

During the design exploration phase an out-of-the-box thinking approach was followed about the possible was to create an IGU. Having in mind that an IGU is like a “glass box” a brainstorming on different ways to achieve the creation of such a geometry were considered.

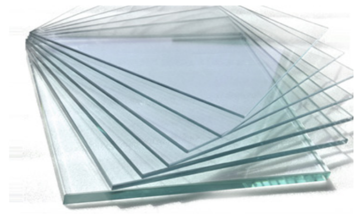


Possible Glass Types

Firstly, the different glass types that can be used were considered. Current IGUs are created exclusively by float glass panes because it is the prevailing glass industry and additionally because the float glass manufacturing process produces the most transparent surfaces. Moreover, float glass can also be heat treated for safer breakage which is necessary for the external pane in a glazed facade. However, float glass is restricted to specific geometries of flat sheets with limited thicknesses. This limitation of shape is also one of the reasons that the only way to connect two float glass sheets into an IGU is using an element for spacer bar and using adhesives to connect in to the glass surfaces.

From the literature review of the connections used in glass structures it was concluded that mechanical clamping fixings and connections using interlocking geometries are the most suitable options in terms of reversibility. Moreover, interlocking connections are preferred when maximum transparency is required due to the fact that they can be less visible than clamping elements.

The research conducted on the different glass manufacturing processes unveiled the potential of the alternative option of casting glass whose greater freedom of shaping seemed intriguing for the design experimentation despite the fact that it cannot reach the smooth transparency levels of float glass and it additionally lacks a safe breaking pattern.



Float Glass

Highest optical transparency
Can be heat treated for safe breakage
Recyclable if not contaminated
Limited shape options

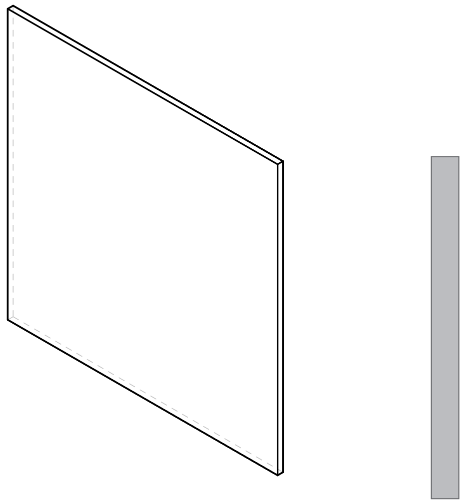
Cast Glass

Varying levels of optical distortion
Lacks safe breakage
Easily recyclable
Great freedom of shape options

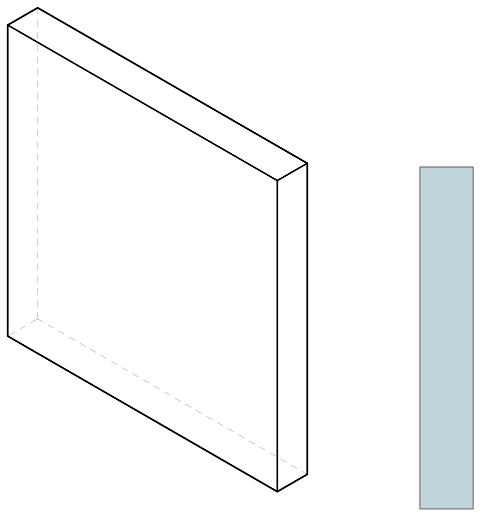
Glass Types Combinations

The next step in this phase consists of an investigation on different glass combinations that could make up an IGU and the possible connections that could be implemented in each scenario.

Three different glass typologies are chosen and their possible combinations are explored. Although during the research phase there were references of insulated glass units of irregular shapes the scope of this thesis focuses only on the development of IGUs of rectangular shape. The first typology is a rectangular float glass pane of thickness varying from 5 mm to 15 mm. The second is a solid cast glass block with thicknesses varying from 10 mm to 20 mm. Solid cast glass is considered as previously mentioned for the freedom of shapes that could enable an interlocking connection as well as for the fact that it can be used for structural loads as well if desired instead of laminated float glass. The third is a hollow cast glass block with uniform thickness varying from 10mm to 15mm. For transparency and safety reasons the hollow glass block can be replaced by a float glass pane with fused cast glass edges. Due to their similar geometry however, in the design exploration they are positioned in the same category.

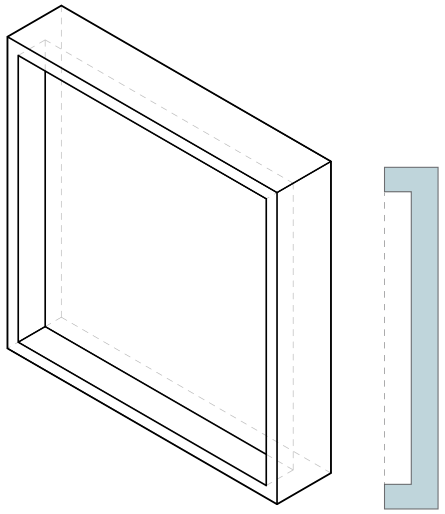


Rectangular Float Glass Pane

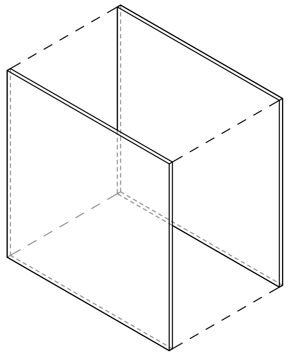


Rectangular Solid Glass Pane

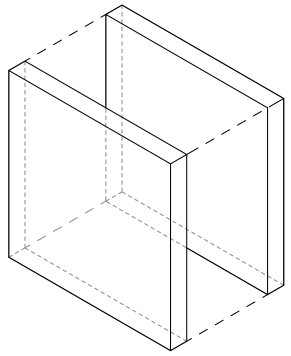
The following page shows all the possible combinations of the above mentioned glass typologies. An assessment table with these combinations and possible connections is presented. The criteria for the assessment are the transparency of the whole unit (glass surface optical quality and connection optical result), the reversibility of the connection and the safety (if heat treatment is possible). The most promising combinations are further developed into preliminary connection design concepts.



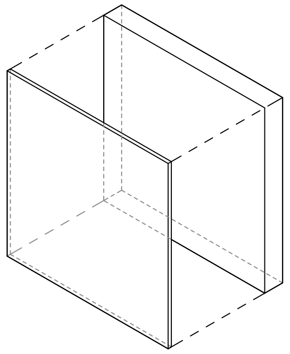
Hollow Solid Glass Pane



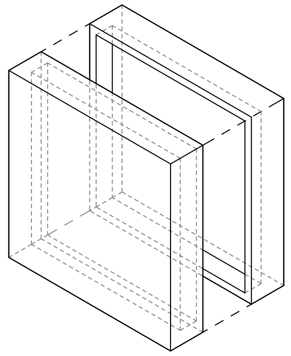
2 Float Glass Panes



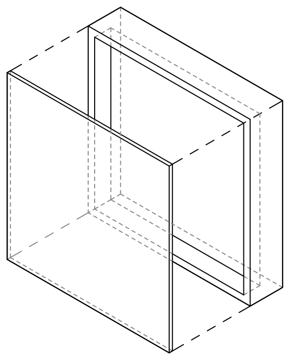
2 Solid Glass Panes



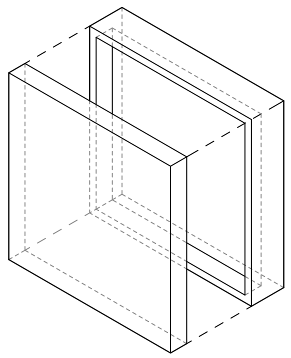
1 Float Glass Pane
+
1 Solid Cast Glass Pane



2 Hollow Cast Glass Panes



1 Float Glass Pane
+
1 Hollow Cast Glass Pane



1 Solid Glass Pane
+
1 Hollow Cast Glass Pane

Evaluation of Glass Types Combinations

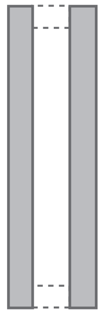
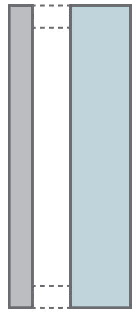
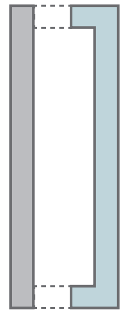
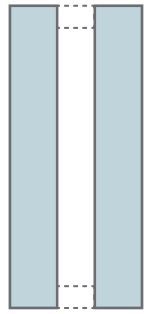
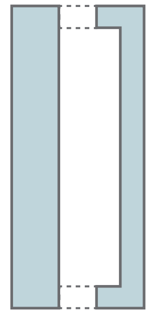
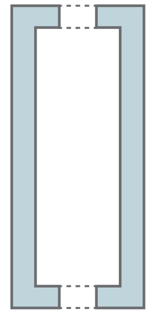
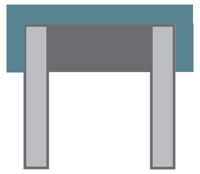
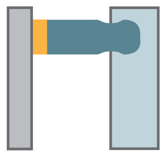
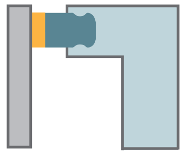
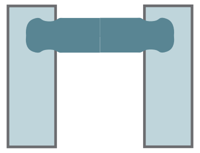
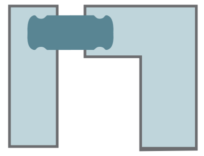
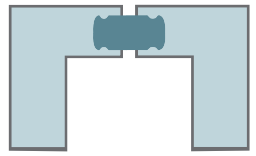
Combination of Glass Types						
Glass Types	Float Glass + Float Glass	Float Glass + Solid Cast Glass	Float Glass + Hollow Cast Glass	Solid Cast Glass + Solid Cast Glass	Solid Cast Glass + Hollow Cast Glass	Hollow Cast Glass + Hollow Cast Glass
Possible Connection Types for each Glass Combination	 Adhesion OR  Mechanical	 Adhesion to float glass Mechanical to cast glass OR  Mechanical	 Adhesion to float glass + Mechanical to cast glass	 Mechanical	 Mechanical	 Mechanical
reversibility	+ ++++	++ ++++	++	++++	++++	++++
optical transparency	+++ +	+++ +	++++	++	++ +++	+++ ++++
safety	++++	++++	++++	+	+	+

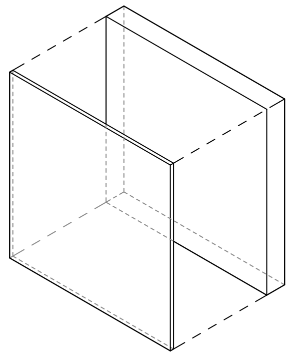
Table 05. Assessment of different possible glass combinations

5.2 Development of Preliminary Design Concepts

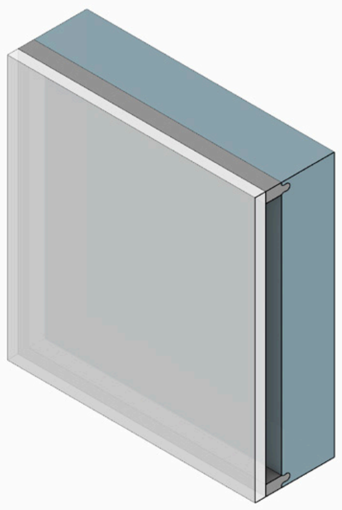
The assessment of the different possible glass combinations did not lead to a strict selection of specific combinations to be further developed. Out of the six presented combinations only two of them were completely ruled out; the two float glass panes and the two solid cast glass panes. The reason for this is that firstly in the case of using only two float glass panes the only possible connections are either adhesives or a very visible clamping element so this scenario cannot combine a reversible design with optically unobtrusive connections. On the other hand, the use of two solid cast glass panes exhibits enhanced optical distortion in the glass surfaces than float glass and does not allow for heat treatment or lamination in for safety or structural reasons.

The remaining four alternative combinations remained open for further exploration in this stage and provided useful inspiration and starting points for brainstorming on the connections. The following sub-chapter focuses on the presentation of the different preliminary design concepts that were developed during the next stage.

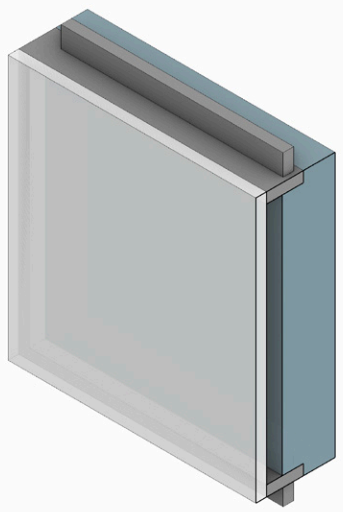
At first, the idea of having only half of the IGU completely circular occurred since in the cases were lamination will be needed and coatings are applied on a glass pane the recyclability of the particular element is already restricted. Hence, the idea was to limit the contamination in one pane and combine it with the use of adhesives if needed. Such an approach allows for more design freedom using elements that can be adhesively bonded to the float glass pane and mechanically connected to the other. The second glass pane is either solid or hollow cast glass so that the freedom of shaping can be used in the connecting element. This design exploration process resulted in seven different preliminary concepts that will be further analysed.



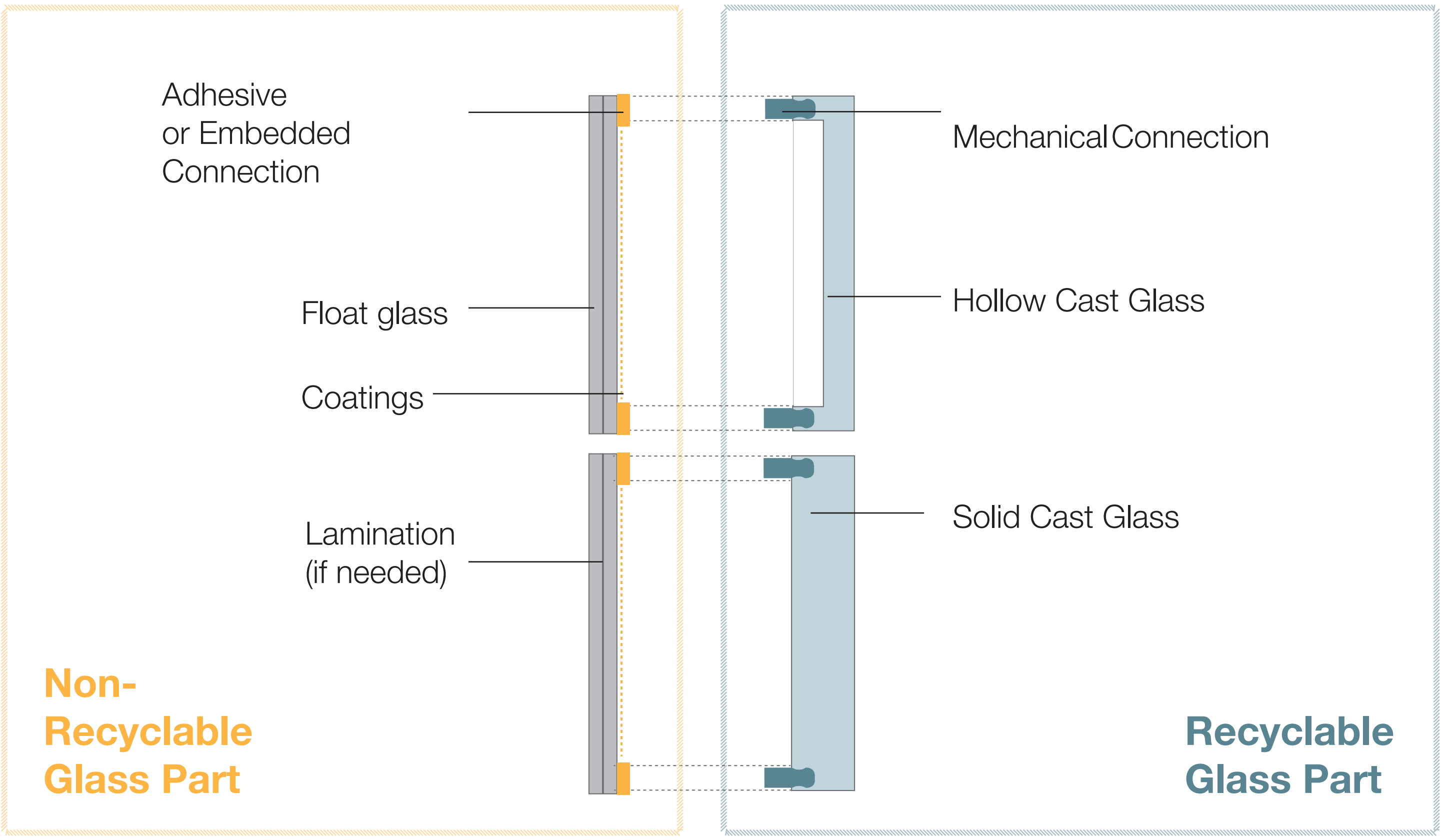
Float Glass + Solid Cast Glass

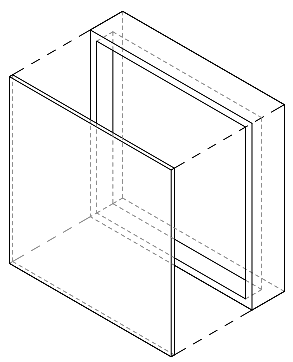


1. Interlocking Gasket

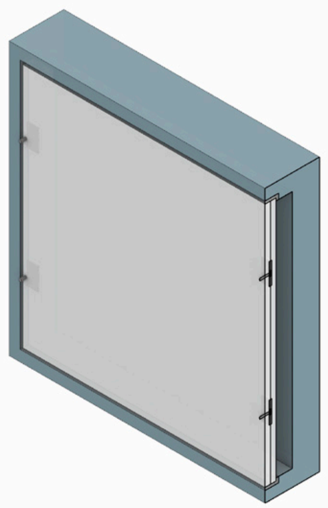


2. “Tetris” Lock

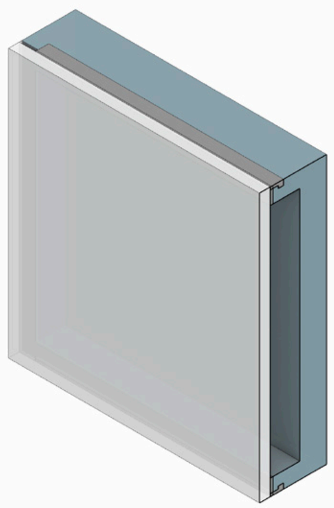




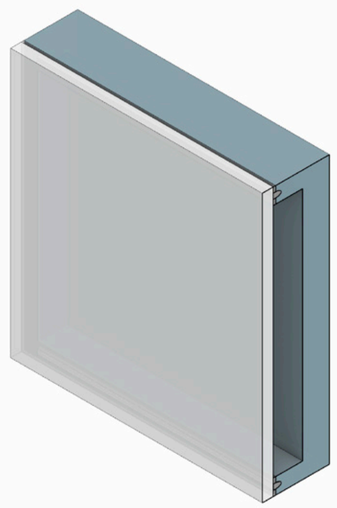
Float Glass + Hollow Cast Glass



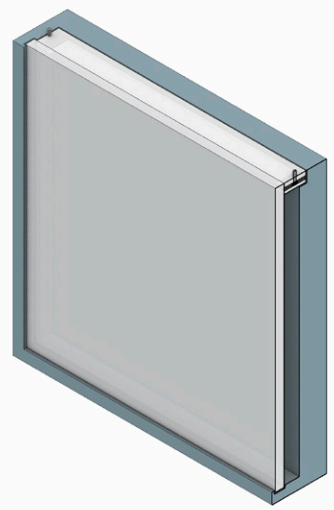
3. Pushed Embedded Lock



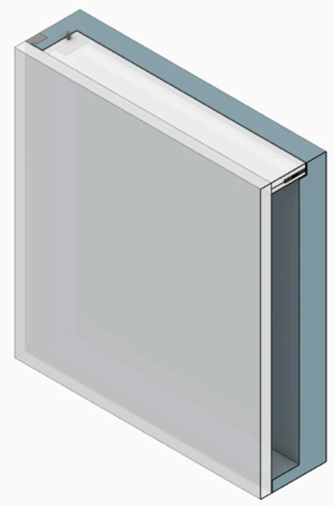
4. “Tupper” Lock



5. Sliding Embedded Lock A

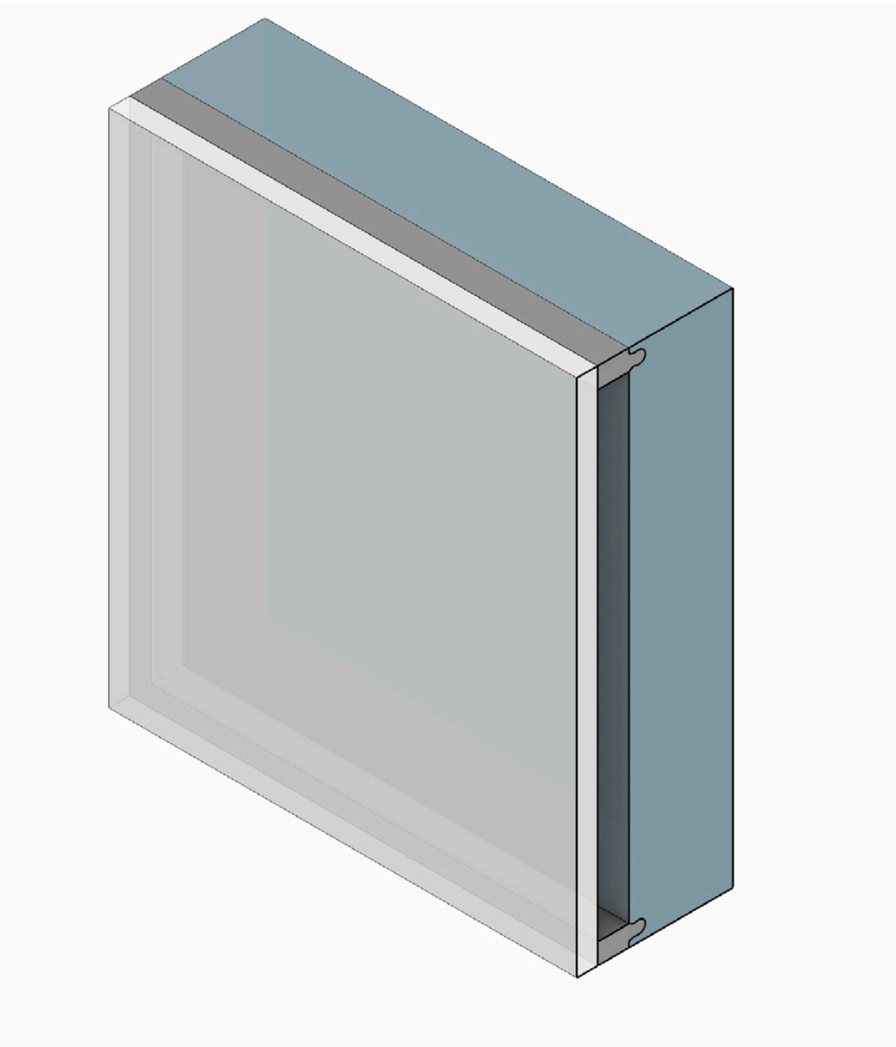


6. Sliding Embedded Lock B



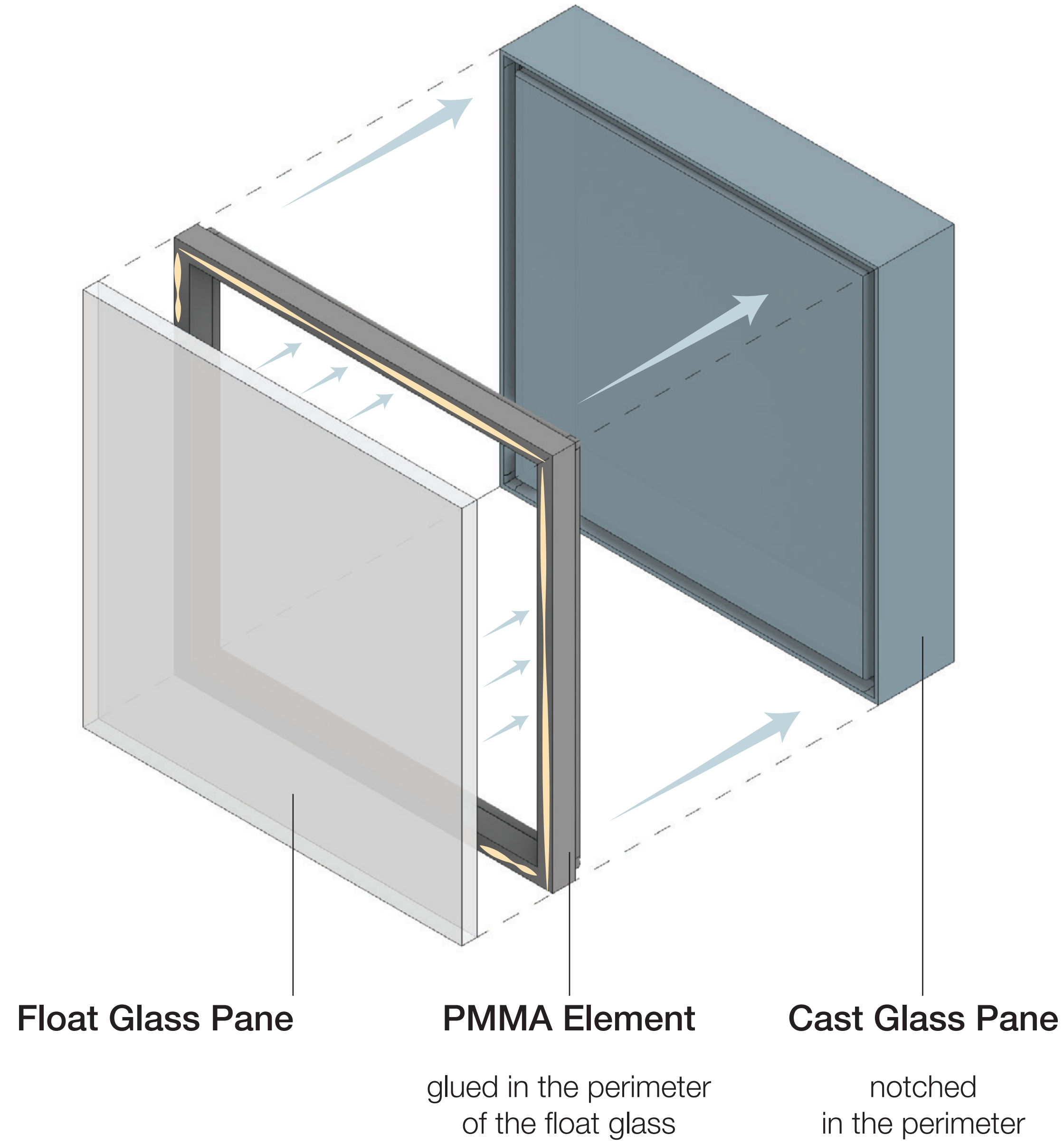
7. Sliding Embedded Lock C

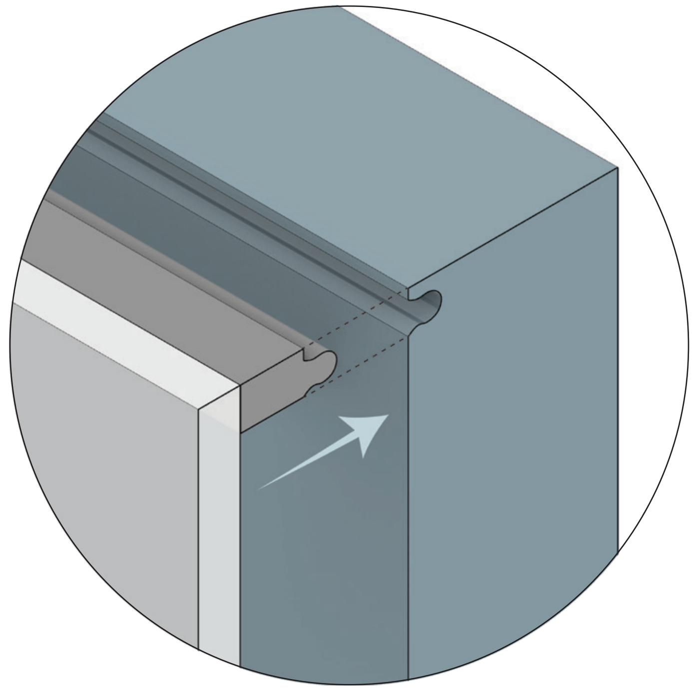
1. Interlocking Gasket



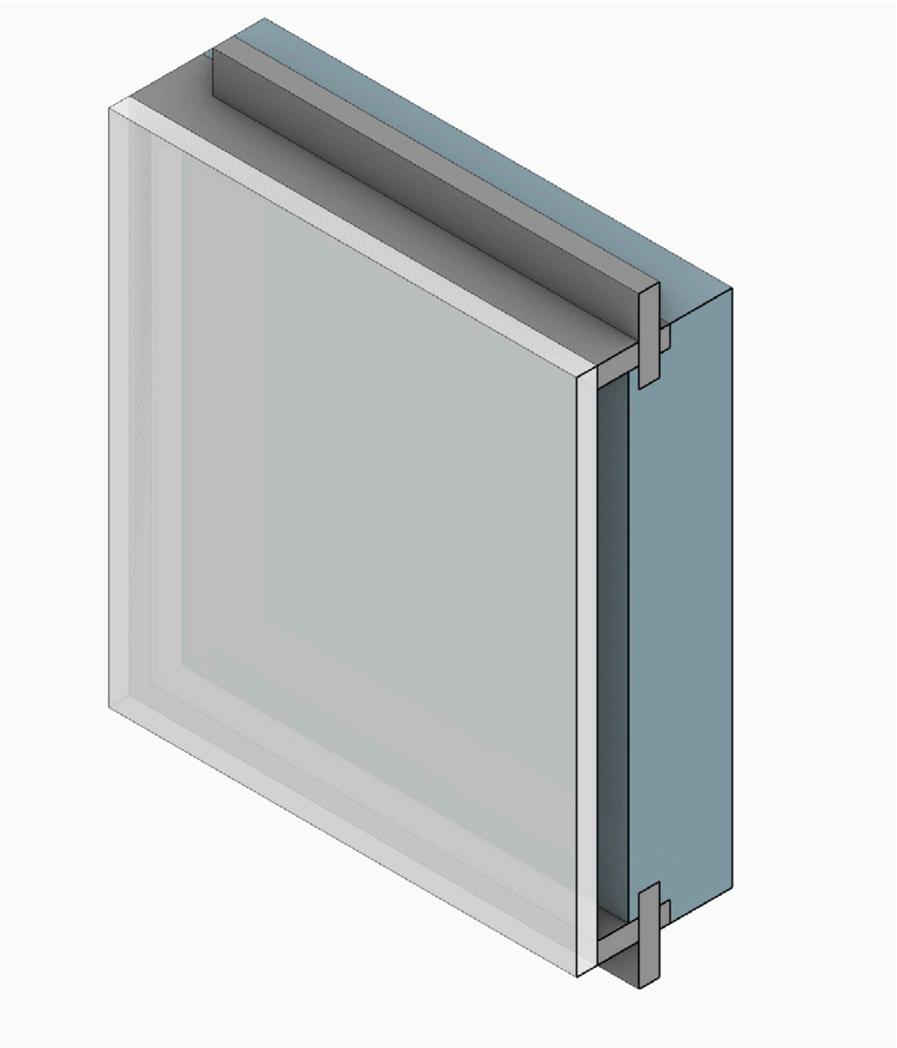
This concept is the first of the two alternative concepts deriving form the combination of a float glass pane and a solid cast glass one and it is inspired by the interlocking geometries used in the dry connections of cast glass solid blocks.

In this specific concept, the solid cast glass block has a continuous notch around the edges of the panel. The float glass has a transparent plastic element glued to its perimeter. Due to the bigger flexibility of this additional plastic element compared to glass, the part containing the float glass is pushed into the notch of the cast glass part and is locked there. This connection is relatively easy in its concept since it uses simple geometries and a very easy mechanism of locking. In terms of reversibility, the glass panes can be easily separated with the use of force to pull them apart. Moreover, this specific edge seal connection can exhibit great transparency levels since the additional plastic material can be made out of transparent plastic like PMMA. Overall, this concept shows great potential for further exploration both in the field of circularity and transparency.





2. “Tetris” Lock

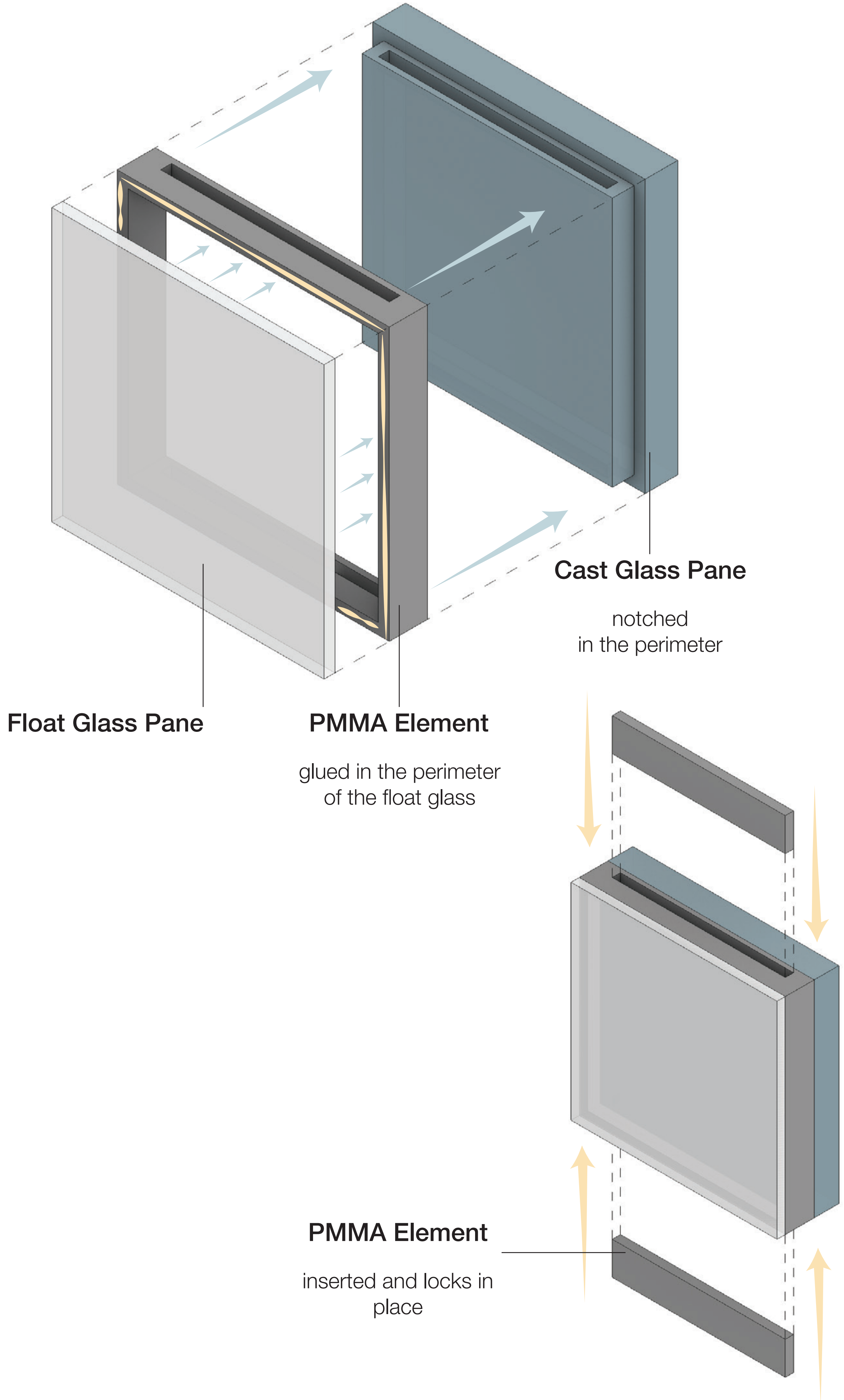


This concept is the second of the two alternative concepts deriving from the combination of a float glass pane and a solid cast glass one. The locking mechanism of this concept is based on a topological connection of pieces that lock together like puzzle or like the geometries found in the tetris game.

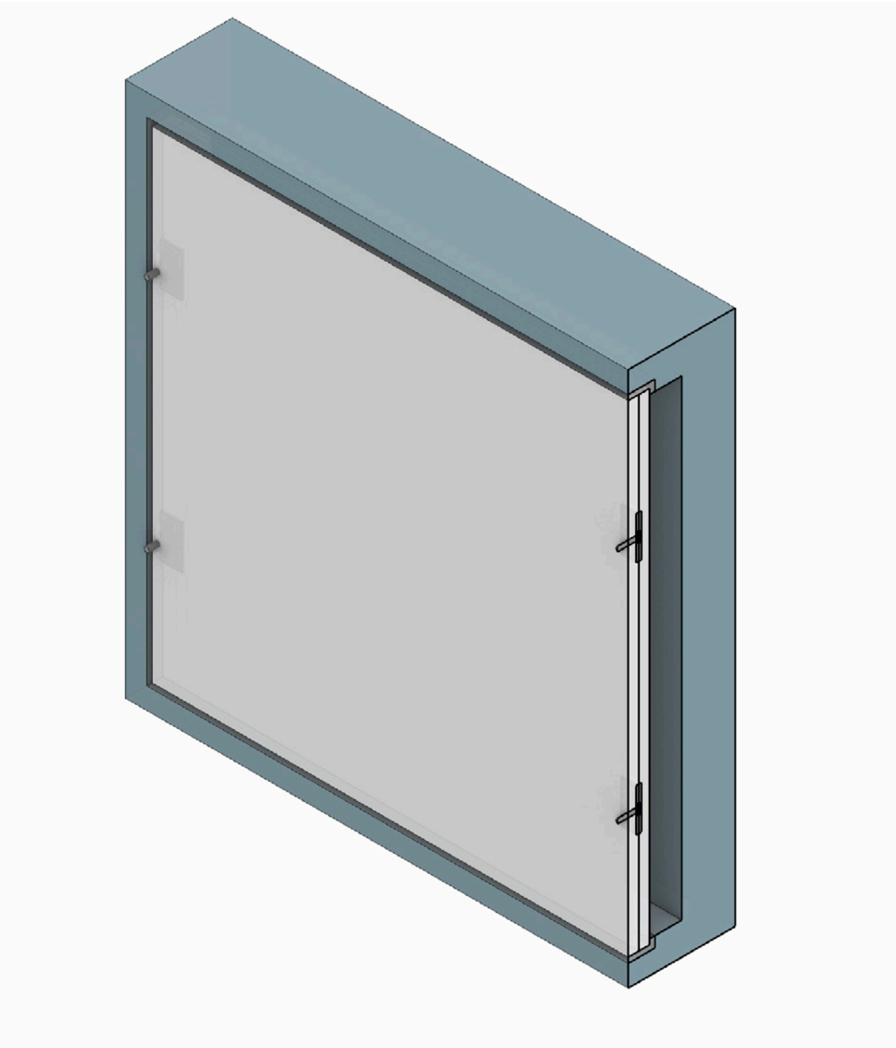
The solid cast glass block has a continuous notch around the edges of the panel. The float glass has glued to its perimeter a transparent plastic element with an hole at the bottom and top parts in the same places as the cast glass block. The two different parts of the unit are brought together and an additional element made of the same plastic material is inserted into the aforementioned holes completing the puzzle geometry.

One of the elements that would need to be solved if this concept was further developed is mainly, the locking of the last element in place, so that it cannot be removed unless wanted, still needs further development.

This concept is based on a relatively simple connection principle that enables easy reversibility. Moreover, the use of a transparent plastic material like PMMA ensures an optically unobtrusive edge connection.



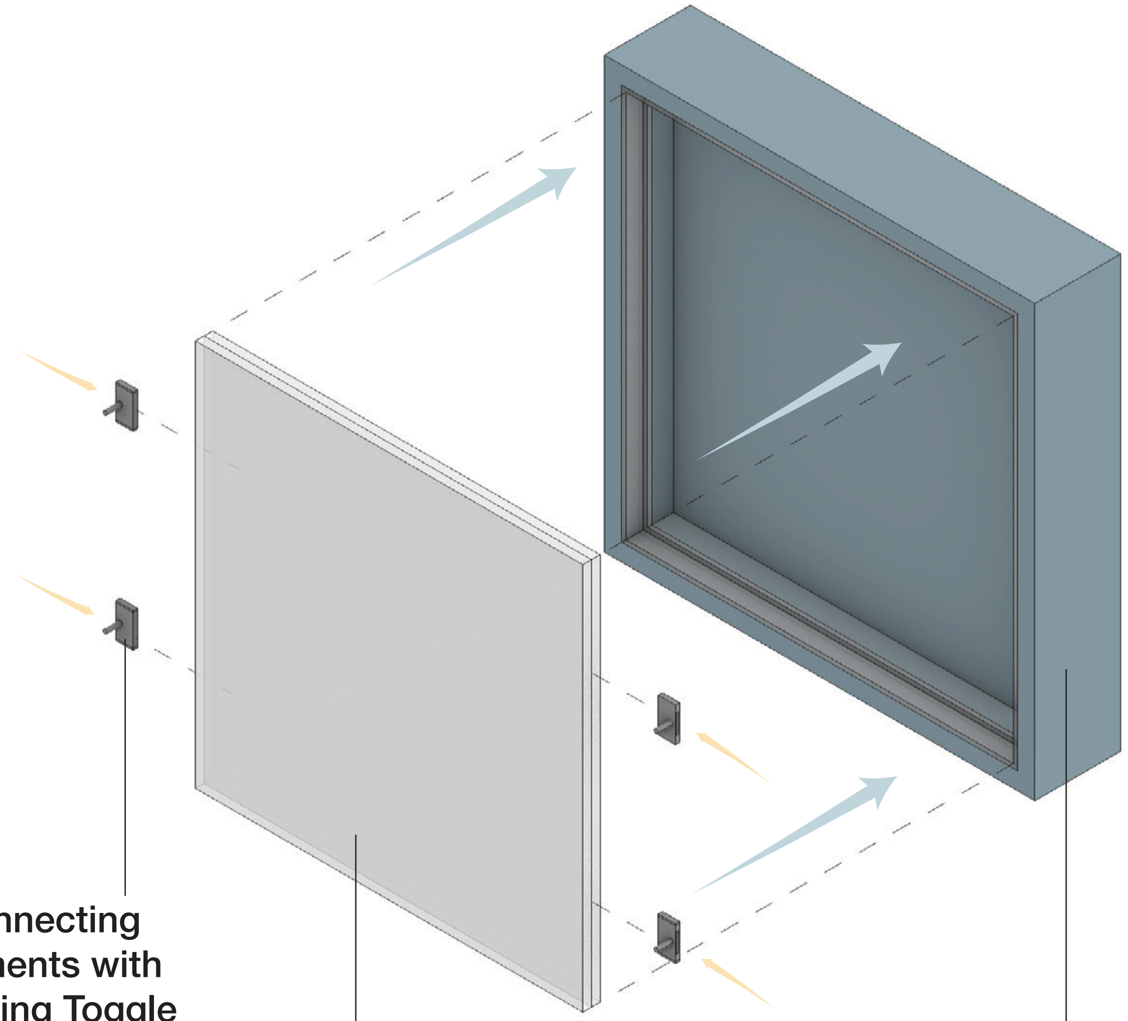
3. Pushed Embedded Lock

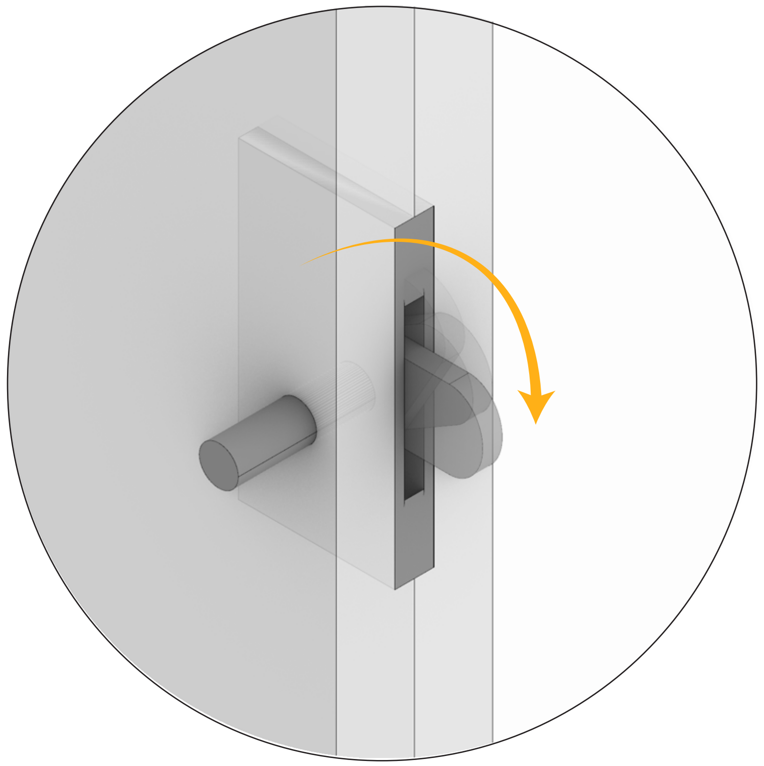


This concept is the first of the five alternative concepts deriving from the combination of a float glass pane and a hollow cast glass pane.

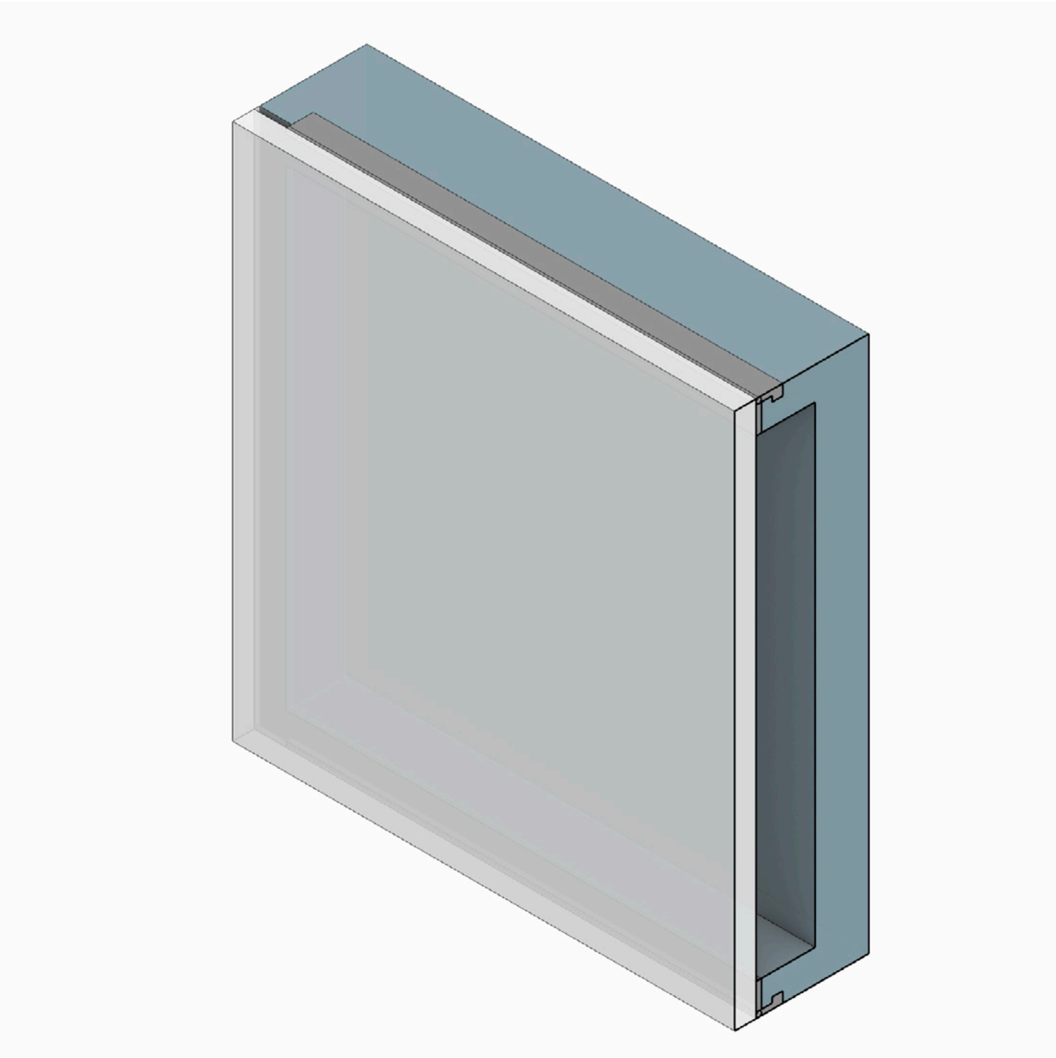
In this concept, the float glass part has embedded elements with a rotating toggle on its two sides that are used for its connection to the cast glass part. The float glass is pushed into a framed cast glass element and locked there with the help of the connecting elements.

This concept is based on a simple connecting mechanism that could be feasible because it relies on the already tried out embedded connections. The presence of these elements requires lamination therefore this part will be completely non-recyclable. Moreover, a big disadvantage of this design is the fact that the because the float glass is pushed into the cast part, a frame is left around that has an impact on the optical quality of the edge connection but also will account for thermal bridges since there is no element to stop the heat flow at these edges.





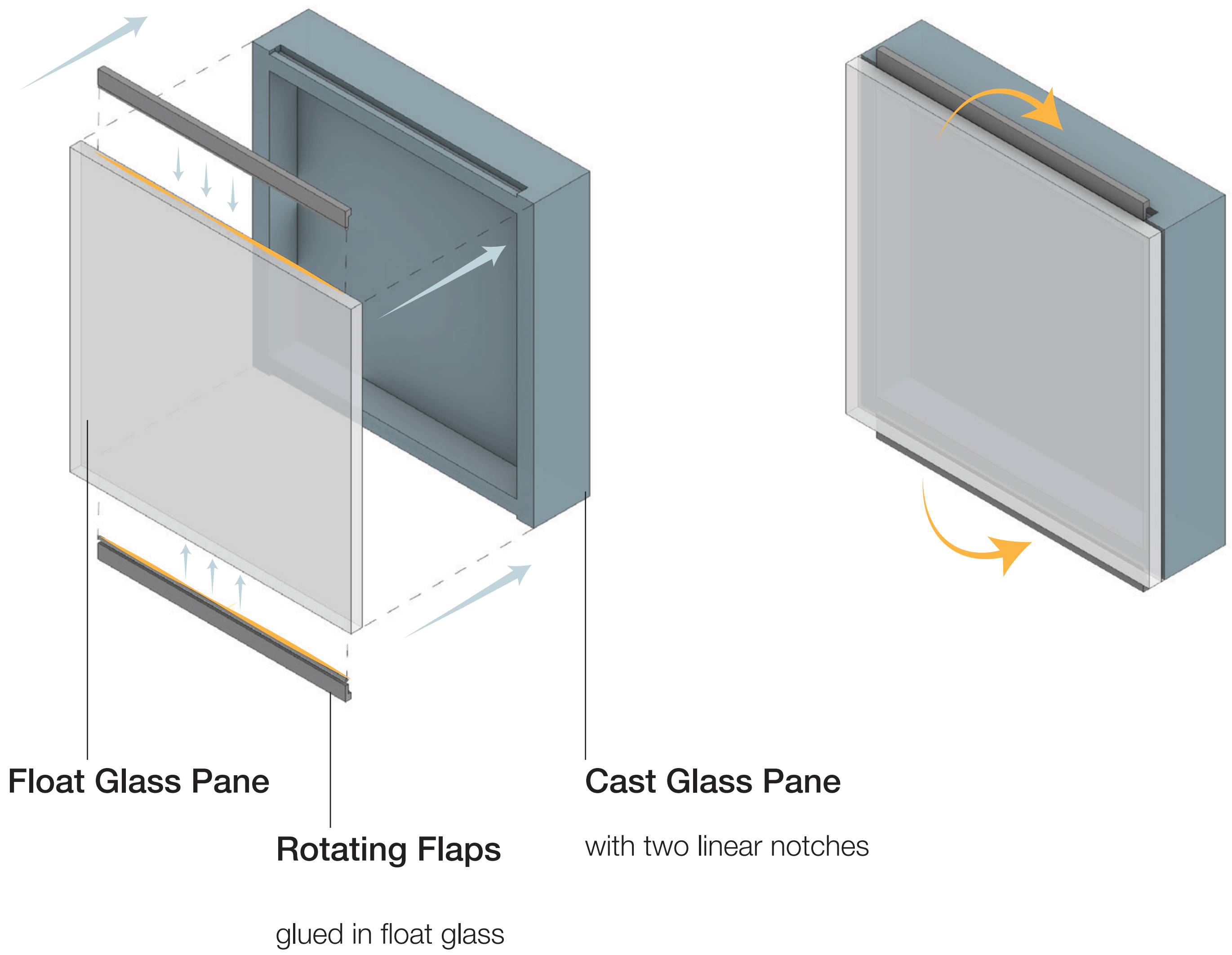
4. “Tupper” Lock

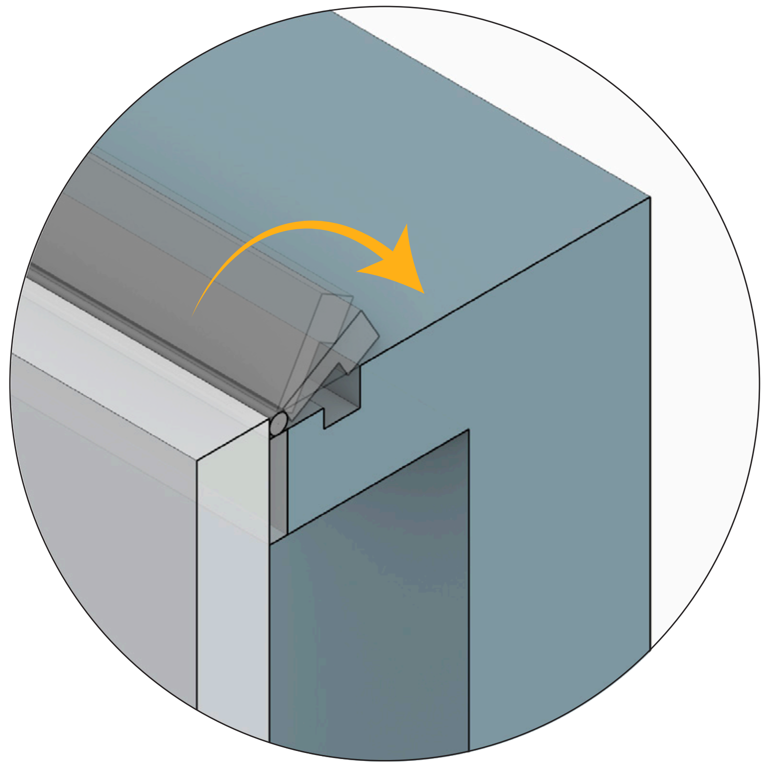


This concept is the second of the five alternative concepts deriving from the combination of a float glass pane and a hollow cast glass pane. It is based on the mechanical connection applied in food containers where a hollow glass part is used as a base and a top, usually plastic or glass, with attached rotating flaps is placed on top of the bottom part and locks in place with the use of these flaps.

The translation of the food container concept in this design occurs in the following way. The hollow cast glass part has a linear notch at the two sides of the element and the float glass has adhesively bonded to its two sides a hinge with a rotating flap. The float glass part is positioned on top of the cast part and once the flaps are rotated they lock in the notches found in the cast glass sides.

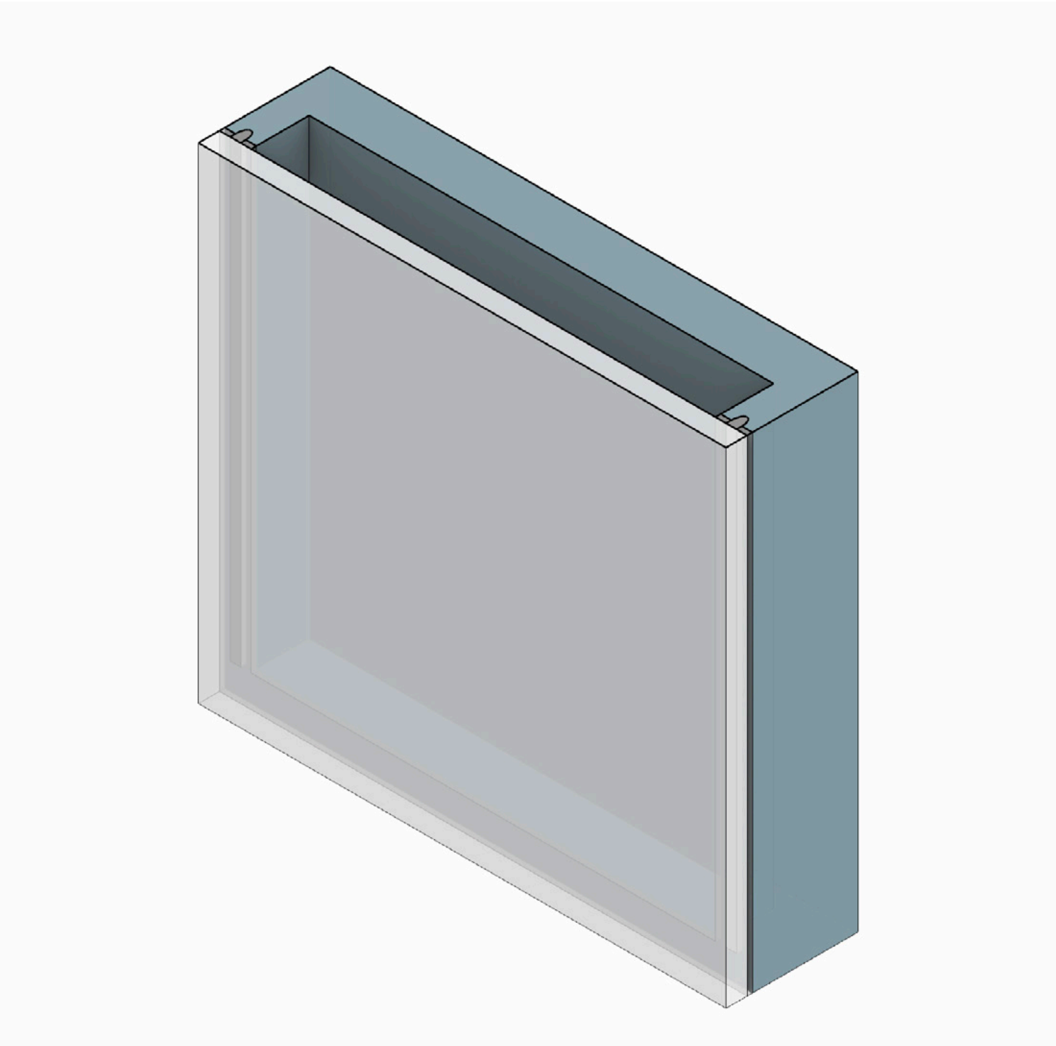
This concept is a very promising one due to the simplicity of the mechanism which is based on a well-proven to work mechanism found in a daily life application. Moreover, the mechanism is entirely hidden from the front part of the glass as it is only visible in the two sides, resulting in optically very unobtrusive elements.





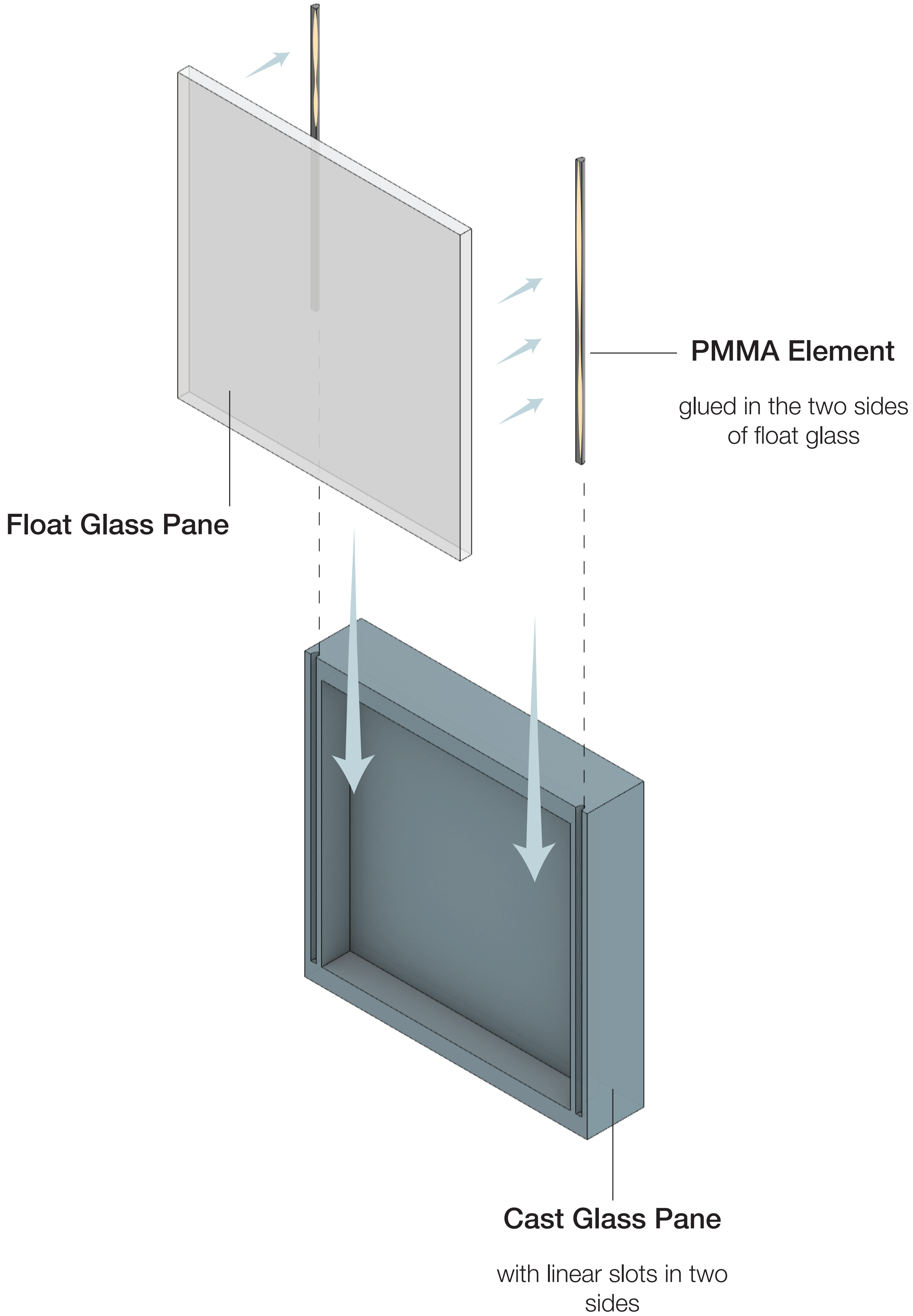
rotate and click!

5. Sliding Embedded Lock A

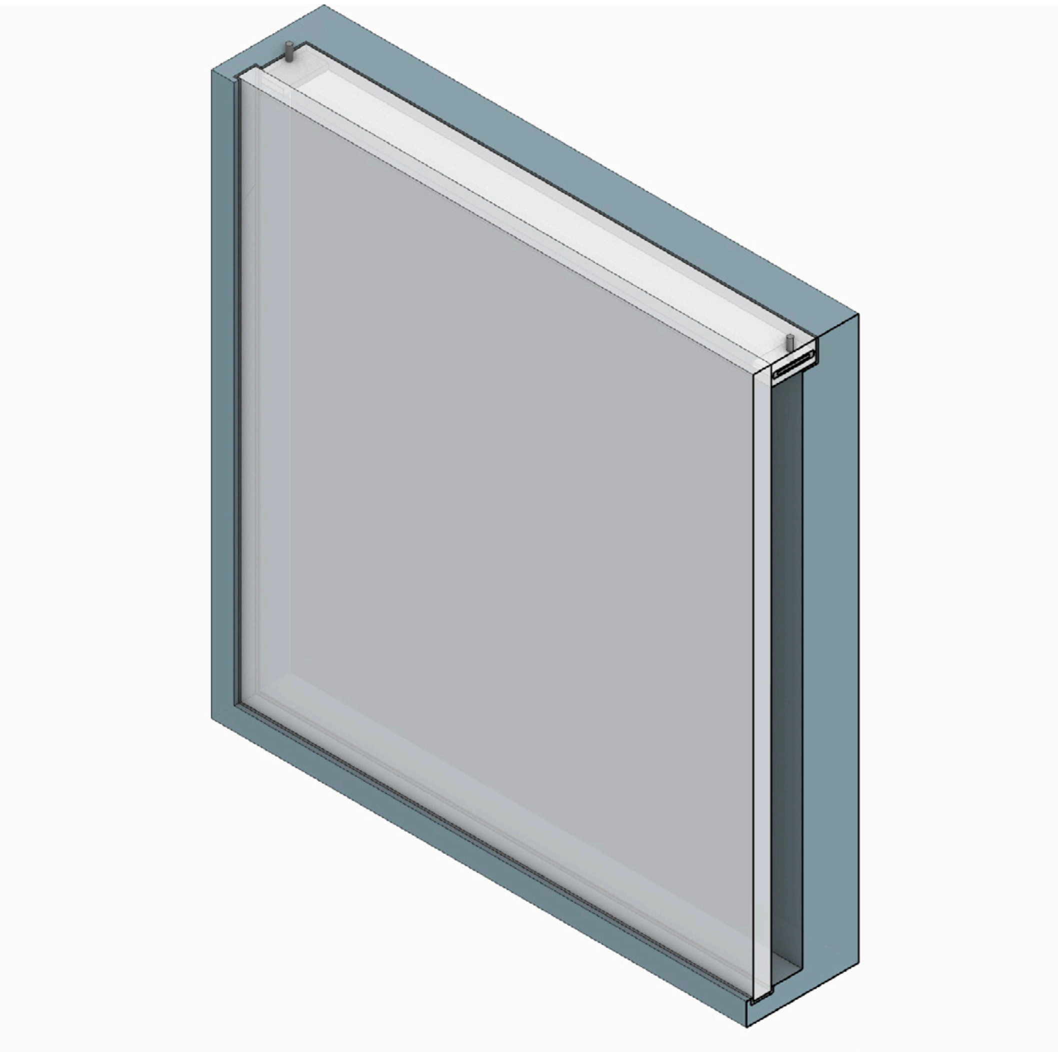


The last three concepts that combine a float glass with a hollow cast glass pane are all based on the principle of sliding elements. The first of these three slightly alternative design approaches requires a hollow cast glass element with two linear slots on its two sides. The slots go all the way up to the top of the unit but stop a little bit before at the bottom so that the sliding of the panel from the opposite side is avoided. The float glass part has glued to its two sides a linear element that could be made out of PMMA for a less visible connection. Finally, the float glass part is slided into the cast glass part.

This is the simplest out of the three sliding concepts although further attention should be given to the development of a locking mechanism at the top of the unit once the two different parts have been slided together.



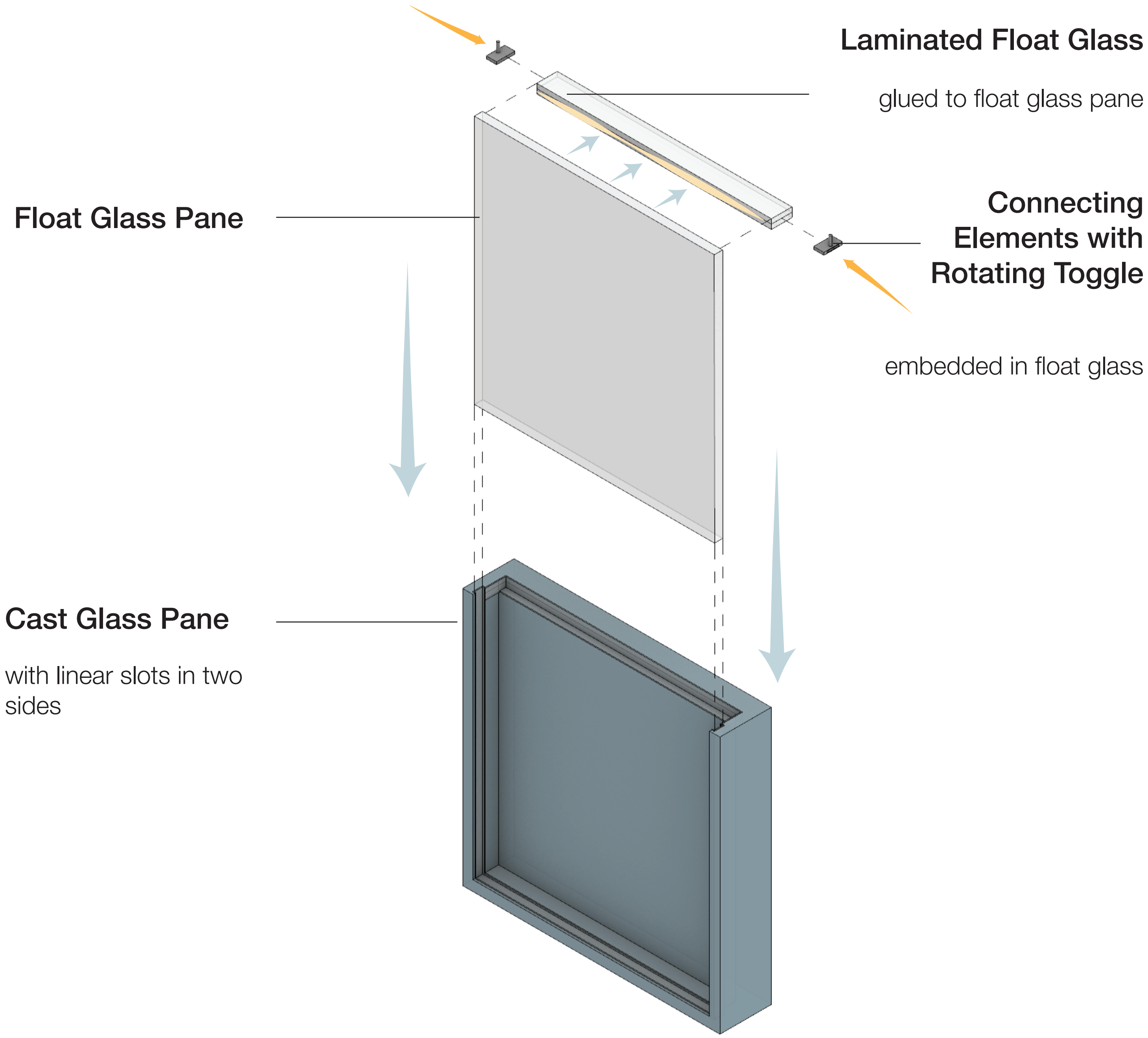
6. Sliding Embedded Lock B



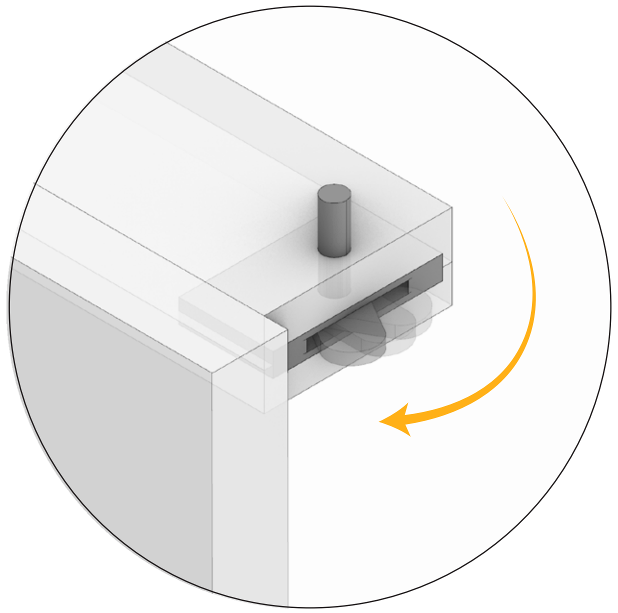
This particular design is the second sliding concept that combines a float glass with a hollow cast glass pane. The float glass consists of the main glass pane and of a second smaller pane with embedded elements, glued vertically to the main one on its top edge. The embedded elements consist of rotating toggles that ensure the locking of the two different parts of the unit together. The cast glass part uses the hollow geometry only on the three sides so that the float glass part can slide into it and lock at the top part of the unit.

The specific design has as a final optical result an IGU with a small glass frame, on the three sides only, because of the way the sliding occurs. Apart from the aesthetic result which compromises the transparency at these three edges, it also creates thermal bridges in these three sides which is not desirable.

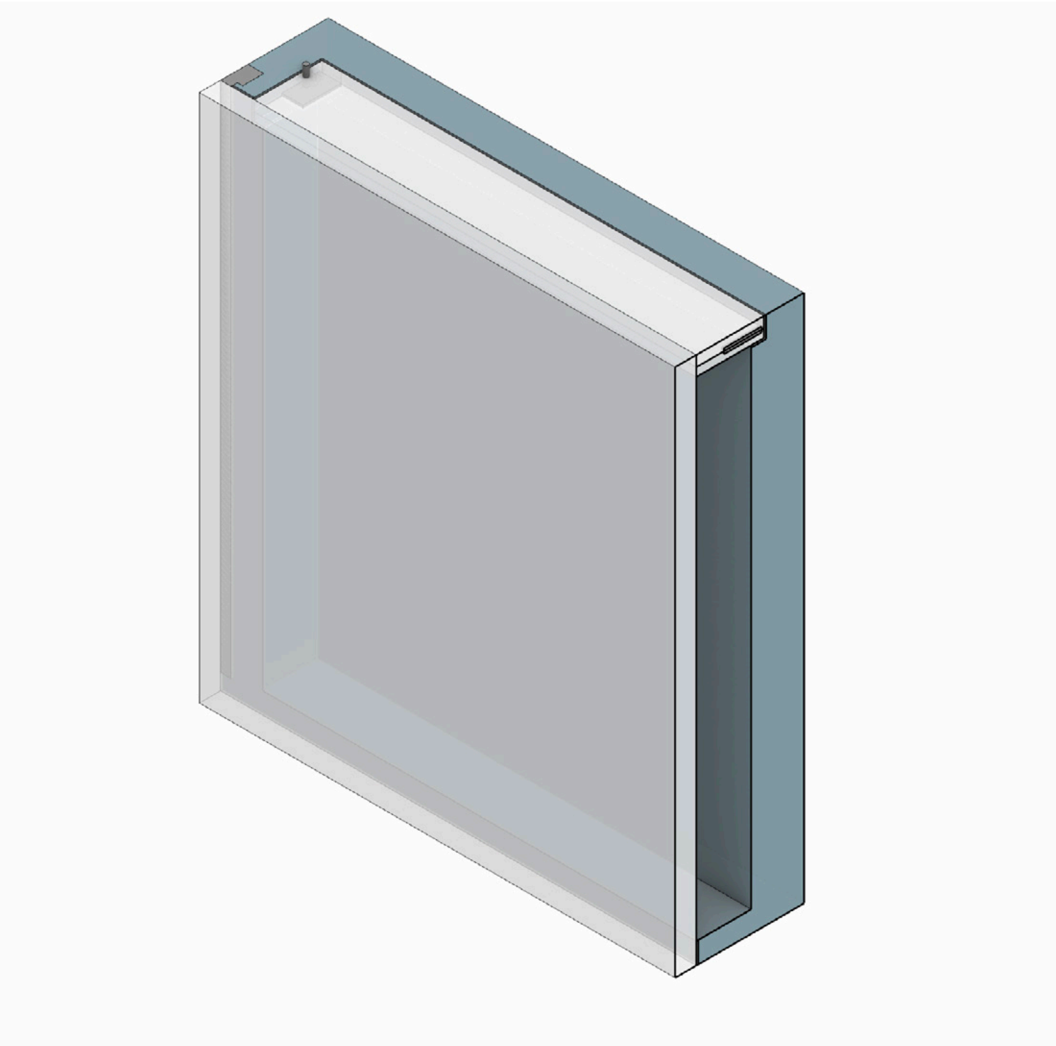
Moreover, the complexity of the mechanism is substantially increased compared to the previous designs. The difficulties are mainly associated with the use of the sliding principle which requires great tolerances and might prove not feasible if applied in IGUs of big dimensions.



slide and rotate!

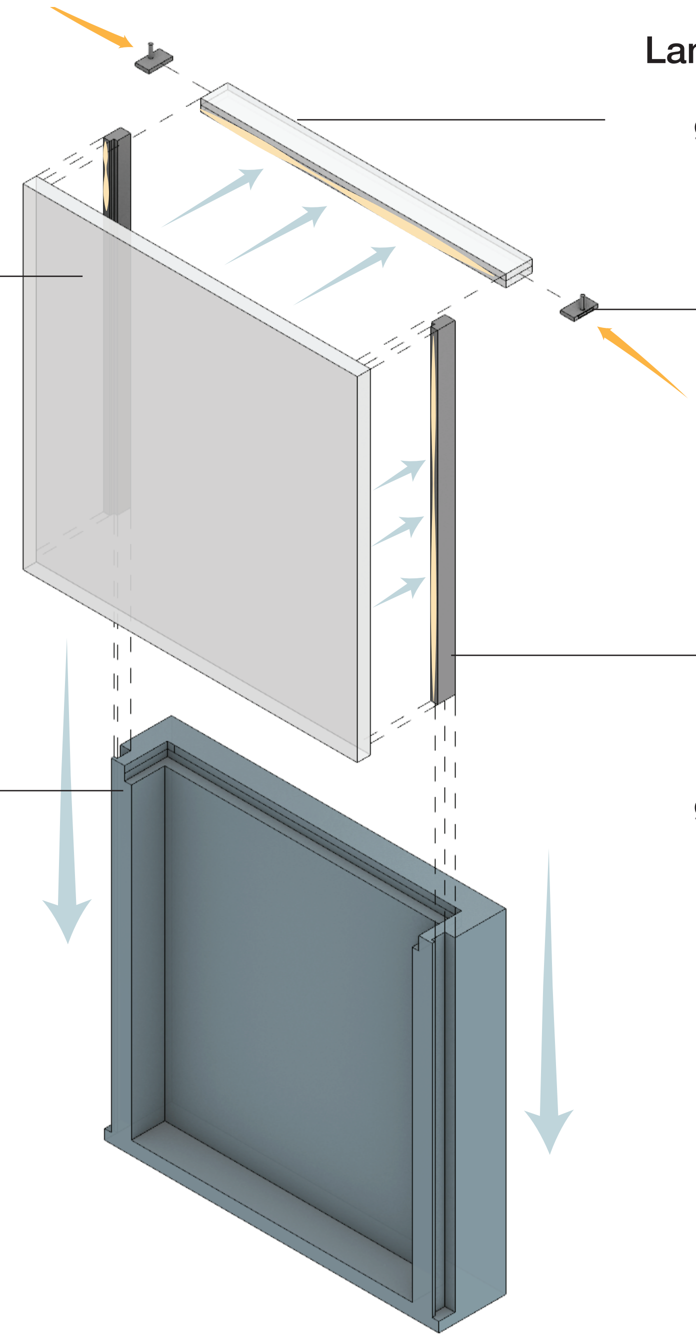


7. Sliding Embedded Lock C

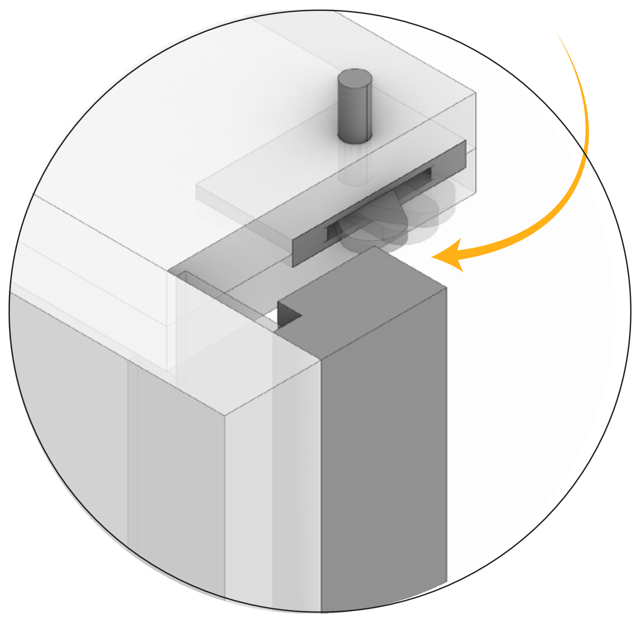


This particular design is third sliding concept that combines a float glass with a hollow cast glass pane and constitutes an improved variation of the previous one. The difference here is the fact that an additional element that is glued to the float part is used to slide into the cast glass geometry so that the visible frames of the previous design are eliminated here. The rest of the locking mechanism principle is the same.

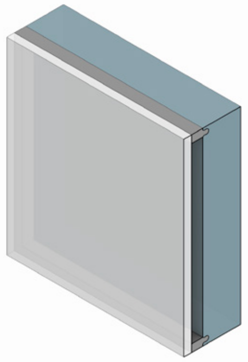
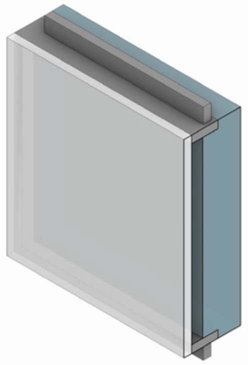
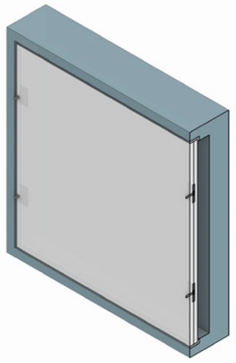
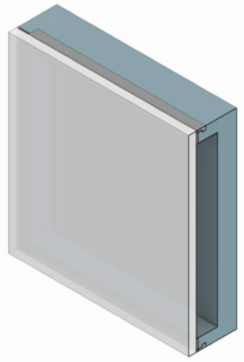
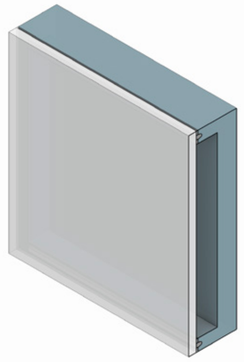
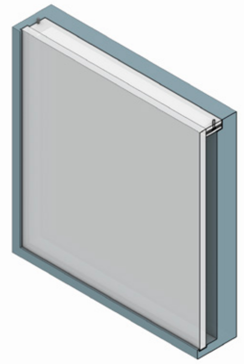
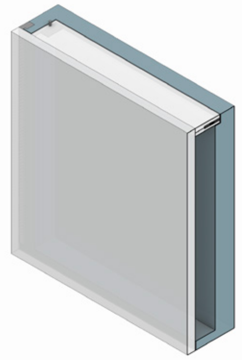
Although the design is significantly improved in terms of the optical result and avoids the thermal bridges of the edge seal of the unit, still possesses the same issues as the previous one in terms of feasibility of the construction.



slide and rotate!



5.3 Evaluation of Different Design Concepts

Design Option / Evaluation Criteria	 1. Interlocking Gasket	 2. “Tetris” Lock	 3. Pushed Embedded Lock	 4. “Tupper” Lock	 5. Sliding Embedded Lock A	 6. Sliding Embedded Lock B	 7. Sliding Embedded Lock C
Optical Quality	+++	++	+++	+++	+++	+	++
Feasibility of Assembly	+++	++	+++	++++	+	+	+
Thermal Bridges	+++	+++	+	++++	+++	++	++
Simplicity of Design	++++	++	+++	++++	+++	+	+++
Potential for Full Reversibility	++++	+	+	++	++	+	+
Potential for 3rd Glass Pane	++++	++++	++++	++++	++++	++++	++++
Notes	Dependent on geometry and material	Difficult to lock in position and seal cavity	Thermal Bridges / Cannot be fully reversible	Simplicity of design / Feasible assembly	Difficult assembly due to tolerances in sliding	Difficult assembly due to tolerances in sliding / Thermal bridges/ Visible frame	Difficult assembly due to tolerances in sliding

All the above designs were developed on a preliminary stage so all the aspects that are necessary for an edge seal were not solved at this point. More specifically, the integration of desiccant is not solved yet although it is an important aspect that will compromised the final edge seal. Moreover, in all the cases that there is glass to glass contact a suitable interlayer material must be applied to avoid stress concentrations. Having these aspects in mind, the concepts are evaluated based on the following criteria so that the prevailing ones can be further developed in the final design stage.

Evaluation Criteria

Optical Quality:

As optical quality the minimisation of the optical impact of the connection is taken into account. A smooth external surface without visible elements is also preferred.

Feasibility of Assembly:

As IGUs have varying dimensions the connection needs to be able to be applied from small blocks to big floor-span units. Therefore, it is crucial that the assembly is feasible for such big elements. Particular attention is given to the effect of tolerances during the assembly. In this sense, connections using sliding element are not preferred.

Thermal Bridges:

For the satisfactory thermal performance of the IGU thermal bridges need to be eliminated. Therefore, there must always be an element of low conductivity separating the two glass panes.

Potential for Third Glass Pane Integration:

The potential for integrating a third glass pane as a convective barrier inside the cavity is very important as it can improve significantly the u-value of the IGU.

Simplicity of Design:

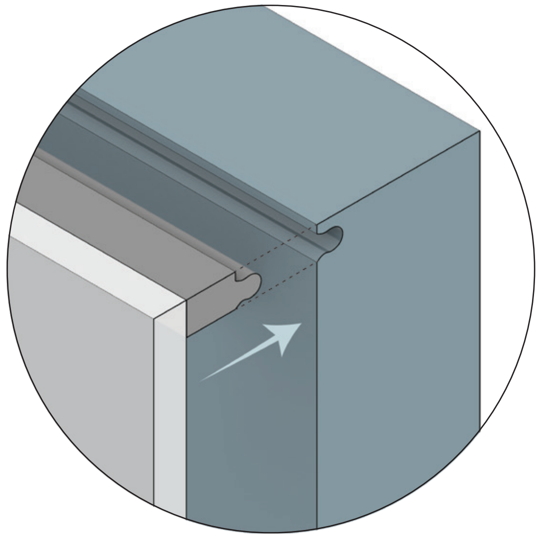
Currently used IGUs are bonded together in a very simple way. It is only logical that the same simplicity of assembly is desired to be applied in the new connection as well.

Potential for Full Reversibility:

The current dsigns are based on a half reversible connection in order to allow for more design freedom during the exploration phase. However, the potential for these to connections to be further developed into fully reversible ones is a very promising aspect that has a big weight factor in the evaluation process.

5.4 Prevailing Design Options

During the evaluation of the seven different preliminary design concepts two of them showed the greatest potential for further development. The reasons for that are simplicity of their design that can lead to a feasible IGU assembly without thermal bridges and with the least optically obtrusive result. The two prevailing concepts are the first one, the “Interlocking Gasket”, and the fourth one, the “Tupper Lock”. This final sub-chapter of the design exploration phase, depicts the further development of these two concepts that will lead to the final design.

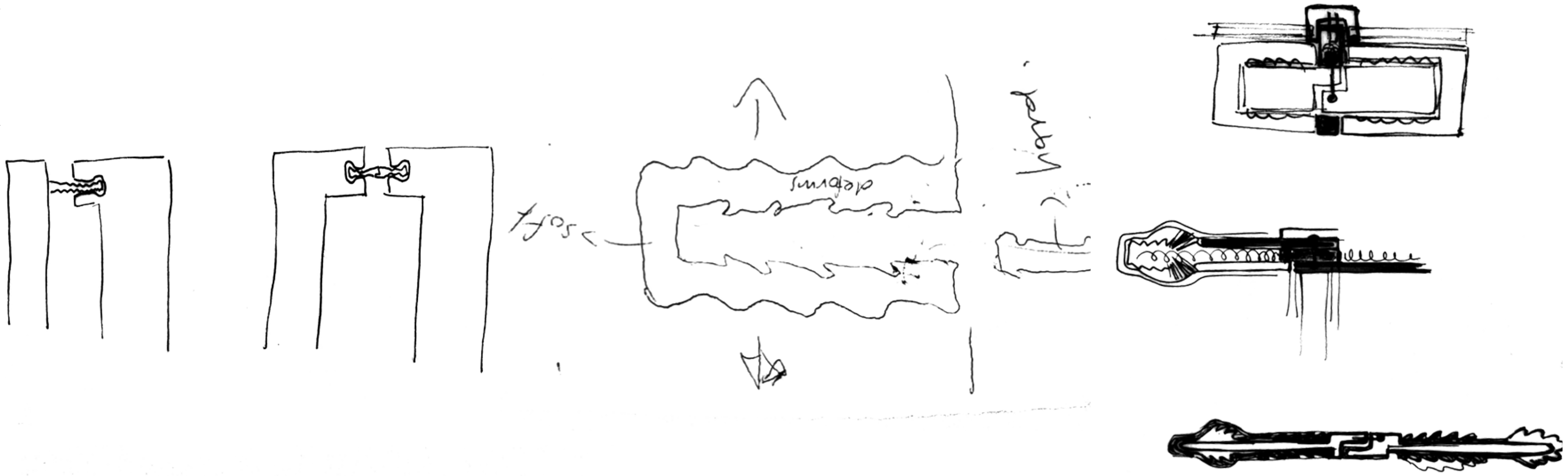


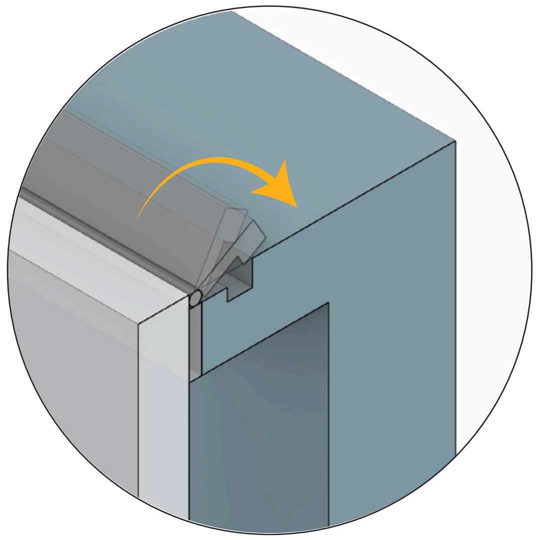
Interlocking Gasket

The design was intially based on a adhesively bonded element on the float glass pane that has a certain flexibility to be connecetd to a continuous notch in the perimeter of the cast glass element by pushing it with force. A similar force would be used for the disassembly process.

In this phase, in the attept for maximum reversibility, a doubly interlocking element in both sides is considered here.

This design ended up being discarded due to its increased complexity.



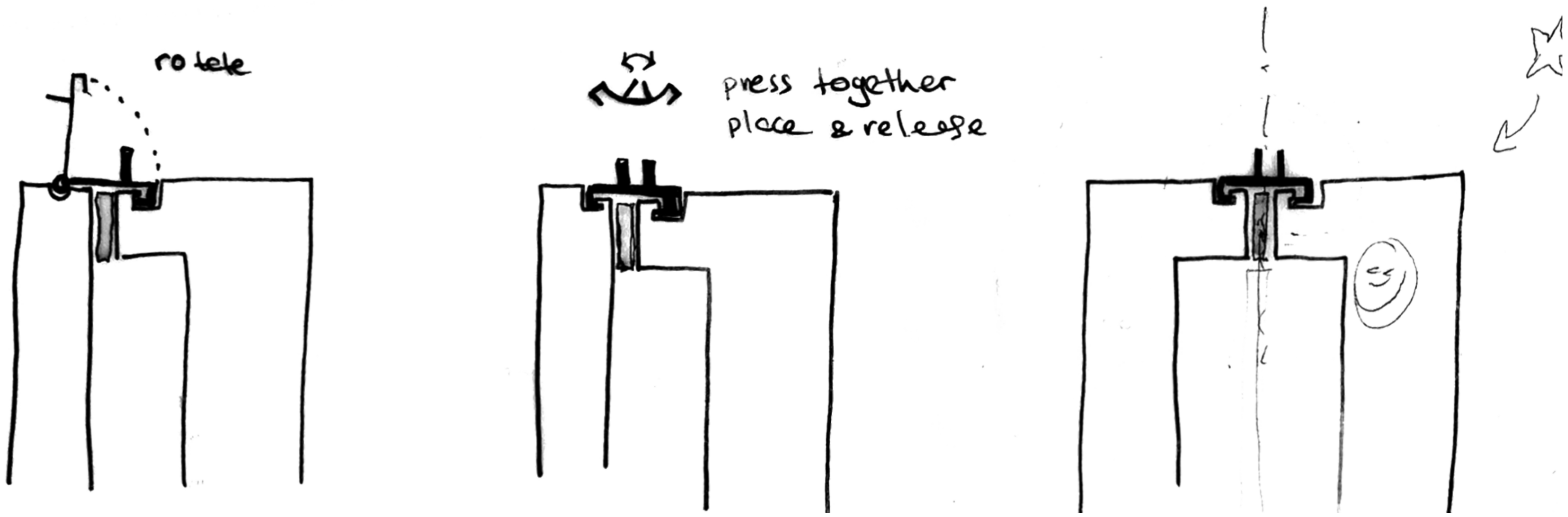


“Tupper” Lock

This design was initially inspired by the way glass food containers work. So the original idea was to have an embedded hinge in the float glass pane that can rotate and mechanically lock in a notch in the cast glass part.

In an attempt for a fully reversible connection, the idea occurred to make the connection symmetrical and use a mechanical lock in both panes. This kind of connection would work as an internal mechanical clamping and for this purpose a suitable material with certain flexibility and rigidity at the same time would need to be found.

Between the two prevailing designs this one showed more potential for a feasible solution due to its simplicity compared to the interlocking one.



06. Final Design

IGU Edge Seal Connection

The next chapter consists of a thorough explanation of the final design. It begins with a more detailed evolution of the final prevailing concept. The final detail with the materials chosen is explained followed by an description of the manufacturing methods and assembly order of each part of the new IGU edge seal connection. Finally, the possible end-of-life scenarios of the unit are explained.

6.1 Final IGU Design Evolution

6.2 Materials

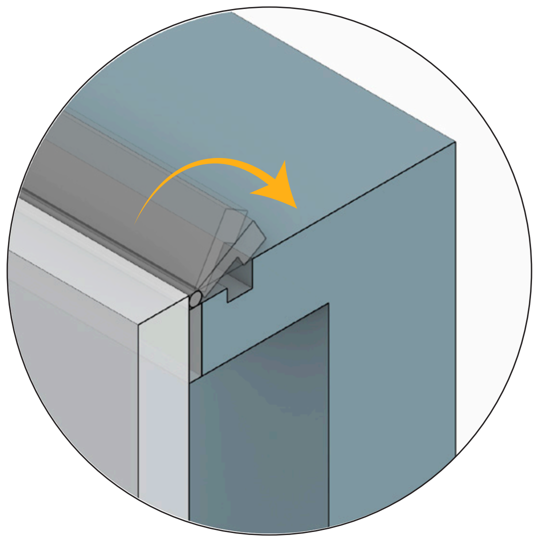
6.3 Manufacturing Process

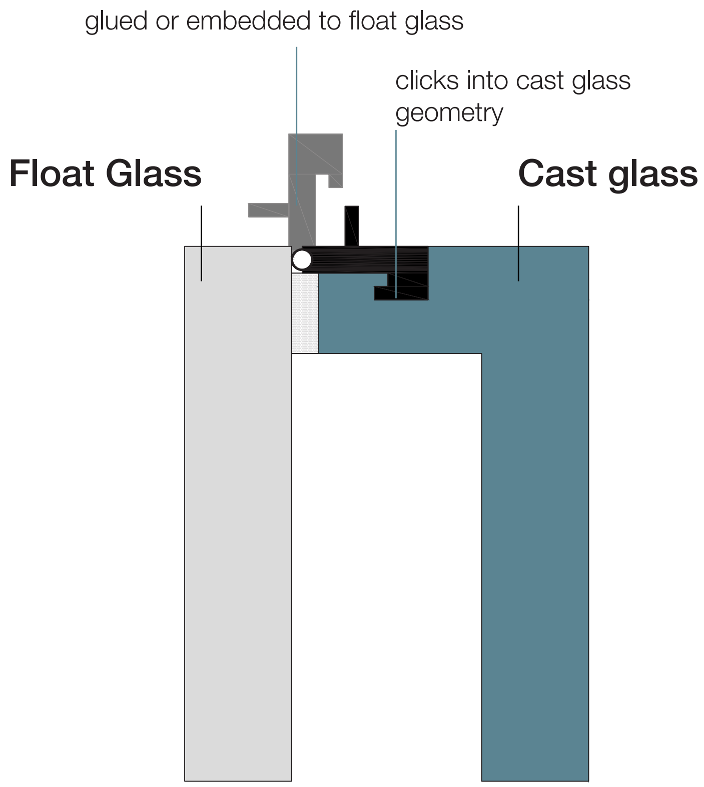
6.4 Assembly Order

6.5 End of Life

6.1 Final IGU Design Evolution

Rotating Flap



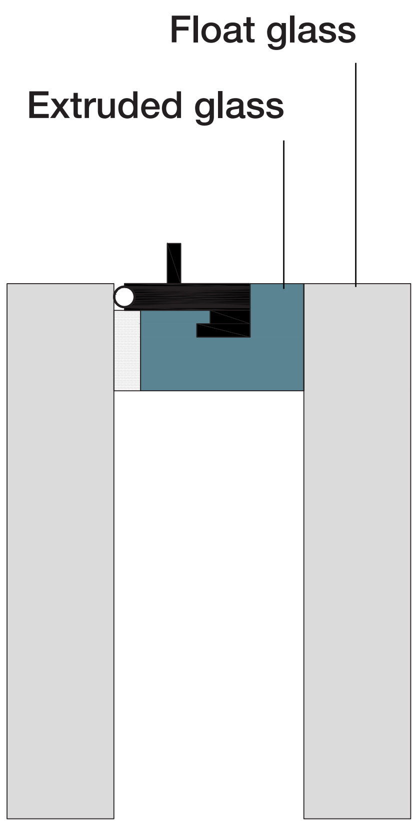


The selected design option was originally conceived having in mind the use of a float glass and a cast glass part as analysed in the previous section.

Nevertheless, at this stage the replacement of the cast glass part with combination of float and cast glass edges through heat fusion arose as a very promising solution that combines the best characteristics of both glass manufacturing processes. Float glass can be used for smooth transparent surfaces and it can be heat treated for safe breakage if needed, while cast glass elements, in shapes that enable a mechanical connection, can be fused around the edges of the float glass.

The reasons for this approach are firstly, the fact that the new IGU aims to be manufactured in a variety of sizes casting the whole element could cause feasibility issues for large glass panes. Secondly, float glass is preferred for its smooth and completely transparent surfaces it produces compared to cast glass. Moreover, float glass is the most economic solution for large surfaces. Finally, float glass can be heat treated for safe breakage, a very important feature for facade applications.

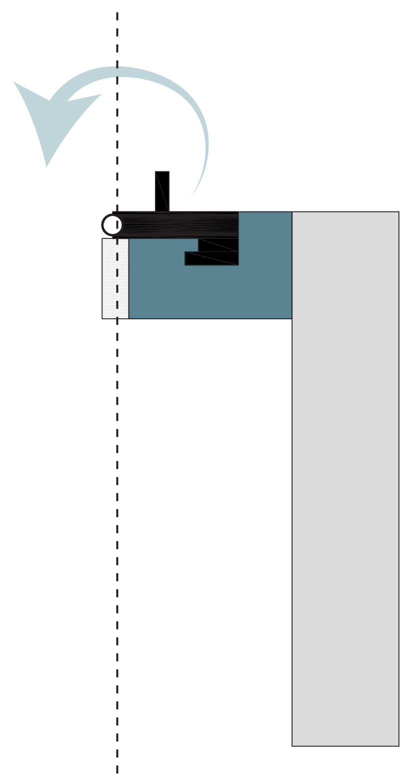
Glass Fusion



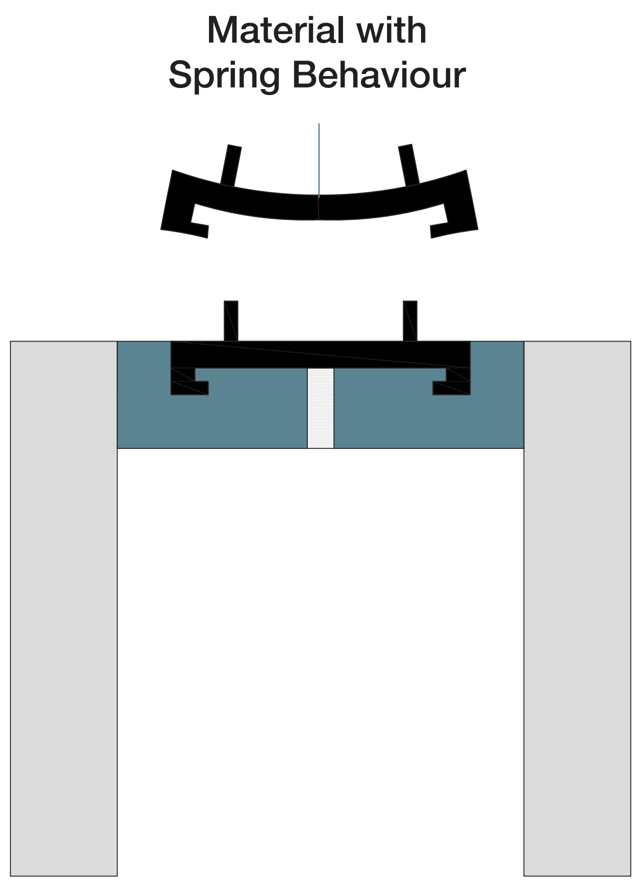
Mirror the Geometry

The connection was initially designed to consist of a circular and a non-circular pat as explained in the previous chapter. This approach made sense since the use of contaminating factors for the glass recycling cannot always be avoided. Moreover, this option gave a greater freedom of design choices in the initial design exploration phase. However, it was found really interesting at this part of the design development to investigate whether this design could be evolved into a fully circular design. This would mean that the use of embedded or adhesively bonded external elements in the float glass part should be completely avoided.

In the process towards a fully circular design the first step was to mirror the circular part of the initial concept and investigate the ways in which a suitable reversible connection could be achieved.



Clamping mechanism



The answer to the question proved to be the materiality of the connecting element. More specifically, a material with a certain flexibility and a spring-like behaviour could act as a mechanical clamping element locking in the cast glass part of the edge seal ensuring the stability and sealing of the unit.

Addition of coated middle glass pane

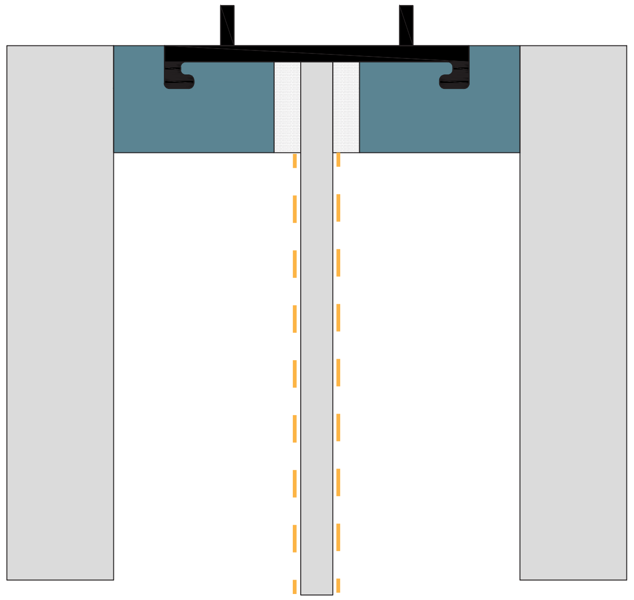
Until the previous steps, the basic principle of the edge seal connection was determined. The next steps focus on the selection of the most suitable materials that comprise the edge seal elements as well as their dimensioning.

At this point, is was found necessary to dimension the glass elements based on the desired thermal performance of the unit. Hand calculations of various combinations of glass and cavity thicknesses were tried out to conclude to a suitable u-value.

These calculations included three different steps; one without any coating application or inert gas filling, one with only one coated glass pane and one with both a coating use and filling of the cavity with argon gas. Finally, an additional calculation to determine whether or not the use of a third middle glass pane is required was conducted.

The best performing result of these calculations, that can be found more analytically in the Appendix A, showed that the best performing combination was that using two float glass panes of 10 mm each and two cavities of 15 mm each that are separated by a thin glass layer of 3 mm that acts as a convective barrier. Finally, a coating application is necessary. For this reason it was decided to apply the coating on the middle thinner glass pane and leave the outer ones contamination-free. This way, the contaminating unavoidable factor is limited to the least material waste by being applied in a significantly thinner glass pane.

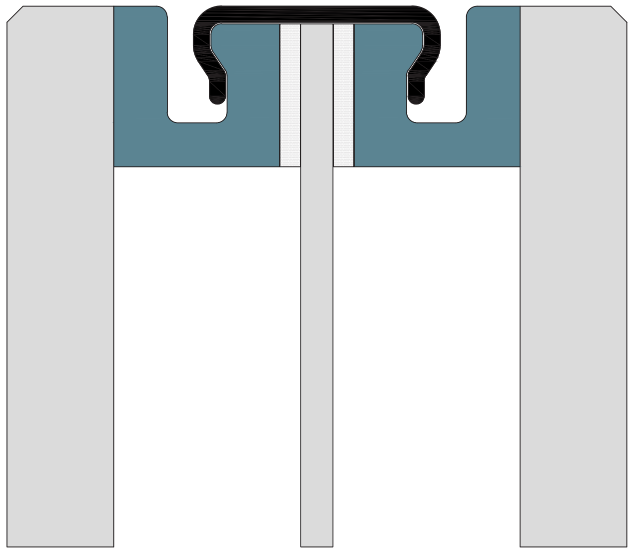
The above used elements lead to a u-vlaue of 1.11 W/m2K which is a value within the desired limits of the set u-value in the design criteria. The use of argon gas filling can further decrease this value to a 0.95 W/m2K but since the improvement of the thermal performance is not so great and the manufacture complexity of introducing an inert gas in the cavity would increase significantly, it was decided that in the scope of this thesis the use of gas filling would be avoided.



Smoothen edges and leave space for tolerances and movements

The next step towards the finalisation of the connection design was the identification of the most suitable materials and their necessary dimensions. For the clamping element a coated metal spring clip of 0.5 mm thickness was chosen which will be analysed in depth in the next sub-chapter.

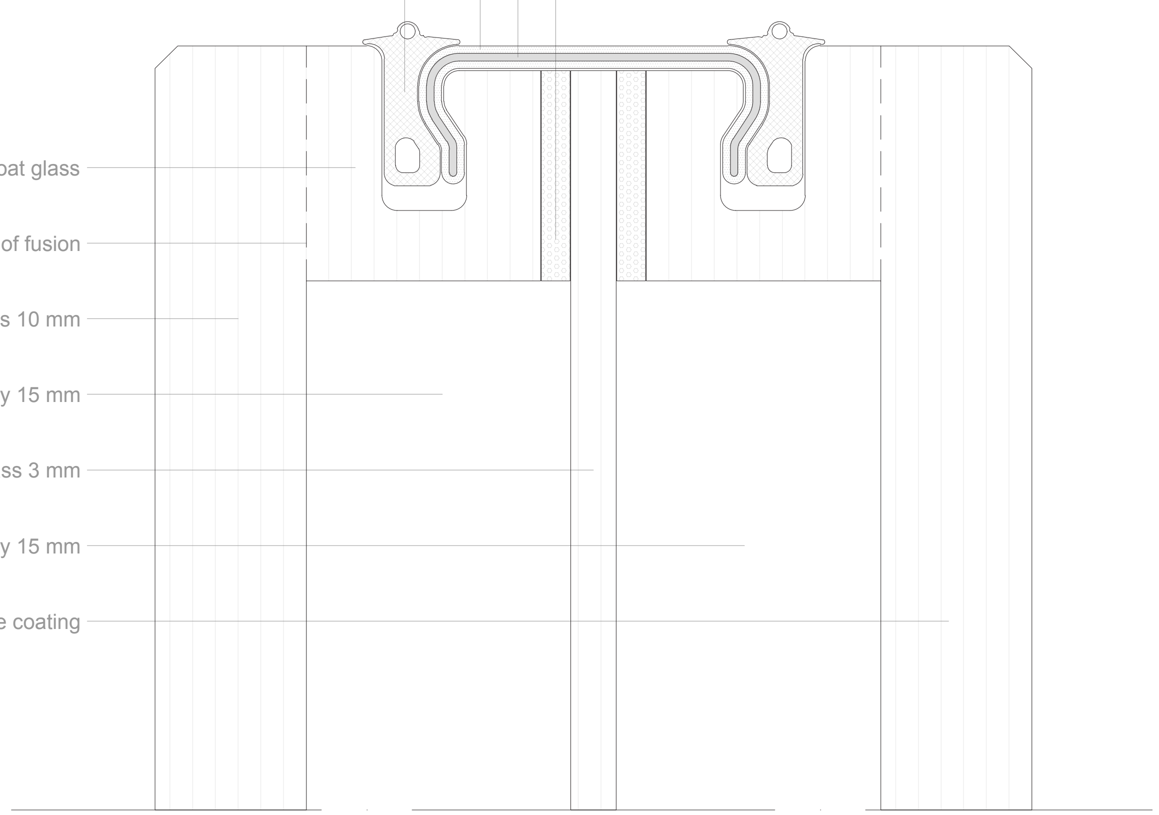
The final step for the realisation of the connection is to take into account the necessary spaces for the tolerances of the construction and for the movements that will occur during the service life of the IGU.



6.2 Materials and Manufacturing

Vertical Section

Scale 2:1



Glass

The design of the new connection of the edge seal is based on the fusion of linear pieces of extruded glass elements to the edges of the float glass panes. Since float glass can be produced in a variety of sizes th scope of this thesis will focus on panel sizes of 3.5 * to 1.5 m that are suitable for application in fully glazed facades where the IGUs used usually span one floor height.

Float Glass

The float glass panes are produced with the float glass process described in depth in the literature review part. The glass recipe used is soda-lime glass since it is the most commonly used recipe in the float glass process and the most cost effective one in general.

During the manufacturing procedure the raw materials are meted in a furnace in a temperature of 1300-1600 ^oC. The next step is the float of the melted mixture on a molten bath of tin at a lower temperature of around 1100 ^oC so that the glass is spread and the desired continuous flat surface of is achieved. The thickness calculated based on the desired thermal performance of the unit is 10 mm although different thicknesses can also be used if found necessary. Finally, the glass sheet is in a state of a continuous glass sheet passes gradually through an annealing lehr of 600 ^oC temperature so that it can cool gradually.

Float glass will come out of the annealing lehr in the form of a continuous ribbon of 10 mm thick, therefore it will need to be cut in dimensions of 3.5 m * 1.5 m. Afterwards it undergoes an edge working process where the rough cut edges are grinded in edge mitres of 45° and polished so that their surface defects are smoothened. This process is crucial since it avoids the risk of cracks and breakage that are is probable with sharp edges. Finally, for safety reasons, the already cut and edge worked glass pane is fully tempered so that in case of breakage it fractures in small pieces making it a safer option for injury prevention especially since it is meant to be applied to a fully glazed facade. The point where the tempering occurs in the assembly order is dependent on the glass to glass bonding and will be further analysed in the next section. For enhanced safety the use of lamination could occur although that would compromise the recyclability of the pane. More on the subject of safety can be found in chapter 7.8 “Safety Analysis”.

Extruded Glass

Glass extrusion is a feasible manufacturing method of glass elements although its use is not very common in the building industry. It has many similarities to the extrusion of metal and plastics and constitutes a simple way of producing tubes and rods of a variety of different shapes and cross-sections. The company SCHOTT AG is currently the principal manufacturer of extruded glass profiles in lengths up to 10 m.

According to (Roeder, 1971), in direct glass extrusion a quantity of material contained in a cylinder is subjected to pressure by a plunger or punch, which forces it through the relatively small aperture of a die. The material is heated before extrusion to increase its plasticity. The profile of the bars extruded in this way is determined by the shape of the die aperture.

It is essential that the glass recipe used for the extruded glass is also soda-lime for the following reasons. Firstly, other glass recipes have different thermal expansion coefficients therefore in the case of fusing together glass made of different recipes fracture is very probable. Moreover, after fusion the different glass elements will behave as one, hence, for the recycling of glass separation will not be possible and the combination of different glass recipes can hinder the recyclability of the component.

As stated by (Roeder, 1971), during glass extrusion a crucial aspect is its viscosity which is determined by the temperature to which the glass is heated. Looking at the viscosity-temperature curve of soda-lime glass (Appendix B), and considering that extrusion is normally carried out at viscosities between 10^5 and 10^7 $Ns/m^{2,}$ it is concluded that a temperature of 700-800 ^oC is adequate.

Glass to Glass Bonding

The final step towards the preparation of the glass elements to be assembled into the IGU is to ensure a connection of the float glass pane with the extruded glass edges. In order to avoid glass contamination, the options of using a colourless adhesive or the use of an intermediate layer to create lamination are discarded since they would cancel out the aim of this thesis. Therefore, for an edge seal of maximised transparency the permanent connection via heat bonding was opted for. Glass heat bonding requires the application of high temperatures that melt regionally the glass elements and allow them to be fused in one monolithic component.

Like glass extrusion, heat bonding of glass elements is a procedure not commonly found in the building construction applications. Nevertheless, its use in other fields like art projects and in the production of laboratory equipment as well as the research already conducted on the subject has shown the feasibility of this method which constitutes an alternative method of permanently bonding glass elements without the use of additional components that compromise its inherent transparency. Moreover, this method can constitute an alternative to the colourless adhesives that are currently used to bond glass structures in the most transparent way but in doing so render the glass non-recyclable due to heavy contamination.

Two alternative heat bonding options could be used here. The first is welding glass and is based on a technique of locally heating pieces of glass and bonding them together as described by Eskes, A. (2018). It is a procedure very similar to that of steel welding where the material is heated to a level where it is workable. Previous research by (Giezen 2008) and (Belis et al. 2006) has proven the feasibility of glass welding in soda-lime glass and has concluded to a very important boundary condition which is the need of an annealing oven to reduce the risk of thermal shock failure after the bond has been made.

For this specific reason, the welded system is limited by the size of the oven. In 2008, the maximum oven used in industrial glass production processes has an order of magnitude of 2,5 by 1,5 by 2 meter (Giezen 2008). Having in mind that this thesis aims to create an IGU for facade applications that spans a floor height in dimensions of 3.5 m * 1.5 m it is safe to say that oven for this size can be manufactured. Moreover, since the potential of this method is great for a wider use in building applications in the recent future bigger sizes could be manufactured. Therefore, in the scope of this thesis the annealing oven size will not be considered a limiting parameter.

The second alternative of heat bonding is via tack fusing whose potential and feasibility has been described by Van Der Velden (2020). Tack fusion requires lower temperatures than welding, thus saving energy. Moreover, although welding might produce a stronger and more homogeneous bond between the glass surfaces, for the application of this connection design, the strength of tack fusion is considered adequate. Tack fusion tests by Van Der Velden (2020) resulted in a strength around half of the structural DELO 4468 adhesive. As stated by Van Der Velden (2020), fusing occurs around the so-called dilatometric softening point which according to tests is approximately at 650°C. This temperature is essential for the success of the fusion so that the glasses are bonded without losing their shape.

The following process of tack fusion is proposed. The float glass pane is located into an oven. The extruded elements are placed in the right positions vertically to the float panel and are held up by a support in a distance from the float pane. The oven is heated up to a temperature of 500-600 °C. Once the glass has been heated a mold press is used to apply pressure on the extruded elements towards the float glass so that the bonding can occur. Once the bonding is ensured, the elements are left in the annealing oven for gradual cooling. An important aspect to consider here is that because of the high temperatures and the hole in the geometry of the extruded glass there is a sagging danger. In order for this to be avoided, an also extruded element made of a heat-proof material is placed inside this hole to ensure the geometry remains intact. Moreover, some supports at the sides might also be needed to make sure the extruded glass is not squeazed out at the sides.

While the tack fusion procedure as described before is very promising for all the aforementioned reasons there is still a matter that requires attention. Currently, there are no application of this bonding method to float glass that has been heat strengthened or fully tempered. Hence, there are concerns about the impact the high temperature of the fusion process might have on the performance of the heat treated glass. To tackle this potential issue, two alternative options are given. Firstly, we could argue that the fusion occurs before the heat treatment and once the elements have been bonded and cooled they are subjected to the heat treatment process as a whole. This method could in theory work but until tested no warranty of its feasibility can be given.

The second alternative option requires the use of an additional element for the glass to glass bond. In this scenario the glass is heat treated on its own before any bonding occurs. Then a clear silicone element developed by DOW CORNING company to be used as transparent spacer is introduced between the glass surfaces. This element is very transparent and with the use of a specific primer it ensures good adhesion to the glass surface in a quick and easy way. Moreover, the product can be easily removed with the application of force leaving behind no contaminating elements. However, due to the fact that this element has a significant thickness, an adjustment in the dimensions of the elements would need to occur in this case.

Finally, it is very important to highlight here that the specific design is highly based on the use of the aforementioned methods of extruding linear glass of the desired cross-sections and connecting them with the application of a heat bonding technique to a float glass surface. While the float glass manufacturing method is a well-proven and widely used technique, the other two are still in a more research-based level. This is because their use has not been essential so far in the building industry although their feasibility has already been proven. Therefore, for the feasibility and success of this specific design to be ensured test regarding these two techniques should me made. Moreover, float glass is currently the most economical way to produce glass for the built environment. The impact of the implementation of these techniques on the price of the final IGU is still unknown. Finally, regarding the sustainability of the design it is important to mention that glass welding requires energy which should be taken into account when judging the whole sustainable character of the design.

Metal Spring Clip

The element designed to perform the role of the clamping mechanism that locks into the geometry of the cast glass element and hold the panels together is a metal spring clip.

According to Machine Design (2022), typical spring clips consist of a self-retaining fastening method that holds an element in place using the spring tension, eliminating the need for secondary fastening elements such as screws and rivets. They are made in one-piece elements that can fit into a hole or they can be placed at the edge of a panel to hold it in place. Spring clips remain static under load and the spring tension does not allow for loosening through vibration. Moreover, they can accommodate tolerances.

Metal spring clips can be fabricated from full spring tempered material or high carbon spring steel such as:

- 301/302/316 spring tempered stainless steel
- 17-7 condition C stainless steel
- 1075/1095 tempered carbon steel
- Spring brass
- Spring tempered phosphor bronze
- Beryllium copper
- 050/1074 high carbon annealed material

The basic spring-clip material is steel with 0.50 to 0.80% carbon with a hardening to Rockwell C 45-50. Varied spring tensions are obtained by controlling the width and thickness of the steel.

Spring tempered stainless steel is selected for the specific application since it is corrosion resistant in contrast to high carbon steel. Typical thicknesses of spring clips are 0.25 - 2 mm as stated by Springfield Spring & Stamping (2022).Therefore, a thickness of 0.5 mm is found suitable for this case.

According to Wermke Spring Manufacturing Co. (2022), an important aspect to consider when designing metal spiring clips is to keep the number of radii to a minimum and to design each radius as broad as possible. This approach helps prevent stress concentrations in the places where the element bends that could lead to material failure. For this reason the curvature of the geometry of the clip is as smooth as possible with only one curve.

Finally, after its shaping, the material needs to go through a post-hardening and tempering process to acquire a spring-tempered state. Heat-treating and quenching processes allow the material to reach the desired hardness level while being able to flex without deforming permanently.

For the clips fabrication procedure two options are possible. They can either be extruded in the required length or roll formed and bent into shape using a metal break. Moreover, since the application of one continuous element could result in assembly difficulties, it is chosen to fabricate and use more clips of smaller lengths one next to the other. In terms of the dimensions of both the thickness and the length of the spring clip only an approximation can be given at this stage, tests would need to be made to ensure their effectiveness.

Clip Coating

When applying mechanical connections in a glass component it is essential for smooth stress distribution in the brittle glass to avoid direct contact of glass with glass and of glass with other hard materials such as metal. Hence, in order to ensure an even load transition between the connections and the glass a suitable intermediate layer needs to be applied. The stiffness of the material is crucial, therefore, the material should possess a young's modulus smaller or similar to that of glass. Moreover, in order to satisfactorily transfer forces, the interlayer should have adequate strength which means that materials with high compressive strength are preferred. Finally, the interlayer has to be durable to withstand corrosion and thermal shock. Plastic, resins, neoprene, injection mortars, aluminium or fibrous gaskets have properties that make them satisfactory interlayer materials for glass structural connections. Since the material used for the spring clip is made out of hard metal and clamps into a cast glass element the use of such an interlayer is crucial.

As stated by RS Components Ltd. (2022), it is quite often for spring steel clips to be covered in protective coatings made from vinyl and neoprene to minimise abrasion damage to the elements they get in contact with. A common and cost effective way to apply protective coatings on spring clips is by dip coating. According to Midwest Rubber Co.(2022), in the dip coating process, the clip is dipped into a coating material and fused to "set" the coating, ensuring it adheres to the metal part it's covering. Dip coating can occur in thicknesses of 0.5 mm to 6.35 mm are achievable, depending on the application.

The material chosen here for the metal clip coating is black coloured neoprene, a polychloroprene rubber. Neoprene is commonly found in many construction applications such as bridge bearings and structural connections.The reasons that constitute neoprene a suitable interlayer coating material are its flexibility which allows for greater elongation and the uniformity of the wall thickness. Moreover, neoprene is resistant to tearing, it is a durable material that requires minimised maintenance and possesses great dampening properties which is ideal for abrorptsion of vibrations and building movements. For these reasons its use is so appealing in in long-term constructions as stated by Dimas (2020).

Desiccant

As mentioned in the literature review, a desiccant integration in the edge seal is of the utmost importance for the longterm service life of the IGU since it absorbs any trapped-inside the cavity moisture during the assembly of he unit.

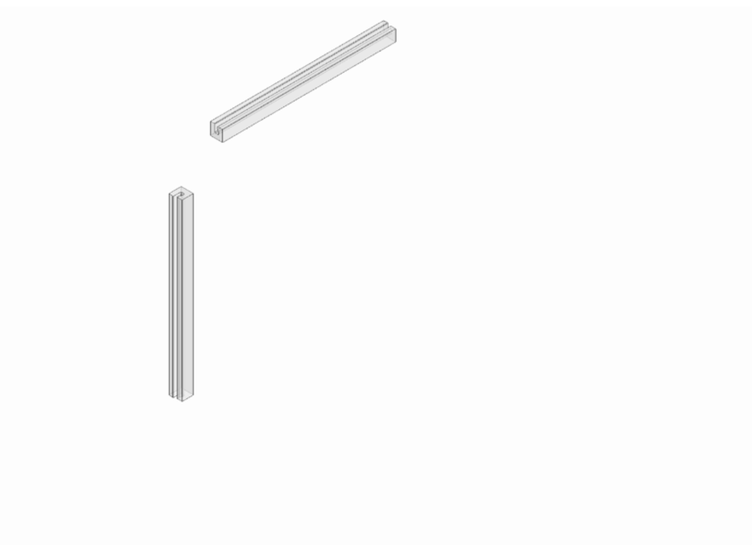
Studying and assessing, during the literature review, the alternative ways in which desiccant is used in current IGUs led to the conclusion that the most suitable option for this design both regarding the reversibility and the transparency of the edge seal is to use a silicone desiccated foam. These foams are a type of currently used warm-edge spacers made out of a desiccated foam with an integrated moisture barrier film. The great advantage of using this type of material is that in one single element three necessary functions are fulfilled. These functions are the requirement of a moisture barrier and a desiccant, both integrated in the same material. Moreover, the flexibility and low thermal conductivity of this desiccated foam constitutes it an ideal interlayer material to avoid glass to glass direct contact, accommodate the movements of the panel and avoid the creation of thermal bridges at the edge seal.

Finally, the indispensable integration of a desiccant in the IGU assembly is a factor that greatly impacts its edge seal transparency since it consists of a visible element that cannot be avoided.

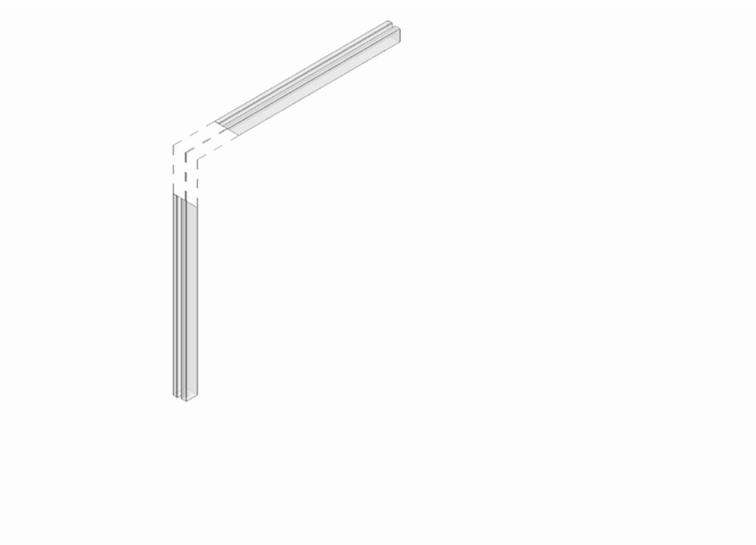
Metal Foil

As mentioned in the literature review, apart from the PIB moisture barrier, that on this case is integrated in the desiccated foam discussed above, the presence of a metal foil is also necessary for the moisture and air impermeability of the edge seal. For this reason an aluminum tape of 0.08 mm thickness is applied all around the perimeter of the edge seal.

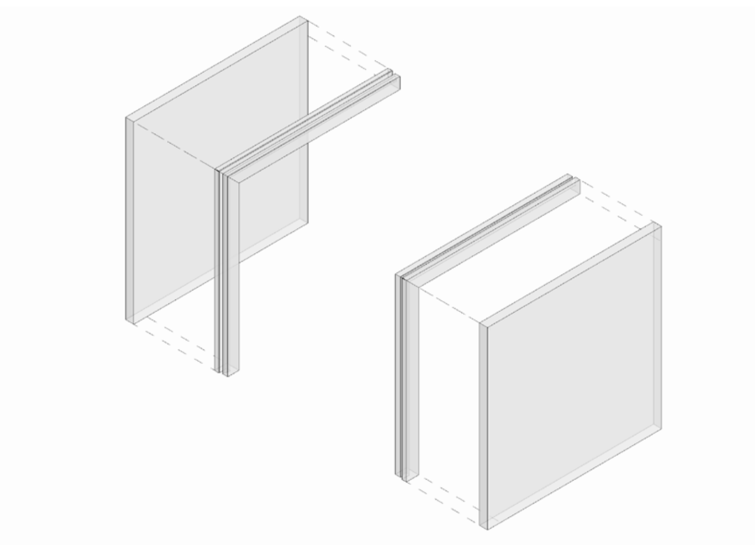
6.3 Assembly Order



1. Extrusion of glass cross-sections

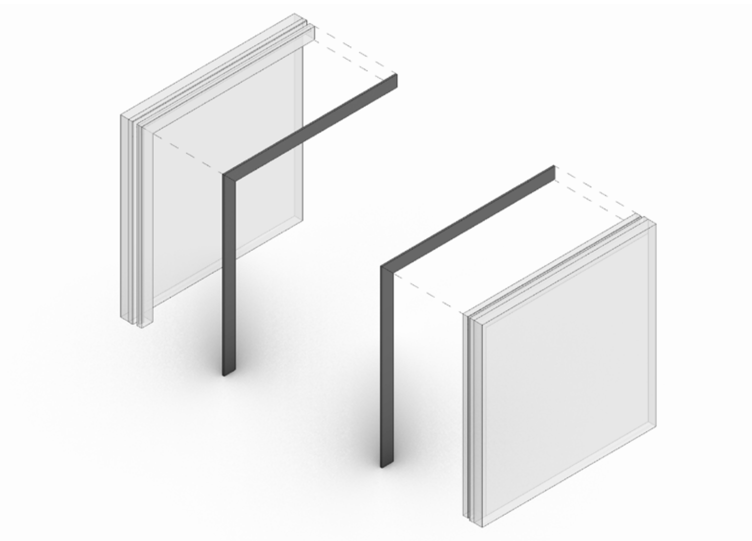


2. Cut extruded glass edges at 45 degrees

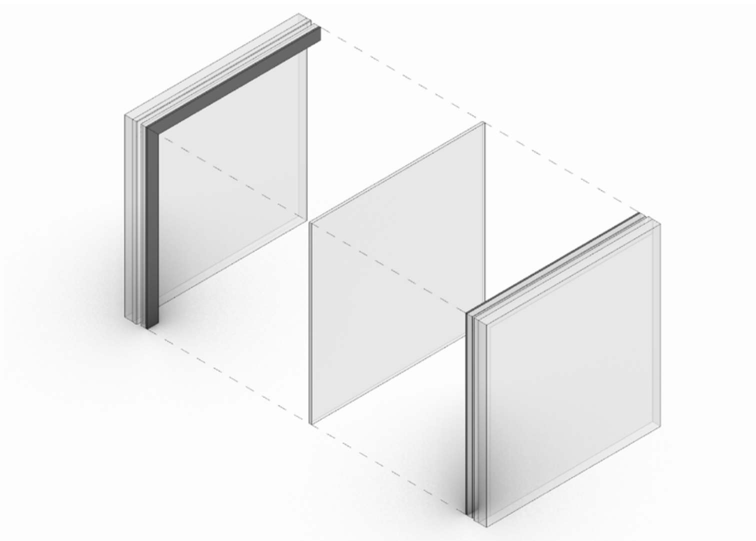


3. Fusion of extruded glass to float glass surfaces and fully tempering of the whole glass element

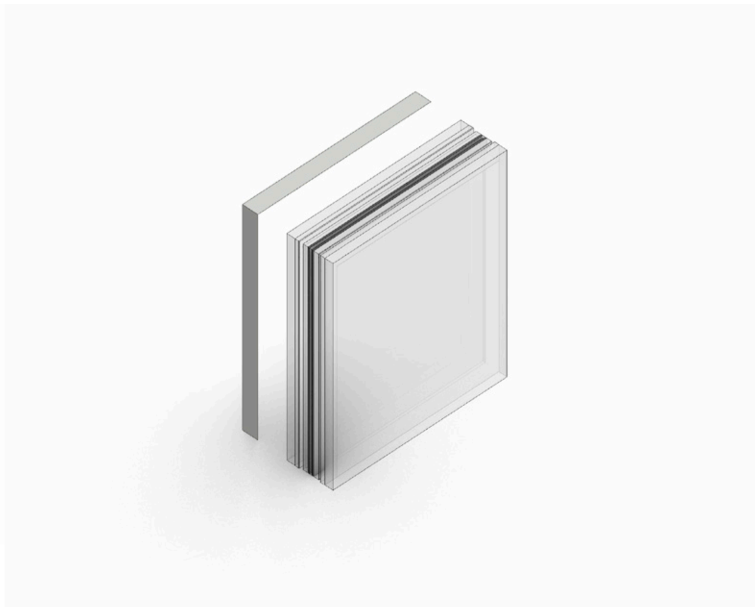
The assembly order consists of nine different steps. The first three steps which are associated with the manufacturing of the glass elements has already been analysed in the previous section. To summarise, the glass pane surfaces are produced by the standard float glass method. The linear glass elements of the edge seal connection are extruded in the appropriate lengths. Finally, heat bonding of the different glass elements occurs using the tack fusion method.



4. Application of silicone foam with integrated desiccant

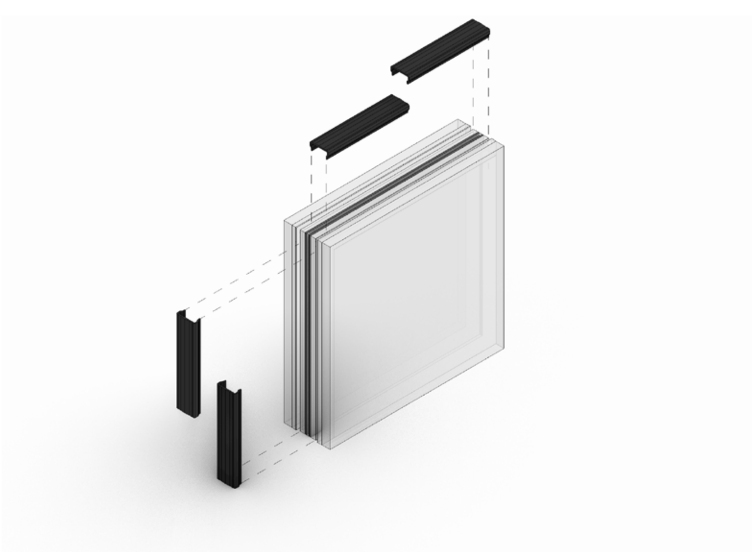


5. Addition of a coated third glass pane



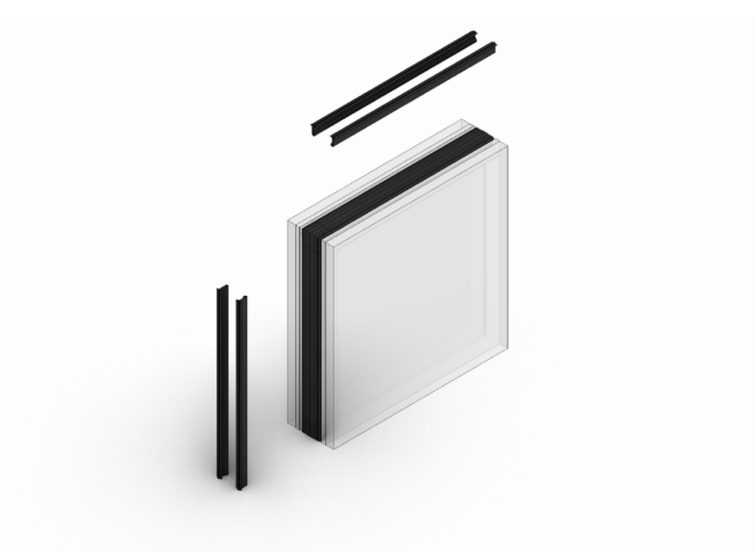
6. Application of aluminum tape around edge seal

The following steps are associated with the application of the necessary elements of the proper sealing of the unit. Firstly, a desiccated silicone foam with an integrated PIB moisture barrier layer is applied around the perimeter of the edge seal. Before the seal of the unit, a coated middle pane is added and the three different components are brought together. An aluminum tape is applied around the edge seal acting as an additional moisture prevention layer.



7. Application of spring clips

8. Fixing of corner pieces

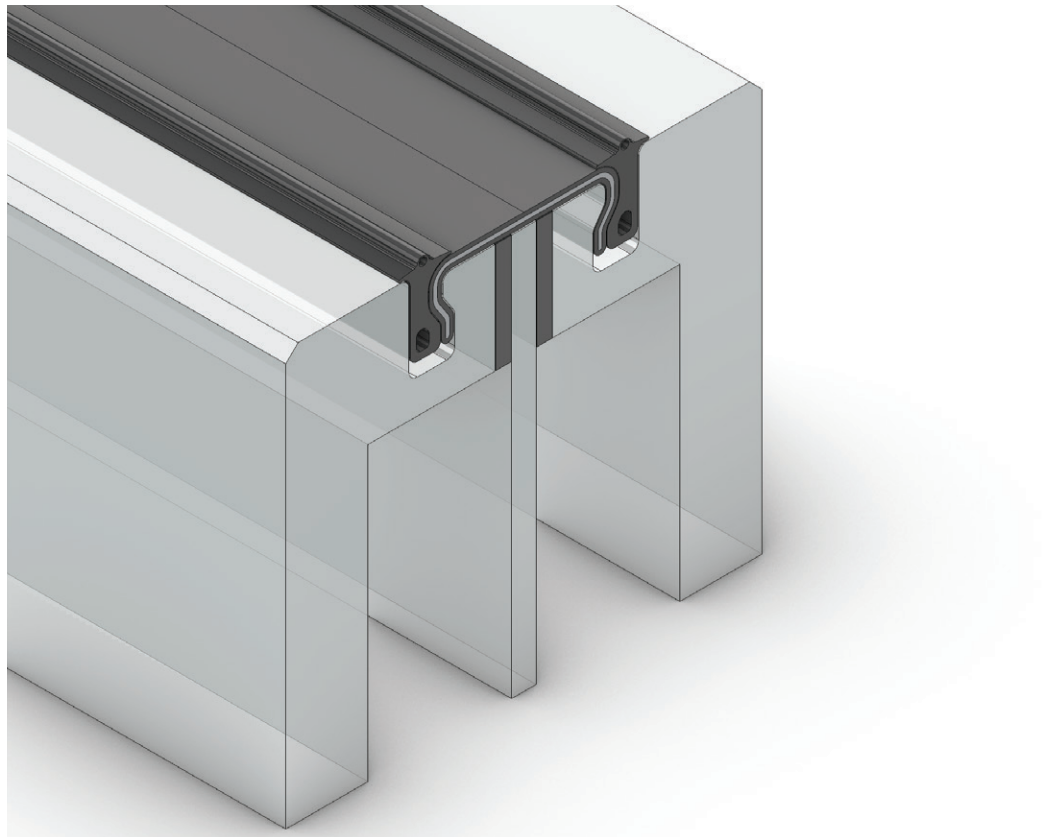


9. Application of neoprene gaskets

The last part of the assembly order consists of the application of elements that ensure the connection. Therefore, the coated metal spring clips are applied in broken down to smaller pieces for easier application. Furthermore, corner piece elements are fixed. Finally, neoprene gaskets can be also applied is desired as a way to avoid water and dist accumulation in the slots of the seal although even if this happened it would pose no threat to the functionality of the cavity.

6.4 End of Life

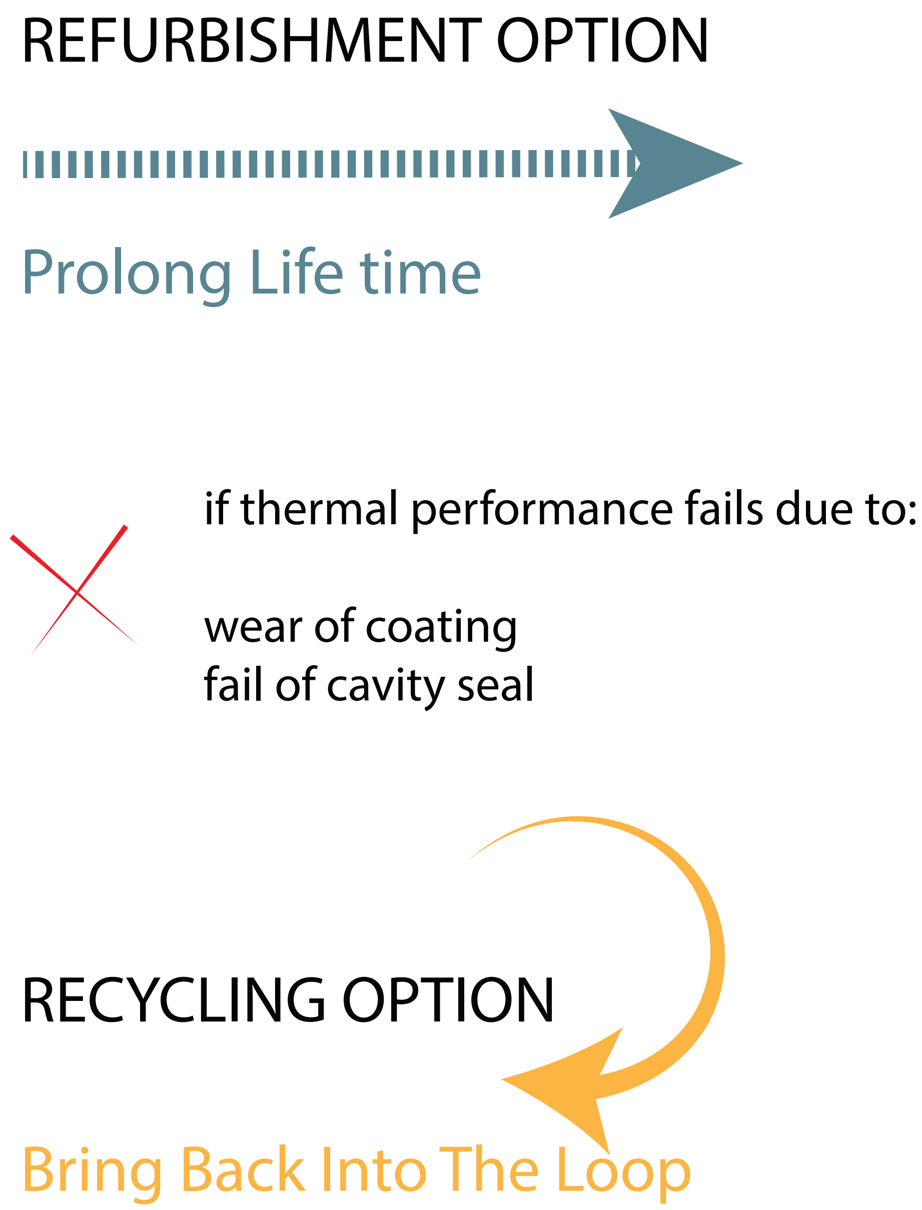
The disassembly process of the unit is the exact reverse of the one used during the assembly. First the gaskets are taken out followed by a removal of the coated spring clips. Afterwards, the aluminum tape is peeled off and the panes pulled apart to be separated. The desiccated foam is subsequently removed with the application of a small force. The glass panes are then left without any additional element apart maybe from small traces from the adhesion of the aluminum tape and the desiccated foam that can be easily removed.



Once the unit has been disassembled there are two possible scenarios. Either the unit will be resealed to be used again as new or, if that option is not desirable, the edge seal components will be discarded to waste and the glass panes that are without contamination will be recycled.

The first option is the most desirable since it is essentially a sustainable refurbishment procedure that does not require significant amounts of additional energy. During this process, the condition of each individual element will be inspected and its potential for reuse will be assessed. It is anticipated that the elements of the edge seal will be discarded due to failure although the lifespan of these elements would need to be seen on practice. Moreover, the glass pane that carries the coating will also be assessed regarding its condition. If the coating's performance is found reduced then the pane will be down-cycled (or recycled if possible - in cast glass for example) and replaced by a new one. Finally, the edges will be resealed and the unit will be ready for use again prolonging its life time with the minimal material and energy wasted.

If refurbishment is not desired for any reason, the glass panes that are left without contaminating factors will be recycled as they are. If fusion is indeed used it will have no impact on the reyclability so the different glass parts do not need to be separated but can be recycled as one element. If the bonding uses the clear silicone from DOW a separation of the different glass parts will also occur and each of them will be recycled independently.



07. Facade Application

7.1 Design Criteria for Facade Application

7.2 Choosing a Facade Typology

7.3 Facade Structure Overview

7.4 Vertical Connections

7.5 Horizontal Connections

7.6 Corner Connection

7.7 Assembly Order

7.8 Safety Analysis

7.1 Design Criteria for Facade Application

The product developed in detail in the previous chapters can be applied in all the scenarios the current insulated glass units are applied; from a typical framed window to a fully glazed facade. The aim of the final design of this thesis is the application of the developed IGU in a facade system that exhibits the maximum possible transparency while constituting a fully reversible structure.

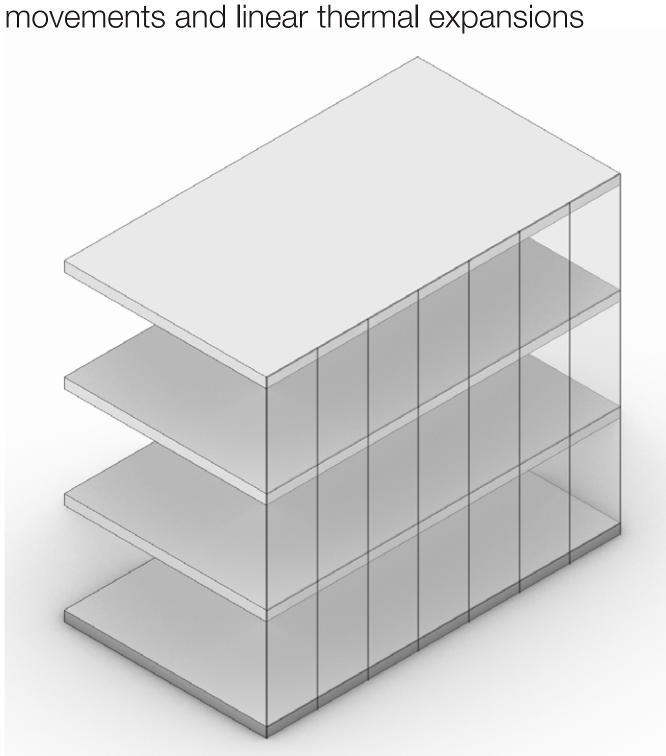
Therefore, the primary design criteria that set the base for the design application are the following. Transparency in terms of frameless vertical joints and optically unobtrusive connecting elements is the first. Equally important is the need for reversibility in the whole facade structure by avoiding the use of structural silicone. The above-mentioned criteria set the basis for the selection of the facade typology and the structural substructure system that will be used.

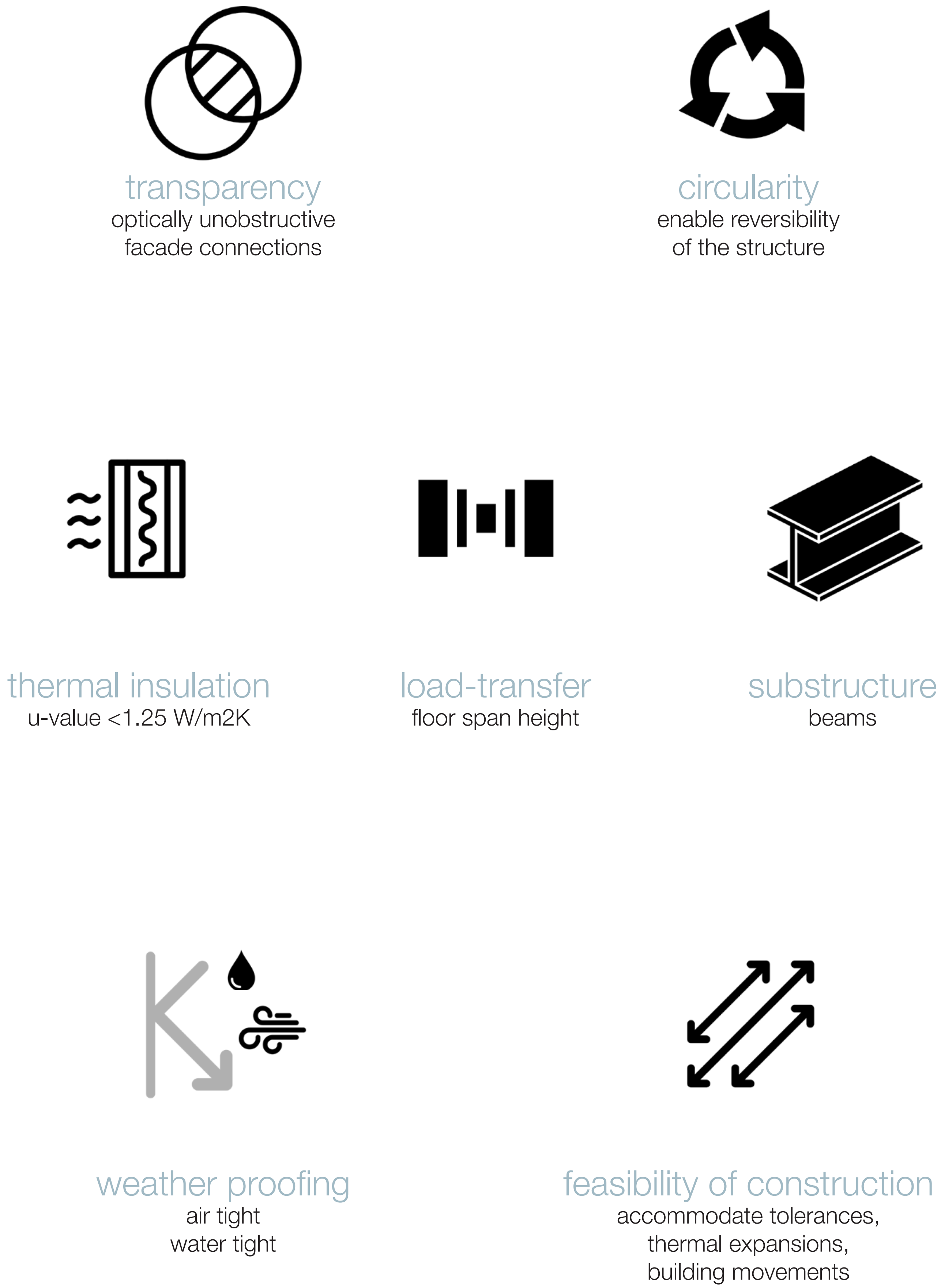
Moreover, in order for the design to be feasible in terms of construction and fulfil all the requirements of a facade system some base guidelines need to be set as well. These regard mainly the thermal and structural performance of the facade as well as its proper weather sealing and accommodation of tolerances and movements that occur during its life use.

What are the main design criteria for a reversible fully glazed facade system?

Design Criteria

Loads: floor span
Substructure: beams only
Thermal: use of insulated glass units
Optically minimised joints
Reversible structure
Water tightness
Acoustic insulation between floors
Fire resistance
Ease of assembly
Accommodation of tolerances
Accommodation of building movements and linear thermal expansions



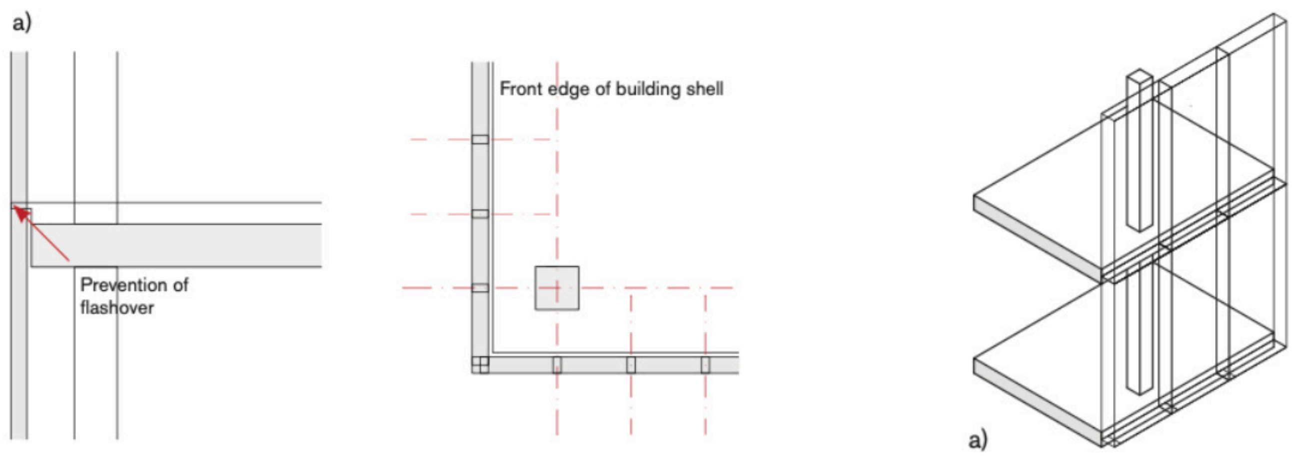


7.2 Choosing a Facade Typology

The facade is the skin of the building, the element that separates and protects the inner space from the external environmental conditions while shaping, to a great extent, the architectural expression of the building. More specifically, a facade is a very complex mechanism that serves the following functions. In terms of building physics properties, it insulates from the heat, cold and noise. It protects from rainwater and moisture penetration as well as from wind forces, and it allows for outdoors views and daylight transmission. Moreover, a facade has a structural role as well, whether as part of the load-bearing structure of the building or as a means to transfer the wind-driven forces and its own weight to the primary structure.

Curtain Wall Facades

For maximised transparency a curtain wall facade application is chosen. Curtain walls are the evolution of the classic window, consisting of glass elements with frames (glazing beads) that are mounted into the solid part of the facade, to construction that facilitates the application of larger areas of glass and consists of special, patented glazing bars mounted on the supporting construction. In this case, the facade can have a uniform transparent appearance and it is separated from the solid load-bearing part of the building.



Curtain Wall Substructures

Different kind of substructures can be used in curtain wall facades, each with a different effect on the transparency of the structure and the load-transfer of the glass's dead load and wind loads to the primary structure.

Post and beam

Post

Beam

Cable mesh structure

For maximised transparency a beam facade structure is chosen in this case.

Curtain Wall Connections

The individual glass panes that comprise a transparent facade must be connected together to ensure the structural stability and water tightness of the building envelope. Glass joints are a crucial part of the facade construction. All the functions that have to be achieved by the individual facade elements should also be found at the joints. The joints of any facade need to be watertight, airtight and soundproof and more specifically in the case of a glass facade, transparency is also a design criterion that is usually taken into consideration in the detailing phase. Nevertheless, the reality of construction has shown that facade joints are weak spots in terms of water tightness, thermal bridges or stress concentrations.

The following typologies of glass facade connections are reviewed in terms of their effect on the transparency and the reversibility of the structure so that the most suitable type can be chosen for the facade application.

Linear Clamping Bar

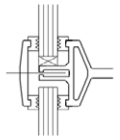
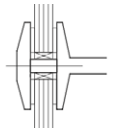
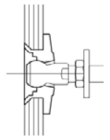
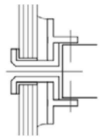
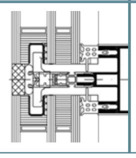
Point Clamps

Point Drilled Fixings

Structural Silicone

Point Mechanical Clamp Fixing

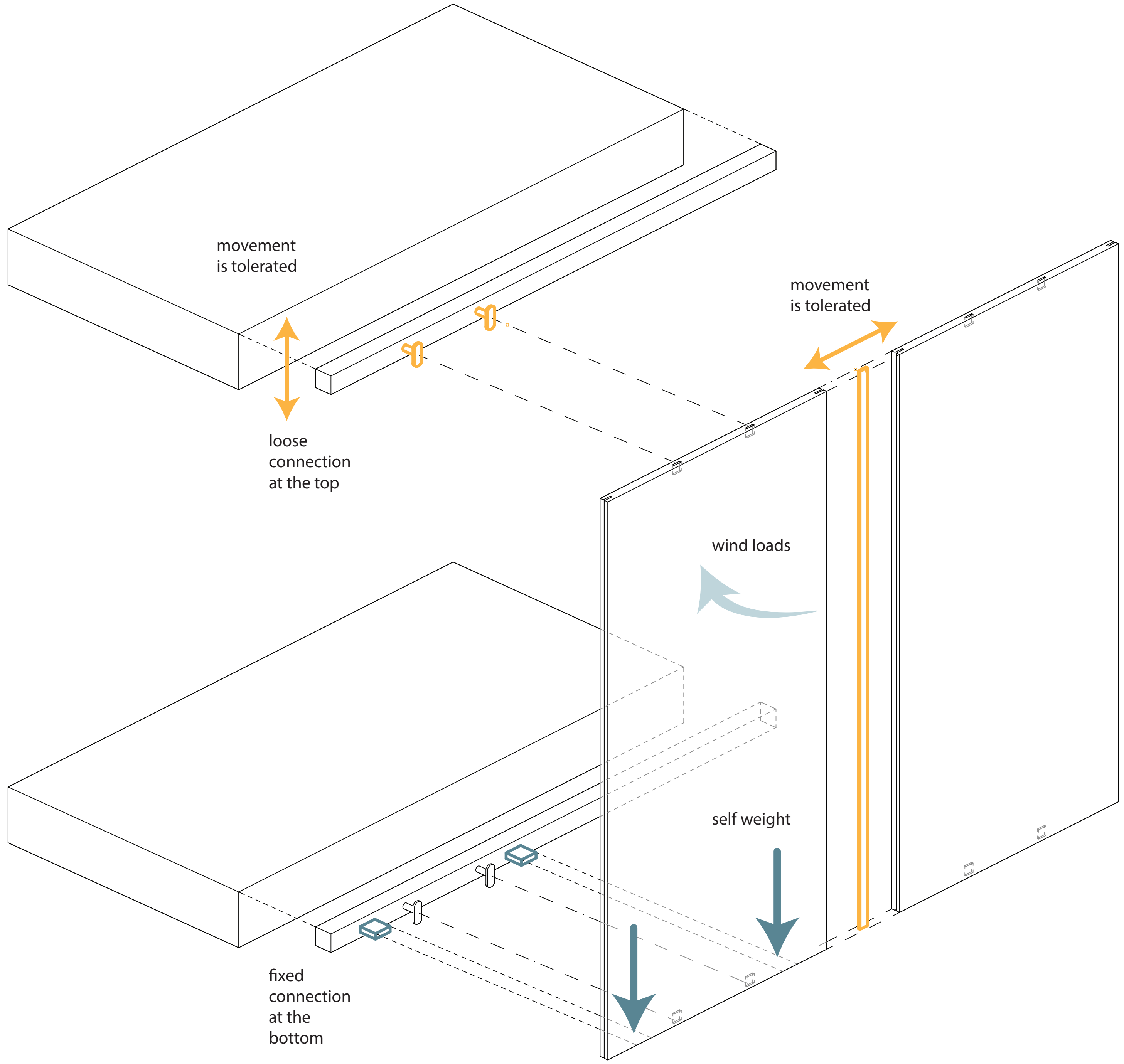
Whenever detailing the fixing points it is important to ensure that movements originating in the primary structure or other components, and also the thermal expansion of metal constructions, can be accommodated without introducing restraint forces. The facade must be attached to its fixings such that adjustment is possible in three directions. Connections, junctions and transitions should be designed in such a way that they remain permanently impervious to air and vapour diffusion.

	Load-transfer	Reversibility	Transparency	Notes
Linear Clamping Bar 	+++	+++	+	Visible Framing
Point Clamping Plates 	++	+++	++	Less visible than linear clamps
Point Drilled Fixings 	++	+++	++	Stress Concentrations, Requires attention at sealing of IGU, Optically Discrete
Structural Silicone 	+++	-	+++	Difficult disassembly, Reversible with glass contamination
Point Mechanical Clamp Fixing 	++	+++	+++	Hidden Fixings Fully Reversible

A mechanical connection of the glass panels to the substructure is chosen with hidden point clamping plates using toggle bar and screw.

7.3 Facade Structure Overview

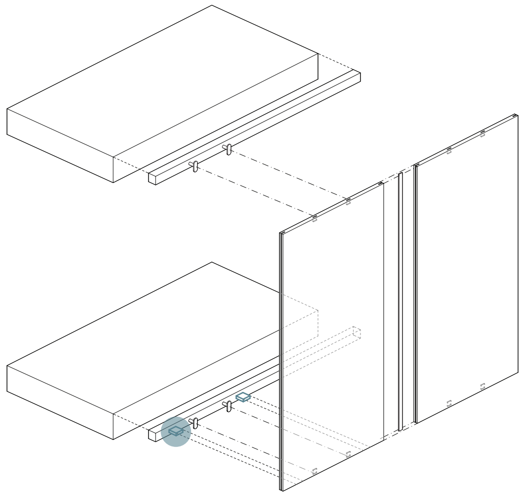
Substructure: Beams
Load Transfer Mechanism: per floor
-> In-plane loads: Supported through support blocks
-> Out-of-plane loads: Supported by point fixing clamping plates

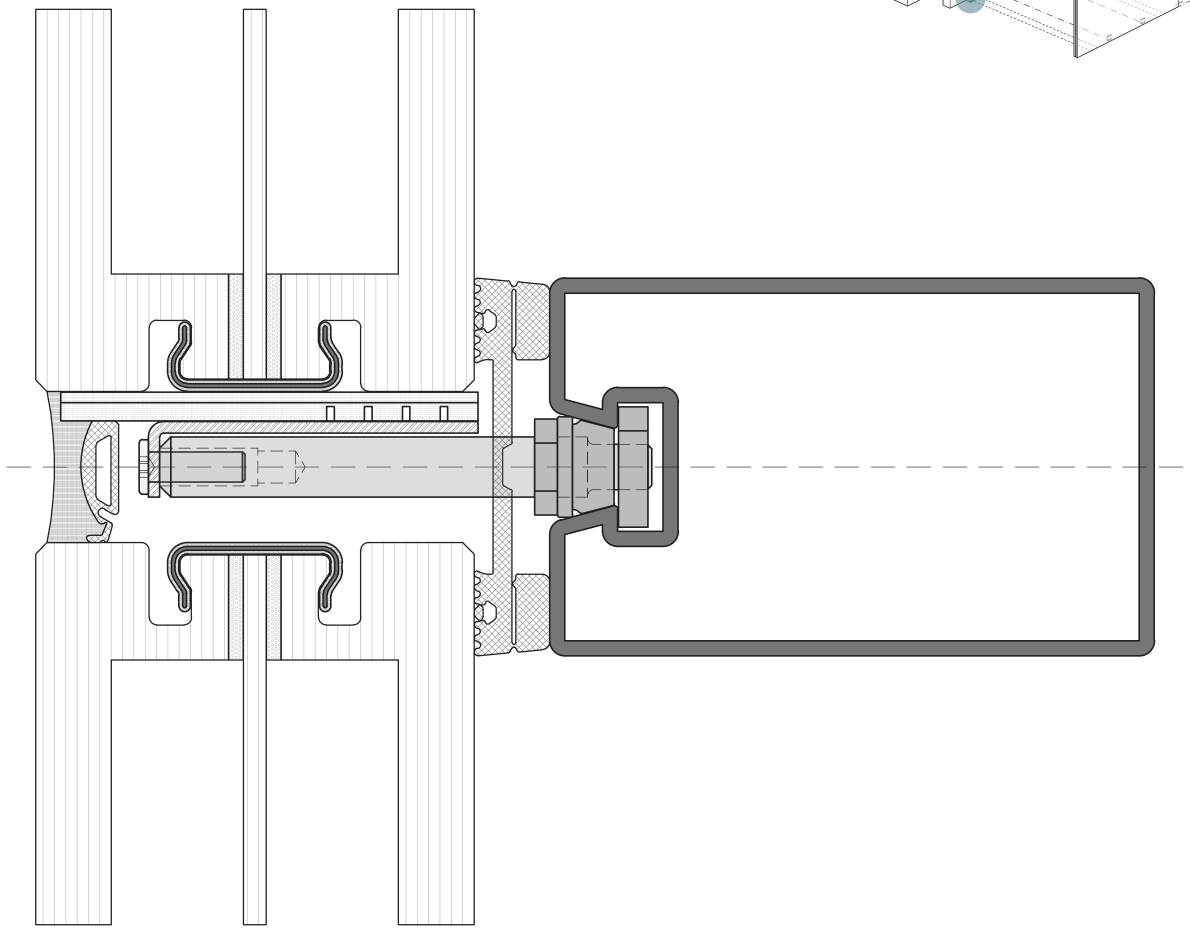


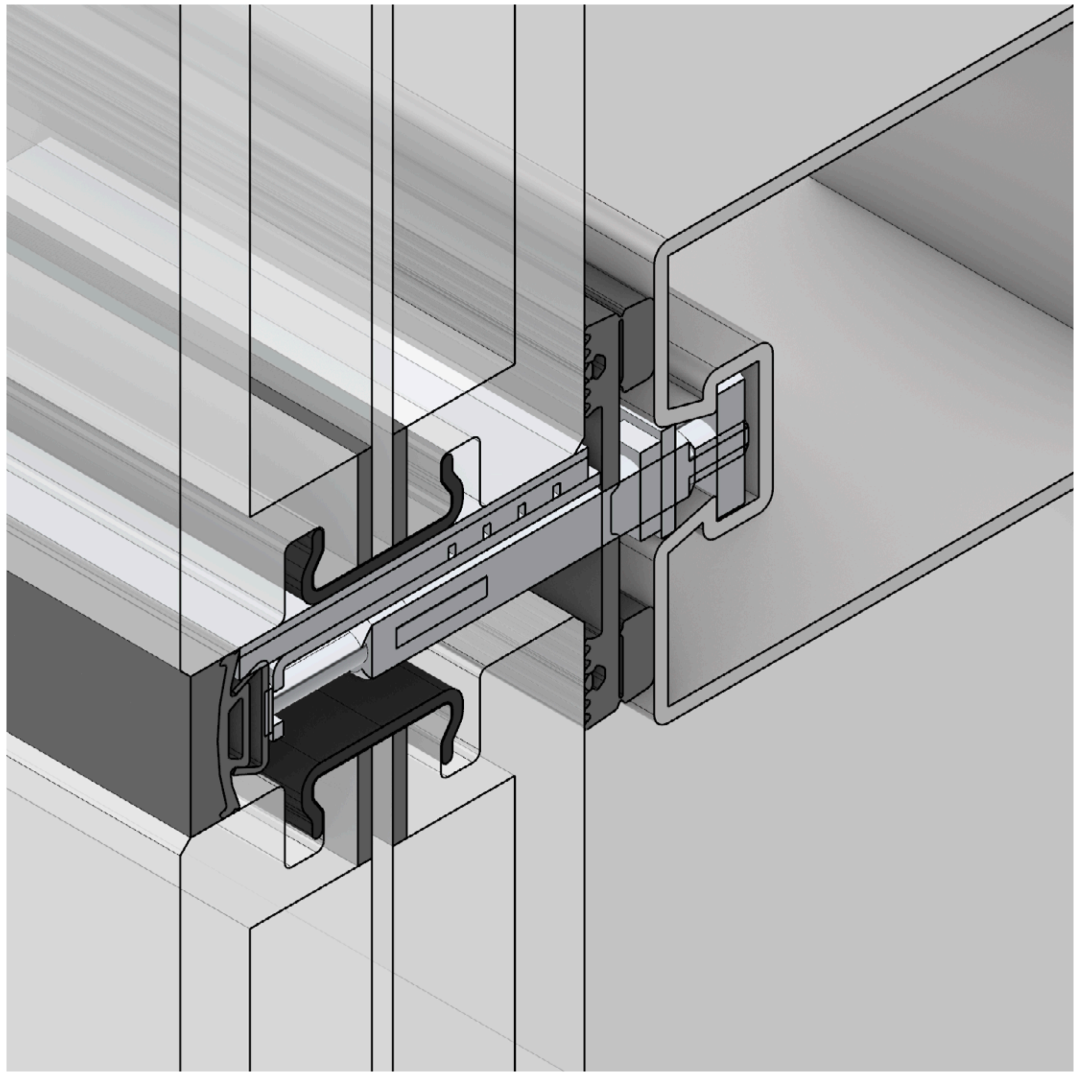
7.4 Vertical Connections

Vertical Section at Facade Support Block

Scale 1:1

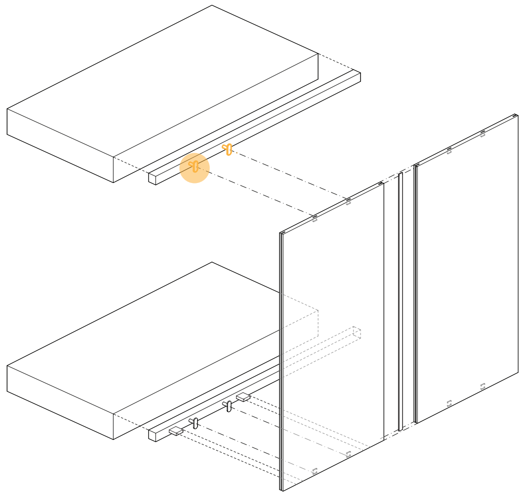


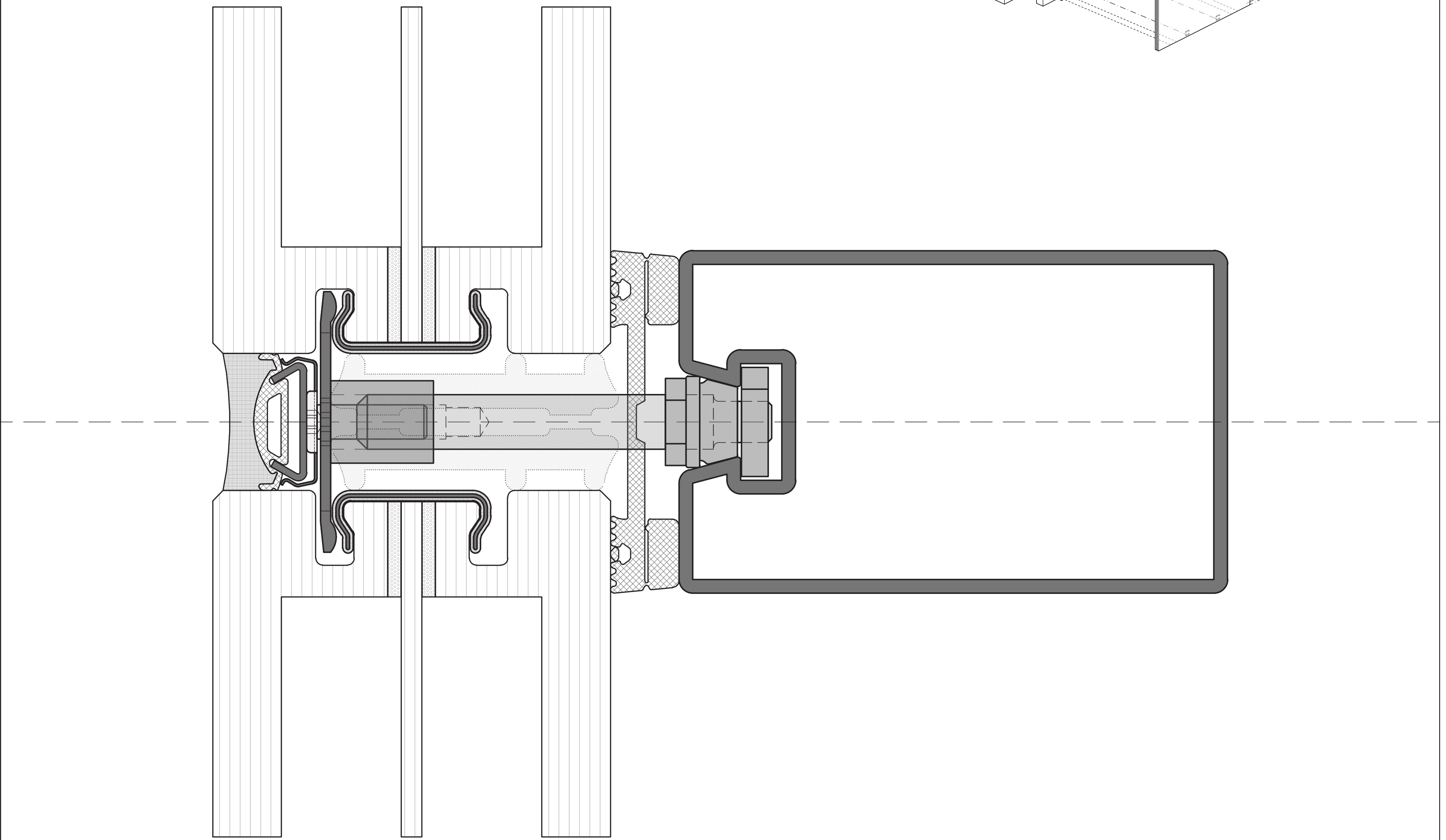


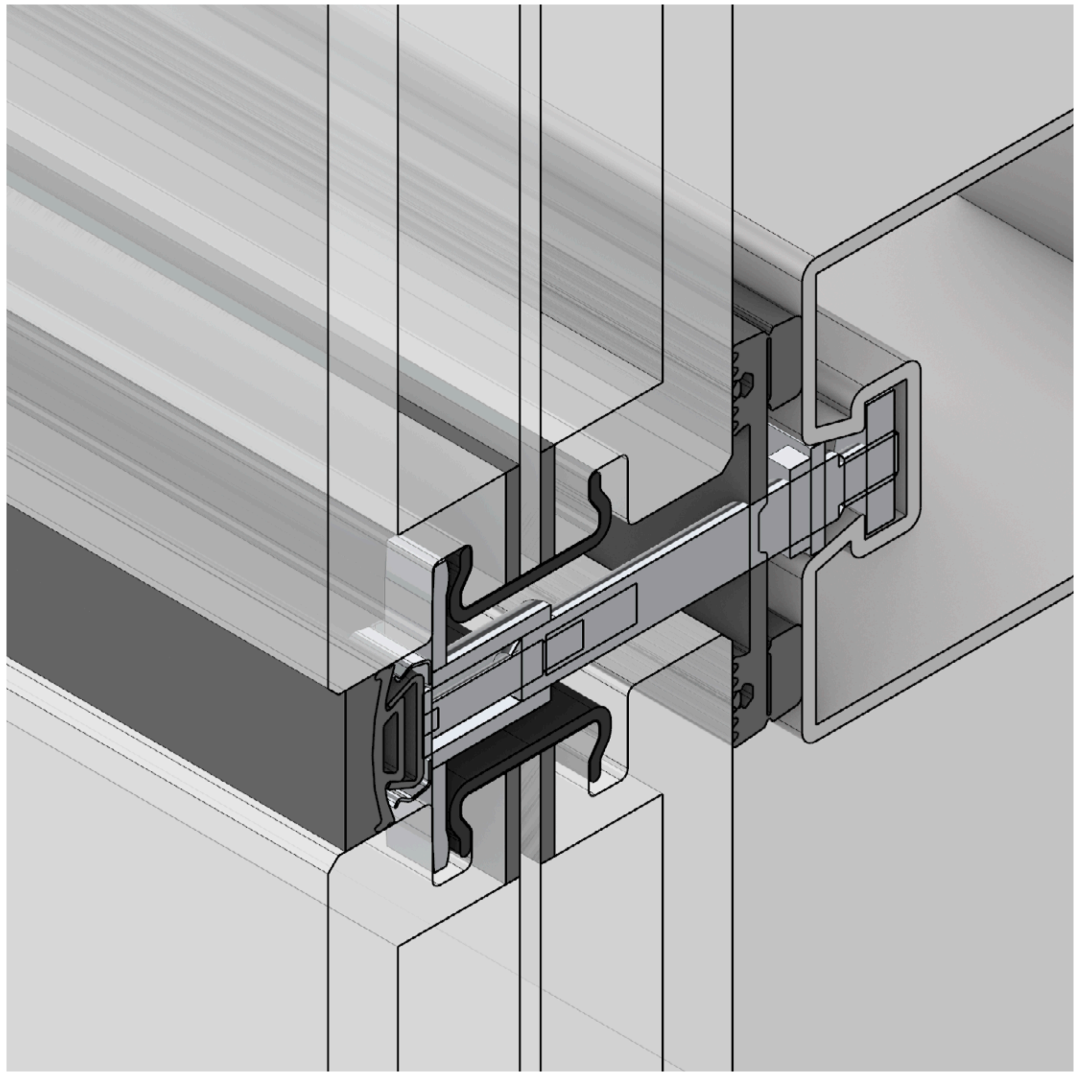


Vertical Section at Clamp Fixing

Scale 1:1



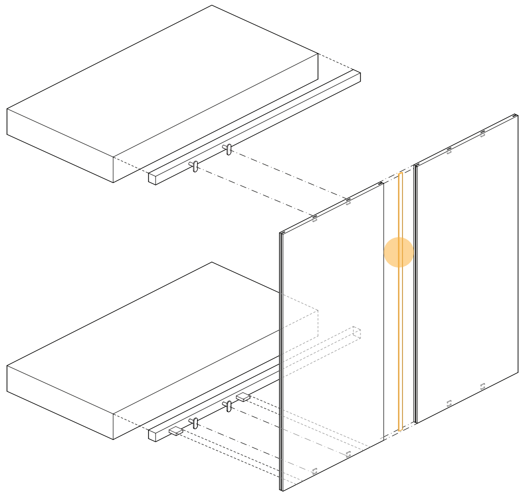


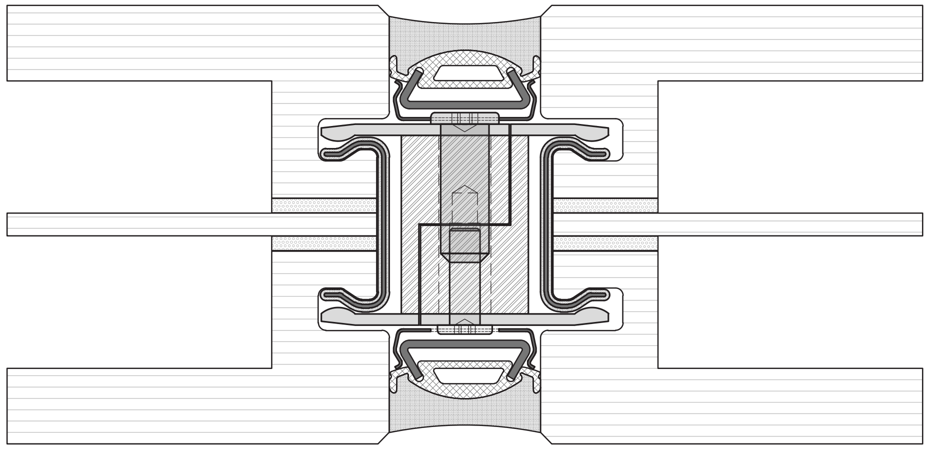


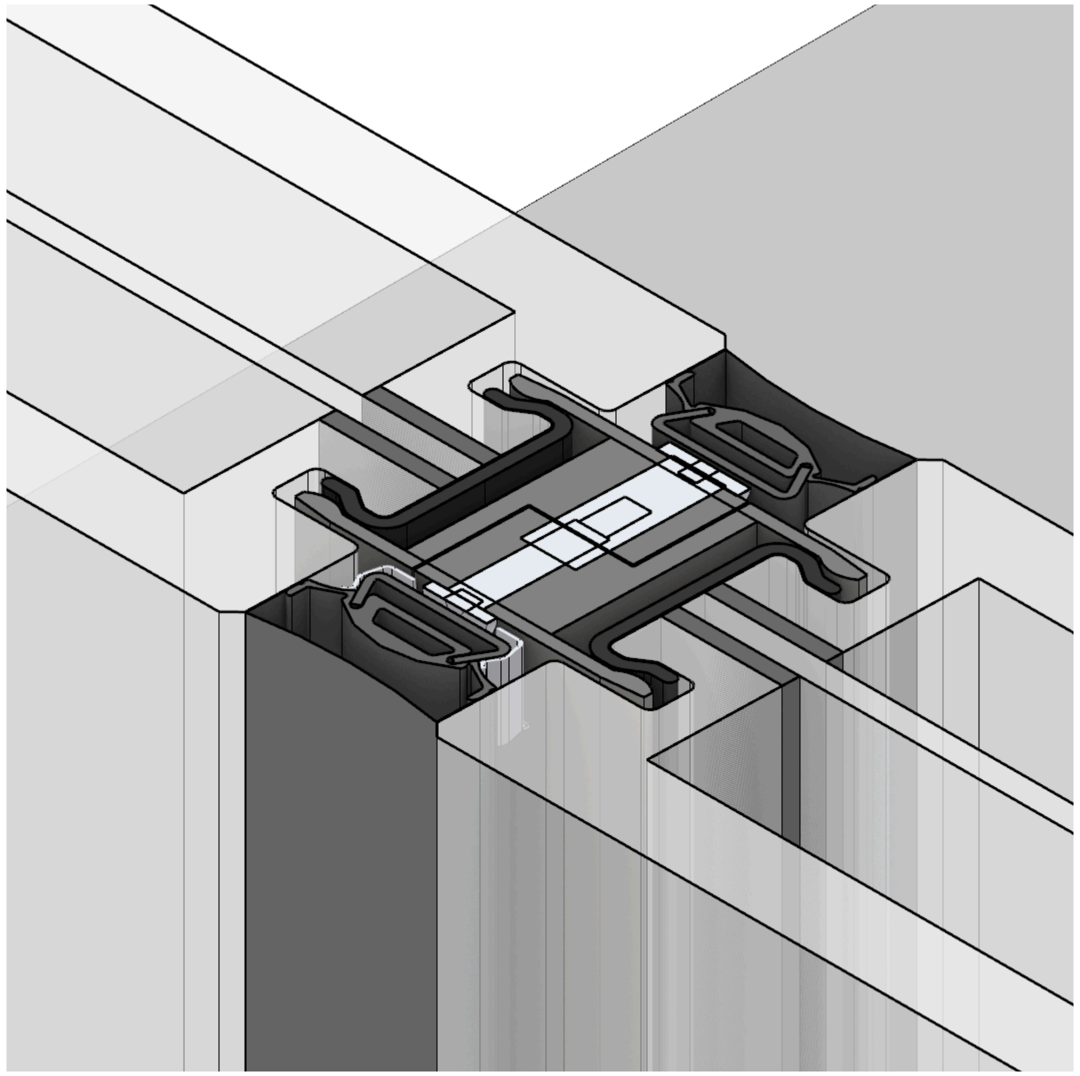
7.5 Horizontal Connection

Horizontal Section between Adjacent IGUs

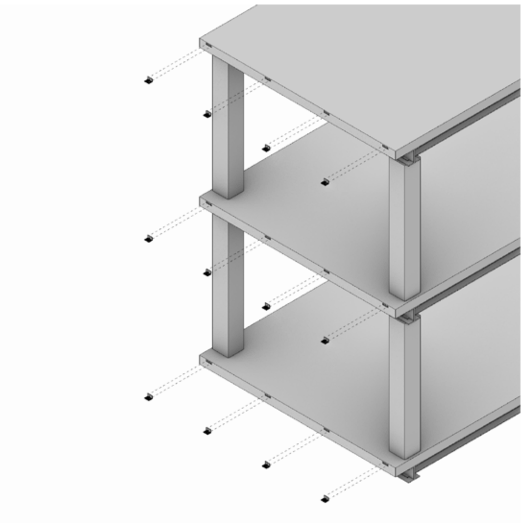
Scale 1:1



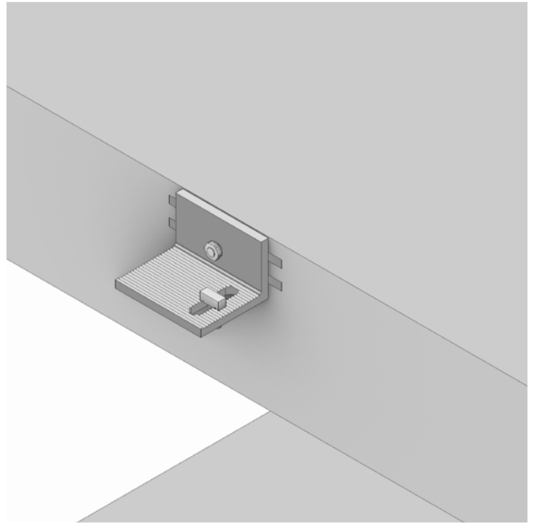


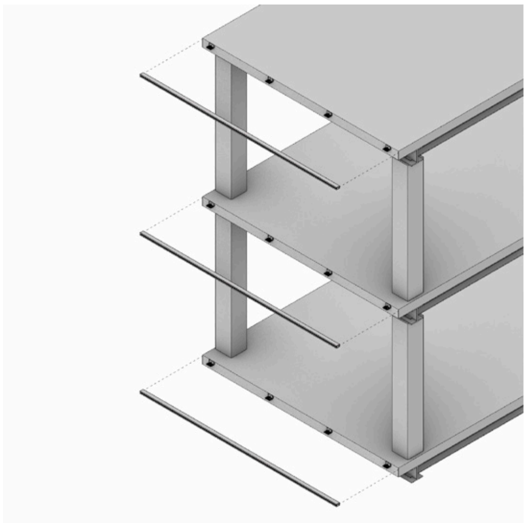


7.7 Assembly Order

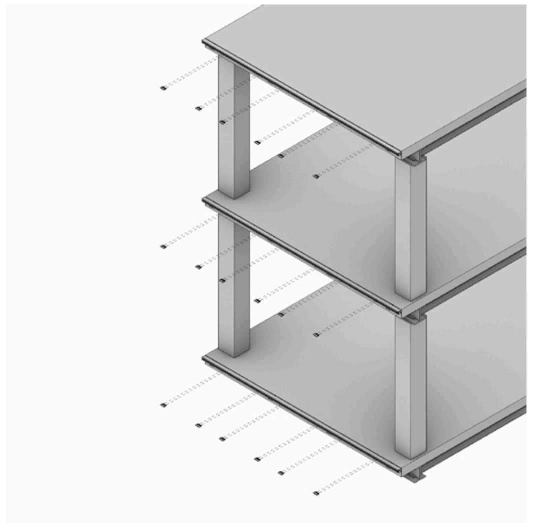


1. Fixing of anchors in concrete slab

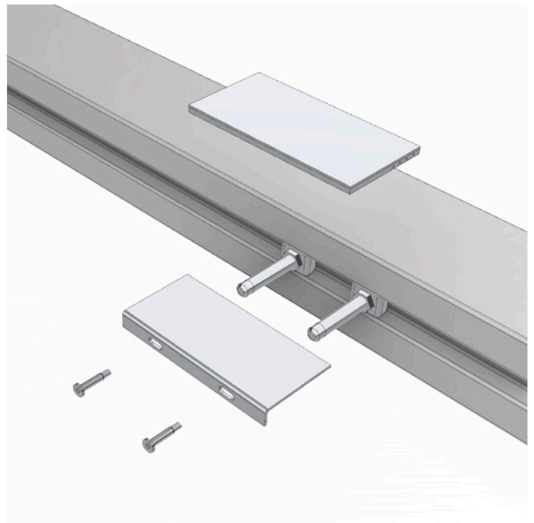


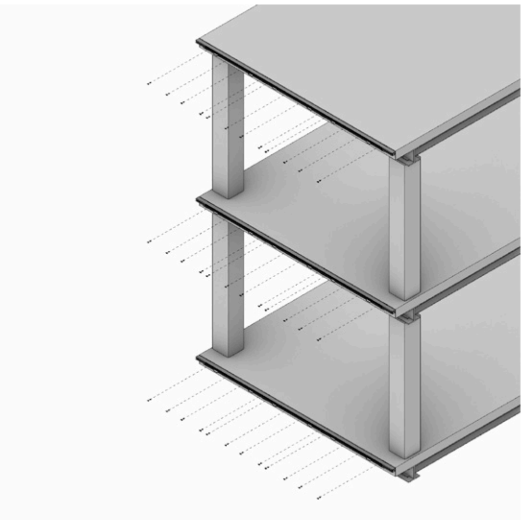


2. Fixing of steel beams to anchors

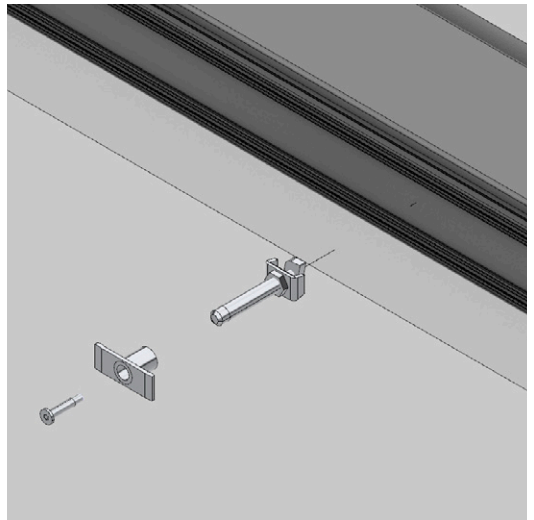


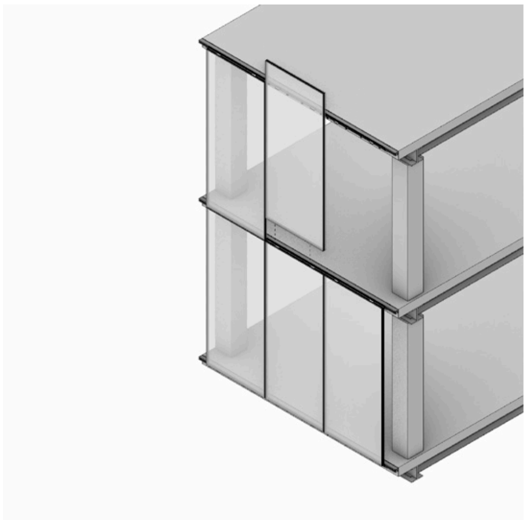
3. Fixing of support blocks



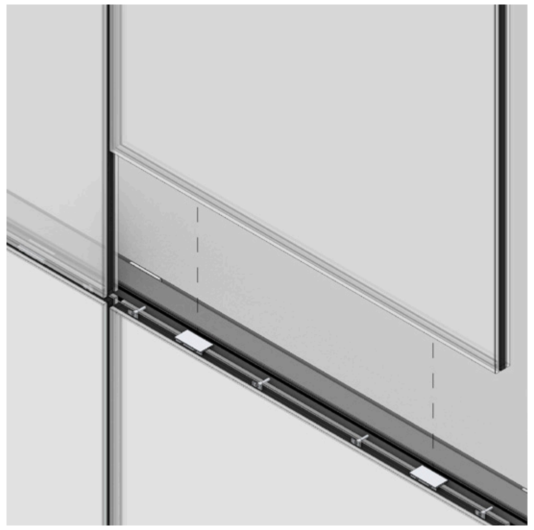


4. Fixing of toggle fixing clips

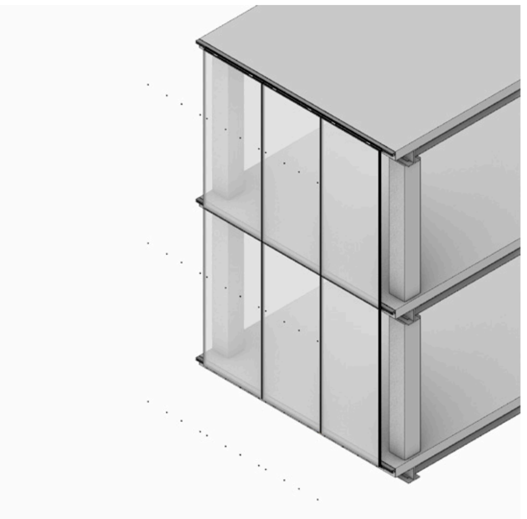




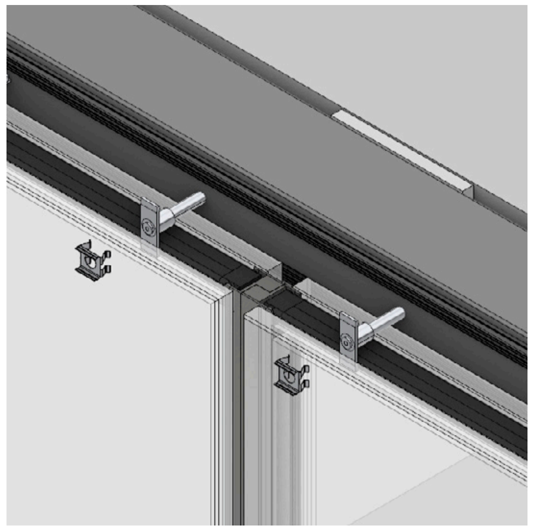
5. Placement of IGU on support blocks

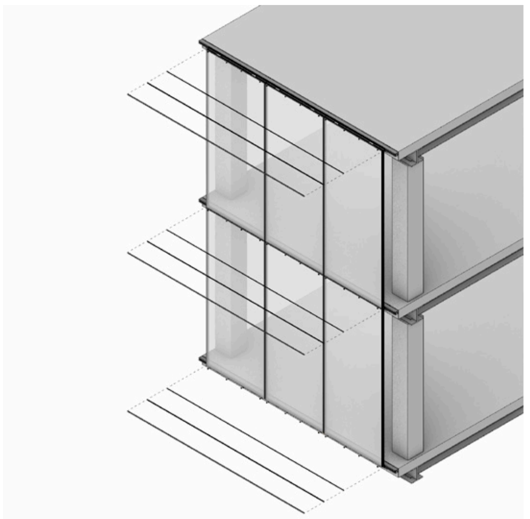


6. Turn of toggle fixing clips

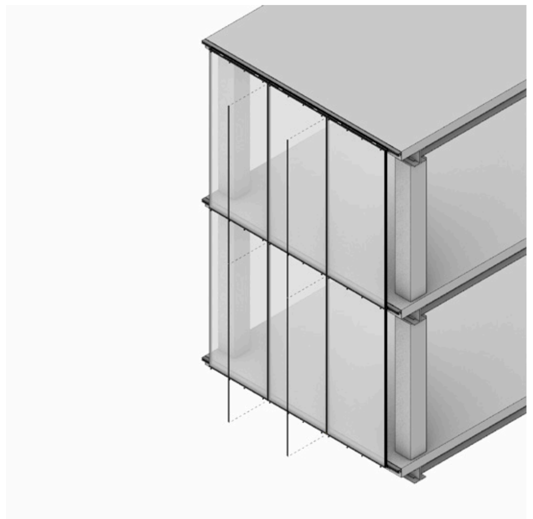


7. Fixing of spring clips for gasket holding

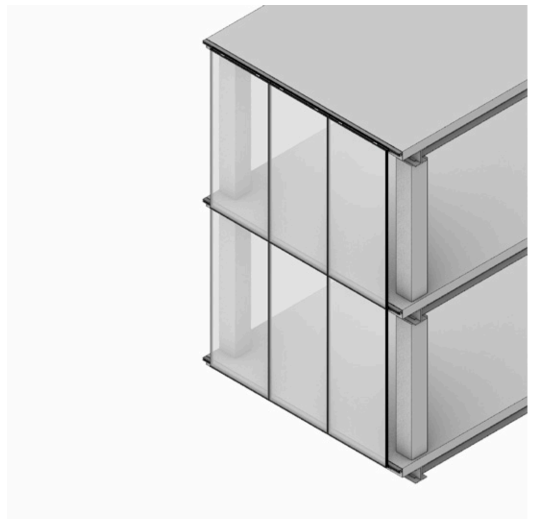




8. Placement of horizontal gaskets



9. Placement of vertical gaskets



08. Conclusions

8.1 Answer to Research Question

8.2 Recommendations for Further Research

8.1 Answer to Research Question

Main Research Question

To what extent can transparency and circularity be combined in an insulated glass unit (IGU) that can be applied in fully glazed facades?

The current master's thesis focuses on the exploration through detailed design of the different ways in which an insulated glass unit can become more circular without compromising its transparency. The term circular here refers to a design that tackles the end of life of the unit by facilitating its remanufacture in case its thermal performance starts decreasing, the reuse of parts of it or of the whole unit and the recycling of the glass panes when neither reuse nor remanufacture are an option.

The proposed way to achieve this goal is twofold. Firstly, in the level of the whole IGU itself factors that impede the potential of the glass panes to be recycled, namely the use of lamination and coatings on the glass surfaces as well as the use of structural silicone adhesives to bond and seal together the different glasses into an IGU, must be avoided to the extent that they don't compromise any the performance and the necessary properties of the unit.

Secondly, the key element towards a more circular IGU is the edge seal connection between the different elements that comprise the IGU. This connection is currently the weakest spot of the whole unit due to the use of these structural silicone that apart from contaminating the glass, lead to premature failure of the entire IGU. Hence, since there is not any provision for its replacement, the IGU is usually discarded without having fulfilled potential life time expectancy. Therefore, this silicone secondary seal is precisely the element that this thesis is aiming at replacing through an alternative reversible connection design. Moreover, the goal is to combine the principles of circularity with the building industry's continuous desire for maximised transparency by minimising the visible elements of the connections in the IGU itself as well as in its application in a glass facade.

The design exploration of the different ways in which an IGU can be created in a more circular way led to a final design that achieves the initial goal in a very satisfying level. Two float glass panes are used as glass surfaces. Extruded glass profiles with slots are fused at the perimeter of the float glass making a permanent and transparent bond of glass to glass without the use of contaminating adhesives. The connection between the two separate glass panes happens with the use of a metal spring clip that locks in the slots of the extruded glass profiles acting as an internal clamping element. Its application internally and not externally of the float glass surfaces, as most clamping mechanisms would, ensures a connection that while not fully transparent is optically unobtrusive. For increased thermal performance of the unit a third glass pane with a low-e coating applied to it is positioned between the two external ones.

As far as the circularity of the unit is concerned, the reversible connection is a big step towards that direction since it enables a relatively easy disassembly of the unit allowing for the non-functional parts to be replaced through a refurbishment procedure. Moreover, the avoidance of the above mentioned contaminating factors both in the main glass surfaces and in the edge seal connection allows for the recycling of the used glass elements. The limitations regarding the circularity aspect are associated mainly with the fact that the use of a low-e coating cannot be avoided for the satisfactory thermal performance of the system. However, its application not on the thicker external glass panes but on the thinner middle one is a design choice that reduces the contamination in the element using the least material resulting in less wasted or down-cycled material. One final limitation in this aspect concerns the potential need for lamination of one of the glass panes if enhanced structural capacity or safety is desired. In this case, the pane carrying the lamination could also be burdened with the coating application so that again the contamination is limited in one element which would need to be down-cycled.

Regarding the aspect of maximising the transparency of the current IGU edge seals, the proposed design of this thesis manages to fulfill this goal as well. The final design has a definitely less visible result that typical IGU edge seals. This goal was achieved for two main reasons. Firstly, the use of a clamping element not externally of the glass panes but in the space in between them minimises this optical effect. However, this design concept relies on the geometry of the edge seal that would not have been able to achieve without extruding glass in the desired cross-section and bonding glass to glass in a transparent way without using adhesives. The proposed method of bonding the glasses through fusion is yet to be verified through testing but is in theory a very feasible option. Finally, limitations regarding the transparency of the edge seal concern the unavoidable use of a non-transparent material for the spring clip element and the also unavoidable integration of a desiccant that consist for which there are not transparent solutions currently.

Finally, the proposed edge seal connection enables the application of IGUs in fully glazed facades using reversible connections without the need for the use of additional frames. This is achieved by taking advantage of the current available reversible facade connections and combining them with the proposed new edge seal.

It is important to mention here that all the aspects mentioned as limitations in the scope of this thesis concern the current technologies available. However, the advancements in these field are so vast that in a few years these limitations could be overcomed. These limitations are more specifically associated with the factors that are currently considered as contamination for the glass recycling, namely the difficult de-lamination process and the extent to which coatings can be recycled or not.

8.2 Recommendations for Further Research

As previously mentioned, this thesis focused on a design exploration though detailing but the proposal of the final design remains in a research level. IGUs are products that have a large number of requirements to be fulfilled in order for them to be able to be applied in the building envelope ensuring the desired thermal insulation.

Apart from their u-value and their structural rigidity the most crucial part of an IGU is the need for an airtight seal and a water, air and moisture barrier all around. Moreover, the need for an integrated desiccant inside the cavity to absorb the remaining moisture from the assembly is equally important. The aforementioned aspects were taken into consideration in the detailing of the connection and were integrated using standard ways that current IGUs also use. Nevertheless, testing should be done to evaluate the performance of the new IGU regarding all these aspects. More importantly, moisture absorption tests should be conducted to measure the performance of the desiccant use and tests regarding the air and moisture permeability of the seal should be made. Moreover, in terms of the evaluation of the structural integrity of the connection tests should be made to lead to proper dimensioning since the used dimensions of the elements are based on the findings of current similar applications.

Finally, as mentioned above, the success of the design heavily relies on the one hand, on taking advantage of shaping glass in different geometries apart from them two-dimensional float glass via extrusion or casting. One the other hand, the proposed connection also relies on the possibility of a glass to glass connection using heat bonding. Both these techniques are not commonly used in the building environment. Therefore, more research and testing should be made to ensure their feasibility. Finally, special attention regarding these matters should be given to possible ways of combining heat bonding with heat treated float glass surfaces necessary for the safety of the structure.

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Appendix

The following appendix includes all the perfomred hand calculations regarding the u-value of the new IGU. Various combinations of glass and cavity thicknesses were tried out to conclude to the most suitable u-value.

The calculations included three different steps; one without neither any coating application nor any inert gas filling, one with only one coated glass pane and one with both a coating use and filling of the cavity with argon gas. Finally, an additional calculation to determine whether or not the use of a third middle glass pane is required was conducted.

Appendix A - themal calculations

Summary Table

	U-values
Double no coating / no gas	**2,923**
Double low-e coating / no gas	**1,844**
Double low-e coating / argon gas	**1,599**
Double no coating / argon gas	**2,811**
Triple no coating / no gas	**2,011**
Triple low-e coating / no gas	**1,114**
Triple low-e coating / argon gas	**0,940**
Triple no coating / argon gas	**1,906**

g	**9,810**
ΔT	15,000
T_{m}	283,000
n	0,380
A	0,035

AIR

ρ	1,232
μ	0,00001761
λ	0,025
c	1008,000

ARGON

ρ	1,699
μ	0,00002164
λ	0,017
c	519,000

Thicknesses

d cavity	0,015
d glass1	0,010
d glass2	0,010
λ glass	1,000
ε_1 **Uncoated**	0,900
ε_2 **Uncoated**	0,900
d glass3	0,003

$$a_c = a_{cond} + a_{conv}$$

AIR

$a_c = Nu * \frac{\lambda}{d}$	a_{c}=Nu*\frac{λ}{d}	**1,664**		
$Nu = A*(Gr*Pr)^n$	Nu=A*(Gr*Pr)^{n}	**0,961**	Nu = max(1, 0,50)= 1	
$Gr = \frac{g*\Delta T*\rho^2}{T_m*\mu^2}*d^3$	Gr=\frac{g*d^{3}*ΔT*ρ^{2}}{T_{m}*μ^{2}}	**8589,152**	2544934063,015	0,000003375
$Pr = \frac{\mu*c}{\lambda}$	Pr=\frac{μ*c}{λ}	**0,711**		

ARGON

$a_c = Nu * \frac{\lambda}{d}$	a_{c}=Nu*\frac{λ}{d}	**1,123**		
$Nu = A*(Gr*Pr)^n$	Nu=A*(Gr*Pr)^{n}	**1,024**	Nu = max(1, 0,50)= 1	
$Gr = \frac{g*\Delta T*\rho^2}{T_m*\mu^2}*d^3$	Gr=\frac{g*d^{3}*ΔT*ρ^{2}}{T_{m}*μ^{2}}	**10817,324**	3205133148,301	0,000003375
$Pr = \frac{\mu*c}{\lambda}$	Pr=\frac{μ*c}{λ}	**0,667**		

U-value Double Glazing (no coating / no gas)

$U = \frac{1}{R}$	**2,923**			
$R = r_e + r_{glass1} + r_{cavity} + r_{glass2} + r_i$	0,342			
r_e	0,04			
$r_{glass1} = \frac{d_{glass1}}{\lambda_{glass}}$	0,010			
$r_{cavity} = \frac{1}{a_{cavity}} = \frac{1}{a_{cond} + a_{conv} + a_{rad}} = \frac{1}{a_c + a_{rad}}$	0,152			
$r_{glass2} = \frac{d_{glass2}}{\lambda_{glass}}$	0,010			
r_i	0,13			
a_c	1,664			
$a_{rad} = 6 * \varepsilon_{res}$ $\frac{1}{\varepsilon_{res}} = \frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1$	4,909 $6 * \varepsilon_{res}$	1,22222222222222 $\frac{1}{\varepsilon_{res}}$	0,81818181818182 ε_{res}	

U-value Double Glazing (low-e coating / no gas)

$U = \frac{1}{R}$	**1,844**			
$R = r_e + r_{glass1} + r_{cavity} + r_{glass2} + r_i$	0,542			
r_e	0,04			
$r_{glass1} = \frac{d_{glass1}}{\lambda_{glass}}$	0,010			
$r_{cavity} = \frac{1}{a_{cavity}} = \frac{1}{a_{cond} + a_{conv} + a_{rad}} = \frac{1}{a_c + a_{rad}}$	0,352			
$r_{glass2} = \frac{d_{glass2}}{\lambda_{glass}}$	0,010			
r_i	0,13			
a_c	1,664			
$a_{rad} = 6 * \varepsilon_{res}$ $\frac{1}{\varepsilon_{res}} = \frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1$	1,174 $6 * \varepsilon_{res}$	5,11111111111111 $\frac{1}{\varepsilon_{res}}$	0,195652173913044 ε_{res}	

U-value Double Glazing (low-e coating / argon gas)

$U = \frac{1}{R}$	**1,599**			
$R = r_e + r_{glass1} + r_{cavity} + r_{glass2} + r_i$	0,625			
r_e	0,04			
$r_{glass1} = \frac{d_{glass1}}{\lambda_{glass}}$	0,010			
$r_{cavity} = \frac{1}{a_{cavity}} = \frac{1}{a_{cond} + a_{conv} + a_{rad}} = \frac{1}{a_c + a_{rad}}$	0,435			
$r_{glass2} = \frac{d_{glass2}}{\lambda_{glass}}$	0,010			
r_i	0,13			
a_c	1,123			
$a_{rad} = 6 * \varepsilon_{res}$ $\frac{1}{\varepsilon_{res}} = \frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1$	1,174 $6 * \varepsilon_{res}$	5,11111111111111 $\frac{1}{\varepsilon_{res}}$	0,195652173913044 ε_{res}	

U-value Double Glazing (no coating / argon gas)

$U = \frac{1}{R}$	**2,811**			
$R = r_e + r_{glass1} + r_{cavity} + r_{glass2} + r_i$	0,356			
r_e	0,04			
$r_{glass1} = \frac{d_{glass1}}{\lambda_{glass}}$	0,010			
$r_{cavity} = \frac{1}{a_{cavity}} = \frac{1}{a_{cond} + a_{conv} + a_{rad}} = \frac{1}{a_c + a_{rad}}$	0,166			
$r_{glass2} = \frac{d_{glass2}}{\lambda_{glass}}$	0,010			
r_i	0,13			
a_c	1,123			
$a_{rad} = 6 * \varepsilon_{res}$ $\frac{1}{\varepsilon_{res}} = \frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1$	4,909 $6 * \varepsilon_{res}$	1,22222222222222 $\frac{1}{\varepsilon_{res}}$	0,818181818181818 ε_{res}	

U-value Triple Glazing (no coating / no gas)

$U = \frac{1}{R}$	**2,011**			
$R = r_e + r_{glass1} + r_{cavity} + r_{glass3} + r_{cavity} + r_{glass2} + r_i$	0,497			
r_e	0,04			
$r_{glass1} = \frac{d_{glass1}}{\lambda_{glass}}$	0,010			
$r_{cavity} = \frac{1}{a_{cavity}} = \frac{1}{a_{cond} + a_{conv} + a_{rad}} = \frac{1}{a_c + a_{rad}}$	0,152			
$r_{glass3} = \frac{d_{glass3}}{\lambda_{glass}}$	0,003			
$r_{cavity} = \frac{1}{a_{cavity}} = \frac{1}{a_{cond} + a_{conv} + a_{rad}} = \frac{1}{a_c + a_{rad}}$	0,152			
$r_{glass2} = \frac{d_{glass2}}{\lambda_{glass}}$	0,010			
r_i	0,13			
a_c	1,664			
$a_{rad} = 6 * \varepsilon_{res}$ $\frac{1}{\varepsilon_{res}} = \frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1$	4,909 $6 * \varepsilon_{res}$	1,22222222222222 $\frac{1}{\varepsilon_{res}}$	0,81818181818182 ε_{res}	

U-value Triple Glazing (low-e coating / no gas)

$U = \frac{1}{R}$	**1,114**			
$R = r_e + r_{glass1} + r_{cavity} + r_{glass3} + r_{cavity} + r_{glass2} + r_i$	0,898			
r_e	0,04			
$r_{glass1} = \frac{d_{glass1}}{\lambda_{glass}}$	0,010			
$r_{cavity} = \frac{1}{a_{cavity}} = \frac{1}{a_{cond} + a_{conv} + a_{rad}} = \frac{1}{a_c + a_{rad}}$	0,352			
$r_{glass3} = \frac{d_{glass3}}{\lambda_{glass}}$	0,003			
$r_{cavity} = \frac{1}{a_{cavity}} = \frac{1}{a_{cond} + a_{conv} + a_{rad}} = \frac{1}{a_c + a_{rad}}$	0,352			
$r_{glass2} = \frac{d_{glass2}}{\lambda_{glass}}$	0,010			
r_i	0,13			
a_c	1,664			
$a_{rad} = 6 * \varepsilon_{res}$ $\frac{1}{\varepsilon_{res}} = \frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1$	1,174 $6 * \varepsilon_{res}$	5,11111111111111 $\frac{1}{\varepsilon_{res}}$	0,195652173913044 ε_{res}	

U-value Triple Glazing (low-e coating / argon gas)

$U = \frac{1}{R}$	**0,940**			
$R = r_e + r_{glass1} + r_{cavity} + r_{glass3} + r_{cavity} + r_{glass2} + r_i$	1,064			
r_e	0,04			
$r_{glass1} = \frac{d_{glass1}}{\lambda_{glass}}$	0,010			
$r_{cavity} = \frac{1}{a_{cavity}} = \frac{1}{a_{cond} + a_{conv} + a_{rad}} = \frac{1}{a_c + a_{rad}}$	0,435			
$r_{glass3} = \frac{d_{glass3}}{\lambda_{glass}}$	0,003			
$r_{cavity} = \frac{1}{a_{cavity}} = \frac{1}{a_{cond} + a_{conv} + a_{rad}} = \frac{1}{a_c + a_{rad}}$	0,435			
$r_{glass2} = \frac{d_{glass2}}{\lambda_{glass}}$	0,010			
r_i	0,13			
a_c	1,123			
$a_{rad} = 6 * \varepsilon_{res}$ $\frac{1}{\varepsilon_{res}} = \frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1$	1,174 $6 * \varepsilon_{res}$	5,11111111111111 $\frac{1}{\varepsilon_{res}}$	0,195652173913044 ε_{res}	

U-value Triple Glazing (no coating / argon gas)

$U = \frac{1}{R}$	**1,906**			
$R = r_e + r_{glass1} + r_{cavity} + r_{glass3} + r_{cavity} + r_{glass2} + r_i$	0,525			
r_e	0,04			
$r_{glass1} = \frac{d_{glass1}}{\lambda_{glass}}$	0,010			
$r_{cavity} = \frac{1}{a_{cavity}} = \frac{1}{a_{cond} + a_{conv} + a_{rad}} = \frac{1}{a_c + a_{rad}}$	0,166			
$r_{glass3} = \frac{d_{glass3}}{\lambda_{glass}}$	0,003			
$r_{cavity} = \frac{1}{a_{cavity}} = \frac{1}{a_{cond} + a_{conv} + a_{rad}} = \frac{1}{a_c + a_{rad}}$	0,166			
$r_{glass2} = \frac{d_{glass2}}{\lambda_{glass}}$	0,010			
r_i	0,13			
a_c	1,123			
$a_{rad} = 6 * \varepsilon_{res}$ $\frac{1}{\varepsilon_{res}} = \frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1$	4,909 $6 * \varepsilon_{res}$	1,22222222222222 $\frac{1}{\varepsilon_{res}}$	0,818181818181818182 ε_{res}	

Appendix B - glass extrusion

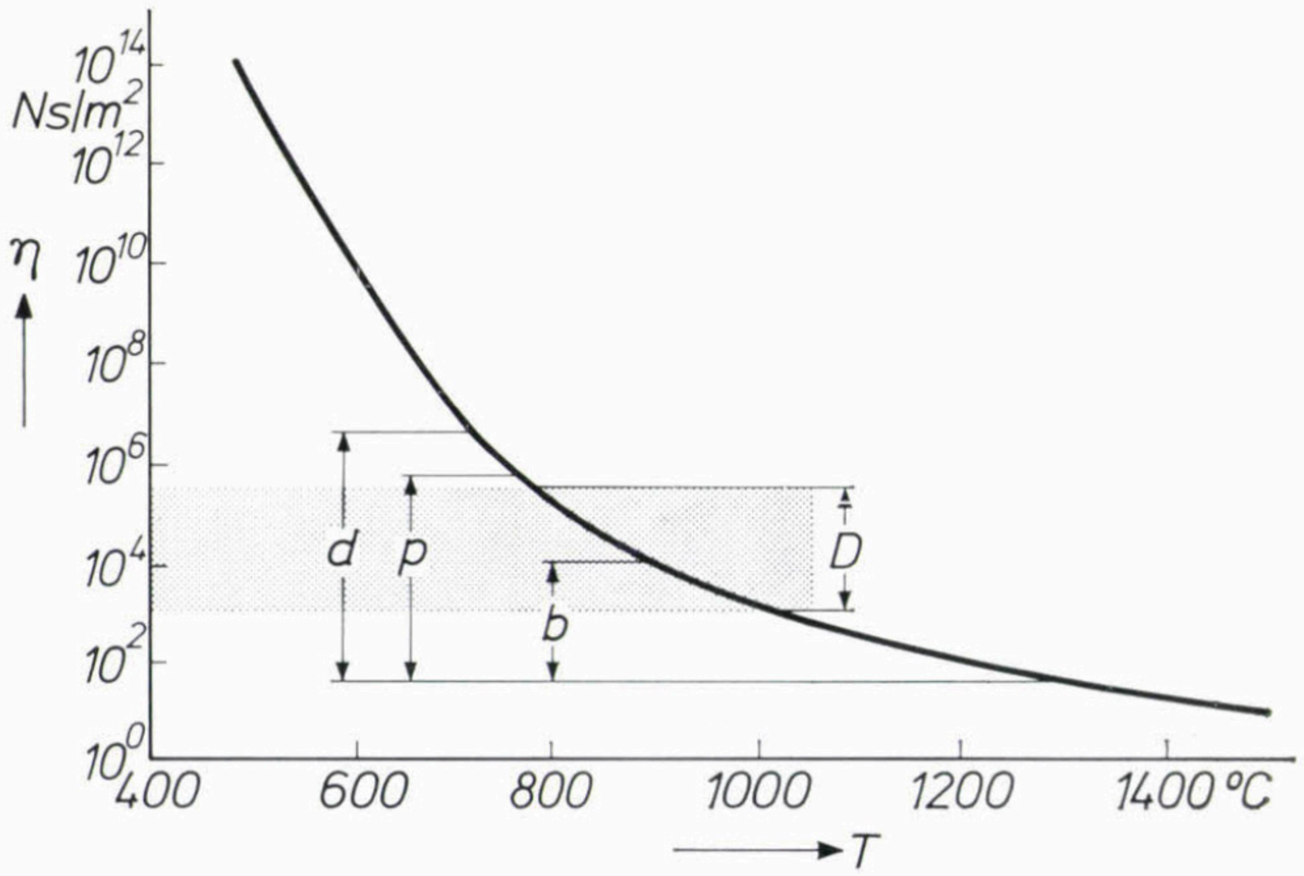

Fig. 2. Viscosity-temperature curve for soda-lime-silica glass, showing the viscosity ranges for blowing (*b*), pressing (*p*) and drawing (*d*). Also shown is the range where devitrification (crystallization) occurs (*D*). Extrusion is normally carried out at viscosities between 10^5 and 10^7 Ns/m^2.

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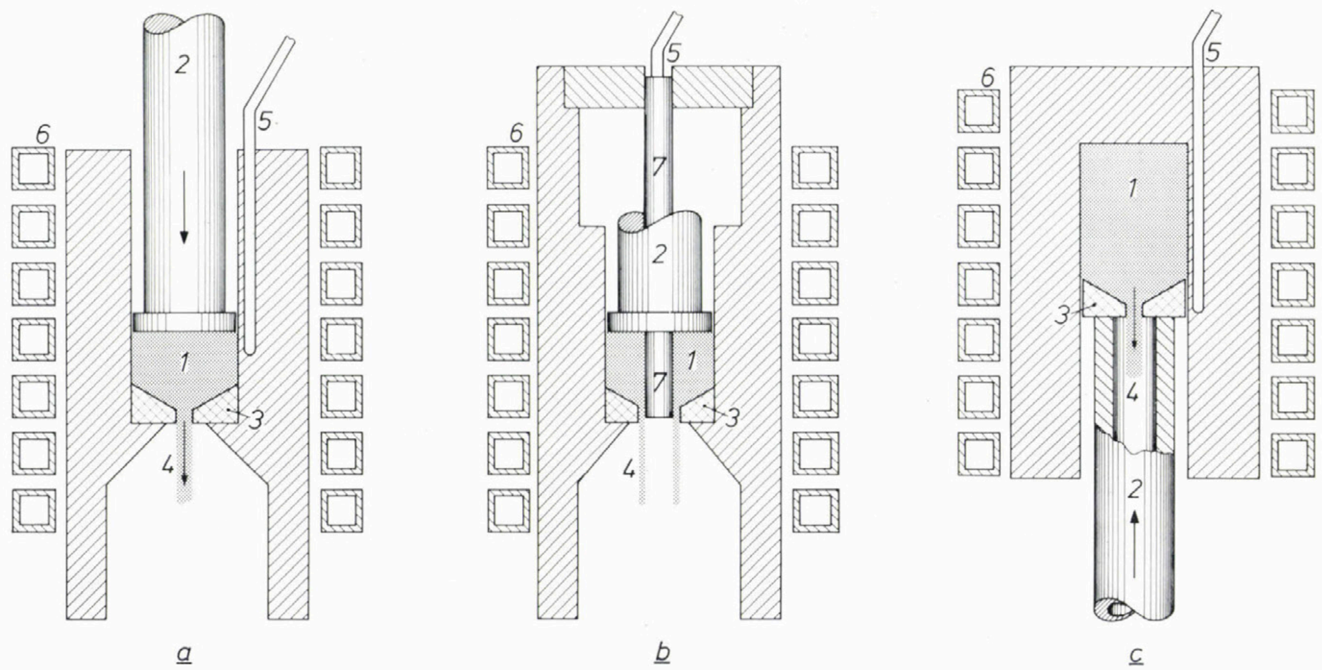

Fig. 1. The three types of extrusion equipment (schematic): *a*) for direct extrusion of rods (punch and glass rod move in the same direction), *b*) for direct extrusion of tubes and *c*) for indirect extrusion of rods (punch and rod move in opposite directions). *1* glass billet. *2* punch. *3* die. *4* extruded product. *5* thermocouple (only partly visible in *b*; the weld here is at the end of the hollow mandrel *7*). *6* high-frequency coil for induction heating.