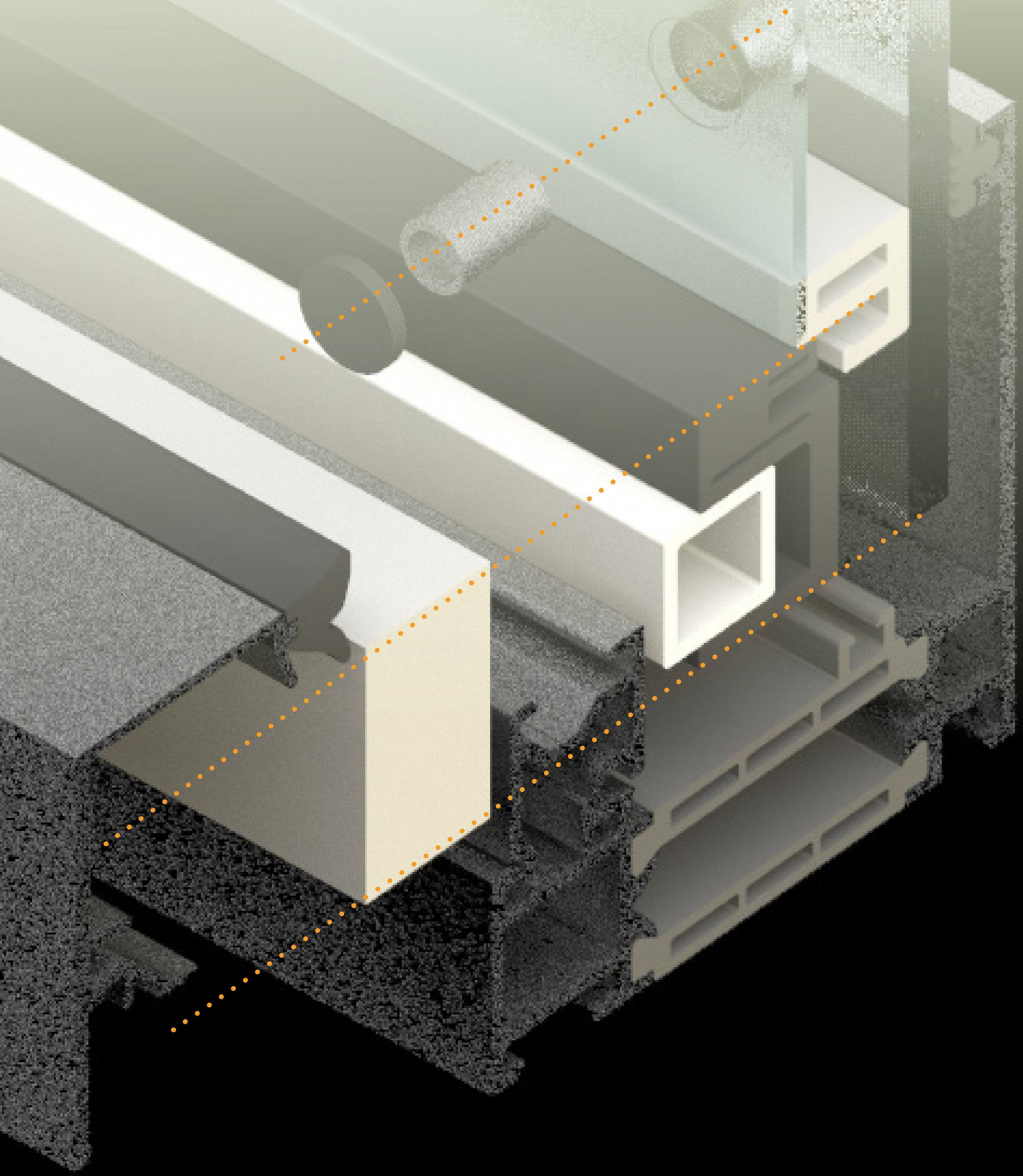
THE RE∞SEAL WINDOW

A Redesign of the edge seal of Insulated glass units to facilitate easy and fast re-manucturing.

Juliëtte Mohamed



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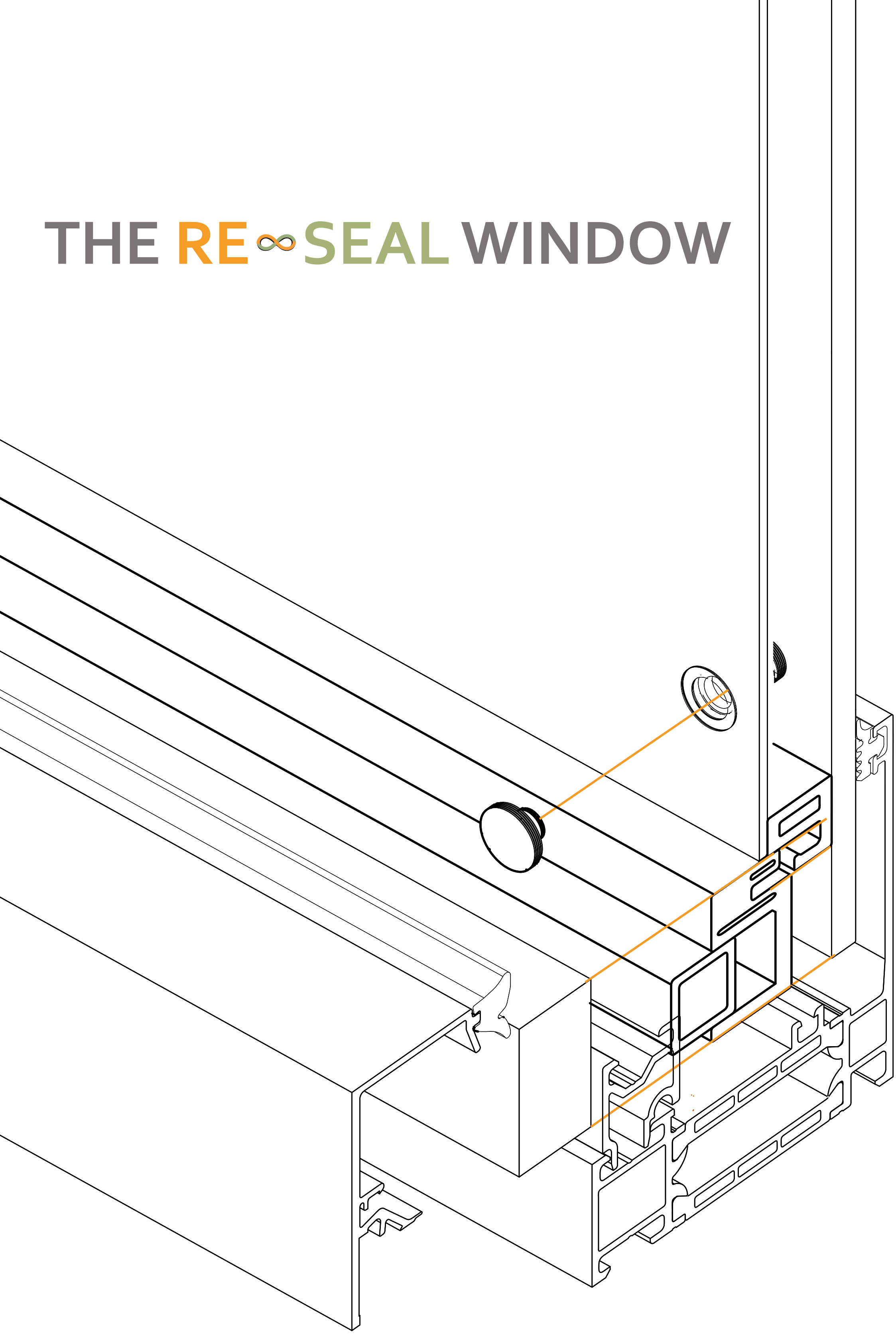

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"A Redesign of the edge seal of Insulated glass units to facilitate easy and fast re-manucturing. "

Master of Science (MSc) thesis

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And of course my two cats,who calmed me down in times I needed- in Remembrance

Abstract

Windows are important elements in a building. They protect the interior from the exterior environment regarding weather conditions, noise, security and so on. While they also, in contrast to walls and floors, connect the two, creating links and providing rooms with daylight, fresh air and views in and out of the building.

The most governing element of the window is the insulated glazing unit (IGU). There are many developments concerning coatings to add functions to the glass ,such as solar control or self-cleaning windows but they contain critical materials such as cobalt, copper and titaninum. Added elements such as coatings, foils for laminated glass and the sealant prohibit the IGU from being recyclable, as the prevailing glass industry requires high quality and clean ingredients only. This makes the IGU a finite, single life product resulting in almost 125.000 tonnes of post-consumer glass waste each year in the Netherlands.

The IGU works optimally as an insulating element as long as there is dry (argon) gas inside the glazing panes. However, the life span of current IGUs is just around 15-20 years and is dependent on the butyl seal which is just 1% of the costs and 0.1% of the weight. During its life span the seal starts failing by allowing water molecules inside the cavity. The panel as a result starts building up water vapor and the coating inside will start to corrode, the glass shows fogging and the thermal performance drops down due to outgassing of the panel. In the current design of the IGU no refurbishment is possible, meaning that the glass panes and the spacer will not be re-used, but instead end up as landfill while these materials exceed the life span of the sealant by a large margin (Veer, 2016).

This thesis therefore focusses on the possibility of remanufacturing the IGU. The re-designed edge seal system for the IGU makes it easy to remanufacture the IGU on-site. The design utilises a detachable butyl seal that functions as a dry gas and vapor barrier and a hollows section that assures the tightness of the seal. This idea shows the possibility to replace the weakest part of the whole glazing panel every ten years so that the glazing panes which have high stored embodied energy and the spacer bar, which is currently approaching the theoretical value in terms of energy efficiency, both can have a life span of more than 100 years.

The interlocking design of the spacer bar and butyl sealant is a result of a form finding process. A fiberglass hollow section can be slid into the butyl profile to assure the load is transfered to the window system. Furthermore, a check valve type is chosen to fill the cavity again with Argon gas with every remanufacturing cycle.

Keywords: Remanufacture , Window , Service life, Insulated glazing unit, Sealant, Edge seal, Resealable, on-site remanufacturing, interlocking

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CHAPTER 1
INTRODUCTION

Content

Inroduction
Problem statement
Methodology

Arup(2018)

1 Introduction

Nowadays, the reduction of energy consumption is more acute than ever. The Netherlands have set the goal to improve the energy efficiency by 33% in 2020 compared to 1990 (Ebbert, 2010) and expects a CO_2 emission reduction of up to 88-91% by 2050.

The building sector, consuming 40% of the materials entering the global economy, is the biggest energy and natural resources user (Asif, Muneer, & Kubie, 2005).

The use of this energy is connected to the depletion of fossil fuels and climate change. Looking at the existing building stock in the Netherlands, 35% is over 50 years old and around two thirds is older than 30 years (Konstantinou, 2014). At this age, facades and technical installations reach their end of life-span: Gaskets become brittle, insulated glass leaks due to permanent thermal expansion and contraction and metal parts of the facade corrodes (Ebbert, 2010). Consequently, these large amount of buildings show poor user comfort and high energy consumption.

From a sustainable viewpoint not replacement by new construction but life cycle extension of existing buildings is the better choice regarding reducing waste streams of materials as resulted from studies from Konstantinou (2014). The energy consumed during the production and transport of materials is stored in the construction itself and with demolition this energy would be discarded as well.

The glass industry was one of the first with a high degree of recyclability from its products. Crushed glass can be recurrently recycled into similar products, with almost the same quality and purity (Silva, Brito, Lye, & Dhir, 2017).However, float glass is still a linear economy ending at land fill after usage. Although the embodied energy of glass is relatively low in comparison with typical building materials, the recycling process of glass still takes a lot of energy due to the three following reasons: impurities, different recipes of glass and adhesives. Therefore, despite the potentials, most of the discarded float glass (in the Netherlands already 125000 tonnes a year) ,fails to pass the high quality standards of the prevailing glass industry making it a finite, single used product.– (Bristogianni, Oikonimopoulou, Justino de Lima, Veer, & Nijsse, 2018).

§1.1 Problem statement

The life span of current Insulated Glass Unit (IGU) is around 15-20 years, after this the butyl seal which is just 1% of the costs and 0.1% of the weight, starts allowing water molecules getting inside. The panel as a result starts building up water vapour and the coating inside will start to corrode, the glass shows fogging, and the thermal performance drops down due to outgassing of the panel. In the current design of the IGU no refurbishment is possible meaning that the glass panes and the spacers will not be re-used but instead end up at landfill while these materials exceed this life span of the sealant by far(Veer,2016).

The idea in reaction to this problem is to design a Insulated glass unit that is resealable. By just changing the edge sealant every ten years, the life span of the total panel could be extended to a life time of 100 years which results in saving materials, embodied energy and money.

§1.2 Goal thesis

The goal of the thesis is to design a different edge seal system for an IGU that is easy to replace and assures the functions of the product for at least ten years. By the ease of replacement the design should enhance refurbishment in order to give the IGU a life span >100 years.

§1.3 Objectives:

The scientific problem is distilled into the following research question for the thesis: "In what way can the edge seal of the Insulated Glass Unit (IGU) be redesigned for easy and fast remanufacturing after every ten years in order to achieve a life span >100 years considering low-rise buildings ."

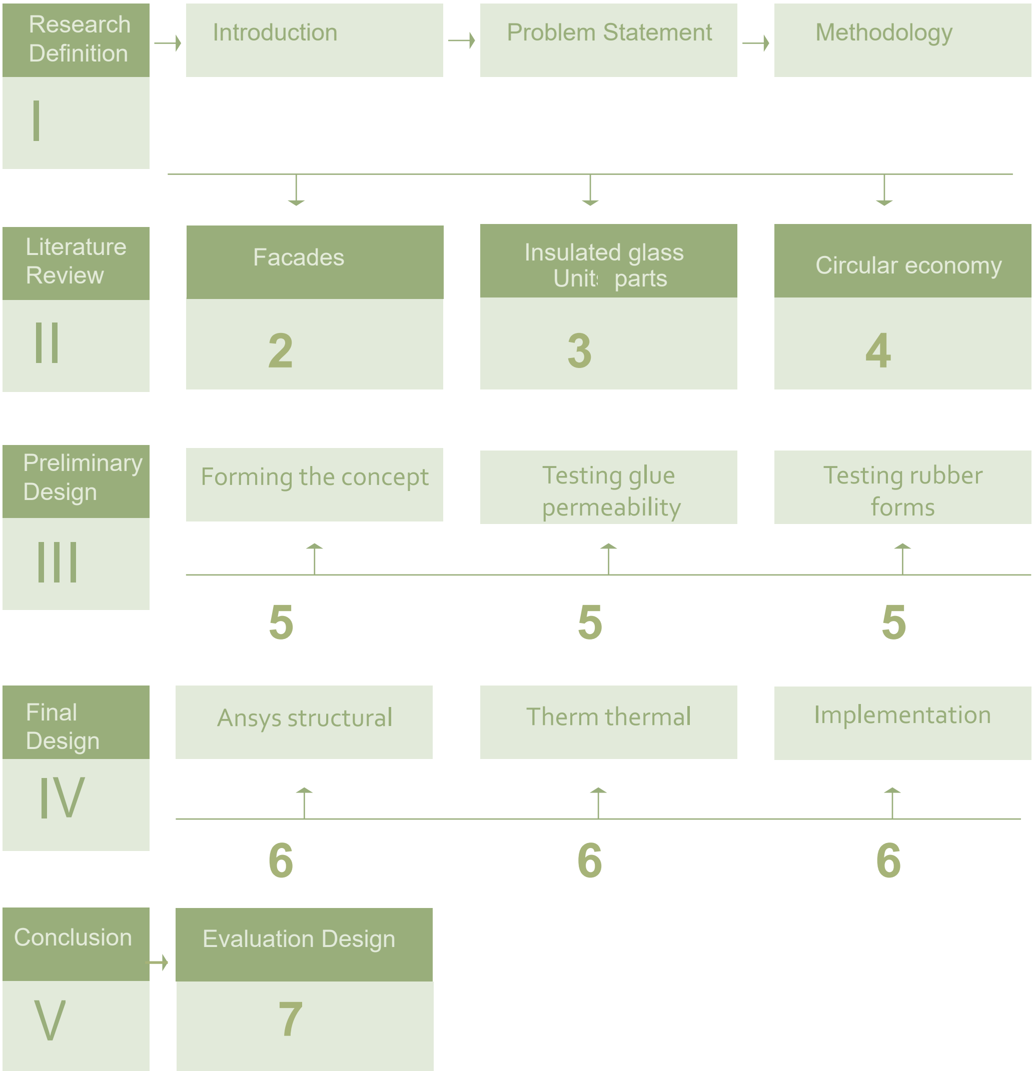
In order to achieve the goal of the thesis several objectives are formulated:
In order to achieve the goal of the thesis several objectives are formulated:

- Create insight of the current situation of the current building stock in terms of façade and window panel principles to answer the question:
What window system is most suitable to start the new design of the IGU and allows easy and fast re-manufacturing?
- Create an overview of the current elements of the IGU. Focusing on materials, manufacturing processes and ageing factors to answer the question:
What requirements should the new IGU meet to last more than 100 years taking into account every ten years of re-manufacturing?
- Create an overview of circular economy principles to find out:
What are the distillated tools to redesign a re-manufacturable IGU ?

- Create a design concept for a resealable window and find a method to evaluate the designs.
- Think of a method that allows fast re-manufacturing in order to make the new circulair IGU a more attractive and comfortable choice for the client.

1.4 Methodology

The thesis is written in the structure ' From broad to zoomed in' and consists of five parts:Part II: The literature review that translates to design tools Part III: The chapter thereafter covers the preliminary design phase which focuses on forming of the concept.
Part IV: The verification through FEM models in Ansys for the final design
Part V:The conclusion and recommendation will be given at the end of this report.



CHAPTER 2
Facade

Content

Requirements of window frames
Window systems
Curtain wall system
Materials
Renovation strategy
Conclusion

2.1 Facade

§ 2.1.1 The requirements of window frames:

Windows are one of the most sensitive parts of the façade not only because of the exterior environment but also in terms of energy performance and the environmental impact of the materials as they form a barrier between the inside and outside but also connect the two for allowing daylight, fresh air and view . Windows consists of two basic elements, the frame and the glazing unit. Whereas the frame, also exists from two parts: the fixed frame and the sash as shown in figure 2.1.1.1. (Asif, Muneer, & Kubie, 2005).Therefore the frames are also continuously improving. The choice of a facade system and therefor also the window frame is based on request of the project developer and among others (figure 2.1.1.2) that set the demands of the quality of the facade(table A 1.1 from the appendix), however all facades have to meet the requirements of the NEN-Norm. The fabricator then chooses the best possible option between products from the suppliers.

There are mainly three types of façade systems.
Window/door systems and curtain wall systems that can again be divided into stick system curtain walls and unitised systems (Reynaers).

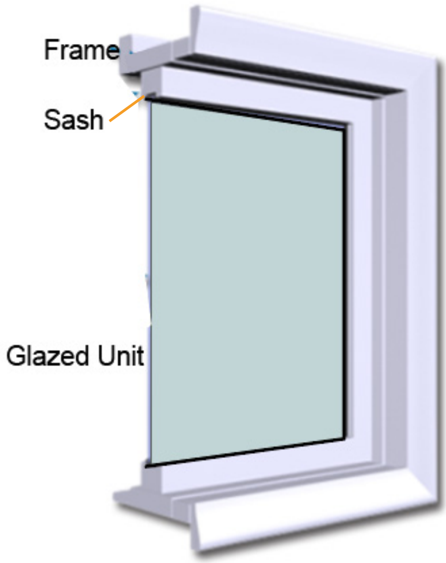


Figure 2.1.1.1: Window in frame unithttps://kitchencabinetkings.com/glossary/sash/

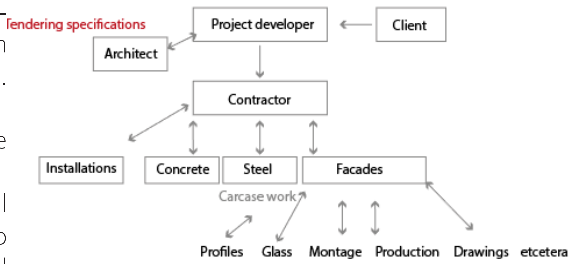


Figure 2.1.1.2: Parties involved in the choice and design of the façade system.

(Hochberg, Hafke, & Raab, 2009) have classified window-opening typologies according to their design and construction: punched windows, strip windows, French windows ,window walls, and curtain walls. Figure 1.3.0 will show the typologies. However, by not looking at the architectural but technical installation, these archetypes can be categorized by three systems: window/door system (this includes the punched windows, window strips , French windows and window-wall) and curtain wall where this last one can be further divided into two categories: unitized and stick system.

2.2 Window system

This system is used for certain window typologies described by Hochberg, Hafke, &Raab (2009) for instance the perforated facades as punched windows where the windows are constructed with a lintel at top, a window sill at the bottom and reveals on the sides. Normally the window gap of this punched window is significantly smaller than the area of the wall. A variant of this is the window strips where a series of (punched)windows are placed next to each other. But also the French window where the opening can be seen as a door, or a window-wall(room-height façade element constructed out of window/door elements) which needs a separated load-bearing construction that allows for more freedom in the façade design by a continuous window do fall in this category window/door system.
Installing an aluminium window/door frame, starts with mounting the aluminium casement to the edges of the gap of the construction .Typical dimensions are around 50*80. Thereafter, silicone sealant will close the connection of the window frame and casement watertight(the so-called 'wet- connection'). However, a drainage channel at the base of the rebate has to be integrated as well (a typical dimension of this is 8mm wide and 3-4 mm deep.)
When the window is placed inside the frame, the glazing bead will be screwed to the frame to hold the window in place. The disadvantage of this system thus is the kit that is used.
window/door frames are mostly used in low buildings and as the construction is usually carried out in just one phase, this kind of projects have most material leftovers (3-5%) as reserve parts are taken into account to prevent more costly additional orders (De Groot & Visser).

As can be seen creating strip windows is repeating the sequence of the single window parts where the outer frame that couples the windows, is in case of the strip window a special coupling profile. (coloured in red). A more detailed of how the IGU fits in the window system is shown in figure 2.2.1.2. It shows how the glass is placed inside a window system and what the requirements are for the IGU maintain a good quality seal. The IGU is placed between two tightness barriers often made from EPDM rubbers. The first tightness barrier is stiffer than the 2nd tightness barrier. In this way the IGU will be pushed tightly to the inside and second barrier so the construction becomes wind tight. The benefit of the soft second barrier is as the window has to be replaced, the glazing bead can be removed easily (the sequence of removing the IGU is shown at the end of this chapter.) The glazing bead

Figure 2.2.1.3: Top: single window; bottom: strip window. and https://www.instagram.com/p/B1XTm-HCHjo_/http://www.pedrokok.com/villa-savoye-in-poissy-france

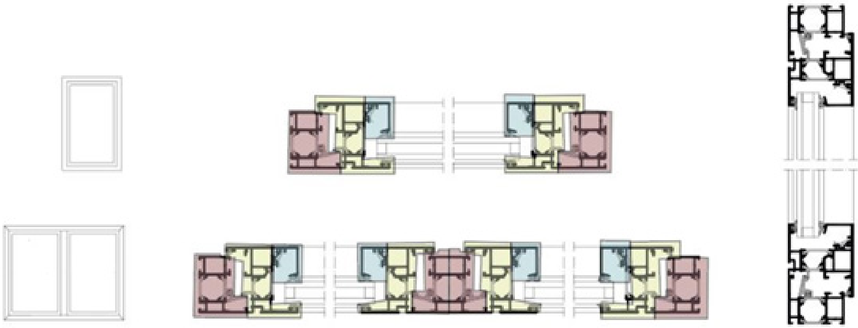


Figure 2.2.1.2: Top:Single window; bottom: strip window.schueco profiles, own figure.

protects the edge of the IGU while it keeps the sight clean. The Joints between the glass and the frame must retain watertight and airtight and the frame should prevent stagnation of water in the rebate as this can result in failing of the glass seal or glass interlayer. For this reason drainage channels are integrated inside the window frame.

Setting block:

The transfer of the weight of the glass and the loads applied to the IGU goes through setting blocks. They are positioned at two sides inside the rebate to prevent any direct mechanical contact with the frame which is made out of hard material. The dimensions are dependent on the glass weight and function of the environmental conditions. A typical height is 9 mm. Furthermore they assure the squareness when opening the frame or using it (AGC Glass Europe, 2014). On top of that a plastic filling plate is placed.

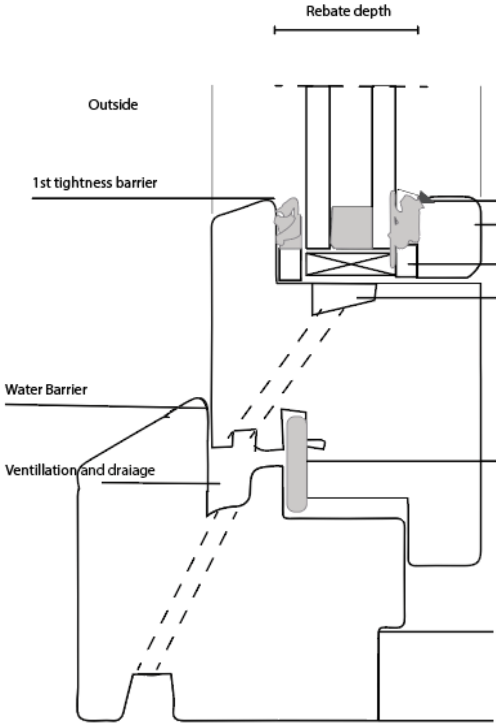
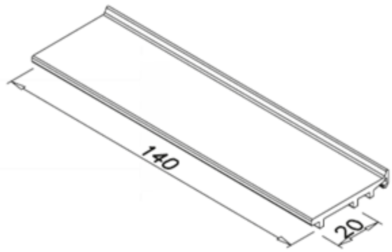


Figure 2.2.1.3 Drainage and tightness of the frame (AGC)



setting block :(AGC Glass Europe, 2014).

Rebate:
The rebate is a recess in the window jamb that works as a stop. The dimension of the rebate and that of the glazing beads must be big enough to allow for proper installation of the setting blocks. Also the dimension of the rebate should be in accordance to the environment (e.g. chemicals). The rebate should be drained.

.For a better understanding of the products of window frames, a small comparison is made between the most well-known façade system companies that deliver in the Netherlands. (Kawneer, Reynaers, Schüco and Jansen). As can be concluded the products look similar from overall perspective. (Figure 2.2.1.4)There is an outer frame (coloured in red), an inner frame also known as the sash (coloured in yellow), a glazing bead that can be removed when a new glass panel has to put in (blue) a. But every producer and model differ from each other with extra focus on one or more quality

points from the table in Appendix 1.

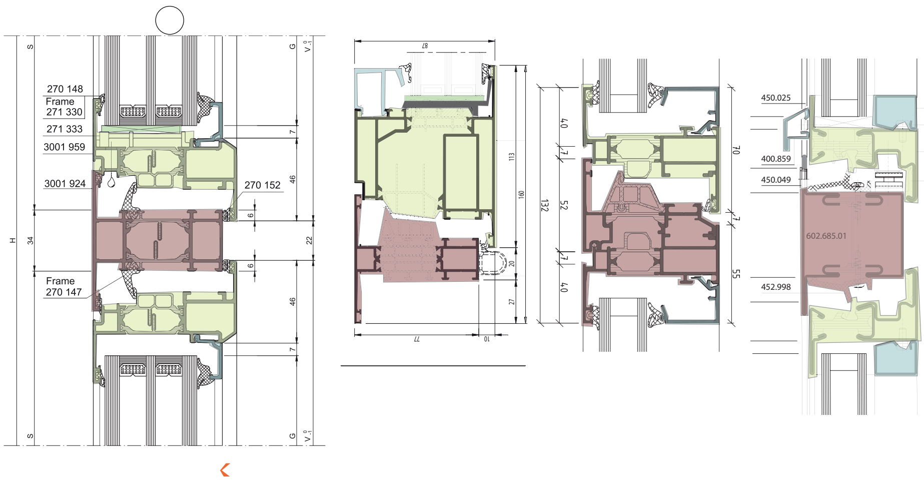


Figure 2.2.1.4 Analysis of different window frames and parts Kawneer,Reynaers,Schüco,Jansen (own figure)

Jansen provides steel (1.4401 (AISI 316)) window/door frames. Steel profiles differ from the aluminium in form. This is due to the manufacturing process. Steel profiles are folded metal sheets that result in cold-rolled hollow sections in T,-Z,I or L-shapes. However, the accuracy is very high. Steel profiles are in particular suitable for aggressive environment such as industrial and coastal areas, since these frames are resistant against (de-icing) salts, it can also be placed near roads. Furthermore the steel frames are more used in occasions where a higher level of fire safety is needed. However, it will not provide thermal insulation to counter the heat produced by the fire. Steel frames are ideal to cover large spans, but they need to be thermally broken since steel has high thermal conductivity.

Wooden window frames and sashes can be made from solid or laminated wood. Common wood types are pine, spruce or redwood etc. The wood is first milled into the required profile shape where after the wood will be impregnated with a wood preservative to protect it from mould and insect infestation. However, wooden frames are one of the most susceptible parts of the façade. The maintenance plus the deterioration and fast technical improvements of the other window frame types makes the change to e.g. aluminium frames during a renovation (Bommel, Schellen, & De Clercq, 2012) more attractive.

There are many different Aluminium frame systems mainly because the frames are lightweight strong , stiff and corrosion resistant and therefore require low maintenance. However aluminium also needs to be designed with a thermal break. Tolerances of 1-1.5 mm/m length have to be taken into account. Taking a look at three aluminium façade manufactures Kawneer, Reynaers Aluminium (Belgium) and Schüco International (Germany). In a rough way, the systems are designed on the same principle: The inner frame that carries the IGU and allows it to be operable(coloured in yellow), the outer frame which is fixed to the setting block (coloured in red) and the glazing bead which is used to fix the IGU in the operable inner frame (blue). Besides this, also from outside to inside a set of three functions is given to the frame: The outside part (left aluminium part in the picture) is mainly for appearance and accommodates the water drainage. The middle part is made out of composite(which is black in figure 2.2.1.5) is for the insulation and for that reason out of different material than aluminium. The Inner (right on the picture) is for structural reason and also made out of aluminium.

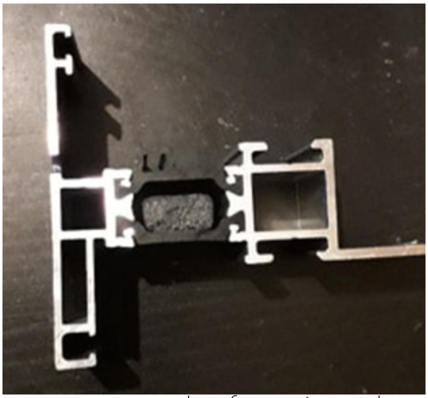


Figure 2.2.1.5: window frame. Image by author

2.3 Curtain wall system

Is a vertically installed façade system mainly with aluminium extrusions and glass components
This system can be used when a floor-to-floor façade is needed. A curtain wall system consists of separate elements which mostly are connected on site. The advantage is the dry-assembly where after certain years upgradability is possible. The curtain wall has two main systems ' the stick system' and the unitised facade

Unitised façade.
A facade panel ideal for high-rise projects as they can be easily installed on place since the panels are prefabricated in the factory. The elements have large dimensions as it spans from floor to floor. The unitised system provides better working conditions as it is produced in the factory and saves on daily transportation in comparison with the stick system. According to (Ebbert, 2010) the unitised system is favourable in the Netherlands.

Figure 2.3: Royal Bank Plaza, Toronto Image by author.

Stick system curtain wall :
Stick system curtain walls are fabricated on site and is a separate external facade frame that is placed in front of the construction elements such as building walls, columns and floor slabs.
During casting of the concrete floors of the building, embeds are usually casted in place whereon the mullions can be fixed. The second step is the fixing of these mullions onto the embeds with brackets.
After this the transoms will be fixed onto the mullions. Aluminium angles are commonly used as material in combination with screws.
The last step is mostly the installation of the glass panels which are fabricated in the factory, they will be mounted onto the aluminium frame of the transoms and mullions with fixing bars (from aluminium or stainless steel).

From architectural view there are different typologies of a curtain wall,
the first one can be called the invisible transom and mullion system. Here a curtain wall consists of (glazed) panels in front of the transoms and mullions, for this type only small sealant (or gasket) joints are visible from the outside, the downside is that the sealant can creep under long term and the width of the frame has to be bigger.
Another type is called the 'visible' transom and mullion system where the cap can be seen from the outside. The (glazed) panels will be clipped onto the framing, Now the panels can be fixed to the framing. Figure 2.3.1.3

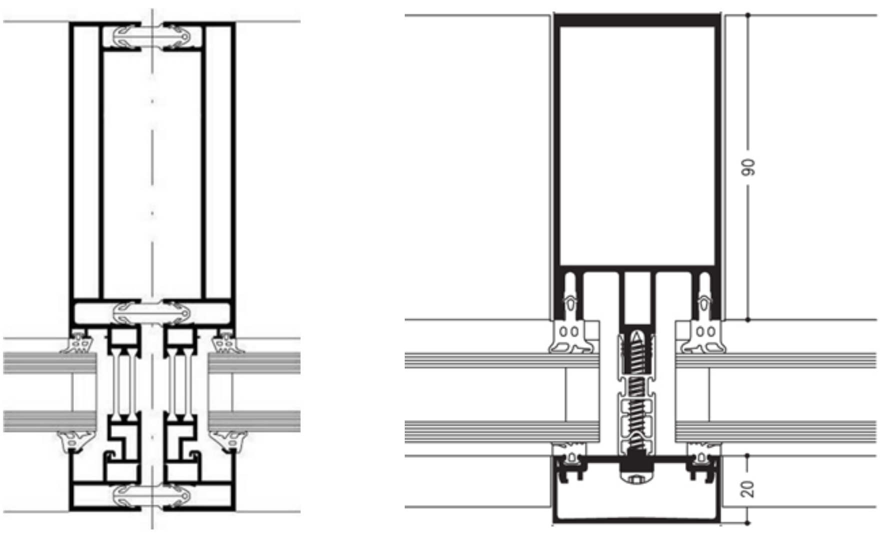


Figure 2.3.1.2 :Left Unitised and stick system right stick system http://aluflor.com/en/te-parafabrikuara/

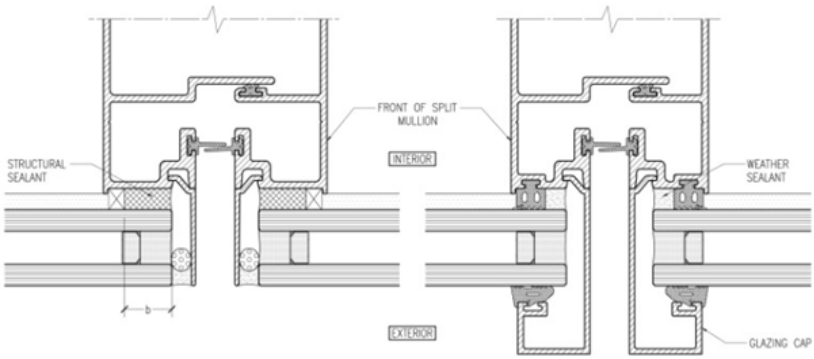


Figure 2.3.1.3: Unitised system invisible and visible. Source: (Lee, Shepherd, Evernden, & Meltcafe, 2017)

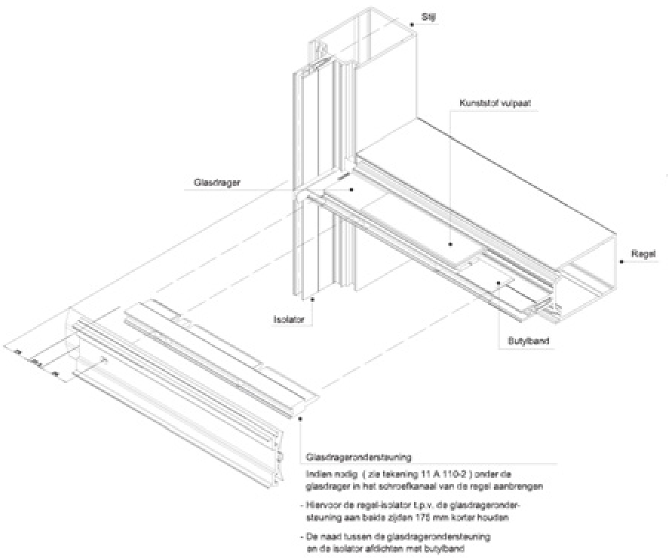


Figure 2.3.2.3: Connections source: Kawneer products

2.4 Materials

Although the three systems differ from each other, the materials used which can cover 20%-30% of the window are either: Aluminium, aluminium-clad timber, polyvinyl chloride (PVC), timber and steel. The material decision has influence on the frame thickness, the weight, durability but also the thermal performance and overall environmental impact. Asif,Muneer,&Kubie (2005) have conducted a LCA research about the different window frame materials. The results of the research are as follow: The energy consumption of PVC windows frames are three times higher than wooden frames. By the production of PVC a number of toxic elements are released. Also, the maximum life time of PVC is just 30 years which is considered as limited. PVC windows are sensitive towards heat and UV radiation unless protected with UV absorbers, stabilizers modifiers or fillers. PVC frames are sold to be maintenance free, however this material is very sensitive for airborne scratches as it becomes brittle due to the sun. And for this reason it is advisable to clean the PVC frames with non-alkaline detergents every 6 months. Once it is broken PVC is not easy to repair.

Wooden frames contains the least amount of embodied energy but need to be repainted every five years and stained every three years against weathering.

Aluminium clad timber windows are considered to be durable enough to last sufficiently long (more than 40-50 years) where just the loads of the aluminium is added to the environmental impact. It requires low maintenance and is easy to repair.

The aluminium frame shows highest embodied energy compared to other materials and uncoated aluminium windows have tendency to corrode even though it is naturally resistant against corrosion, however if the right coating is applied (anodizing and powder coating finishes for instance) the aluminium is protected for approximately 20 years and thus low maintenance is required.

The next paragraph describes the production process of the materials aluminium, wood and pvc.

Aluminium

Aluminium is found in Bauxite. After mining of this ore, Bayer refining takes place where alumina is refined. Then primary smelting is applied. After this casting of the aluminium happens. The profiles can now be formed. Producing Aluminium is expensive because of the large amount of energy that it takes, also lots of pollutants come free by the processes. But after the service life the aluminium can again be recycled which requires just 5-7% of the primary process (Asif, Muneer, & Kubie, 2005). Figure (2.4.1.)

Timber

Wood is the oldest window material and is still on the market because of the good thermal insulation, the availability and ease of work. In the research of (Asif, Muneer, & Kubie, 2005) wood is classified as a renewable source if softwood such as Baltic redwood or pine is used.

After cutting, a treatment is applied to the timber such as vacuum impregnation to gain a longer life span. The requirement of the wood is that it has grown uniformly and is resistant to warp. After the end of service life the timber product can be down cycled to for instance animal bedding or to chipboard production.

PVC

Polyvinyl chloride is made out of chlorine (51-57%), carbon and hydrogen derived from fossil fuel (natural gas and petroleum) (Asif, Muneer, & Kubie, 2005). Normally it is produced from sodium chloride (salt) ,natural gas and oil being cracked. The production of PVC requires a lot of energy and damaging substances such as emissions of chlorine gas come free. Appendix Life cycle of Aluminum, timber and PVC. The recycling depends on the purity of the material. As many additives have to be added the PVC to make it stable, the waste stream becomes a complex mix of materials from different sources which can make recycling technical and economical difficult, therefore PVC is mostly just down cycled.

Conclusion: The materials used in facade systems carry big amount of embodied energy. In case of renovation it is from sustainable viewpoint better to remanufacture the current systems instead of replacing them. In this way the waste stream will be limited. (Konstantinou, 2014). Because even tough materials can be recycled such as aluminium, in practice the maximum percentage that can will be recycled is just 68 percent (Schüco).

	Aluminium	PVC	Al clad timber	Timber
Service life (mean years)	43.6	24.1	46.7	39.6
Maintenance level	Low	Low	Low	High
Ease of repair	Not needed	Difficult	Easy	Easy

Figure 2.4.1:(total embodied energy of a complete window of each type. The embodied energy values for standard (1.2 m_/1.2 m) krypton (Kr) filled double-glazed. (Asif, Muneer, & Kubie, 2005)

2.5 Renovation strategy

Ebbert (2010) describes the different location of the thermal barrier line of the façade panels in relation to the structure which is shown in the Figure 2.5.1.1.The vertical grey lines illustrate the construction. The dotted lines show the possibility of a non-interrupted balcony where the dotted grey lines define an interrupted balcony. The black lines represent the walls and or floors. Yellow is used to show the thermal separation on which line also the windows are placed.
As can be seen there are several ways of placing the façade/ window panels onto the building. The detailing of these structures determines how the replacement of the windows takes place and in what order parts have to be replaced.
Looking more into detail, figure 2.5.1.2 shows the difference of a window wall in contrast to the curtain wall. The window wall installed from the inside and spans only from the upper side of a floor slab to the underside of the floor above. Therefor in case of a curtain wall there may appear a thermal break on the floor above or under while removing a panel so this has to be taken into account when planning to replace (parts of) the facade 2.5.1.2.

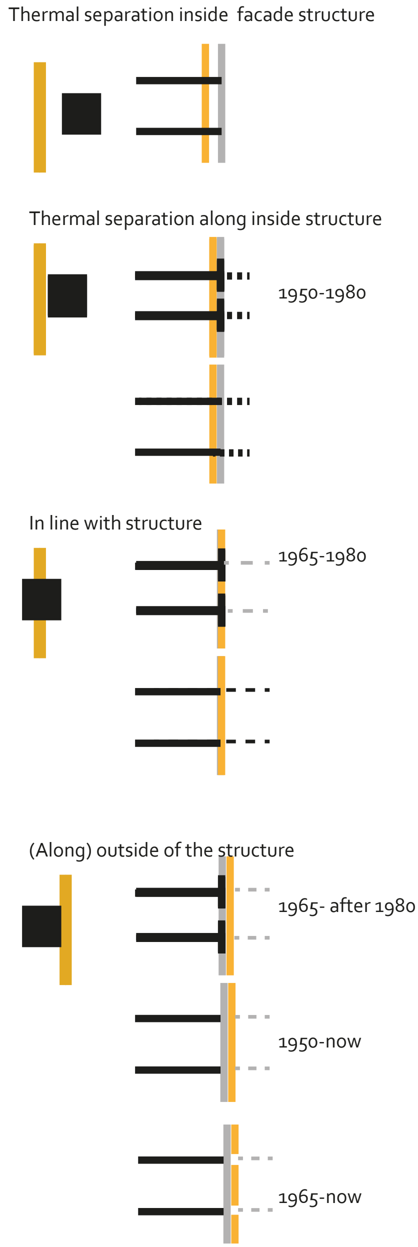


Figure 2.5.1.1: Place of the thermal separation (Ebbert, 2010)

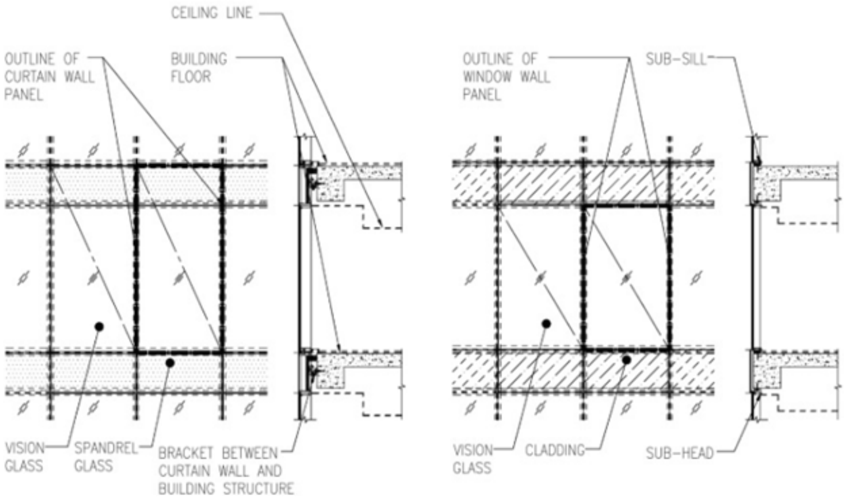
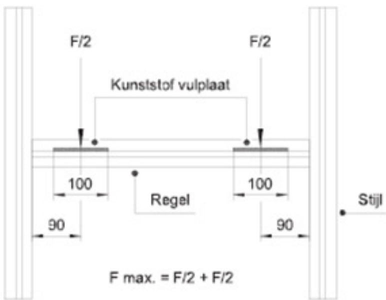


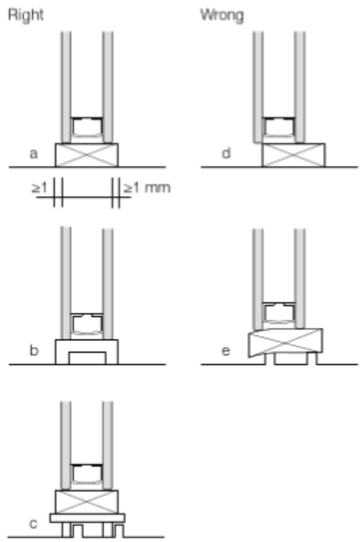
Figure (2.5.1.2): Outline in case of a curtain wall (left) and a window wall (right) (Lee, Shepherd, Evernden, & Meltcafe, 2017)

The position of a window and rebate inside the building envelope in an important decision. A reference for this is Hochberg (2009). The decision of the position of the window and rebate depends on several factors such as:
-Architectural vision: about the form, colour and visibility of the window
-Functional: Opening type, ventilation requirements, shading, operation convenience
-Economic: Ease of placement, intrusion protection.
-Technical: Safety regulations relating to balustrade, fall heights, water tightness of joints, sound insulation, fire safety.
(Hochberg, Hafke, & Raab, 2009).

Place of insulated glass within the rebate
To prevent local stresses that can cause failure in the glass panel due to construction inaccuracies and not intended impacts, there are a few design principle made to building with glass.
One of them is no contact between glass and harder materials or damaging mechanical actions. This can be prevented by placing an intermediate pad between the glass and the façade material to absorb deformations of the supporting construction. The pads can be made from various materials such as synthetic materials, casting resins or aluminium alloys. Also setting blocks which are usually made from hardwood or plastic are used to support the panes vertically, they are normally positioned 100-250 mm from the corners are 80-100 mm long and usually 2mm wider than the thickness of the glazing panel (Figure 2.5.1.3).
Furthermore the façade itself should also guarantee a certain level of serviceability, a suitable connection method and ensure durability of weather resistance. (Weller, Unnewehr, Tasche, & Härth, 2009)



(Figure 2.5.1.3): Position of the setting block(Weller, Unnewehr, Tasche, & Härth, 2009)



A:Setting block positioned right
b:Bridge packer positoned right
c:Setting block placed on packing shims in profiled rebate positioned right
d: Setting block positioned incorrectly, load distribution not guaranteed
e:Setting block positoned incorrectly in profiled rebate, the profiling and weight of the panes deform the setting block.

Figure (2.4.1.3) :Position of the setting block, right and wrong, (Weller, Unnewehr, Tasche, & Härth, 2009)

Service life

As concluded at the 2ndSkin demonstrator, all parts and materials used for a building, reach the end of their technical life span at a different time. The load bearing structure can for example last a century while the facades and technical installation only reach 30 years. Where even materials in the façade have different service life. Joint's seals and fastening elements are one of the most determining factors for the service life of the whole façade as they cannot be removed from the inside without compromising the system (Simmering, 2019), resulting in failure of the whole system. It should be favourable to use materials with the same service lives or bundle them with the same multiple of service lives in order to optimise the use and ease of replacement of those materials (Figure 2.5.1.5).

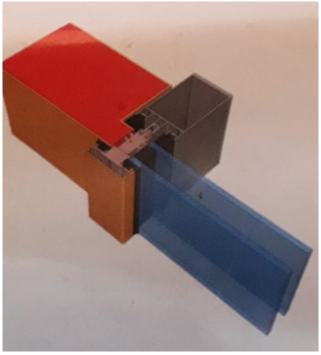
Elements	Materials	Service life of the elements		Ts in Years
		min	max	average
Claddings	Rendering	20	81	50
	Paint	4	10	7
	Stone	20	70	45
	Glass	80	120	100
Supporting structure	wood	25	35	30
	steel	30	50	35
	Stainless steel	30	60	45
Window door frame	Hardwood	40	60	50
	Softwood	30	50	40
	Aluminium	40	60	50
	Steel (galvanized)	40	50	45
	PVC	40	60	50
Window, doors and protection elements	High quality wood	10	69	40
	Aluminium	10	58	34
	PVC	10	49	30 24.1*
	Aluminium clad timber	10	-	46.7*
Joint's seals		3	20	11
	EPS			15
Fastening Elements/Doors and Window fittings	Galvanized steel	10	10	10
Glazing	Single glazing	60	100	80
	Insulated glass	20	30	25
	(EPDM)Gaskets	15	25	20
	Movable sun blinds	20	30	25

Table 2.4.5: Estimated service life for each façade element (Ebbert, 2010) *are the values retained from (Asif, Muneer, & Kubie, 2005) which differ significantly with Ebbert (2005).

table 2.4.5hows estimated service life values for different components in facades. The numbers shown in the table are calculated as its theoretical life multiplied by a series of factors (depending on the quality of the design level, execution level, usage conditions and maintenance level). The durability of the windows also depend on the weathering performance due to interaction with the exposed environment such as UV, temperature, humidity oxygen and pollution.

Upgradability

There are many ideas of creating an upgradeable façade in order to extend the service life of certain parts. A recent plan of De Groot & Visser for instance is the adaptable facade pin that can be integrated in a stick system curtain wall where the requirements of the new norms can be implemented using the same frames but with additions to the infill(figure 2.5.1.4)In this way the list of Table 2.4.1.5 can be adjusted through time. The thickness of the façade panel or glass including the edge seal can be as thick as necessary in a next renovation.



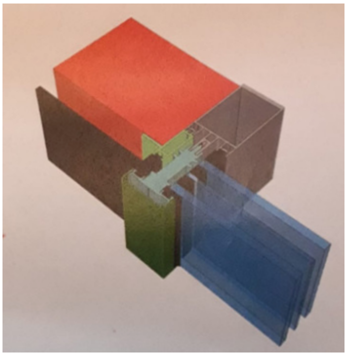


Figure 2.5.1.4: Example to make an existing façade adaptable, with the light green pin (DeGroot&Visser).

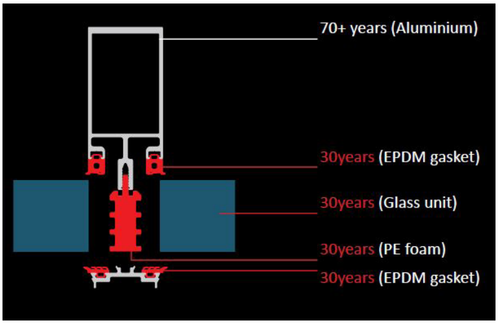


Figure 2.5.1.5: Different elements service life(Thalia Kakolyri, 2015)

2.6 Conclusion

The type of window frame used in buildings depend on several factors such as the architectural view the use but also the height of the building. Different materials can be used for these same window type systems which depend on the requirements set by the different parties. However, choosing for the aluminium window/door system where the window is installed from the inside would cover lots of low-rise offices in the Netherlands while avoiding extern construction differences described by (Ebbert, 2010) such as balconies. At the moment there are many ideas to renovate buildings with the idea of restoring the embodied energy of the elements. An example is 2ndSkin demonstrator but also upgradabiliy ideas. Concerning window: When looking for minimum hindrance during maintenance of the surrounded elevations it is favourable to choose windows that covers the height of one elevation only. The thesis therefor will focus on window/door systems as the windows in contrast to curtain walls can be changed from the inside.

The three steps picture(Figure 2.6.0.1) shows how easy it is to change the IGU:

The first step is to take out the four EPDM gaskets this can be done with a simple push with e.g. a screwdriver to tilt the EPDM gaskets and pull them out.

Once the EPDM gaskets are removed, the glazing bead can be taken out as well which leaves the glazing panel the only thing to remove. The glazing panels can be picked up with a suction lifter that clamps on the glass (figure2.6.0.2).

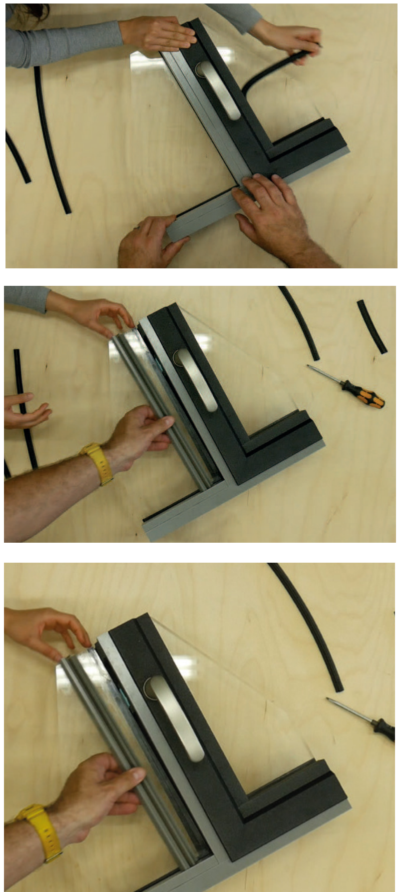


Figure 2.6.0.1 The three steps for removing the IGU in a window system(Vargas, 2019)

Figure 2.6.0.2: Window suction lifter https://www.zuignap.com/

CHAPTER 3
Insulated glazing unit

Content

Functions of the IGU
Components of the edge seal
Ageing of the edge seal
Glass panes
Ageing of glass
Conclusion

Functions of the Insulated Glazing Unit (IGU)

The first use of glass known in buildings was used more than 2000 years ago and used to seal off entrances. Even back then, the main functions of glass were already utilized: allowing light entering the space while protecting the inside of the outdoor environment (AGC Glass Europe, 2014)

The concept of double glazing for insulation became important during the 1970's and various products have been evolved since.

This chapter will give an overview of the current elements of the IGU. Focusing on materials, manufacturing processes and ageing factors to answer the question: What requirements should the new IGU meet to last more than 100 years taking into account every ten years of remanufacturing?

3.1 Components of the edge seal

Insulated glazing units are constructed out of a number of different elements, including glass panes, spacer bar, desiccant and sealants Figure (3.1.1.)The quality and lifetime of an IGU depends on the (lowest)quality of the individual components and the quality of the manufacture. Failure can visually be noticed through fog and can be felt or measured by a significant temperature difference within different but similar rooms (Garvin &Wilson, 1998).

For the report it must be noted in order to understand the position numbering of the layers of glass and coatings or foils. Counting starts from the outside to the inside as is depicted in figure (3.1.2.).

§3.1.1 The sealant

The sealant at the edges of the glass panes bonds the glass panes and spacer bar structurally together while it seals the cavity hermetically from infiltration of water vapor or leaking of the gas between the panes. It also allows flexibility to accommodate glass movement. IGU were previously fabricated with just one sealant but nowadays dual-sealed IG units are more used with both sealants in different materials .

Durability problems of an IGU is most commonly caused by water vapour which naturally occurs in every IGU. The water vapour is absorbed by the desiccant until saturation. After this, it may lead to condensation. Therefor it is important that the edge seal has a high resistance against vapour .
The cavity is filled with argon or krypton for improvement in thermal performance. The difference in pressure of the gas within the IGU and outside the IGU,

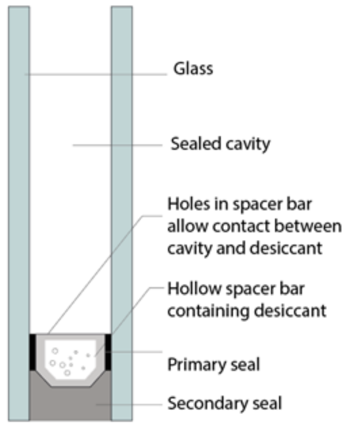


Figure 3.1.1: Elements of IGU.

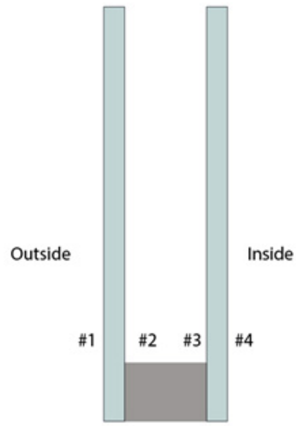


Figure 3.1.2: Index numbers of IGU.

causes the gas to diffuse from the seal. For the seal it is therefore necessary to have a low gas. Based the current product norms, gas leakage is maximum one percent per year and the Ug value of the IGU is calculated for a 90 percent gas filling. With a tolerance of five percent, this means that after 15 years there is still enough argon inside to claim the same Ug value(kenniscentrum glas).

There are three different types of condensation that can occur at IGU's . The position on which this occurs can indicate the quality or issues of the seal.

-Surface condensation on position four (facing the inside of the building). This occurs if the room behind the glass has a high relative humidity or when the surface temperature of the position four glass pane is too low. It indicates a low insulation value of the whole IGU.

-Surface condensation on the inside of the cavity shows that the edge seal is no longer hermetic against vapour and humidity and so the IGU is defect.

-Surface condensation on position one can occur at specific weather conditions (e.g. dawn after a clear night with little wind). This indicates a well-insulated window as the outside of the pane has such a low temperature that condensation forms on the outside.

The primary seal together with the spacer bar assures the low gas and vapour permeability. Metal is typically used as the vapour and gas barrier in the form of the metal spacer bar or as an integrated foil in the spacer bar. The bigger the width of the primary seal the more mois-

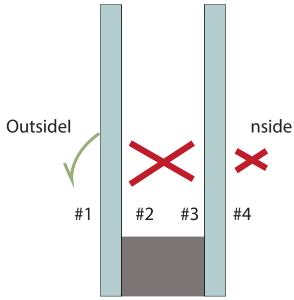
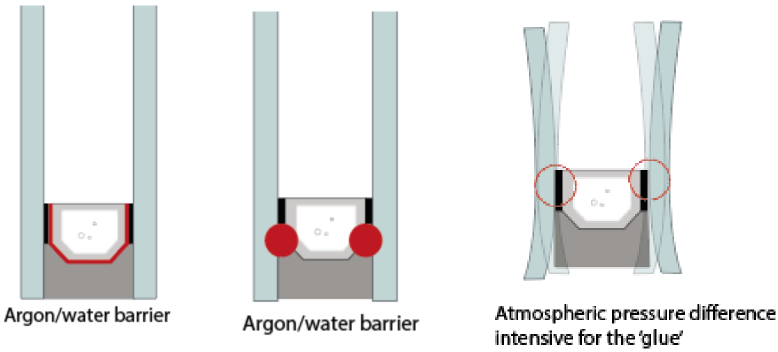


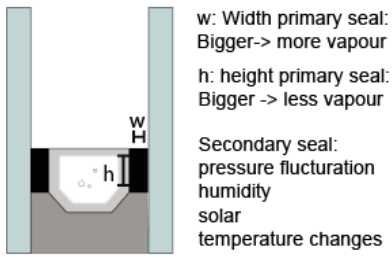
Figure: 3.1.1.1: top: condensation on the IGU https://pixels.com/featured/condensation-on-surface-of-a-window-science-photo-library.html. And **down**: the favourable place to see it.

ture diffuses through it while the higher the primary seal is the less moisture diffuse . For the primary seal mostly rubbers such as polyisobutylene (PIB) are used. Since the vapor permeability of the butyl is much less than of the secondary seal, only the primary seal functions as diffusion resistance.

The main function of the secondary seal is thus maintain good adhesion when exposed to the environmental situation such as: temperature differences, thermal cycling, high humidity, solar radiation, atmospheric pressure fluctuation, wind loads, working loads and the relevant loads during manufacturing, transportation, installation and



maintenance. (Van Den Bergh, Hart, & Petter, 2013).



- For this type of sealant Polyurethane (PU), silicone (Si), polysulphide (PS) , hot-melt butyl or epoxy-based sealants can be used. The choice of the secondary sealant should be based on the environment situation. Typical thickness of the secondary seal is around 4 mm while the primary seal has a thickness of 4-6 mm (Wolf, Silicone sealed insulated glass units, n.d.). The majority of failures of IGU are caused by adhesion loss of the secondary seal. The Three requirements of the secondary seal are:

- Low moisture and gas permeability under service conditions,
- *-Structural strength that constrains movements in the edge-seal to minimize changes in the effective diffusion cross-section of the primary seal (figure 3.1.1.3),*
- *-Resistance against environmental factors in terms of physical properties and adhesion*

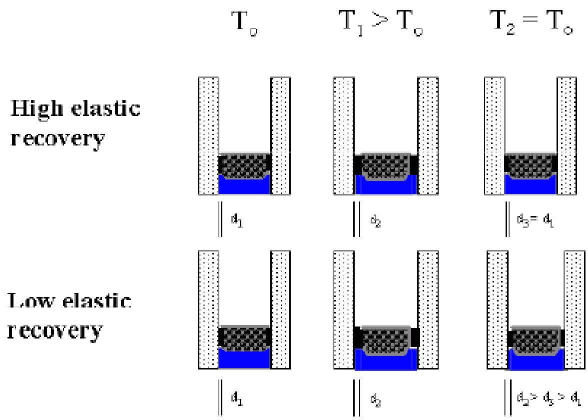


Figure3.1.1.3: Elastic recovery (Wolf, Silicone sealed insulated glass units, n.d.)

§3.1.2 Spacer bar

The main function of the spacer bar is to create a fixed airspace between two or more panes of glass and to stop gas and moisture vapour of getting in and the insulating gas of escaping out of the sealed unit. Filling the spacer bar with desiccants helps increasing the life span of the IGU as the water vapour that still enters the cavity will be absorbed. There is no limitation to the shape of the bar as long as it allows tightly sealed corner connections , usually with plug-in type corner keys from metal or plastic. The condition of the spacer bar is the rigidity. It should be stiff enough to guarantee clean sightlines in the double or triple glazed unit without sagging and easy manufacturing process when the glazing unit is put together. This last requirement can be explained as following: When the spacer bar is ridged enough, the centre does not sag much during mounting of the frame and thus is easy to assemble. The typical profile height of spacer bars is in between 4 mm and 8 mm and the width varies between 12 mm and 14mm.

Traditionally, spacer bars have been made from aluminium or galvanized steel, however these materials can be thermal bridges if not detailed properly. The edges of the glass could become low in temperature which can lead to condensation inside the glass panes, which in return, can lead to mould growth and deterioration of the frames. Nowadays, new edge seal designs are on the market with improved thermal performance the so called: Warm Edge Technology (WET) (Van Den Bergh, Hart, & Petter, 2013).

Studies have been done about improvements of spacer bars for warmer temperatures of the edges of glass. Elmahdy(2006) tested spacer bars that were placed in between two clear glass panes, air in the cavity and without frame shown in figure 3.1.2.1. The tests were performed with four different materials (vinyl, thermally broken aluminium, redwood and foam-filled fiberglass) and in different shapes of the spacer bars. The IG1, IG7 spacer bars of are designed with grooves for an enlarged layer thickness of the seal to reduce the mechanical stress on the primary sealant as (Wolf, Studies into the Life-Expectancy of Insulating Glass Units, 1992) suggested.

The conclusions of the research stated that the warm edge spacer bars have a positive effect on the edge-of-glass temperature which results in condensation reduction and a higher R-value in comparison to the conventional spacer bars. Non-metal spacer bars performed better but combining materials can lead to premature failure of the edge seal as result of the different thermal expansion/contraction coefficients, (Higgings, Hubbs, & Finch, 2016).

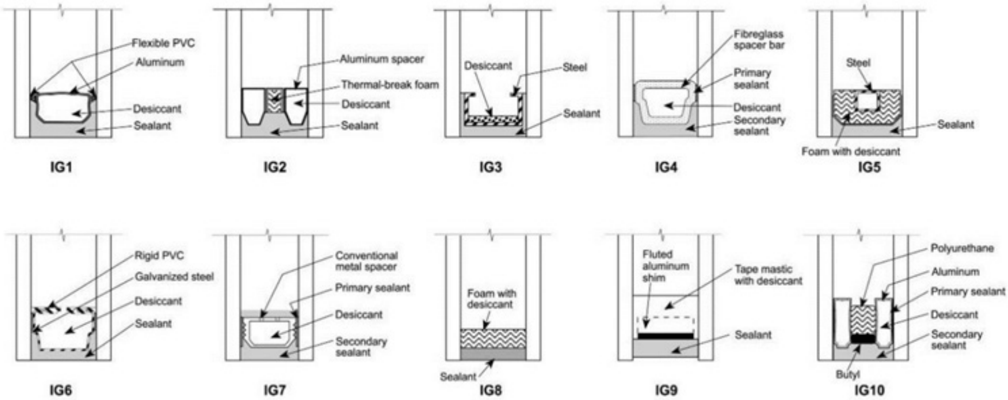


Figure 3.1.2.4:WET spacer bars tested by (Elmahdy, 2006)

Production of the spacer bar,

Large glass panes enters the mounting factory by truck. The dimensions depend on the type of glass as different types are made with other machines. (for instance the maximum panels are 6*3.21 for Strasobel or 2.25*3.21 for Pyrobel as the width of the float bath of AGC is 3.21m). The glass panes will then be cut to size and depending on what type of glass or the size it needs to have, this will be done in an automatic process or manually. With manually cutting, water is needed to cool down the heat from the friction. The automatic process for AGC Oosterwolde is also divided into three categories namely: clean float and coated, another machine can handle coated and laminated glass until two panes and the third production line is specially for laminated glass with more than two panes. The cutting of the panes is automatically done but the final breakage is done manually. For laminated glass a hot wire will make sure that also the foil will be cut properly.

In the meantime the spacer bars are bend and cut on size.

The most common way is with the help of a bending machine where just one spacer bar that is already cut to length is bent. For this method a heating device is needed to help bending the profile and film. With this method only one linear connector is needed to attach both ends to each other. The frames have rounded corners but tools are available for after processing in case 90 degree edge sharp corners are required. After this, the spacer bar will be filled with desiccant by a machine.

After the edges of the spacer bar is spread with butyl, the ends are filled with a foam to plug the ends so that the bars can be filled with desiccant individually without trickling out. Next the corner keys are inserted and the frame will be fitted together. Afterwards butyl will be applied on the sides of the frame by the butyl coating machine. Hereafter it is ready to be assembled on the panes.

Now the first pane of glass will be placed with a crane on the production line after it is washed and dried. A sticker with the specifications of the order is attached on the outer side of the pane. Now the spacer bar is aligned to the first glass pane. The same routine goes for the second glass pane and second spacer frame that is mounted and aligned at an equal distance from the edge of the glass . Then the third glass pane is attached to it as well and as last the package goes to the press to fill it with inert argon gas so it can be pressed into one unit due to the butyl. After the press the edges will be automatically filled with the secondary sealant. And if needed the corners can be smoothened with rollers. Since the fresh sealant is not able to carry any shear, the pane cannot be carried with the vacuum suction cups so therefore a fork has to lift the unit off the production line. It takes around 2-3 hours for the pane to completely dry (AGC interview) where after the panel will be transported (figure 3.1.2.5) .

Figure 3.1.2.5 Corks will be placed on top of the glass pane for it to transfer (AGC)

Innovations on the technology of bending the spacer bar are also to be found for instance

spacer bars that are welded by an ultrasonic machine. With this method four corner keys are needed. This process is mostly chosen if large amount are needed. According to ' swissspacer' a frame can be produced in just 30 seconds with machines such as:' Forel bending machine' from Forel Italy,' BOZA bending machine' Boza China and rotla rudiger systems.

It is also possible to bend the spacer bars in a round shape:

The processing is now as follows: The cut to size spacer bar is put in a heating chamber (Rockler and Boudicca Germany Swiss) of 135 degrees Celsius where it stays for three to five minutes, after this the spacer bars can be moulded into shape by placing them around a template and fix it with clamps.

After cooling down, the shaped spacer bars can become rigid again and the clamps can be removed, now the ends are cut to size. At last a linear connector is inserted and the ends can be connected to each other. The standard dimensions are:

Dimensions:

- *Width: 08, 10, 11, 12, 14, 15, 16, 18, 20, 22, 24, 27 mm*
- *Height: 4-8 mm*

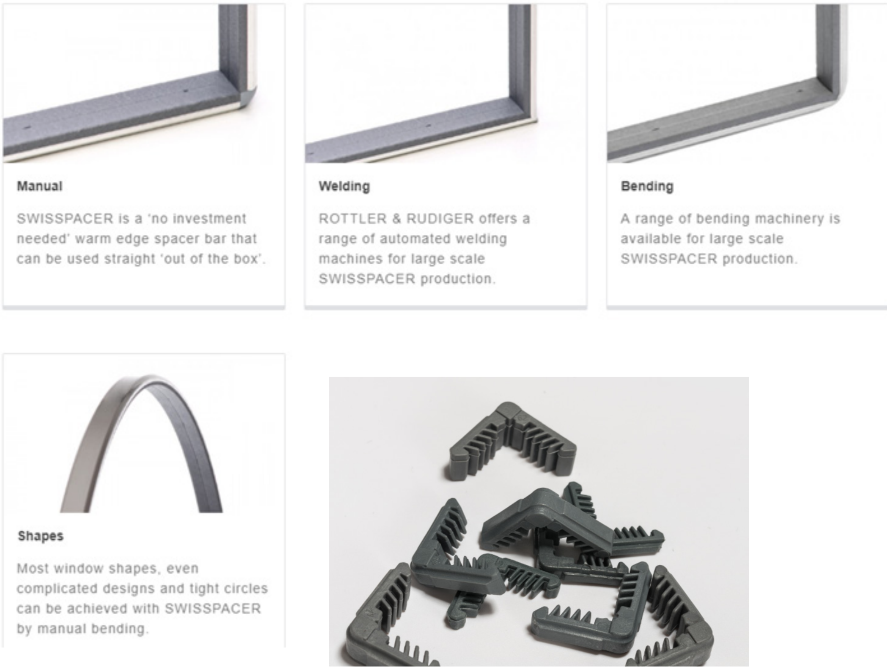


Figure 3.1.2.6:Ways of producing spacer bars. (Swissspacer and China glass Network)

Flexible spacer bar

A different design approach is a flexible, silicone foam spacer bar. This spacer bar has integrated the desiccant in the foam and pre-applied side adhesives to achieve a fast and easy manufacture process of the IGU (figure 3.1.2.7). This design variant is a warm edge spacer bar that uses multi-layer moisture vapour seal and acrylic adhesives for preventing moisture ingress and bonding to the glass panes. Furthermore the manufacturer of this edge seal claims that this spacer bar reduces also noise pollution up to 2dB (edgetech 2019).

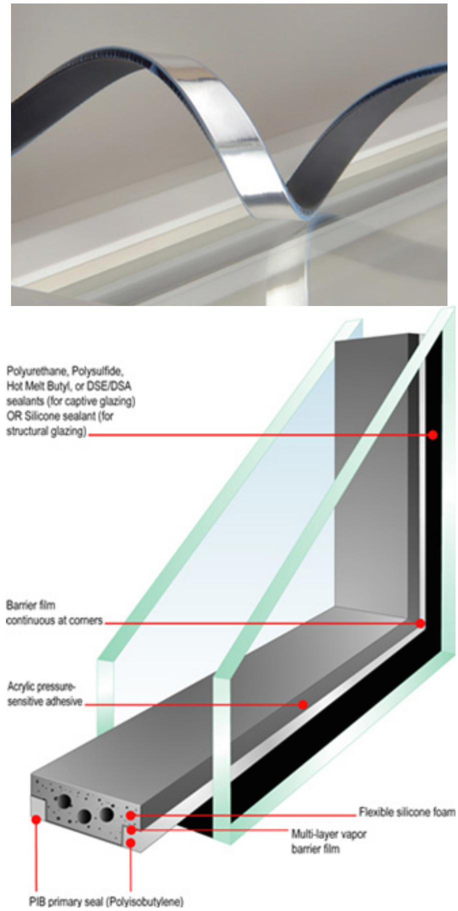


Figure 3.1.2.7Flexible silicoane foam spacer Super Spacer Alpha from edgetech

Spacerbars that control the air flow

Swisspacer has a product that contains a spacer bar with a valve(Figure 3.1.2.7) to solve the glass breakages when dealing with climatic and atmospheric stresses. Differences in air pressure can lead to build-up of excess or negative pressure inside the insulating glass especially when the glazing unit will be transported over different heights. With air valves the pressure can be equalised between the outside and inside of the panes.

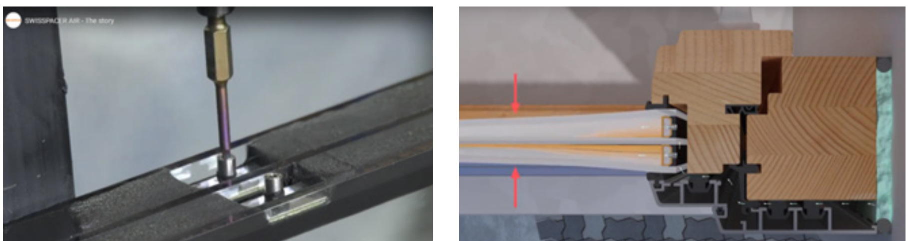


Figure3.1.2.8 :The swissspacer air slows down the in- and outflow of the airflow. But in this way an equilibrium is achieved.

§3.1.3 The desiccant

Desiccant is a substance with hygroscopic properties and has the function of preventing condensation of moisture between the panes. It is important as they increase the life span of the IGU, controlling the water vapour pressure and gas pressure to the same level as when being manufactured. The function of the insulated glazing unit works until the capacity of the desiccant is reached after that point the thermal conductivity will increase.

An example of this material is zeolite(hydrated alkali-aluminium silicates minerals) or fumed silica. In case of the fumed silica, opacifies (carbide powder) are sometimes added to make it opaque to the infrared for less conductivity. However, the water absorbance capacity for the desiccant depends on the percentage of relative humidity (figure 3.1.3.1)

The desiccant (shown in figure 3.1.3.2) is poured inside the spacer bar where the side that faces the air space between the two panes of the IGU is perforated to allow the air inside the double glazing to communicate with the desiccant within the spacer bar. In 1992 (Wolf, Studies into the Life-Expectancy of Insulating Glass Units, 1992) formulated that ' a spacer bar on four sides should be capable of holding a minimum of 40 grams of desiccant per running metre'.

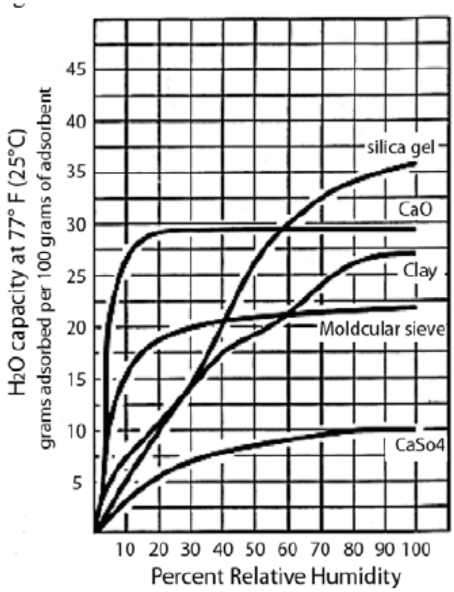


Figure 3.1.3.1: Comparison of different desiccant material by relative humidity and water absorbance (Van Den Bergh, Hart, & Petter, 2013)

Figure 3.1.3.2: (Desiccant CAS number: 1318-0201)(https://www.sigmaaldrich.com/catalog/search?term=1318-02-1&interface=CAS%20No.&N=0&mode=partialmax&lang=en&region=NL&focus=product

3.2 Ageing of the edge seal

One main role of the IGU is to keep the thermal insulation properties for a comfortable climate at the inside environment. The degradation of windows can lead to an increased heating energy demand in buildings (Asphaug, Jelle, Gullbrekken, & Uvslokk, 2015).
Loss of gas inside the IGU as result of the ageing of the edge seal can occur by degradation of the sealing of the IGU's. The aging factors of the glazing units are influenced by : Thermal stresses, atmospheric pressure fluctuations , windborne debris, the uniform lateral load of short or long duration, interior pressure due to building stack effect, sunlight and water vapour.

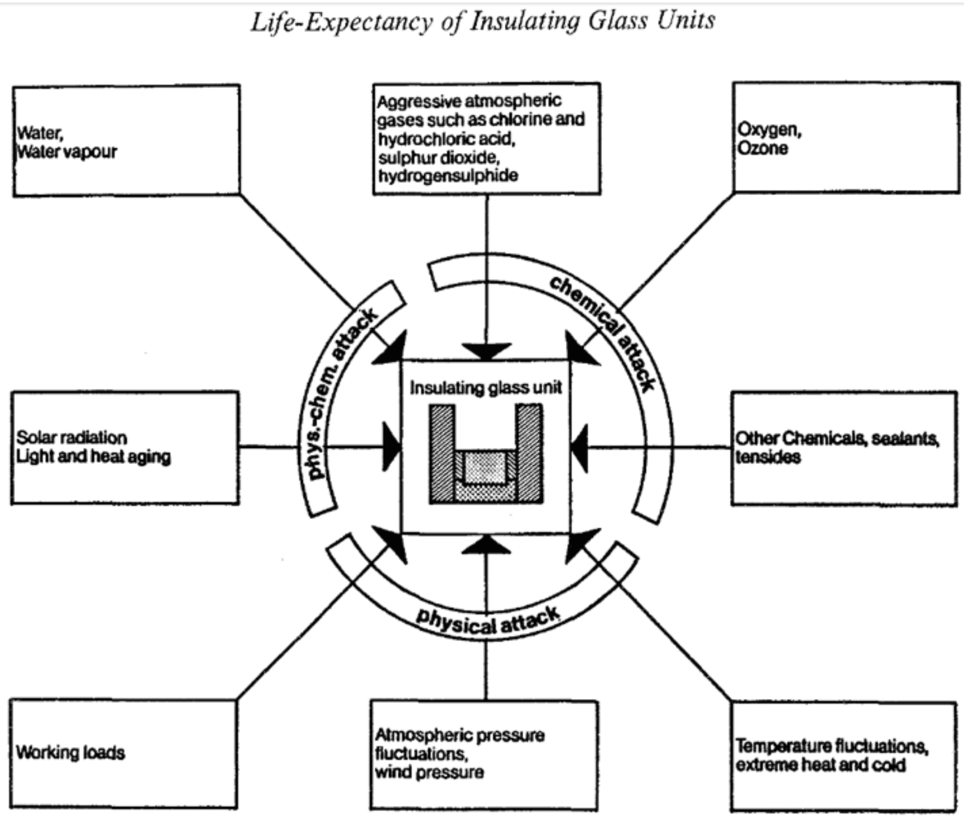


Figure 2.2.1: Light effect on the edge seal through internal glass pane reflection (Wolf, Studies into the Life-Expectancy of Insulating Glass Units, 1992)

§3.2.1 Temperature

Temperature fluctuations results in pressure differences within the IGU that causes mechanical stress and will lead to shearing and peeling forces on this edge seal. Low temperatures have negative effect on the flexibility of the edge seal while high temperatures cause ageing through a chemical process of the edge seal that lead to diffusion of water vapour. The proportions of the window also matter as can be seen from figure 3.2.1.1 where units, with one long side and one short side as well as units with wide cavities are unfavourable (Wolf, Studies into the Life-Expectancy of Insulating Glass Units, 1992).

The ‘Swisspacer bar’(already discussed in paragraph 2.2.2.) has applied on its product a strategy to deal with this ageing factor that can cause abrupt breakage of the glass. However, in contrast to the Argon filled IGU's, the Swisspacer bar allows air flowing in and out of the glass unit bringing in water vapour what will increase the thermal transmittance inside the cavity. Furthermore rapid wind changes by wind gust can still produce mechanical stresses in the edge sealant.

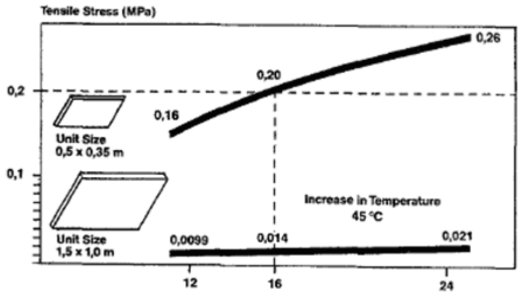


Figure 3.2.1.1: Stresses on the edge seal caused by thermal influences (Wolf, Studies into the Life-Expectancy of Insulating Glass Units, 1992)

Figure 3.2.1.2: Appearance of deformation of glass panes Source:own illustration.

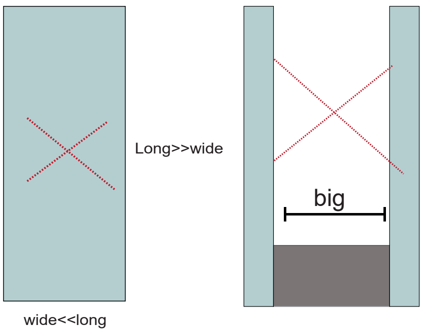


Figure 3.2.2.3: unfavourable dimensions for the IGU based on (Wolf, Studies into the Life-Expectancy of Insulating Glass Units, 1992).

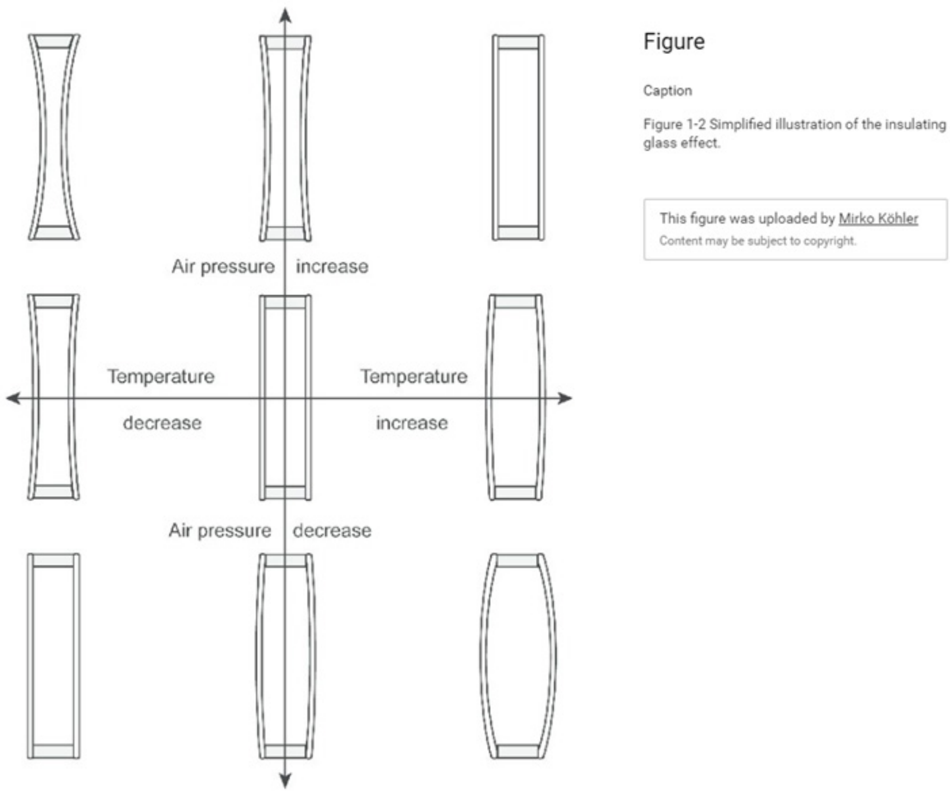


Figure 3.2.1.4.: Influence of the pressure differences Source: (Döbbel & Elstner, n.d.)

§3.2.2 Water

Water and water vapor can also cause physical and chemical stresses on the edge seal. When water vapour goes through the sealing , absorption of water will lead to swelling of the sealant. This swelling of the edge seal will lead to opening of the primary seal causing a higher water vapor into the cavity. Furthermore water can also lead to chemical reaction in the bonding of the glass which can cause damage to it.

§3.2.3 Sunlight

Despite the casement of the IGU, still three% of the total light (UV around 280 nm in wavelength)on the window reaches the edge seal due to internal reflections in the glazing unit as illustrated in figure 3.2.3.1. The sunlight can therefore cause both physical and chemical stresses on the edge seal. This process is even accelerated when tinted glass is applied because of the percentage of visible light that is converted into heat. To prevent this situation, the edge seal should be protected with e.g. attaching strips, gaskets or tapes (Wolf, Studies into the Life-Expectancy of Insulating Glass Units, 1992).

Clear glass edge sealings can reach temperatures of 40 degrees Celsius in central Europe, however in warm climates the temperatures for the edge sealing of tinted or coated IGUs may reach even temperatures of above 80 degrees Celsius for longer time-periods (Figure 3.2.3.1). Especially in combination with higher temperatures, oxygen and ozone can cause gradual oxidation of organic sealants.

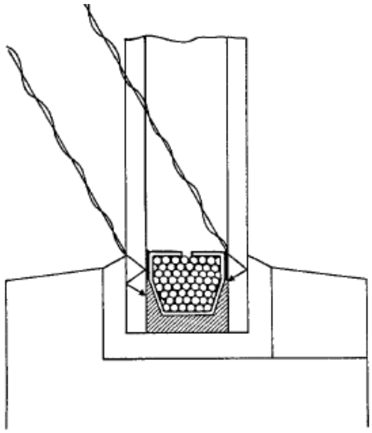


Figure 3.2.3.1: Reflected sun waves reflected (Wolf, Studies into the Life-Expectancy of Insulating Glass Units, 1992)

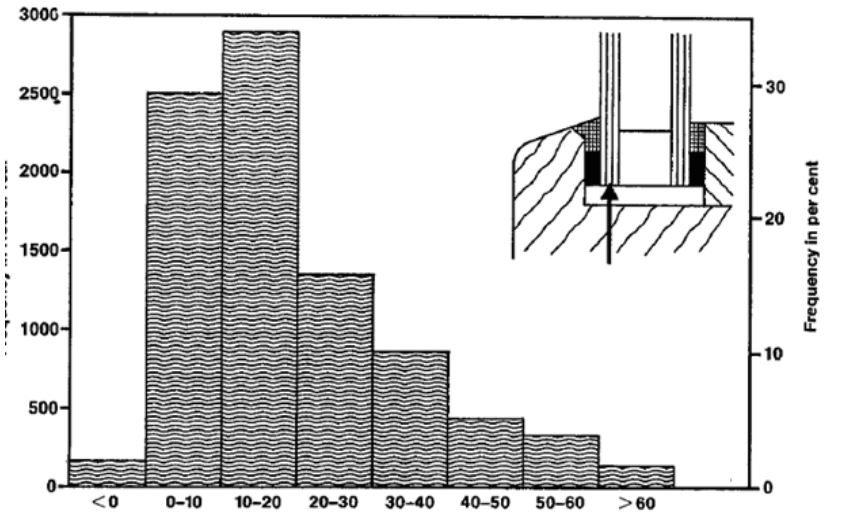


Figure 3.2.3.2:Temperatures measured in an IGU Wolf, Studies into the Life-Expectancy of Insulating Glass Units, 1992).

3.3 Glass panes

The improvement of the glass industry.
Float glass is used in many applications. Due to its optical quality, low cost, production speed and possibility to produce large sizes and different substances (thickness availability is varying from 1-25 mm) it is ideal to produce windows or mirrors for architectural, automotive purposes and commercial purposes such as displays and screens.
The glass industry has always been developing its product to achieve a better heat resistance. The first insulated glass with dehydrated air invented in the 1960s gave a heat loss reduction of 50% compared to single glass (U-value of 5.6 W/m2K). It took around fifteen years for it to be widely used (Ebbert, 2010). In the 1980s low e-coatings were developed and also this improved the U value to 1.8 W/m2K. After this development, new cavity filling with a lower specific heat capacity were applied for a lower u-value, argon (1.1 W/m2K), krypton (0.8 W/m2K)or xenon. Argon is widely used since this gas is relatively cheap in comparison to the others for the reason it is more easy to filter from the air.
For the window cavity a boundary condition of around 16 mm width is found to limit convection therefor the next huge development was triple glazing with argon filling that can reach an U-value of 0.7 W/m2K. However triple glazing panels can become heavy due to the glass pane weight, therefor the inner glass pane can be replaced by a low-e coated plastic foil. The current development has a different system based on vacuum insulated glass. The explanation of these parts, how they are manufactured can be read further in this section

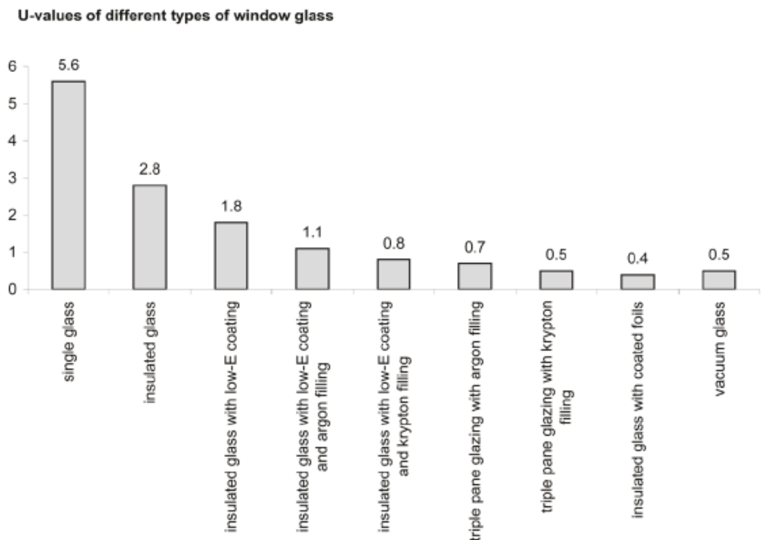


Figure 3.3.1: Development of different types of window glass and its U-value. (Ebbert, 2010)

§3.3.1 **Definition of float glass:**

Sir Pilkington developed in 1959 a process to produce the float glass we still use nowadays for making of flat glass. Before this development sheet glass was produced by cylinder blown sheet, cast rolled, automated rolling or drawing method(table 2.4.1.1). However, when high optical quality was required, both grounding and polishing were necessary which made it very costly and time-consuming.

Process	Glass thickness	Surface	Air inclusion
Cylinder blown sheet Pup to 1900		wavy, uneven and not plan-parallel	yes
Cast rolled	6-8 mm	strongly wavy	yes
Drawn (Fourcault process) around 1904	from 0.8 mm	moderately wavy drawing lines uneven	little
Drawn (Libbey-Owens/Pittsburgh) 1904-1928	from 0.8 mm	moderately wavy drawing lines uneven	little
Float glass (Pilington (From 1959 onwardsa)	15-25 mm	not wavy	very few

Table 3.3.1.1: Glass manufacturing methods over the years

Glass is made of the raw materials: silica (sand), soda ash (NA_2CO_3), $CaCO_3$ (limestone), CaO (gained from dolomite but additionally also from limestone),MgO (found in dolomite) and other minor ingredients such as K_2O, Al_2O_3 and Na_2SO_4. The ingredients determine the quality of glass at different aspects, such as optical quality and weathering resistance. Alumina for instance contributes to the weathering resistance of glass, while the sodium carbonate that may exists in glass after manufacture even assist in weathering. An additional amount of crushed recycled glass which is called the ' cullet' is also added to lower down the needed furnace temperature both as the CO_2 emissions. Using one ton of cullet saves approximately 1.2 tons of raw material whereof 850 kg sand and reduces around 300 kg CO_2 (Saint gobain, 2018).

The cullet consists of different waste stream:
Recycled content: is defined by the mass proportion of recycled material in a product.
Only pre-consumer and post-consumer materials are considered as recycled content. And only material that would otherwise have entered the solid waste stream but instead being recycled can be seen as recycled.
Following LEED v4: Building product disclosure and optimization-sourcing of raw materials criteria, the recycled content is 5.5% by weight and has the following formula:
Recycled content according to LEED v4= post-consumer content+(1/2) pre-consumer content.
pre-consumer material: material that is rejected from the production line during manufacturing before the final product reaches the market. Pre consumer waste flat glass is made out of cut-offs, losses during laminating, bending or other processing, including the manufacture of insulating glass units or automotive windscreens. 11 % of pre-consumer material is used for the cullet (Saint gobain, 2018).
Post-consumer material: materials that do not longer function for its intended purpose generated by end users such as households or industrial facilities. In practise these are the materials coming from glass recycling waste. Less than 1 percent is used for cullet (Saint gobain, 2018).

§3.3.2 Production of annealed float glass:

The widely used float glass line is showed in figure (3.2.2.1) .
First, raw materials including the cullet are blended together(figure 3.3.3.1) and heated up to a temperature of about 1500 to 1600 degrees Celsius in large tank furnaces using oil or natural gas as fuel to form molten glass. In this process the gasses CO_2 (evolved from decompositions of carbonates), H_2O (from the wet batch) and N_2(from trapped air in the batch) come free during the melting process.
The oxidation state has to be in control in order to get the desired product.
The Reynolds number which determines the viscosity of the molten glass is relatively low (<10) therefor the molten glass has a laminar flow in the tank furnace which is not beneficial for a homogeneous mixture therefor, mixing is necessary.
After melting the glass will go to the refining process where any remaining air or gas bubbles will be removed for a standard quality of less than one small bubble per 40 m^2 of glass (source Buckett, 2000). In order to help gasses such as N_2 and Co_2 refining agents such as Na_2SO_4 will be added to the glass batch. Removal of the bubbles and redox reactions however does not fall in the scope of this research.

The Next step of the process is the float bath where the molten glass (density of 2350 kg/m^3) will float onto molten tin (6500 kg/m^3) due to the density differences. Gravity and surface tension assures the flatness of the glass and a nitrogen/hydrogen atmosphere is created to keep the glass surface as clean as possible and prevents oxidation of the tin.

Changing of the Lehr speed, the volume rate of glass flow, the viscosity gradient (controlled by heaters or coolers) , using fenders to create thick substances and the use of edge/top rolls are ways to control the thickness of the float glass.

§3.3.3 Float glass composition

Element	Composition	Source	Function
SiO2	70-74 %	Sand	
Na2O	12-16 %	Soda ash	Ease of melting
CaO	5-10 %	Lime stone	Durability
MgO	1-5 %	Dolomite	Weathering
Al2O3	0-3 %	Alumina	Weathering
K2O	Minor		
Na2SO4	Minor		
Fe (as FeO /Fe2O3)	Minor		

(Debrincat & Babic, 2018)

Figure 3.3.3.2: Float glass composition based on (Debrincat & Babic, 2018)

When the glass is pulled off the tin bath by rollers at a controlled speed, the glass is cooled down gradually in an oven from 600 degree Celsius to anneal. This annealing point of standard clear float glass is around 550 °C. The function of the lehr is to cool the glass down at optimal velocity to relieve it from stress but to maintain sufficient stress in the edges of the glass ribbon for an easy cut. If glass is held at higher temperatures than the annealing point, stresses are built up in the cooled down final product because the middle of the glass will have tension while the surface is placed under compression. Also stress relief at cooler temperatures is not an option as it will cost too much time. (Kumar & Buckett, 2017)

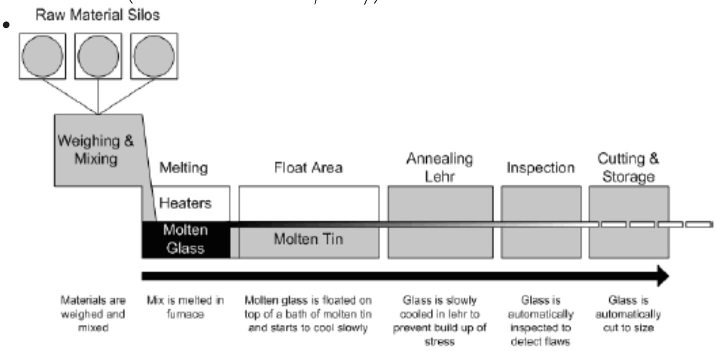


Figure 2.4.2.2: Production process of float glass

§3.3.4 Post processing:

The glass types used in the building industry are mainly produced by float process, but it is the post processing that determines to a great extend the properties of the final product. Different applications therefor will be described in this part.

Coatings

Since the 1980s coatings were developed to add extra qualities to float glass. In particular technology for coatings to be put onto the glass either as the float glass is manufactured or in the batch process. As window glass is by nature highly thermally emissive, thin film coatings are applied to the raw soda-lime glass. Certain coatings of these are the reason why glass cannot be recycled as they include critical materials such as Copper, Titanium and Cobalt (Veer, 2017).

Nowadays a wide variety of products are available such as:

- solar control coatings, to reduce solar heat
-low-emissivity coatings to allow more heat inside a room but keeps the longer wavelengths inside
-transparent conductive oxide film coatings for technical devices
-antireflective coatings to reduce unwanted reflections.
-mirror silvering
-dielectric coatings for the allowance of more light transmission
-dichroic coatings
-Self- cleaning windows
-etc.

There are mainly two ways of applying coatings to glass namely: on-line and off-line.

There are mainly two ways of applying coatings to glass namely: on-line and off-line.

On-line is directly online during the float process on the still warm ribbon, these coatings are mostly referred to as 'hard coatings' can be applied on the outside of the pane also they can be toughened. (AGC Glass Europe, 2014)

In contrast to hard coatings, soft coatings are applied to individual panes after manufacturing and being cut. Soft coatings have higher infrared reflection and are more transparent than hard coatings but require protective layers. An example of the process is the magnetron sputtering An option of position for soft coatings is showed in figure 3.3.4.1.

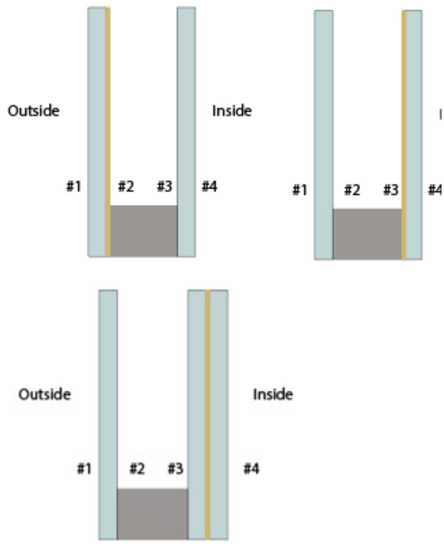


Figure 3.3.4.1: Soft coating positions must be protected.

Cutting glass

As glass has to be cut to the required size it gets damaged to the edge surface therefor the irregularities have to be removed to eliminate the tensile stresses that can build up here.
Glass can be chamfered, reducing the sharp corners from the edge. However also with doing so, tension can build up, therefore grounding and polishing is needed. The best way to get rid of these introduced tension is to fire polish it (brand polijsten in dutch). A flame of around 900 degree Celsius will heat up the edges until the glass will reallocate the stresses. When this happens, the glass edge will be clear again instead of matte white of the grounding.
Cutting the glass is possible with different techniques (Figure 3.3.4.2).
Using a special bandsaw with diamond grains is continuously watered to avoid the glass to be heated too much is a possibility for long and/or straight cuts. But also waterjet cutting is an option for achieving figure cutting of the glass.
Glass used for insulated glass units must not contain any visually edge damage, meaning no chips or dents.

Foils

Laminating Safety glass is produced by laminating multiple panes of glass together and bonded by an interlayer such as PVB (polyvinyl butyral), EVA (ethylene vinyl acetate) ,silicate, gel or safety resin. When a glass pane would break, the interlayer will ensure that the pieces remain in place. Usually the thickness of a PVB film is 0.38mm (AGC Glass Europe, 2014).

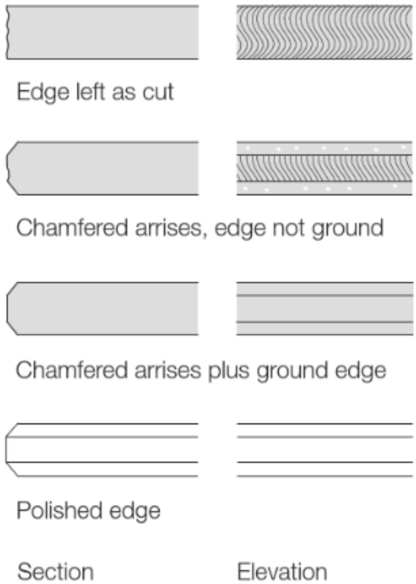


Figure 3.3.4.2: Finishing the edge of glass (Weller, Unnewehr, Tasche, & Härth, 2009)

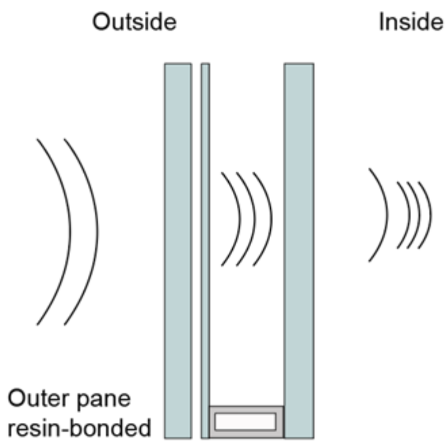


Figure 3.3.4.3 :Based on (Hochberg, Hafke, & Raab, 2009)

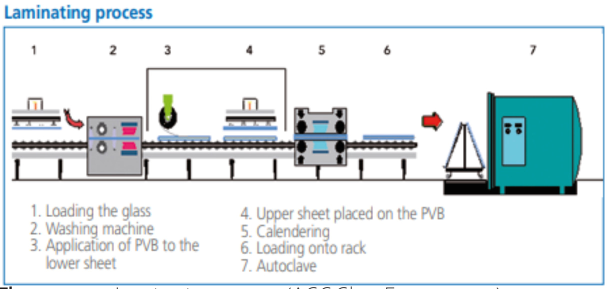


Figure 2.4.3: Laminating process (AGC Glass Europe, 2014)

Laminating the glass can be useful to gain high performance level of the glazing unit. A couple of improved qualities are:
Sound insulation
Fire protection
Burglar protection (bullets and explosions)
Safety glass (limiting injury risk by breakage)

The following steps are made for applying an interlayer:
First the film will be applied on the first pane of glass. Next, the second glass pane will be placed on top of the just applied film so it can bond. After this, these bonded glazing panes will go into a calendar where a roller passes over it at a very high temperature to remove the air bubbles and to let the PVB foil bond.
The last step is to process the glass in an autoclave for final curing of the PBV layer.

There are also extern placed foils that protects glass.
An example is the self-adhesive foil (SAFE) which is made out of a polymer film. The glass can be bonded with a primer and silicone. The applied foil can protect the glass from scratches and if the glass breaks, the splinters will adhere to the film which prevents possible injury or damage. The films are only effective for breakage if it is applied to the glass pane before placing it in the frame (AGC Glass Europe, 2014).

Windows furthermore protect the inside from noise of the outside. The required sound insulation Rw needed is derived from the outside noise level and functionality of the room behind it as can be found in the (Appendix 2). Heavier panes increase the sound insulation but more effective is blocking resonance by using different pane thicknesses on the in and outside(Figure3.3.4.3). (Hochberg, Hafke, & Raab, 2009). However, a side effect of laminated safety glass with a PVB layer is that it offers even enhanced sound insulation as it separates the two glazing panes and prevents it from acting as monolithic glass.

§3.3.5 2.4.4 Strengthening of glass

Glass is a brittle material and susceptible to a thermal gradient. When a scenario of the glass usage points out that the glazing panel can be subjected to a temperature gradient of more than 30 degrees, a thermally treated glass such as toughened safety glass or heat strengthened must be chosen. A scenario for example is shadows cast by blinds or roof glazing.

Toughened glass / fully tempered glass

The principle of tempering (also referred to as toughening) is to heat the glass past its softening point and cool it rapidly afterwards. In this way the core of the glass cools down slower than the surface face to create prestress: tensile stresses in the core and compressive stresses are introduced near and on the surfaces. With this method the glass plate can take higher loads and prevents the growing of cracks that occurs when subjected to tensile stress. The bounding factor of achieving higher stress is the glass thermal expansion coefficient (which depends on the type of glass). The glass thickness is also a limiting factor for achieving higher compressive stress in the body since reducing the thickness also reduces the possibility of create a significant temperature gradient a minimum of around 3 mm is practical (Guglielmo, 2017). The advantage of fully tempered glass is the small glass pieces after breaking. Toughened glass is used when strength, thermal resistance and safety is required since it is around four to five times the strength of annealed glass. After the toughening process 'heat soaking' can be applied to reduce the chance of spontaneous breakage. In this process the toughened glass is kept heated at moderately high temperature for a while. Heat soaking is applied to the toughened glass for structural glass or (laminated) roof panels.

Heat strengthening glass is heated up to 550° and cooled down (slower process than fully tempered glass) to around 60°. The break pattern of the glass becomes different which is important regarding safety. Heat-strengthened glass breaks into larger pieces which are capable of transferring the forces after breakage.

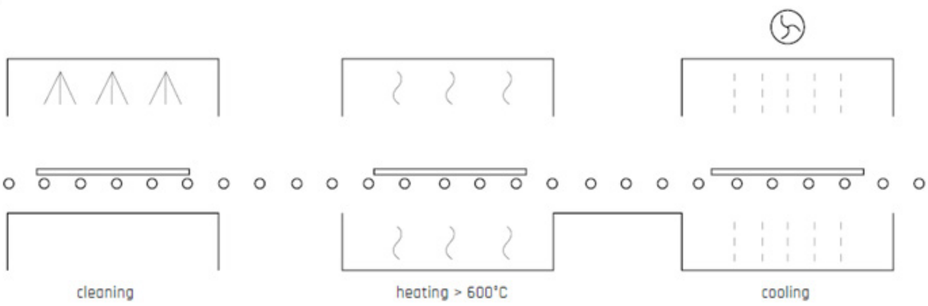


Figure 3.3.5. Tempering process float glass((Barou, 2016)

Chemically strengthened glass
By submerging float glass into a solution of potassium nitrate at 450 º celcius the sodium ions in the glass surface will exchange with the bigger potassium ions whereby compressive stresses are introduced at the surface. In contrast to heat treated glass, chemically strengthened glass can be cut afterwards although it has no added strength within 20mm from the cut. The break pattern of chemically strengthened glass is similar to the float glass. Therefor it should be laminated if safety glass is required.

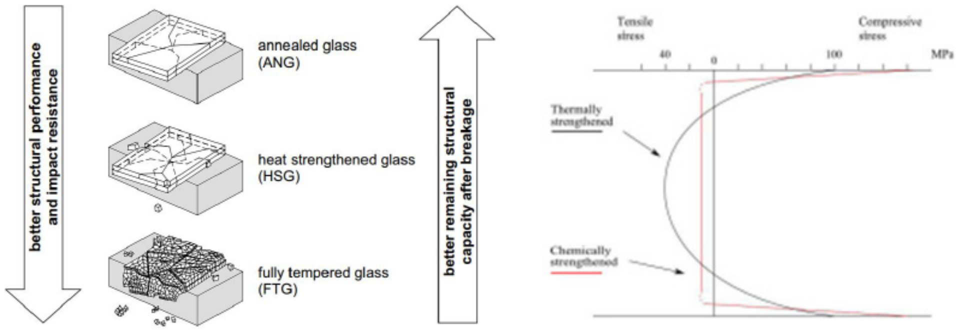
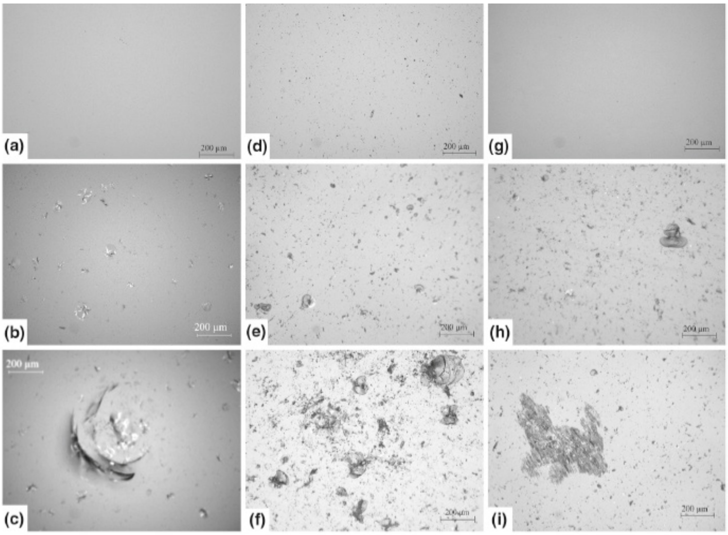


Figure 3.3.5. Influence of strengthening glass ((Barou, 2016)

3.4 Ageing of glass

While the surface of glass is very susceptible to damage the characteristics of this surface is related to the strength of the glass. Most of this accumulated damage is gained during service life of the panel and with the focus on extending the service life of these glass panels, it is important to have insight in the strength data on aged glass even though this report is just about an infill panel without structural bearing. Datiou &Overend (2017) have performed tests to artificially retrieve information about the strength and weathering data on aged, annealed, thermally toughened and chemically treated glass. For their research three types of glass were used: annealed, fully toughened and chemically toughened glass. With sand and gravel abrasion they simulated the weathering of glass with a service life of 20 years. The results for sand abrasion (figure2.5.1) and abraded gravel impact(figure 3.4.1.1). The surfaces of the panels before the test of the annealed and chemically toughened glass were almost defect free while the fully toughened glass already had multiple digs on its surface, probably caused during transportation or manufacturing. After testing the chemically toughened glass showed the largest resistance to surface abrasion during the artificial ageing followed by the fully toughened glass. The deepest flaws were found in annealed glass. Based

on this research surface tension does help with preventing aging of the glass where chemically threatening offers the best results.
However, the price of treatment of glass has to be taken into account when considering these options.



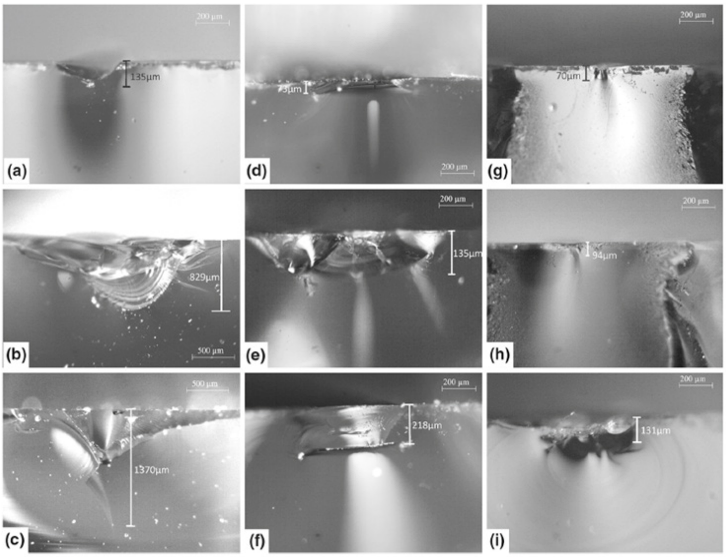


Figure 2.5.1a and b: Sand and gravel impacts on glass. a-c annealed, d-f fully toughened,g-I chemically toughened glass. (Datsiou & Overend, 2017) b: the depth

3.5 Conclusion

Windows contribute to both the outside as the inside of a building. Other than walls and floor elements, windows also connect the outside to the inside and because of this, windows have extra functions what can also make it a sensitive part of the façade in terms of thermal and solar transmission.
The components of the edge seal are also discussed, Many designs and alternatives are available above the traditional metal spacer bar. Elmhady (2006) has tested ten of those types where it is concluded that WET spacer bars positively influence the edge-of glass temperature. However, the choice of a non-conductive façade system such as fiberglass contributes even more.
A rough indication, as the percentages may vary depending on the glazing configuration, of the proportions of material in a glazing unit with the size : 1m*1m and the thickness of the double glass set to two times four mm with a cavity of 16 mm as is given in Table 3.5.1.1 It can be seen that the main component, glass, of the whole panel is the glazing panels covers 97 % of the total weight. This chapter described the amount of work in order to create a glass pane with the right sizes.

• **components**	• **Weight in percentage**
• Glass	• 97 %
• Coating (Metal oxides which bring all the thermal properties to the glazing)	• <0.01 %
• Butyl sealant	• 0.1%
• Sealant (polyurethane, polysulfide or silicone)	• 1%
• Spacer bar (aluminium or warm edge (plastic composites(	• 1%
• Desiccant (CAS number 1318-02-1 zeonites)	• 1%
• Gas(Dehydratedair,argon,kryptonor xenon)	• 0.1 %
• PVB interlayer if one (0.38)	• 0.2%

Table:3.5.1.1: Mass percentages according to Saint Gobain.

Concerning Post processing of glazing panes it is possible to change the properties of the panes in all sorts of ways. By adding coatings, functions such as solar control can be added, self-cleaning windows can be obtained and furthermore specific colours can be chosen for the panes to fit the architectural idea of the building.
Special requirements for windows can also be set such as safety glass. For this purposes laminated glass is an option. Above this, it is also possible to strengthen glass when needed both chemically as with heat strengthening.
Since the surface of glass is very susceptible to damage but also related to the strength and as most of the surface damage accumulates during service life while the report wants to extend the service life of these glass panels it is interesting to look at the option to strengthen the glass. Therefor the paper of Datiou &Overend (2017) is conducted. The paper shows that heat or chemical threatening glass can improve the surface quality to increase the durability. However applying these methods the glass panes become actually more vulnerable to stress build up and eventually breakage. An alternative to protect glass from surface damage is by the use of extern adhesive foils that can take up the scratches from the debris from the street and could be replaceable also since the integrated functions increases the price of the windows.
When thinking of a system to increase the service life, it makes sense to think immediately about the glazing panes. However, keeping the panel precisely together with the least amount of dirt and chance of the coating to corrode it could be an option also to let the glazing panes attached to each other for their whole service life.

To answer the question: What requirements should a re-manufacturable IGU meet in order to last more than 100 years taking into account every ten years of remanufacturing?
Regarding the glass : Normal float glass with high quality demands for the edge sides and 1 mm extra thickness to compensate for the extra years of life and thus impact chance (impact dept of sand abrasion) . Furthermore the ratio of the dimensions of the glass pane should be kept in a certain range as the difference in height and width should not be too big, this concerning the fatigue on the bonding connection between spacer bar and glass panes .
Regarding the spacer bar: As the new warm edge spacers already approach the maximal theoretical performance the spacer bar should consist of a composite or polymeric material without combining too many materials. Furthermore it should be rigid, must work as a vapour barrier and it should be capable of holding at least 40 grams of desiccant per running meter.
Regarding the seal of the IGU: It should be good resistant against water, ozon, oxygen, UV-light, temperature differences (with a maximum minimum service temperature of up to 80 degree Celcius).It also needs to have a high elastic recovery even when it turns cold.

CHAPTER 4
Circular design

Content

Circular economy principles
Circular economy approaches
Circular economy business models
Conclusion

4.1 Circular economy principles

The ambition of the Dutch government is to achieve a reduction of the resource materials of 50 percent already in 2030. In general we should use resource materials more efficient in a way we could re-use it several times with the least amount of downgrading. But in case of usage of new resource material it should be gained as sustainable as possible with the least social and physical damage to the living environment(Nederland circular in 2050). Currently most of the float glass products end up in landfill (table 4.1.1), one solution for preventing this is recycling of the glass which already happens with container glass. But circular economy goes beyond recycling only. It is considered as a promising approach to help reduce the global sustainability pressure (Bocken, de Pauw, Bakker, & van der Grinten, 2015).

As described by: (Potocnik, 2013) "a circular economy is an industrial system that is restorative or generative by intention and design and replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair re-use, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models."

The idea of a circular economy is however not new, already since the 1980's many theories have been developed on how sources of nature can be restored by new sustainable system models.

Leising (2017) has set out a table with the most important principles on which the concept of circular economy is based. Looking at these strategies the covering words are: waste reduction or even waste elimination, minimalize material and energy consumption,minimalize the environmental impact but also ideas on how to prevent ownership of products or parts. In this chapter more about these circular economy design approaches will be covered.

Fields of study	Key principles
Performance economy (StahelReday-mulvay, 1981)	**Product-service systems:** Paying per use to prevent ownership and disposal of used products/parts Performance-based: Paying for the perfomance to reduce resource use and waste production
Industrial Ecology (Graedel, 1994)	It is seen as the toolbox for sustainable development. A concept that combines the **technosphere and biosphere** and aims to minimize energy use, material consumption and environmental impacts along the liecycle of a product or service.
Regenerative Design (Lyle,1996)	The design method that renews sources of energy and material
Biomimicry (Benyus, 1997)	An approach to sustainable solutions to human challenges by looking at the methods of nature and imitate that. taking nature as mentor
Cradle to Cradle (mcDonough & Braungart,2002)	Waste=food. celebrate **diversity** . ecooeffectiveness above eco-efficiency. Use solar income and separate bio-and tecnocycle
The Natural Step (The Natural Step, 2015)	The concept where all natural processes (including humans) can fulfill their basic needs and where the **extraction of raw material and creation of unnatural material is minimalized**

Table 4.1.1: key principles of which the concept of circular economy is based upon. Based on : Mentink (2014); (Leising, 2017)

The circular economy in short is based on the thought of elongating the service life of products in a way that at the end of the life span the least amount of energy is used. Figure 4.1.1.1 shows a principle diagram for reducing resource use of materials Bocken et al. (2016)
This diagram is based on the three ways of dealing with resource reduction.

Slowing down resource loops through designing long- life goods and product-life extension.
Long-life goods can mean a robust design that lasts long as the product can take wear and tear without breaking. while product-life extension can imply adjustability, repair or remanufacturing but also intensification of the use of the product. In these ways, the flow of new resource materials is slowed down.

Closing resource loops: Through recycling, the loop between post-use and production is closed, resulting in a circular flow of resources.

Narrowing resource flows: If fewer resources are used per product, material can be saved. however, it should not conflict with the idea to design a long-life good.

The butterfly diagram (figure 4.1.2) shows that materials are separated in two separate cycles: the techno and bio cycle (ellenmcarthurfoundation) The distinction between these two cycles helps us to understand how materials can be used in a high quality way so that they can be properly separated from each after service life.. The focus on this diagram for this report is however only on the techno cycle or synthetic material , but the key message for both cycles is that the less process steps a material has to undertake in order to be re-used, the higher embodied energy the material can contain.

•

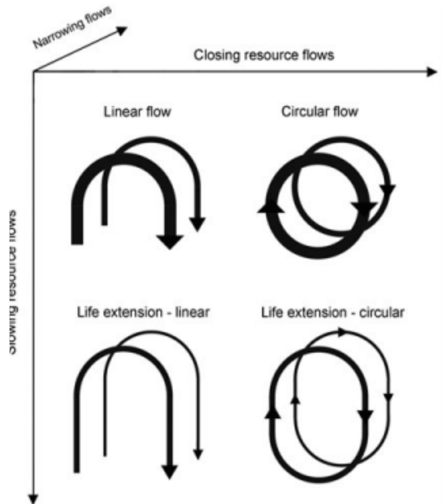


Figure 4.1.1: Resource flows from linear and circular economy approaches(Bocken N. M., de Pauw, Bakker, & van der Grinten, 2015)

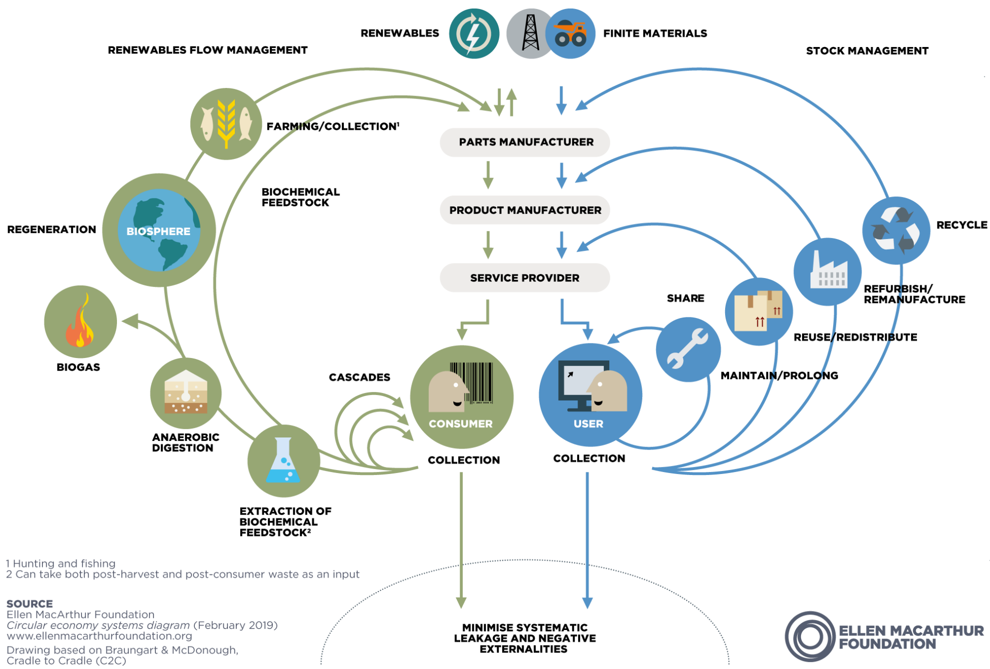


Figure 4.1.2.: butterfly diagram(based on Mooc course engineering-design-for-a-circular-economy/Ellen Macarthur foundation)

The first step is the finite resources such as fossil fuels and most plastics and metals. As they have limited availability and are difficult to recreate they must be properly managed what means they should only be used instead of being consumed.

The inner cycle shows as the loop of the circle expands the more energy, time and resource materials have to be invested to achieve the same value.
Repair or maintenance during use to extend the lifespan, direct reuse or redistribution by re-marketing a product , re-manufacturing or thorough refurbishing by a (re) manufacturer and then recycling successively is the preference order of intervention

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Repair or maintenance during use to extend the lifespan, direct reuse or redistribution by re-marketing a product , remanufacturing or thorough refurbishing by a (re) manufacturer and then recycling successively is the preference order of intervention. .

Collection of materials is an underrated but important step also because it is important to know how to measure circularity in order to make choices between processes, products and even companies. According to (hetgroenebrein, 2016)
there is no generally accepted methodology for measuring this yet, however there exist several websites that can help gathering information to measure the circularity for projects. (Appendix)
this report however is based on the butterfly principle. This chapter will cover circular economy approaches according to the inner circle of that diagram (figure 4.1.3).

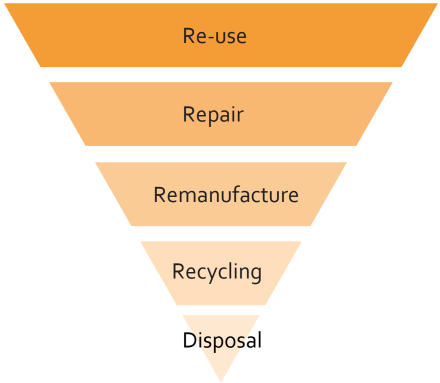

Figure 4.1.3: Inner circle of the butterfly diagram(based on Mooc course engineering-design-for-a-circular-economy/

4.2 Circular economy approaches:

§4.2.1 Design for re-use

When designing for reuse the main focus is to extend the service life of products to reduce the resource necessity of primary materials.
The material choices for the product have to be in line with that same idea. This means that the product is not only built to last as long as possible but the idea of using a durable design is also in the idea to make multiple life cycles possible. Materials for this approach should be durable enough for the task, therefore materials that might lose strength , become brittle, are susceptible for wear, can easily corrode, suffer from stain, get discoloured or might later on be banned because of the chemicals should not be used in the design.

But besides the materials also additional design and connection have to be considered :one of them is maintenance: avoidance of dirt collection in the design is important. Furthermore the design should allow easy access without permanent connections (such as glue or welding) instead use screws, snaps, clips etc. Ideally demounting the product can be done without tools but if necessary it should designed for the least amount of tools to be used.
To make repair of the design as simple as possible, modular structure of the product should be designed with compart ability of components so parts can be easily be upgraded, repaired or replaced. Adaptability also has to be taken into account for the product to be upgraded with the newest technology or requirements for a longer time span if wished for, this is related to modularity.
With regard to this, all parts that are planned to be updated or replaced in a coming remanufacturing should be placed in the same module so cross-dependence between modules should be avoided. Additionally good documentation is really important to know what materials are used.

§4.2.2 Design for repair

The second step in the circular approach is: design for repair. It covers the repair and if necessary replacement of the product components. Usually this can be handled without the need for extensive planning. As a part of the product has to be repaired it consumes more energy.
When design for repair is the chosen method, a repair service to the customers can be considered. Important for this strategy are the spare parts that should be (widely) available to replace the broken ones. Next to a repair service, in most markets the products should also have the possibility to be easily repaired by the customer himself. Therefor the availability of manuals and a simple, modular structure of the product without critically security conditions appear during maintenance is important.
In this way the product doesn't need to be transported and no technician has to travel all the way in order to repair the

product which saves again energy.
Also in this approach a good documentation is crucial.

The part that is usable from the repair approach is the repair service. And the availability of spare materials. Since IGU's are heavy and with the need of inert gasses with a special pump and besides this the IGU's need care to be installed without thermal loss it is better to provide a service for the bigger market such as the social housing companies but also high-rise buildings or offices. Due to this new jobs can develop to maintain the IGU's in buildings.

§4.2.3 Design for remanufacturing

Remanufacturing is the process of restoring a used product to its original value with at least the same performance as when the product was still new with the warranty that is equal or even better than initially. For remanufacturing the product is mostly dismantled and the to be repaired components will be replaced and tested to ensure the original specifications for the customer. Remanufacturing is important to reduce the recourse-consuming activity by keeping components and thus their embodied material in use for longer. By remanufacturing better information about the product is gained whereby a more accurate warranty can be given.
Remanufacturing however is a step that asks more energy than re-use as replacement of parts have to be taken into account.

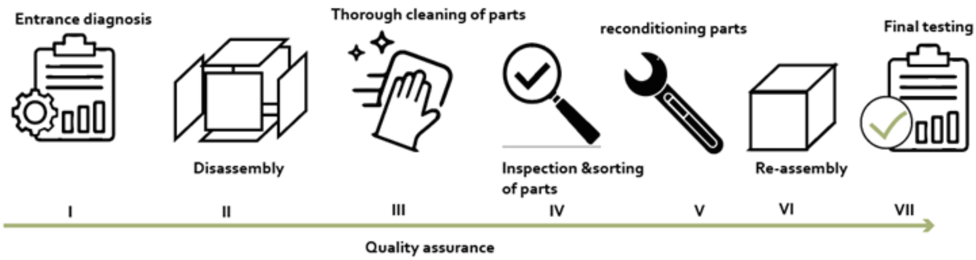

Figure 4.2.3.1: Remanufacturing process according to (Sundlin, et al., 2016) based on image of (Vargas, 2019)

Remanufacturing however is a step that asks more energy than re-use as replacement of parts have to be taken into account.

The steps for remanufacturing of the system is (shown in figure 4.2.3.1):

I) Diagnosis of the product at entrance

II) Disassembly of the parts. The parts that cannot be reused should be left out.

III) Thorough cleaning: Degreasing , and removal of contaminants with deep cleaning of all parts according to their state.

IV) Inspection and sorting: The left out materials should be examined and sorted out for their circularity potential according to quality of the current state. The three classification categories are:

a) Reusable without reconditioning

b) Reusable after reconditioning

c) Not suitable for reconditioning

V)Product reassembly.

VI) After reassembly of all parts the remanufactured product has to be tested to assure its quality.

§4.2.4 Design for recycling

Recycling is important as it benefits the environment in saving the embodied energy but mainly it reduces the amount of virgin materials and thus the depletion of natural resources. After a product is disassembled and the parts are classified by material, the materials can be re-introduced in the material stock and less materials have to be mined or go through the manufacturing processes. What gets recycled will be saved from landfill. Material pollution will lead to pollutants in the environment for instance it can dissolve into the air, water or ground and it is not only from the material itself when it ends up at the landfill after service life but also from the constituents of these materials when working on them (for example electricity gained from different resources). (Bocken N. , de Pauw, Bakker, & van der Grinten, 2016).

Bocken et al (2015), describes different ranges of recycling principles:"

primary recycling is the most known one and also referred to as closed-loop recycling. The definition of it is : "mechanical reprocessing into a product with equivalent properties. However, a still new and underexplored concept is 'upcycling' which is even improving the properties of the material.

Secondary recycling is known as downcycling. The mechanical reprocessing forms the material into products with lower property requirements. An example of a 'low' value transformation is industrial grade rubber being reprocessed into a general grade rubber.

Tertiary recycling ,also referred to as chemical or feedstock recycling. It is the structural breakdown of materials into their original raw core components and build-up of material with properties equivalent to the original material.

Quaternary recycling, Also described as thermal recycling, energy recovery and energy from waste.

However as the recovery of the energy from materials is only partial, it is not considered as recycling but fits in a linear system."

4.3 Circular economy business models:

Shortly introduced by the theory of performance Economy and afterwards included at the theory for circular economy, a way of preventing ownership and thus disposal of used products should also be thought of while designing the product. A business model namely can help incorporating strategies for a more circular design as all parties involved benefit from it while by not incorporating a suitable business model the effort of creating the product can go to waste as not every party involved will work in the same idea.

Remanufacturing companies need to retrieved the parts themselves. There are seven strategies for collecting cores that are set out in Table4.3.1.1(from Östlin et al, 2008)
The strategies chosen can lead to advantages in the relationship between the user and the (re)manufacturing company. With reverse logistics the supply chain management can for instance have a higher control on the core supply by having contract between the user and the (re)manufacturer. In this way a dynamic pricing can be achieved both as value information of the product can be gathered. But also a long-term relationship can be achieved by integrating service to the product which can assure remanufacturing (Figure 4.3.0.1).

Ownership based: The product stays owned by the manufacturer but operated by the customer. Examples for this strategy is: rental, lease or product-service offer.
Service contract: A contract between the manufacturer and customer where besides the purchase of the product also remanufacturing is included.
Direct order: When needed the customer can return the used product to the remanufacturer that will send the same product back after it is remanufactured (if possible).
Deposit based: When the customer purchases a remanufactured product it must in return exchange a similar used product, in this way the customer is also acting as a supplier to the remanufacturer.
Credit based: The customer receives an amount of credits after returning a product at the manufacturer. The credit can be used as discount when buying a remanufactured product.
Buy back: The remanufacturer buys the wanted used products from a supplier. This supplier can be the end user, a scrap yard or similar, a core dealer.
Voluntary based: The supplier gives the used products to the remanufacturer. The supplier can also be a customer but does not have to be.

Figure 4.3.0.1: Collecting cores (Östlin, et al., 2008) based on image of (Vargas, 2019)

§4.3.1 Types of remanufacturer

When thinking about designing a product suitable for remanufacturing a suitable way of closing the circle has to be tought of as well to achieve the best possible scenario for remanufacturing , business plan and strongly wanted product as both the price and service for the client can be the best in this way.

There are mainly three types of remanufacturing companies that are categorized based on their relation to the product manufacturer as is explained in (Sundlin, et al., 2016).The remanufacturer can be the original equipment manufacturer (OEM) but it is also possible to have an OEM subcontractor also referred to as: Contracted remanufacturers (CR) which is the second option. This remanufacture party is in between the supplier-producer and producer-customer to achieve a bigger production capacity. The third possibility it the independent remanufacturer (IR) and becomes a direct competitor of the OEM as it can retrieve the parts on its own without collaboration with the OEM.

OEM -	Remanufacturer from its own product. It retrieves ts own products arriving from service centres,trade-ins from retailers or end-of-lease contracts.	The company has and gain all the needed information concerning product design, availability of spare parts and service knowledge. The remanufacturing process could be integrated with the ordinary manufacturing process as the parts from te remanufactured products could be used in manufacturing.
CR-	Remanufacturing Companies that are contracted to remanufacture products on behalf of other companies. This usually means that the OEM owns the products but does not need to perform the actual remanufacturing of them.	Because the OEM still owns their products but have them remanufactured they can offer it to their customer for a lower price. For the remanufacturer the pluspoint is the consistent stream of business with fewer working capital requirements and risks also the company can ask for assistance from the OEM in terms of replacement, parts, design, testing specifications and tooling
IR-	Manufacturing companies with little or no contact with the OEM. Sometimes these companies are payed by the last owner or distributor to pick up discarded products. The typical IR is a private corporation with closely held ownership.	IR need to buy or collect cores for their process and spare parts for their products that are to be remanufactured. Generally, exchange of experience between IR and OEM concerning reprocessing to the proeduct is minimal

Table4.3.1.1: Type of remanufacturers(from Sundlin et al, 2016)

Despite the different type of manufactures that can focus on remanufacturing, there are still barriers related to remanufacturing. Those problems are dividable in mainly three different groups: Business model, Design and process.

Figure 4.3.1.2: Barriers towards remanufacturing Business model, Design for remanufacturing and process. based on (Vargas, 2019)

4.4 Related to the first group : **The business model,** (Introduction to a Circular Economy course), consumers have the image of a remanufactured product as inferior to a new product. This is a contradiction as dr. Nabil Nasr explains that " a remanufactured product is fully equivalent and sometimes even superior in performance and expected lifetime to the original product as more information is retrieved from it over the years."
2018) Lund 1983). The consumer is thus unaware of the definition of remanufacturing.
Under the **design** part falls the lack of design principles for Design for remanufacturing in a product such as poor disassembly and selection of non-durable materials which makes reversible logistics impossible. Where Reversible logistics falls also into the category process for remanufacturing. Furthermore an open market access would make it more easy to enter and transport cores between countries what benefits to the availability of the cores overall. Legislation and regulation would be able to change this open market but as this falls under the third category **process** it becomes clear that the three categories of barriers to remanufacturing intertwine.

Conclusion

The concept of Circular economy has evolved from the ideas of many theories that were already conceptualized since the 1980's. The focus with the butterfly diagram for this report is only on the technical cycle.
For the design part therefor no finite materials should be used.
Furthermore table 4.4.1 shows a list of requirements that a circular design needs to fulfil in order to be reusable, remanufacturable and at last, recyclable

To close the system, a collection point for the cores have to be thought of. The CR would be a handy choice because the OEM still owns the product but needs less capital requirement and risks than the case when the OEM itself has to remanufacture the equipment. But since the CR have a contract with the OEM,assistance and information can be exchanged between the two parties. New job availability is as a plus point created as well.
The design requirements of the insulated glazed unit has to deal with aspects such as the architectural design (shouldn't touch the identity of the building in case of monumental buildings), the original materials and the range of sizes of the window frames, the façade construction principles and place of thermal separation.

Standardizing the dimensions of the such as the (EPDM) rubbers, screws etc. This would be an improvement to be able to have the same life span, and it would im-

prove the easy accessibility and replacement of the elements. If glass producers would use the same elements then spare parts are more easy to find.
Standardizing the glass formats will not be appreciated as Jacques Herzog and Pierre de Meuron once told "architecture has never been about pragmatism and function only but also identity and emotion where the façade is a obvious choice to expresses this all" in (Schittich, 2014).The design requirements of the insulated glazed unit has to deal with aspects such as the architectural design (shouldn't touch the identity of the building in case of monumental buildings), the original materials and the range of sizes of the window frames, the façade construction principles and place of thermal separation.

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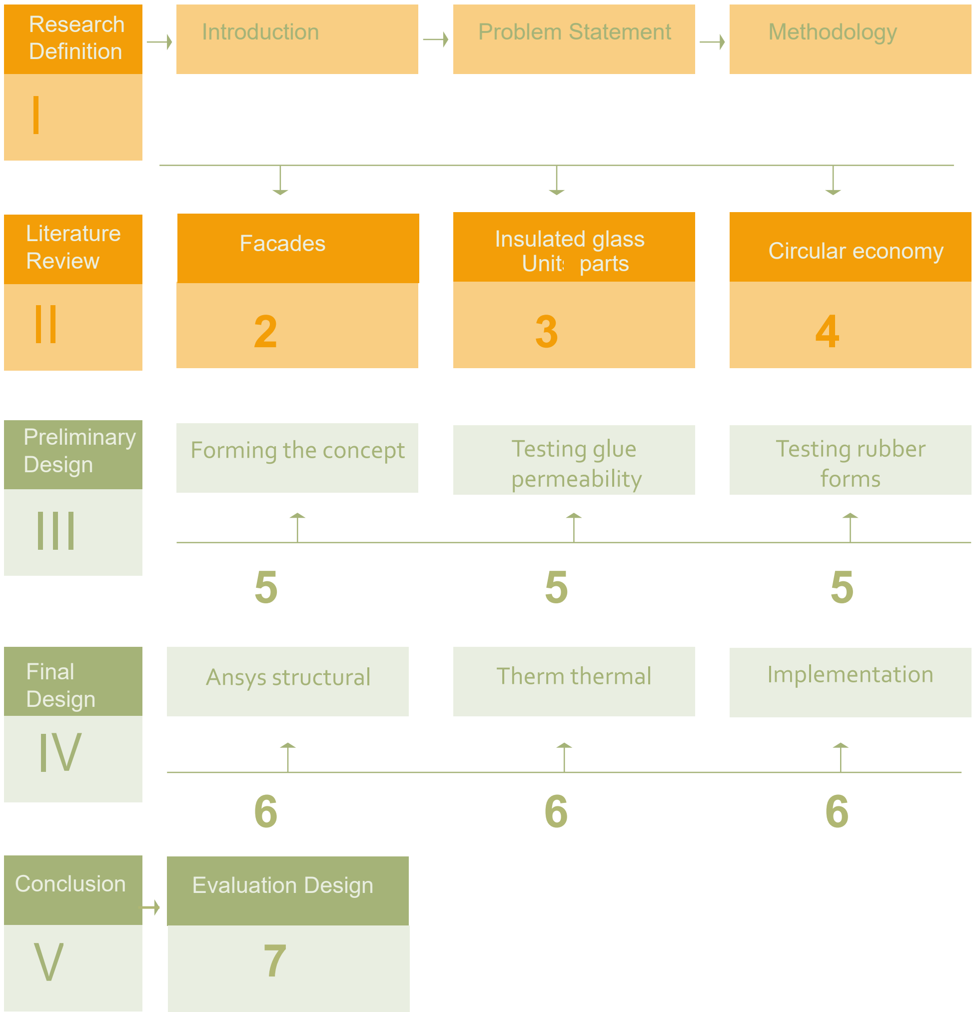
Documentation	• Identify the materials used and in what conditions they are. Also the information on the building manufacturing, along with the assembly and disassembly sequence, should be provided. • A structural way to obtain a diagnostic of the used product to clarify what should be repaired or replaced for remanufacturing.
Materials	• Materials should be chosen that could stand multiple life cycles. Materials that might lose strength , become brittle or, are susceptible for wear, can easily corrode, suffer from stain, get discoloured or might later on be banned because of the chemicals should not be used in the design. But also unnecessary parts or layers (such as some coatings) can complicate remanufacturing or can even cause damage to other components in a longer time span because of debris. • Use as few different materials as possible

	• Add extra materials on surfaces supposed to be machined during remanufacturing. -dimensioning
Disassembly	• Make demounting as easy as possible to use the same (or the least amount of) tool (s). Screws, snaps, clamps in the same type and size and screws on the same side. • If needed, divide the product into parts or modules. And try to keep all parts that should be replaced at the same remanufacturing period in the same module. Avoid cross-dependence between the modules. • Assembly methods and sequences should be standard • Think ahead for the design: Materials should be chosen that minimize pollution during extraction, processing, usage and recycling. • Use a minimum number of different types of connections and fasteners. • Avoid secondary finishes, adhesives, and coatings
Standardizing	• If possible make use of standardized elements, so they would be available over the years and always can be replaced as spare parts are then widely available. • Use a minimum number of components and connections types. • Specialist technologies should be avoided.

Table4. 4.1: Synthesis of the found guidelines on Design for Disassembly based on Deniz and Dogan (2017), Mule (2012), and Durmisevic (2006)+ tania en de mooc course.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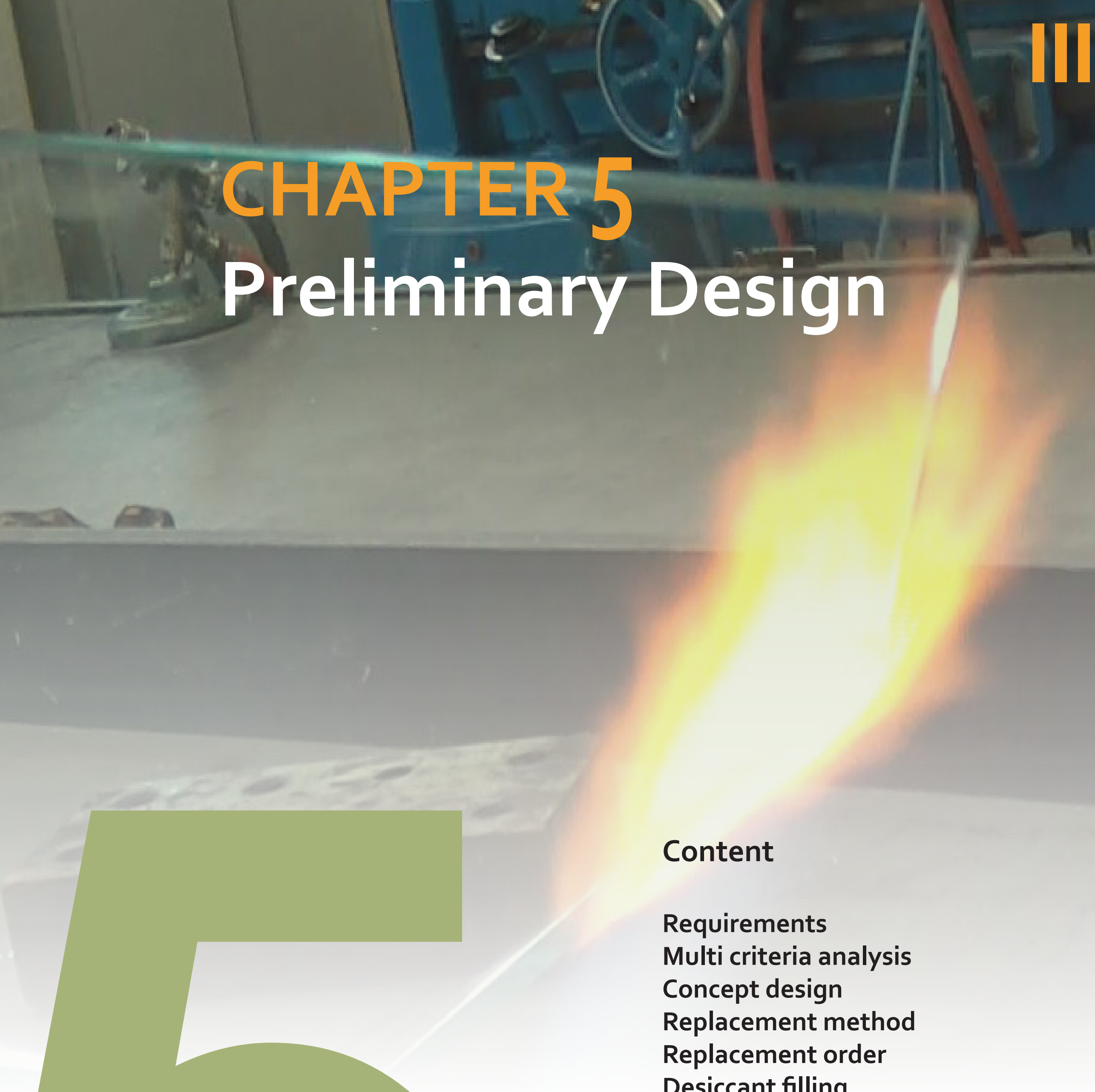

CHAPTER 5
Preliminary Design

Content

Requirements
Multi criteria analysis
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Replacement method
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The glue
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Requirements

If façade systems are maintained properly, most frames from aluminum or composite material can be used for over 40 years, after this period a refurbishment can take place to measure and repair the state of these components. There are many ideas developing on how to upgrade façade systems in order to keep the embodied energy of these systems. E.g. adding elements to it in order to fulfill the national building decree on e.g. the R-value but also to change the functions of the building inside. Because from a sustainable viewpoint ,not replacement by new a construction but life cycle extension of existing buildings is the better choice regarding reducing waste streams of materials(Konstantinou, 2014).

This leads to the opportunity to extend the same idea for the IGU. Keeping also IGU's for a longer time span would contribute to a more sustainable factor in the building industry.

As can be seen in chapter three, the glass panes themselves carry a lot of embodied energy. Apart from being molten and produced into glass, the glazing panes have to be coated, layered or has to undergo a strengthening process according to the special requirements for the project.

What further is shown in chapter three is the development of the warm edge spacers and how they already approach the maximum thermal performance. A composite spacer bar therefore can be used for over 100 years to make maximal use of its embodied energy as no replacement for a better warm edge performance is needed.

Putting the spacer bar and glass panes together is a precise work where no dust or grease should interfere, it would be ideal to undergo this process just once in a controlled environment such as the glass production hall.

The starting point of this design is therefor: How to design an IGU with the glazing panes and spacer bar bonded together for over 100 years while the seal can be replaced every ten years to make maximal use of the embodied energy of all components. At the end of life the different elements should be separable to fulfill the butterfly diagram (described in chapter four) Furthermore the new design should share some of the requirements of the conventional IGU as well.

-Remain low gas permeability

-Resistant against environmental factors such as atmospheric pressure fluctuations and wind pressure but also it should be resistant against ozone and uv.

-Provide a proper thermal insulation (cavity +- 16 mm).

-Provide clear sight between inside and outside by not letting moisture getting inside the IGU which causes fogging and even corrosion of the coating.

-The edge of the IGU needs to hold at least 40 g desiccant per running meter.

-For easy production and straight sightlines during service life the edge of the IGU should be stiff enough.

- All materials should have a service temperature between -10 and 80 degree Celcius.

5.1 Multi criteria analysis

In order to make a choice between the design variants, a multi-criteria analysis (MCA) will be conducted.
Although the criteria of the MCA are described in an independent manner and defined to avoid overlapping it can occur that improvement of one criterion can lead to improvement or diminish of other criteria (dependence). Furthermore, judging of the criteria depends on expertise of the decision maker. For this reason, a structure is needed to increase the reliability of the MCA. There are two defined methods to cope with a MCA: Ordinal methods and cardinal methods.
Ordinal methods: also referred to as a qualitative method, gives a rating from 'worst' to 'best'. The advantage is that criteria can be judged, without precisely described as long as a clear distinction between the options is listed, they can be ranked.
To mark the importance for the design process the criteria can also be ranked . As only qualitative properties are judged, no definitive conclusions can be based on this matrix and thus the final judgement has to be made by the decision maker.
Cardinal methods: is described as a quantitative method and requires every criterion being qualified. This way every option is judged independently mostly according to a grading scale. Therefore the independence of the criteria needs to be assured to avoid skewed outcomes. The criteria should have the same chosen scale for a fair comparison. To mark the importance of the criterion it is possible to have different weighting factors decided by the decision maker.
The advantage of this method is that a score can be calculated which gives a clear judgement.

Method choice

For the MCA the cardinal method is chosen with a simple scale of either negative, neutral or positive as most criteria are not judged to an exact score because the available technical information is insufficient to achieve such a grading .
This simple scale leaves furthermore room for personal interpretation for a final decision so it can be used more as a guiding tool instead of a definitive decision tool.
The following criteria are weighted for both the original system ,which is in use at the moment and the concept designs.

5.2 Concept design

§ 5.2.1 **Requirements:**

Ease of replacement:

Ease of replacement with regard to disassembly. Each component should preferably allow for easy demounting on site as not all the components have the same life span. For this evaluation there is taken into account the assembly method (using the least amount of tools), the amount of time it would take to remanufacture the product, and the finishes used such as adhesives.

-1: Components at their end of life time cannot be replaced without damaging other parts or leave traces.

0: Every component can be replaced without damaging other parts. However, there are many or small components that make it difficult and time consuming to replace.

1: Every component can be replaced without damaging other parts without too many difficulties.

Tension on the permanent bonding:

Adherents such as Glue and sealants are weak on tension, cleavage or peel forces. Because of this it is undesired to create a moment with the seal that will cause tension to the bonding of the glass and spacer bar which will result in failing. Adhesions are on the contrary better resistant against loading in shear or compression. A too large shear is however also graded as negative as this can also cause the whole system to fail.

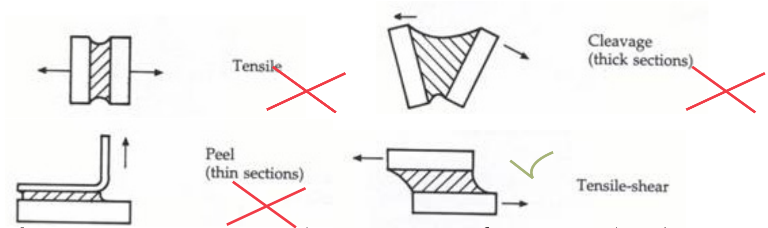


Figure 5.2.1.1: Positive and negative ways for putting the glue on stress/www.adhesivestoolkit.com/

-1: Due to the design an unfavourable moment is created pushing the glass panels further from each other which creates unfavourable stresses in the permanent bonding.

0: There are big shear stresses on the glue.

1: No unfavourable stresses are applied on the permanent bonding.

Transfer of the loads:
This requirement is based on transferring the structural loads by dead load, life load (wind) but also on incidental loads e.g. during transportation or shifting of the panel. Stress build-up on some small components can cause failure when e.g. the panel is not placed carefully enough while if all the load from one glass pane is transferred to the other it would restrict the design of the glass in regards to the dimension but also for strengthened glass. Hence, the transfer of the loads is also taken into account.
-1: Permanent Stress build-up on one or more components can be problematic.
0:Incidental force can cause problems regarding stress build-up e.g. in one or more components.
1:All components seem to be able to transfer or take-up the force applied to them.

Seam tightness:
The quality of the seal and its tightness is evaluated here. A seal that does not prevent gas outflow or water vapour entering inside the IGU sealing at the most vulnerable places, where the glass and spacer bar come together, does not meet the requirements and is graded negatively. The other quality the seal ideally holds it that it can be sealed in all corners without having an open seam, just like an o-ring the connection should be seamless by vulcanizing or welding the ends of the seam together.
-1: The seam does not cover the space where the spacer bar and the glass are connected.
0: Gas can flow out at the corners because of the open seam at the corners.
1: The seams are tight so no gas transportation can occur furthermore no water can be trapped very easily.

Fabrication process:
Material choice, the shape of the components and the manufacturing process plays an important part when it comes to fabrication. Very complex shapes that ask too many operations for it to work make the IGU unnecessarily too expensive. Preferably simple connections and shapes makes the available for mass production in different standard sizes.
-1: Very complex parts with too difficult or many fabrication operations.
0: Complex connections that ask for high precision but less operations that '-1'.
1:Components are built of simple shapes and connections.

Heat flow:
Heat flow by conduction should be eliminated as much as possible to achieve a warm edge and thus a well-insulated IGU.
-1: Heat transportation does occur.
0: Not the entire length of the window is transporting heat flow but just points cause heat transportation.
+1: Well insulated.

§ 5.2.3 The design variants

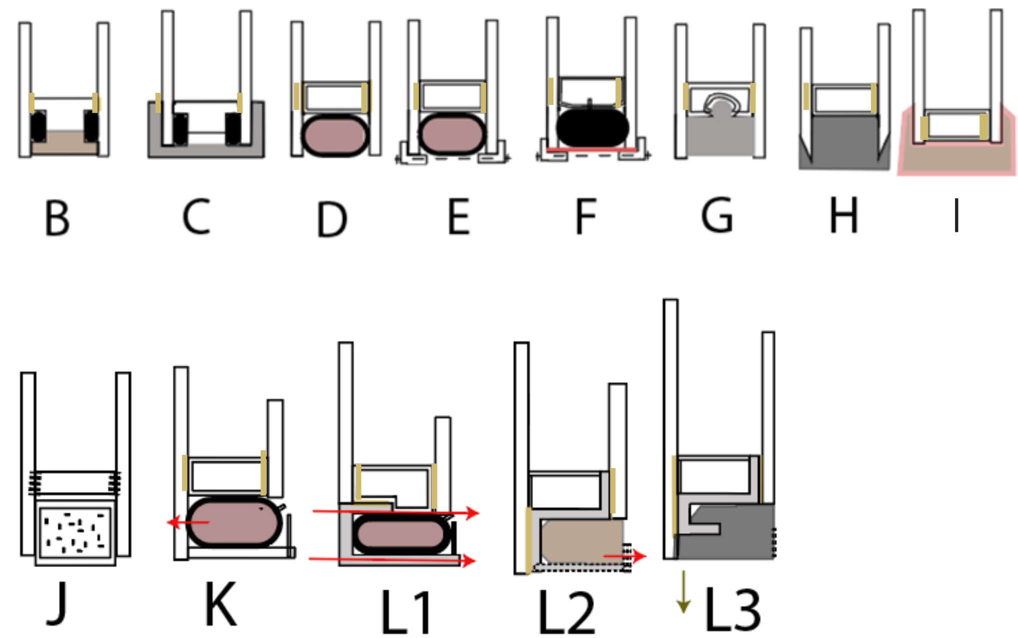
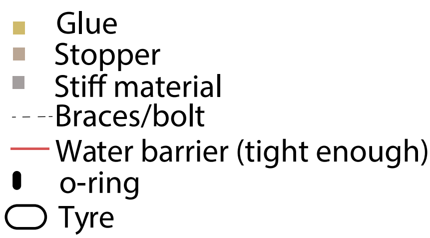
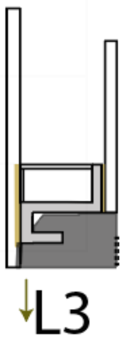


Figure 5.2.3: Edge seal variants



Aspect	Ease of replacement	Tension on the perma-nent bonding	Transfer of the loads	Seam tightness	Fabrication process	Heat flow
Original design	-	-	+	+	+	
B	+	-	+		+	+
C	+	+	+		+	-
D	+	-	+		+	+
E		+		+	+	
F	-	-	+	+	+	
G	+	-	+		+	+
H	+	+	-			+
I		+			+	+
J	+	+	+		-	+
K	+	-	-		-	+
L1	+	+	-	-	+	-
L2	+	+	+	-	+	
L3	+	+		+	+	+



The conclusion is that in L3 the most potential is seen. Transfer of the loads has be solved by conducting a deeper study on this variant.

§ 5.2.4 Remarks on each variant

Now that all the requirements and grading ways are described, a short description on the negative parts of each design according to the above written method. The first discussed design is the original / currently used IGU sealing. Because of the possible quality seen in design L1, following designs are based on L1.

A: The problem of the original design is that it is not demountable at all because of the adhesives used. Furthermore, the secondary sealant pushes the glazing panels out of each other, causing tension on the butyl seal which is unfavourable.

B: Between the glazing panes a cork sealant is pushed inside together with 2 O-bars. The cork stays in place since it is pushing outwards on the glass panes just like the sealant of a whine bottle. However, this is very unfavourable for the bonding glued spacer bar which is connected to the glass panes with a UV curing glue.
Furthermore, the cork connection and the rubber bands do not have closed seams at the corners.

C: Around the glazing panel, a clamp is placed that would take up the moment from the glue. Two O-bars are held between the T-shape. This concept is unfavourable regarding heat transportation and moisture could enter at the sides outside of the glazing panes where it easily gets trapped. Furthermore the rubber bands are not closed at the corners.

D: In between the glazing panes a rubber tyre with in it a swell seal is placed for better insulation. However, when choosing for a swell seal it would take minutes to hours before the seal is totally formed. Also with this design, the seam at the corners would be open and the swell seal could cause permanent tension on the glued bonding between the panes and spacer bar.

E Has in addition to variant D a foil and local clamps. This makes the moment on the bonding not a problem anymore but the points where the clamp sticks out are transporting heat. Furthermore, as the clamps are sticking out these clamps could form a problem to load bearing when they are put onto the setting blocks .The foil is an extra barrier against water ingress and could also work as a temporary gas and vapour barrier until the swell seal is formed Furthermore it could make the seam tightness at the corners better and for this reason this seam tightness is graded with '+1'.

G A rubber material is placed in between the glazing panes but clamped into the spacer bar to position this seal exactly and keep it in place. By this option the rubber material is pushing onto the glazing panes in order to achieve a tight seal but this is unfavourable for the bonding between glazing panes and aluminium bar. Furthermore the seam tightness at the corners is questionable as it is not made out of one piece.

H By making a cut on the edge to slide the panes into the rubber profile a tight connection is created however, making such edges in the glass is a costly process and above all stress will build-up at those corners that can cause sudden breakage of the panes.

I Around the glazing panels a rubber or insulating plus stiff material with a water barrier is placed. Also due to the shape of the outer edges less water will go through the space between glass and edge of the rubber.
It is complicated to fit the rubber exact around the panel and it will hold the glass from expanding in hot days when needed which can cause stress in the glass.

J The bonding of this variant is welded glass. Due to the welded bonding, the glass panes do not need to be separated at the end of life from the spacer bar that is also made from glass. Therefore the panes do not have to be heated up after service life. The sealant is made out of silicone where the desiccant is integrated into. Desiccant and silicone are due to this not separable but makes it more easy to place inside the window. Also the same problem as with the original IGU occurs, namely that the sealant need to push the panes outwards. This is again not a great situation for the weld, but assuming the weld to be stronger than glue it forms a better situation.
Welding of glass is however a very complicated process and should not be taken into account.
K This variant has a glass lit at the bottom to keep the sealant (shaped as a rubber tyre) in place. Big loads are transferred by only the outside glazing panel while a big tension stress is created to the bonding of the outside glass pane and spacer bar.

L1 This variant has many similarities to variant K. The shear stress is less big on the extern chamber for the seal. However heat can easily be transferred and the seal does not cover the area between the glass and the spacer bar.

L2 As this design is evolved from variant L1. The heat transfer is now by just points instead of the whole length. Furthermore since the spacer bar now also can transfer weight, less trouble concerning load transfer to just one glass pane is created. However the other requirements are just as negative as in L1

L3 Is an even more evolved form from L1 where the seal can now also reach the most vulnerable spots. Furthermore the thermal transfer is less because the seal is hold in place by just half of the spacer bar. Transfer of the loads should be through the sealant material.

§ 5.2.5 Elaboration

The chosen variant is just a concept based on the requirements described, however it is just a rough design without any details yet. To develop it further it has to take also more refined problems into account. Therefor an analysis is conducted to gain insight about the most vulnerable spots in the design.

The first critical point is the gas barrier where the glass and spacer bar meet. These points are be most important barriers and these points need to be closed as tightly as possible.

The second critical issue is the moisture coming in. Of course the same spots (where the glass and spacer meet each other) are the critical points, However in this case moisture has to be stopped around the perimeter of the seal.

The other issue that has to be taken into account is the force transmission of the glass pane . As the force of this glass pane does not go directly to the setting block but first through the seal, it must be prevented that unwanted shear forces applies on the spacer or that the outer glass pane has to carry both weights. For this another concept design is conducted on the next page.

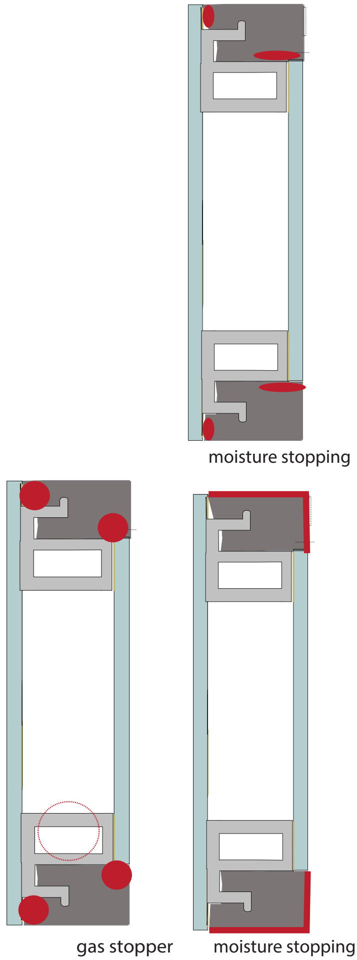


Figure 5.2.3.1: Critical parts of the chosen variants

Variant **A:** In this design all the load of the inner glass pane will be transferred through the spacer to the outer glass pane. Also, here there is no good insulated window Variant **B:** Force goes through the spacer but then directly to a bar towards the setting block. The surrounded rubber elements are hanged up to prevent force flow that may cause deformation in the critical parts. This variant is not performing well for heat flow. Variant **C:** Direct transfer of the force with the two most crucial parts covered with a sealant For this system it is however still complicated to find an interlocking geometry for this as both the spacer as the construction bar under it are stiff elements. Variant **D:** Load transfer from the glass pane is directly transferred through a construction element, however tolerances should be taken into account and therefor this does not work. Variant **E**: Building further on variant C, the bar will carry the glass weight while tolerances and the most crucial gas barrier spots are covered.

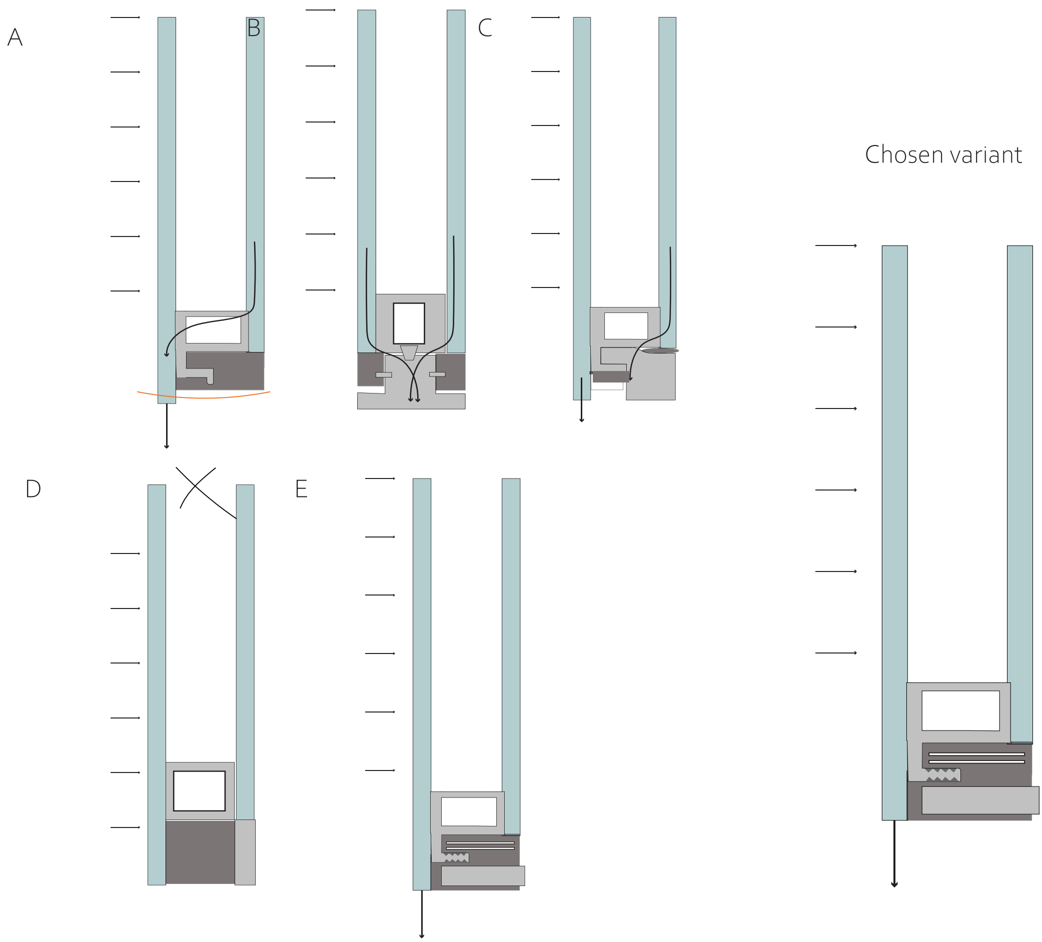


Figure 5.2.3.2: Conceptual load bearing variants

5.3 Replacement method

When designing an IGU for remanufacturing, a re-glazing strategy has to be thought out as well to reduce the costs and hindrance for the client. In this part of the report several methods are weighted against each other to find the easiest way to introduce the remanufacturable window. Although already concluded in the literature research of chapter 2 that the window system would be the most suitable system, it still will be discussed in this part as well taking the literature results into account.

There are mainly four different strategies of where to replace the IGU. The first distinction is in the method of how the IGU can be taken out of the window frame. It can be from the inside or outside but this is determined by the facade system. As already described in chapter 2, the window system will allow the window to be removed from the inside, the stick system and unitised system from the outside. (A side note to the unitised system, it can be designed to have the windows also placed and removable from the inside if desired. A side effect of this adjustment is the measurements of the windows are restricted to the elevation height.) The second distinction is the place of remanufacturing. It can be done in place so the window does not have to be taken anywhere or it can be done at a special LAB. A diagram is shown in figure 5.3.3.2.

The mobile Glass LAB would be allow for an ideal and controlled environment to install the new seal on the IGU. Also the machines for pumping the Argon could be placed in this ' vehicle' . The positive point furthermore is the ability to have a vacuum room to achieve a higher degree of Argon. The sizes of the panels however, would be restricted to the dimensions of the Glass LAB. In the Netherlands this would mean: a width of 2,60 m, a length of 12,00m and a height of 4,00 m (evofendex, 2017) if the glass LAB is not foldable or extendable in a way.

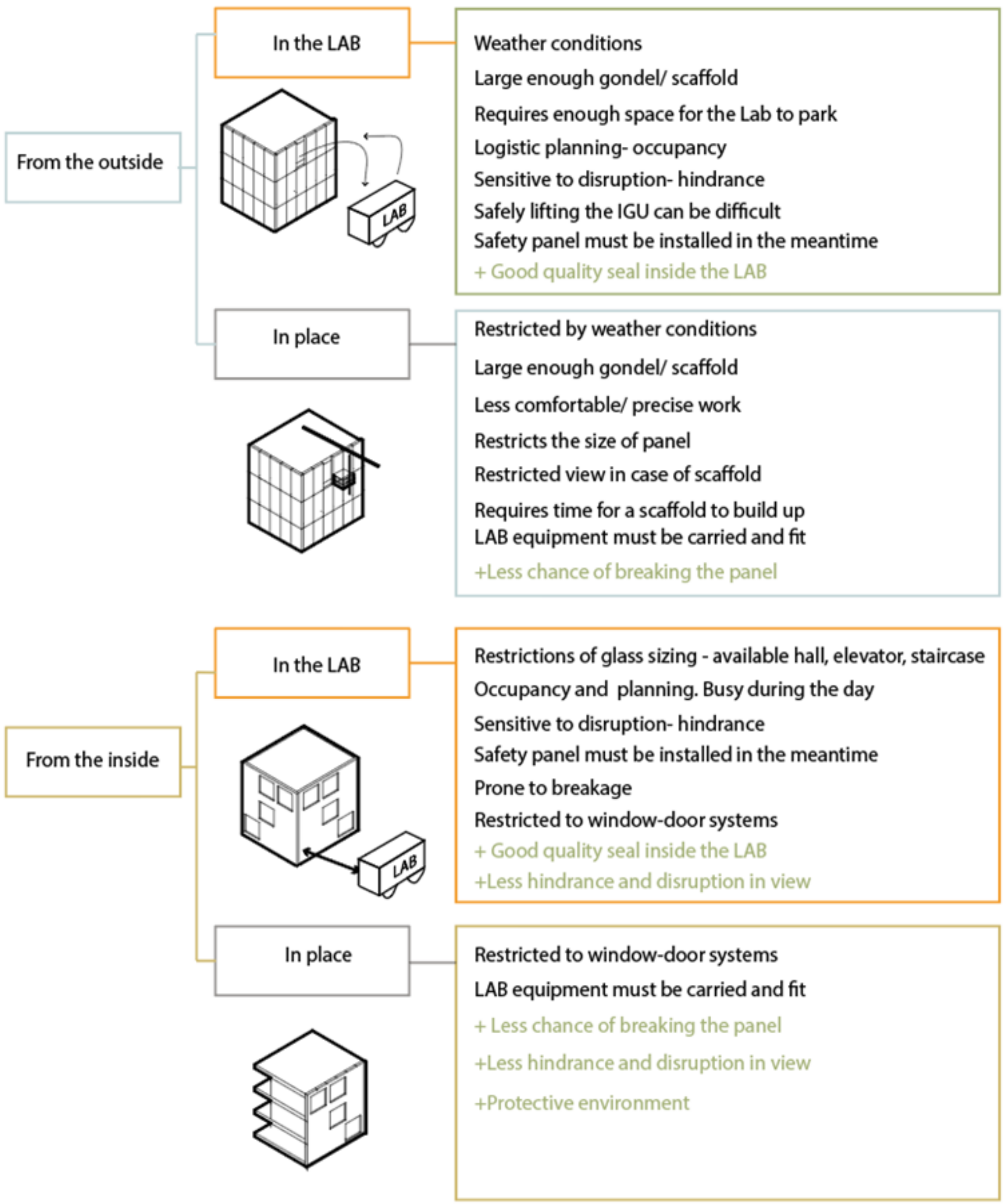


Figure 5.3.3.2: Concepts of replacing sites.

Evaluation
Evaluating the negative sides for each method and looking at the positive factors as well.

When a window has to be changed from the outside, a scaffold that fits closely around the face of the building is needed if the building has not a Glass Replacement Unit (GRU). However even if the building is equipped with this GRU ,pulley and bar in areas with rainy seasons, replacement work that takes place from the outside (which is usually the case with curtain walls and unitised systems) has to be completed during more agreeable weather conditions to make the gondola or scaffolding safe. This, thus limits the flexibility in time of the year.

Furthermore, when a scaffold is needed, it obstructs the view from the whole façade. In case of hotels this is option highly unwanted as the same with (prestigious) offices.

When glass panes are removed the occupants should remain out of that room or office during construction. This would mean in an office that the staff should stay elsewhere during their work week. Of course, this is highly unwanted and therefore replacement should be as fast as possible.
When the glass panel has to descend or ascend from the outside, less hindrance inside the building occurs as no elevator or staircase has to be ‘ reserved’ for traveling the IGU.
By not removing the glass panes, travel time would reduce. Also less chance of breakage of the glass is a positive point.

Glass removal from the inside of the building would restrict the type of façade systems to window-door systems as already discussed in chapter two of this report.
In case when the glass panels are transferred to the glass LAB vehicle, the dimensions of the panels have to fit into the elevator or staircase. In the case of remanufacturing the window in place from the inside, the LAB equipment must be carried along with the installers.

Conclusion
When evaluating the diagram the most suitable method for remanufacturing IGUs : from the inside and in place as it has the least amount of negative points and the most positive factors. This conclusion does not say that the other methods are impossible but more measures have to be taken in order to make the other methods work.
The positive points of the inside and on place is:
No gap will occur in the façade and thus work in the office will be the least hindered.
Besides this, no time will be spoilt by transferring the IGU.
Working from the inside also has the benefit of a warm, comfortable and protected environment.
However it is restricted to the window-door façade system which is mostly used in low-rise buildings and offices.

A working scheme is showed below in figure 5.3.3.3
First you remove the glazing bead in order to reach the IGU.
As now the suction lifter is clamped onto the IGU, it is safe to work on the edges of the IGU. The concept proposal of this thesis is based on keeping the IGU on its place while working on the edge of the IGU. This means that the IGU has to be lifted to eliminate shifting and rotation of the panel.
A device like a glass lift can help with this. Attention has to be given to the size.
The requirements for this glass lift are based on the accessibility for the manufacturers to the IGU and the dimensions to fit the glass lift inside any floor.
Based on Bouwbesluit online 2012 an elevator should be at least 1.05 by 1.35 m therefor this sets the limit to the dimension of the glasslift to a length of 1.05m .
To have a stable glass lifter with these dimension requirements it could be necessary to make use of autopoles to clamp the lift in place making use of the floors and ceiling
The glasslifter should be operational with just two men and manoeuvrable by (telescopic) lifting arms to position the suction cups even on a distance of 2 m.
Furthermore, once the autopoles are installed, the machine should be able to function in a radius of 3-4 m around it. In this way the poles don't have to be adjusted for every single window. Additional to this, a cart has to be taken with the two men to carry the argon and materials with them. ' Folding out' the glasslift should take around 15 min.

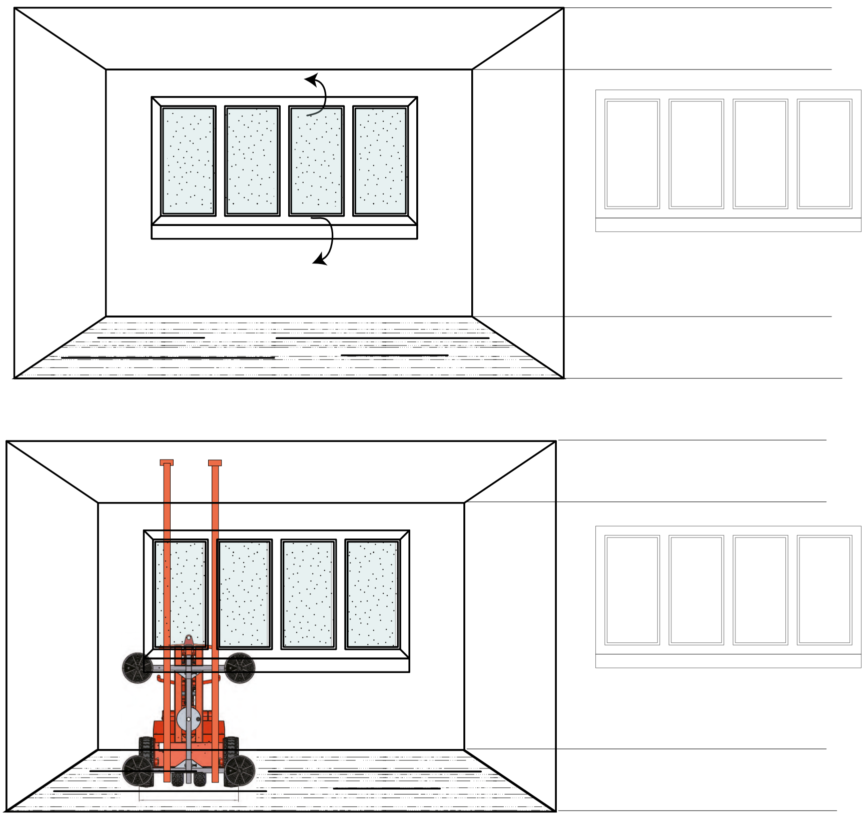


Figure 5.3.3.3: Working order when remanufacturing the edges of the window on the inside

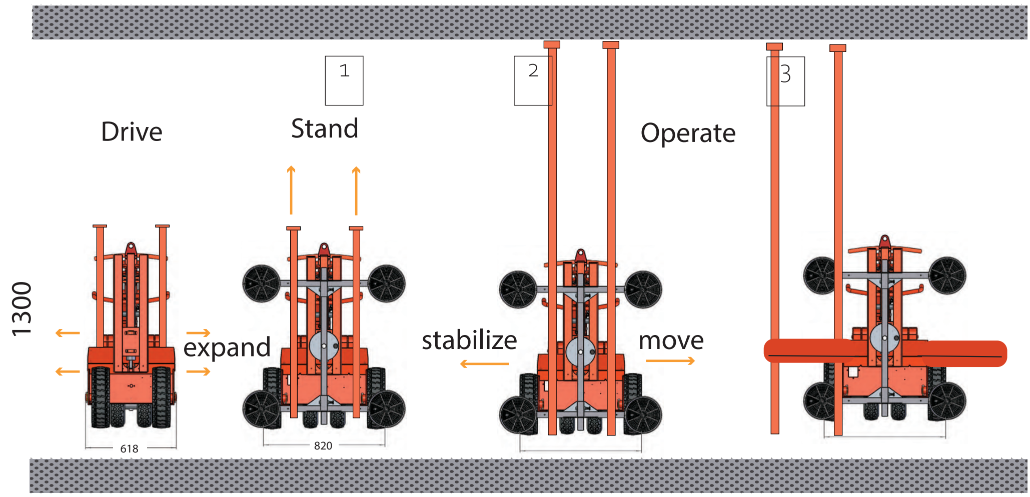


Figure 5.3.3.4 :Glasslift working order based on http://www.glgcan.com/ (width= 618 mm to drive through hallways).

Figure 5.3.3.5 :Glasslift operation and expansion to move to the next IGU based on http://www.glgcan.com/

5.4 Replacement order

The position of the valve, determines in a certain degree, the order of remanufacturing the different components. In the ideal situation the order would be:
1) Taking out the hollow section,
2)Taking out the rubber profile.
3) Getting out the desiccant and refill it.
4) Filling the IGU with the valve.
Because the spacer bar and the valve are both closed to the gas it would be a gas barrier for at least 10-15 min under the condition that the bonding between the glass and spacer bar is also gas tight enough. § 5.4.1
5) Slide the new rubber seal inside.
6) placing the hollow section back inside the rubber seal.

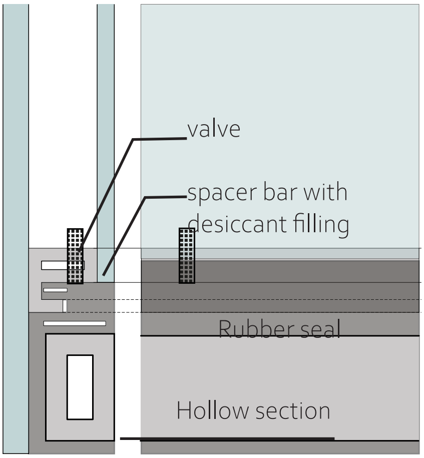


Figure 5.4.1: Ideal situation for the ease of replacement.

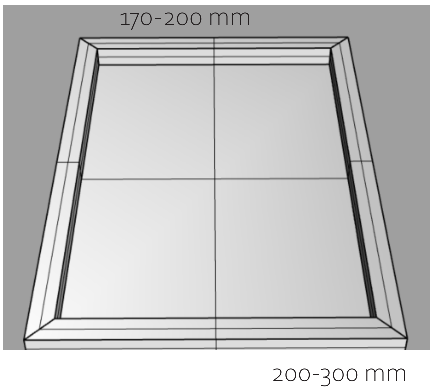
The assumption of a bonding that can be used as a gas barrier is taken from the current IGU situation where the butyl as primary seal holds the gas for even the whole life span of the IGU. As for the new design a glue instead of a butyl layer is chosen to assure a longer life-span this should be tested since no information about the gas permeability of glue is available therefor a test will be conducted. When this test is showing that glue can be used for a short time. gas barrier, a UV-test will also be tested further to see if under UV light the chemistry of the glue will not be affected by time.

Test:

Can glue be used as an air-tight sealing for +-15 min?

Equipment:
Aluminium sheets 2* (210*297) mm
Aluminium Koker profile: 2*(180) (15*15*1.5) mm
Aluminium Koker profile: 2*(297) (15*15*1.5) mm

all sawn in a corner of 45 degrees to be as close to the reality as possible



Glue properties
Thixotropic
peel strenght: 23 pli
240 min for hardening
Gap filling -v
resistance:
chemical :E
heat :G
moisture :G
impact :M
suitable for vertical application

Figure 5.4.1.1. The used Glue. Own image

Preparation:
For this test Aluminium panes are used instead of glass. Both materials are gas tight but drilling a hole inside the aluminium pane was more practical. Furthermore, not the delo glue but araldite is used for this test as with the aluminium plate no UV curing could take place. The Aluminium panes have to be cleaned properly. Acetone is used for this. Next, the Araldite is prepared in the special gun to mix the two components in the right proportion. Figure 5.4.1.1 shows a picture of gluing onto the surface. Applying the glue is done in four shifts with 24 h in between as the glue has to dry. The first day the upper half was glued together, while the second day the bottom part was glued. The third and fourth day another layer was put on top of the first layer just to make sure the whole seal was glued properly.

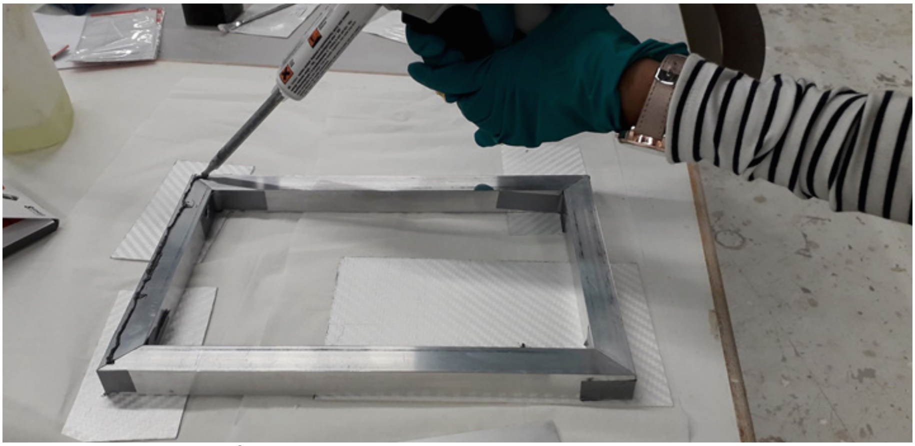


Figure 5.4.1.1. Gluing the frames (Authors image)

The air pressure test

Since it took almost two whole minutes before the manometer showed the ‘0’ (zero over pressure) I was already quite satisfied. However, the second time, the whole test had a total different outcome, it had a stationary value on the manometer as long as the pump was pumping. In short, due to the test, some holes have been created where the leakage is as big as the air pumped in-stationary condition.

In order to know where to seal to cover the holes, the pump was pumping while at the same time a thread was hold next to the model to find the vector of the air blowing out. On the spots where leakage was found, a mouldable glue ‘Sugru’ was applied.
After this next test, still some air leakage was occuring and to determine the exact spot, steam has been blown into the model with a steam device. It pointed out that the leakage occured at the hole inside the aluminium plate. Silicone glue was later on applied onto the hole in the aluminium plate to stop it from air leakage as the foil was apparently not covering enough.

Multiple tests have been conducted with every time the same conclusion. Although the time that the overpressure existed inside the model had increased to three minutes after re-sealing the model,the manometer showed a high level of decreasing in overpressure the first half a minute and the last 0.05 bar in +- 2.5 min. The same issue occurred each time, as new air gaps were created.

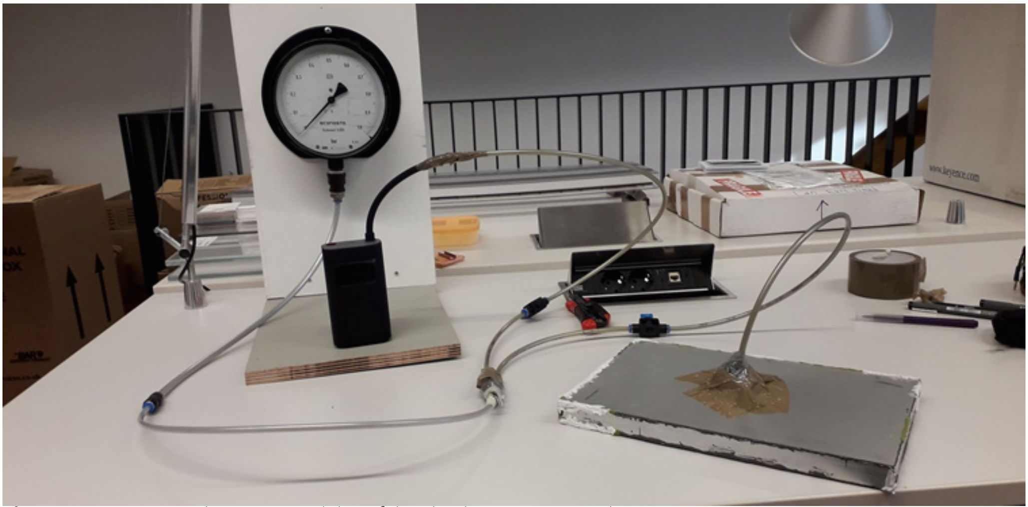


Figure 5.4.1.2 Testing the air permeability of the glued connection.(Authors image)

Altough hot melt butyl is nowadays an example that the sealant can both bond and be used as the gas barrier, this glue testing does not confirm the same for glue. Testing a glued connection in this 'simple' model gives not adequate results to build a scientific research on.The inaccuracy of this method is basically too much:
The two-component glue can have microscopic permeability because of the bubbles created during mixing.
Gluing airtight by hand is not precise enough and flaws in gluing will create holes during testing. For this reason the assumption of using glue to create a gas barrier for a short time can not be confirmed with this test.

Figure 5.4.1.3: Moldable glue Sugru. (Authors image)

Substrate Performance		Araldite® 2010-1	Araldite® 2011	Araldite® 2012	Araldite® 2013
Metals	Mild Steel	E	E	E	E
	Stainless Steel	E	E	E	E
	Aluminum	E	E	E	E
	Copper	E	E	E	E
	Brass	E	E	E	E
	Galvanized Steel	E	E	M	E
Thermosets/ Composites	GRP (UP)	G	E	E	E
	GRP (EP)	G	E	E	G
	CFRP	E	E	G	G
	SMC	G	E	G	E
Thermoplastics	PVC	G	M	G	E
	PA	M	G	M	M
	ABS	M	E	G	M
	PC	M	G	G	M
	PMMA	M	M	M	G
Misc. Substrates	Ceramic	E	E	E	E
	Glass	E	E	E	E
	Rubber	M	E	M	M
	Wood	E	E	E	E

Key: E= Excellent, G= Good, M= Moderate

Figure 5.4.1.4: The used glue and its properties

§ 5.4.2 As the conclusion of the performed test can not confirm the assumption, another re-assembly order has to be found that is fast and reliable. Therefor three variants are drawn and set out to each other.

Option 1:

This option has the valve at the same place as in the ideal situation. However, an air tube is added to the process. as the whole seal need to be closed before the argon will be pumped in.

order of re-assembly after filling the desiccant:

1) The rubber seal together with the air tube will be pushed in place
2)The air tube will be pushed into the valve on the right position
3) The special cut hollow section will be slided into the rubber seal to push it tightly onto the critical places.
4) Now the argon can be pumped through the air tube towards the valve.
5) As the air tube goes through the sealed area, a rubber cap could be pushed into the air tube to make this also gas tight.

positive/negative

- Slow remanufacturing process. each time also
-every element has to be in the right position (gap in the rubber, the air tube inside the valve)
very sensitive with the bar, it should not hit the air tube but also it should be covering as much as possible to push the seal around the air tube as tight as possible

Option 2: Hole in the spacer bar

This option requires a hole inside the spacer bar and inside the rubber in order to avoid a hole inside the glass.The glass pane will be shifted upwards . For the seal to close properly, its extrusion has to close be adjusted as well creating a higher edge of the rubber sealant.

Order of re-assembly after filling the desiccant:

1) The rubber seal will be pushed in place.
2) The hollow section will be slided into the rubber seal.
3) Use the valve to pump the argon inside.
4) Re change the O-ring around the valve

positive/negative

- Hole in spacerbar
- Hole in the rubber has to be at the same location as the hole in the spacer bar which makes it more difficult and less fast to change the seal.
- Position of the inner glasspane is placed higher in regard to the spacer bar.
- To compensate for the hole in the spacerbar and rubber. an O-ring has to be used.
-gas flow through the desiccant
+No valve in sight
+- medium remanufacturing process speed

Option 3: Hole in the spacer bar and glass

This option requires a hole inside the spacer bar and glass. The better quality from this variant with respect to 'Option 2' is that the holes are positioned from each other inside the production hall so this is only needed once. Order of re-assembly after filling the desiccant = same as option 2

- Hole in spacerbar and glass
- gas flow through the desiccant
- To compensate for the hole in the spacer bar an O-ring has to be used around the gap of the valve.

+No valve in sight
+Fast remanufacturing process

hole in glass, drilled from just one side->fractured (own image)

Option 4: Hole in the glass

This option requires a hole inside only the glass. However, the valve needs to be placed above the spacer bar. **Order of re-assembly after filling the desiccant = same as option 2**

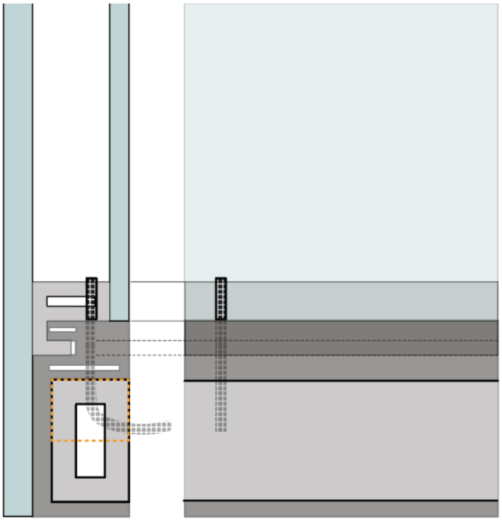
- Hole in spacerbar and glass
- To compensate for the hole in the spacerbar an O-ring has to be used around the gap of the valve.
-valve requires extra place

+Fast remanufacturing process
+gas goes directly inside the cavity

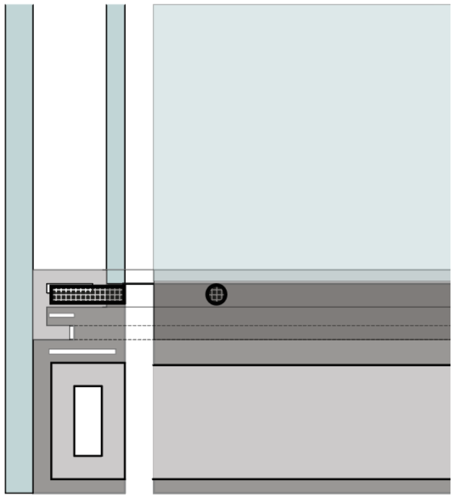
Conculsion

It can be concluded that option 4 is the most favourable as there is only one hole needed (in the glass) and it helps with a fast remanufacturing process. To prevent cracks around the hole of the glass, the glass plate need to be drilled from both sides halfway. (Interview with the LIS) although it may be a bit difficult having the centre of the drill on the same line. Another technique which require more time is often used: Using a kit (for example Christal bound) to attach two pieces of glass on another in this way the glass will not crack at the bottom. After the desired drill hole is made, the kit can be removed with acetone or evaporate in the oven (interview at the LIS).

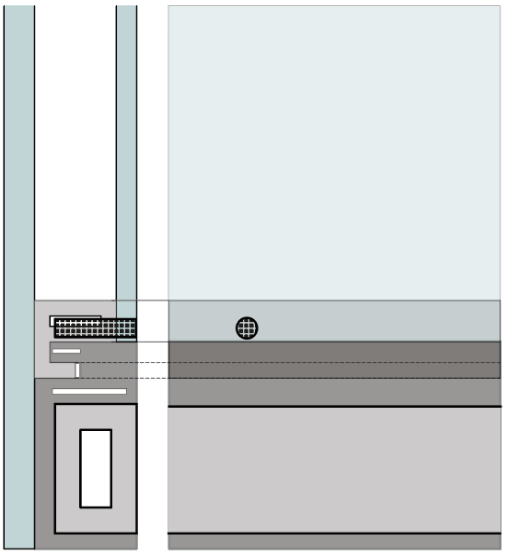
Exterior



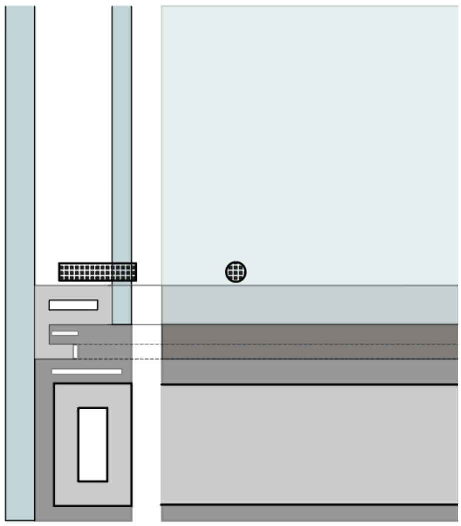
option1



option2



option3



option4

5.5 Desiccant filling

In the design for the spacer, it is taken into account that it needs to be filled with the desiccant. In order to do so a method is described here.
On both the upper and down side of the IGU is a hole in the spacer bar. These holes will have plugs inside to cover it. Both holes /plugs are placed on the right side to help installing the IGU with the right side up. **To remove** the dessicant, the spacer bar the plug on the bottom side will be unplugged and a machine can suck the dessicant out and the plug will afterwards be installed again. **Filling** the dessicant can be executed from the top part, where it can easily be seen if it is filled enough. The plug will first be removed, then filling can take place where after the plug can close the gap again.

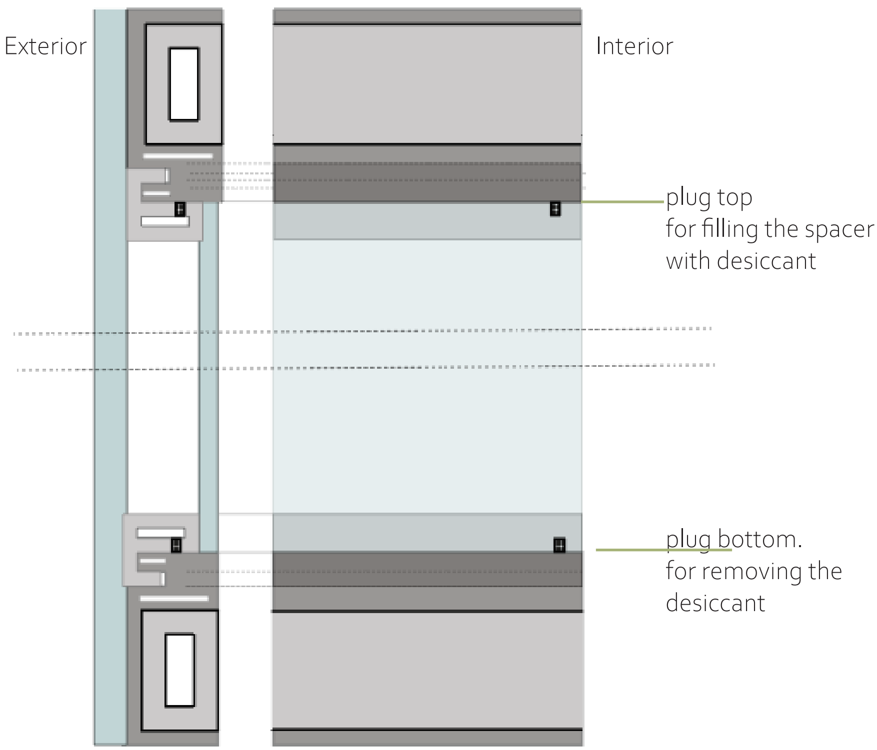


Figure 5.5.1: Scheme of the desiccant in and outlets.

5.6 The glue

There are many different types of glue. But concerning bonding of glass to a spacer bar while taking into account the additional requirement of having a connection that is durable for over 100 years but still needs to be taken apart after service life, brings two valid options: The Two-epoxy glue or photobonding. As the spacer bar is not transparent there is no strict requirement for the bonding to be transparent but it does need to look clean. The a two-epoxy glue as have been experimenting with, is therefor not ideal as it is clearly visible. The following requirements are for the glue:

- It should be able to accomodate the tolerances in spacer bar and glass -> thickness
- Service temperature minimal: -10; minimal maximal temp: +80 degree Celcius
- Fast (initial) curing
- Excellent UV light resistant
- Excellent humidity resistant
- Excellent bonding between glass and fiberglass
- High tensile strength
- Bonding guarantee (>100 years)
- at >100 degree Celcius the bonding should break as ingredients will evaporate to make recycling possible

Delo AD491 would be a suitable glue that can resist moisture and can be used for other materials than aluminium or glass. It is colourless/transluscent which is perfectly fine/ However DELO does not give an life span/guarantee on adhesives (see Appendix 6)

5.7 The spacer bar

Fiberglass, usually known as thermal insulation can also be used to produce façade profiles and even spacer bars as the research of ((Elmahdy, 2006)) already suggested. Swisspacer Advanced and Ultimate using 35% glass fiber in their product. FRP is favourable since it has a low dead weight, not flammable, does not need a lot of maintenance and ,because it is a composite, the mixture can be optimised for the material properties of the product such as chemical resistance, low expansion coefficient, fatigue resistance and thermal insulating properties. (van Dijk, nd)

Fiber reinforced plastics can roughly be divided into two groups: synthetic materials reinforced with short fibres, and with long (continual) fibres. Composites that are reinforced with short fibres are primarily used for smaller applications that can be made in combination with injection moulding or extrusion. While composites reinforced with long or continuous fibres are usually used in large structures such as ships or wind turbine wings (Thorning, 2003). The glass fibres are impregnated with a matrix material, usually a thermosetting resin such as epoxy resin. The pultrusion process pulls continuously fibres from rolls which are then drained in resin, the combined mixture is then pulled on through the heated equipment where the profile is cured in its final geometry. The fully cured profile is then pulled forward to a floating suspended saw which cuts the profiles into length.

According to Fiberline standard tolerances for structural profiles:
Profile width and height: +/- 1%
Thickness +/- 10%
Length: -0/+20
Weight: +/- 10%

The above tolerances are standard. Special requirements can be met by agreement.

Figure 5.7.1.1: Pultrusion process of GRP at fiberline .

The thinnest strip that can be made (at dpp-pultrusion) is in the range of 0.12 mm but in order to create a rigid profile, a wall thickness of 2-3 mm is the lower limit for a pultrusion process.
Once the profiles are cut to size with a hard-metal or diamond tool, gluing or using corner keys is the best way of connecting the profiles together. For gluing a two-component epoxy or a polyurethane glue have proven good results according to testings(Thorning, 2003). Bending a FRP profile 90 degrees is not the right way because of the glass rowing that apply the strength to the profile is not isotropic. Welding is not an option with FRP either. Applying small holes in the spacer bars and in the profiles has to be done afterwards and not in line. When holes are drilled inside the profiles would need to sealed with a lacquering system afterwards in order to protect the profiles. Because of this, the ' Swisspacer Ultimate' has reduced the amount of holes by making long gaps in the middle of the spacer bar. Just narrow enough to prevent the desiccant of going through it (Figure 5.7.1.3).

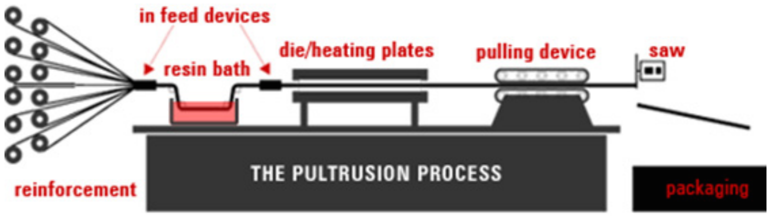


Figure 5.7.1.2: Pultrusion process (van Dijk, nd)

Figure 5.7.1.3: Swisspacer reducing the amount of holes by making longitudinal air gaps.

§ 5.7.2 **The shape of the spacer bar** is developed from the overall concept design with the following background requirements:
First of all the spacer should allow for enough desiccant inside. Where at the same time this filling should be replaceable. For this reason enough space should be left for a plug to remove the desiccant and a plug to fill the spacer on a place that is easy to access.

The sides of the spacer bar should be as high as possible for maximum bonding area with the glass.
The ideal width of the cavity is 16 mm as previously described in the literature part, therefor the spacer designed for this report is also 16 mm wide as no other obstructions occurred (figure 5.7.2.1).
As the spacer has the function to keep the butyl component in place, the arm where the butyl component slides into has to be as long as possible while it still needs to accommodate the space for the plugs and should limit the worsen of the thermal transmittance. A balance is found with an arm of 8 mm, which is half of the width of the whole spacer but leaves also 8 mm in total for opening for the plugs(-figure 5.7.2.2) whereof 3.2 mm can be used for the width of the plug itself.

A groove in the arm of the spacer bar allows for a better settlement of the connection between the butyl component and the spacer. The thickness for the spacer is chosen to be 3 mm except for the groove inside arm, at that place the thickness varies to 2.5 mm. A further explanation about this is given at section 5.8.2

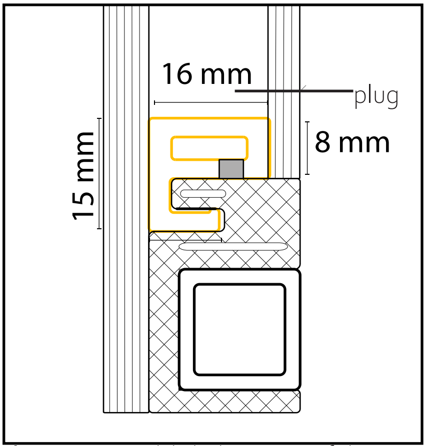


Figure 5.7.2.1: Global dimensions of the spacer. Authors illustration

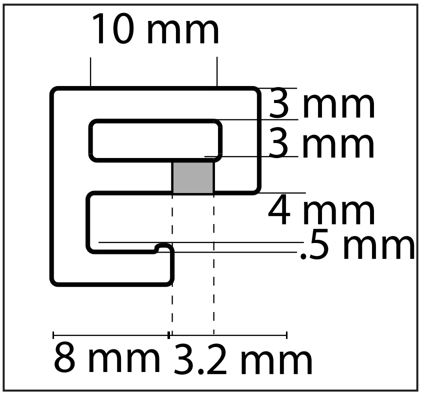


Figure 5.7.2.2: Dimensions of the spacer. Authors illustration

5.8 Sealant material

The material for the rubber seal element has to be decided. The selection of materials discussed in this part will be based on the different rubber material already used in the building or automotive industry. There will be looked at the following materials : Natural rubber, Butyl, EPDM, TPE-SEBS and EAM in the criteria of: Gas permeability ,processing method, vapour permeability, temperature range,durability for UV,ozon,water and also flammability.

Natural Rubber

Natural rubber is a polyisoprene. By vulcanizing it the resistance against chemical, environmental impact and mechanical properties are improved. Natural rubber however is 20 times more permeable to air as it has fewer methyl groups and is more unsaturated than butyl. Typical applications are tires and other automotive parts (McKeen, 2017).

Isobutylene Isoprene Rubber (IIR).

Butyl is a synthetic rubber that is built by polymerization of monomers where after it is vulcanized. Two percent of Isoprene is added to the 98 percent of isobutylene for providing sufficient double bonds to allow vulcanization with sulfur. Because this material can be vulcanized, seamless designs can be made with it. Butyl furthermore has very low permeability to air and other gases and is good resistant to UV. That is the reason for its application in tire innertubes and in conventional IGU.
A disadvantage is that according to CES this material is highly flammable.

- **[cm3 (STP)·0.5 mm/m2·day·atm] [1010·cm3 (STP)·cm/cm2·s·cm Hg] Normalized Units, Permeability Coefficient (cm3·mm/m2·day·atm)**
- *Air 45 23*
- *Nitrogen 50 25*
- *Oxygen 195 98*
- *Propane 475 238*
- *Butane 4360 2180*
- *Freon® 12 22.8 1497*

(McKeen, 2017)

Butyl / Halobutyl rubber (IIR, 30-50% carbon black)

Datasheet view: All attributes — Show/Hide

Absorption & permeability				
Water absorption @ 24 hrs	* 0.01	-	0.02	%
Water vapor transmission	* 0.002	-	0.004	g.mm/m².day
Permeability (O2)	* 4.38	-	16.6	cm³.mm/m².day.atm
Processing properties				
Polymer injection molding	Acceptable			
Polymer extrusion	Acceptable			
Polymer thermoforming	Unsuitable			
Durability				
Water (fresh)	Excellent			
Water (salt)	Excellent			
Weak acids	Excellent			
Strong acids	Limited use			
Weak alkalis	Excellent			
Strong alkalis	Excellent			
Organic solvents	Limited use			
Oils and fuels	Unacceptable			
Oxidation at 500C	Unacceptable			
UV radiation (sunlight)	Good			
Flammability	Highly flammable			

Figure 5.8.1.1: Butyl properties (CES Edupack 2019)

EPDM

Ethylene-propylene-unsaturated dieneterpolymer this is a Polyolefin thermoplastic elastomer (TPO).made from polypropylene and ethylene-propylene rubber (EPR) . EPDM has a small amount of a third monomer for sulphur cross-linking.

This material is used mainly for gaskets, lock-strip gaskets and foam gaskets as it is excellent resistant against weathering, ozone and UV. Besides this it has a good heat stability and is excellent water resistant rubber (CES Edu pack 2019). EPDM can also be extruded.

This material is not likely to be welded. Joining EPDM together requires therefor another adhesives like e.g. polyurethane adhesives, silicones, nitrile or neoprene spray.

- **Permeant Permeability Coefficient (cm3(STP)·0.5 mm/m2·day·atm) Normalized Units, Permeability Coefficient (cm3·mm/m2·day·atm)**
- *Air 1,615 808*
- *Oxygen 3,470 1,735*
- *Nitrogen 1,180 590*
- *Carbon dioxide 15,385 7,693*
- *Helium 2,720 1,360*

(McKeen, 2017)

TPE-SEBS (styrol-ethyleen-butyleen-styrol)

As already in the definition of its name this material is a thermoplastic elastomer and has both thermoplastic as elastomeric properties.
thermoplastics elastomers are relatively easy to produce in comparison to rubbers, for example, by injection molding or extrusion. The other advantage of thermoplastic elastomers is that the material melts when heated above its melting point (figure 5.8.1.2)and solidifies when cooled and which gives it the possibility to be recyclable and therefore a product can be manufactured with relatively low production costs. TPE-SEBS have comparable mechanical properties as EPDM.
TPE SEBS is elastic and resistant to tear and perforations. Besides this, the material is good resistant against acids, liquid and UV and is save for body contact. As this TPE-SEBS is a thermoplastic material it can be seamed to each other or even to other technical polymers which is an important ability to achieve a seamless product.
The O2 permeability of TPE-SEBS differs with the shore rating. The higher the shore number, the stiffer the material. 'A' stands for flexible material while 'D' gives rating to the harder material. And the scale goes from '0-100'.
According to CES Edupack the higher the A rating, the less permeable it is to O2 gas.

Figure 5.8.1.2: TPE, melt to (re)shape (Sonnega, 2014)

Absorption & permeability

Water absorption @ 24 hrs	0.05	-	0.06	%
Water absorption @ sat	* 0.306	-	0.366	%
Humidity absorption @ sat	* 0.0919	-	0.11	%
Water vapor transmission	* 51.9	-	69.3	g.mm/m².day
Permeability (O2)	* 865	-	1.16e3	cm³.mm/m².day.atm

Figure 5.8.1.3: TPE_SEBS properties (CES Edupack 2019)

With testing of the 3D printed models a shore hardness of around 70-80 would be suitable for the design.
Silicone rubber/polysiloxane
Silicone rubber consists of chains from silicon and oxygen atoms and not like other rubbers from carbon and hydrogen atoms. The molecular structure of silicone rubber results in a very flexible—but weak—chain. Silicones are very stable at low and high temperatures. Although fillers may improve properties somewhat, tear and tensile strengths remain relatively low. Silicone rubber can be produced by vacuum casting. And are used as sealings, nonstick coatings and gas separation membranes.

- *Gas Source Document Units, Permeability Coefficient × 109 (cm3 cm/s·cm2·cm Hg) Normalized Units, Permeability Coefficient, (cm3·mm/m2·day·atm)*
- *Hydrogen 65 42,700*
- *Helium 35 23,000*
- *Carbon dioxide 323 212,000*
- *Nitrogen 28 18,400*
- *Oxygen 62 40,700*
- *Methane 95 62,400*

(McKeen, 2017)

Ethylene Acrylic Elastomers

Ethylene acrylic elastomers (AEM) is a copolymer of ethylene and methyl acrylate. The ethylene is added for good low-temperature properties, while the methyl acrylate content provides oil resistance. Typical uses are in transmission seals.
The qualities for AEM are high-temperature durability, good oil resistance,excellent water resistance, good low-temperature flexibility and ozone/weather resistance mechanical strength, compression set resistance, flex resistance, vibration-damping consistency and is excellent in extrusion.

Ethylene acrylic rubber (AEM, unreinforced)

Datasheet view: All attributes | Show/Hide

Optical, aesthetic and acoustic properties					
Refractive index		1.6	-	1.61	
Transparency		Translucent			
Acoustic velocity	*	24.9	-	40.7	m/s
Mechanical loss coefficient (tan delta)		0.2	-	0.5	
Critical materials risk					
Contains >5wt% critical elements?		No			
Absorption & permeability					
Water absorption @ 24 hrs	*	0.1	-	0.2	%
Processing properties					
Polymer injection molding		Acceptable			
Polymer extrusion		Excellent			
Polymer thermoforming		Unsuitable			

Figure 5.8.1.4: AEM properties (CES Edupack 2019)

As there is no information about gas permeability available for AEM in CES Edupack 2019, these values are retrieved from the(McKeen, 2017) Also profiles for windows and door weather stripping are also made out of AEM.

- *Permeant Gas Coefficient (10–8·cm3·cm/cm2·atm·s*
- *Normalized Units, Permeation Coefficient (cm3·mm/m2·atm·day)*
- *Air 0.3 25.9*
- *Nitrogen 0.3 25.9*
- *Methane 1 86.*
- *Freon® 12 1 86.*
- *Oxygen 1 86.*
- *Freon® 22 5 432*
- *Carbon dioxide 7 605*
- *Hydrogen 2.9 251*
- *Helium 2.7 23*

§ 5.4.2 A conclusion

From the different sorts of sealant material that is illustrated above, both AEM and butyl seem to be good choices for the seal because of the low out gassing (altough CES does not confirm this). As AEM is more a special rubber used for applications with oil is it much more expensive than most standard elastomers, the most logic material will be

butyl that provides low vapour transmission and inert gas permeation .

5.9 Sealant form

The possibility for the shape of a rubber profile is infinite as the material(s), thickness and function influence the design. However, by looking at the basis of the most common profiles there are some typologies recognizable.

'D or O' - shaped design of figure 5.9.1.1 are made to be easily compressed and also shear force can make it transform. Profiles in this shape are sometimes produced from EPDM with sponge rubber. Because of the open cells, this material requires a closed outer skin in order to return to its original form after stress release. The choice of sponge rubber can be considered because of large the amount of material that is used for this usually bigger D/O shape and thus a thicker material while still using the flexibility of the shape.

In smaller profiles and where less rigidity is required, the material can be set to TPE-SEBS. As in all sorts of rubber also with this material different stiffness can be achieved by adjusting the mixture.

Another form that is widely used is the ' folded profile. Again an air ' chamber' is constructed that can be compressed easily. When the profile is released from stress the chamber will come back to its original form (figure 2). The difference between the transformation of this shape and the O/D shape is that the 'folded'one behaves like an auxetic structure. By compressing it, the fold also goes inwards whereby the tips of the form goes down in a straight line whereas the O/D shape expands when applying a compression force on it.

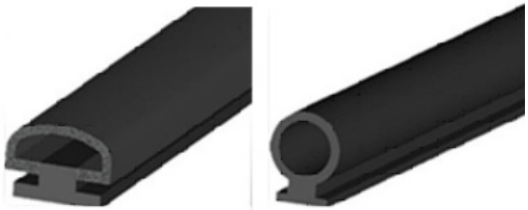


Figure 5.9.1.1:Foam rubber D/O shapes

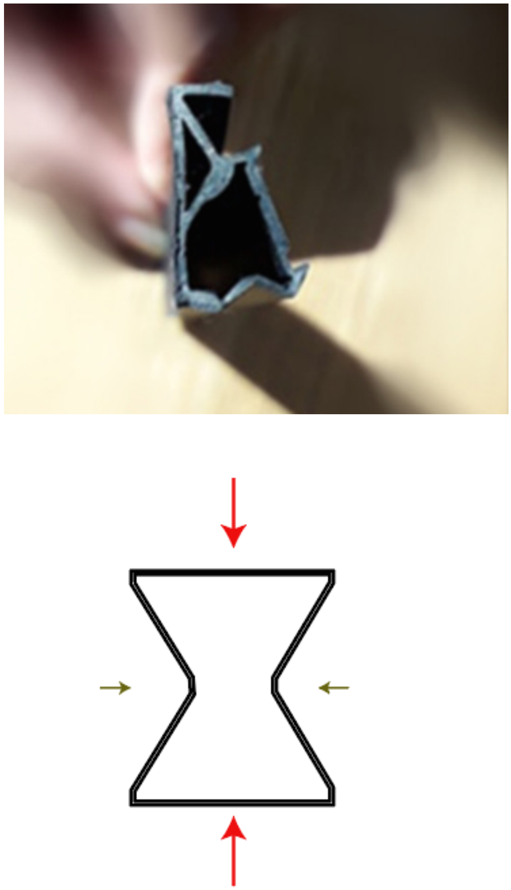


Figure 5.9.1.2 a/b: Auxetic form, compression in one direction leads to compression in the other direction as well.

The ' grooves/arrow' shape is mainly used to push very easily in place but the hook (weerhaak in dutch) prevents it from getting out of the grooves. Also with the precision of the arrow thickness the D/O shape can help covering uncertainties as written above (figure 5.9.1.3).

Carriers are used to give rigidity to one end of profiles in order to clamp.
This is called 'inlegging' in Dutch.
By using a partly solid strip or wire inside the rubber profile a clamping effect without using tape or glue can be achieved. The use of a partially solid strip has a stronger clamping effect than a wire support. On image5.9.1.4 the most common insert types are shown.

Figure 5.9.1.3: Arrow shape (Authors illustration)

a wire carrier (also seen in 5.9.1.5)is usually used for a sealing profile that consists entirely of rubber while the steel or plastic clamping strip is usually used in the PVC clamping profiles and contain a "center bar" or "double bar". Those strips can be solid but in order to achieve a better bending radius the solid strips have breaks in them.

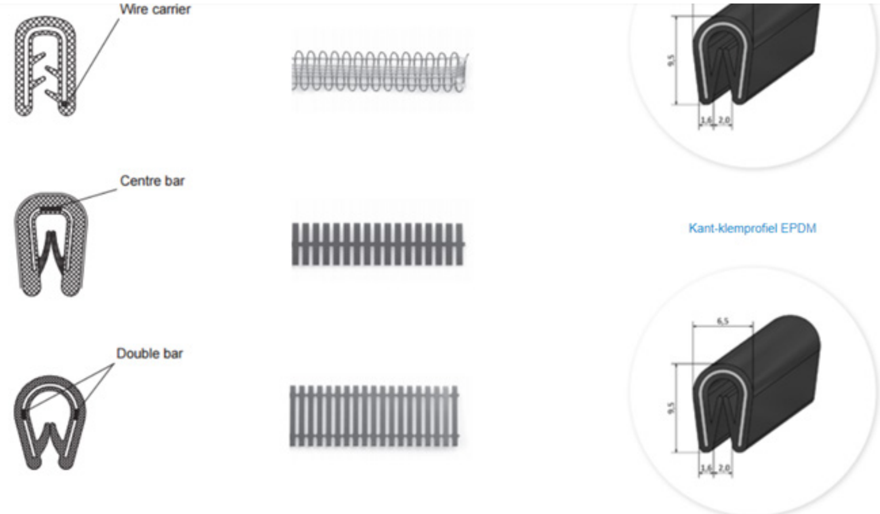


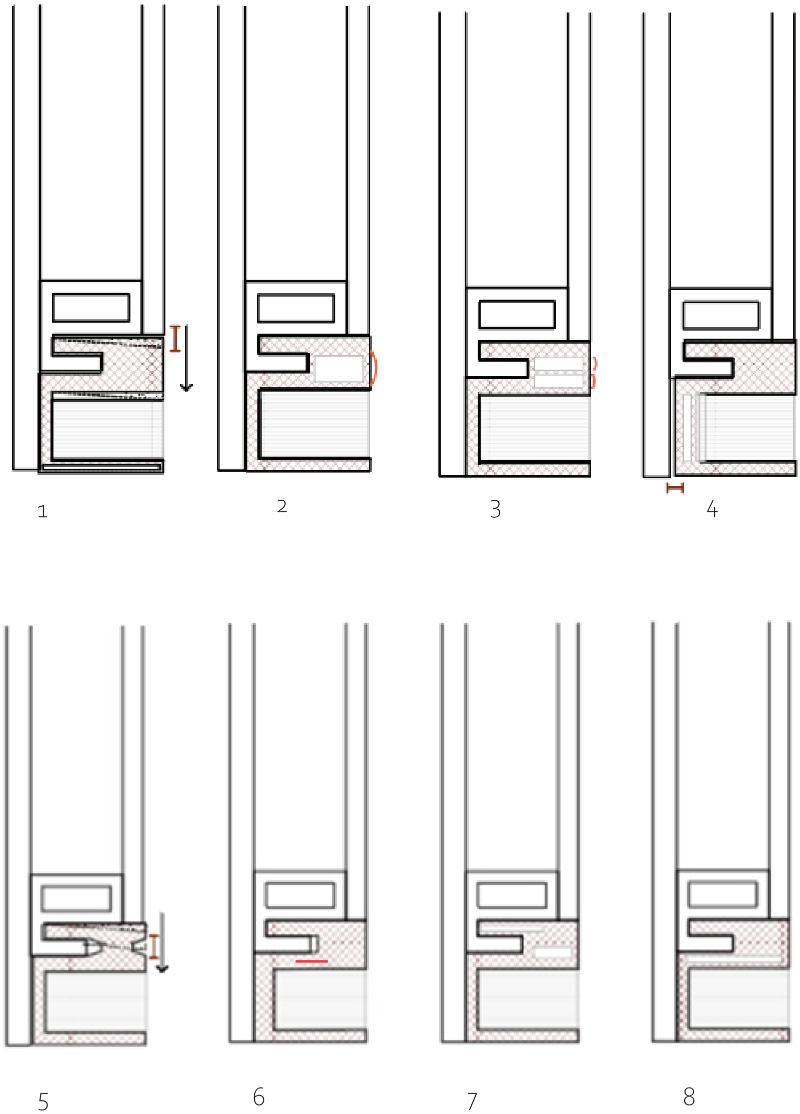
Figure 5.9.1.4: Types of metal inserts (www.carmat.nl).

By 3D printing with flexible material several design principles were tested integrated in the model for the re- manufacturable sealing of windows for this report. There has been experimented with the shape of wholes, varying of thicknesses, and the already shown principles in this section.
Furthermore small alterations have been made on the spacer bar design to experiment with grooves and profile.

Figure 5.9.1.5:clamped profile (Authors image)

Figure 5.9.1.6: Economical holes in rubber

§ 5.9.2 Variants for the form of the rubber component



The first design option has a compartment at the bottom part from the rubber in order to let the core slide easily inside the construction.
However the whole rubber would have a gap between the bar and the rubber at the upper side when the bar will press on the rubber at the bottom, the bar will not work to press the rubber to the glass pane for it to seal tightly the whole edge of the window.
The other downside to this compartmentalization at the bottom is that the glass pane could be tilting for it to rest on the stiff bar or another unwanted effect can occur: the glass pane would transfer its load to the spacer bar which causes shear in the connection.

The second and third option are to understand the principle to make an O compartment(s) at the top side and how the amount of compartments differ from each other even if the gap area is the same for both. The one big compartment will cause a bigger expansion to the side. The option with two compartments is therefore preferable in case there is enough distance between the glass pane and the top of the compartments.

Option four shows a vertical compartment next to the glass pane that is facing the outside. Eventhough the bar can be pushed inside, it will not help to assure a tight fit to the glass. As the compartment will prevent the bar from pushing the rubber to the glass pane.

Option five is the 'folded' principle where the auxetic form should prevent the rubber to expand in horizontal direction. However this results in almost the same sag problem as with design one, the compartment at the bottom.

Option six is evolved from the folded profile. It is about the gap next to the spacer bar elongation.
Due to this extra space, the bar can be pushed inside as much as possible to assure a good seal tightness at the glass pane that is facing the outside. This works well

Option seven is about making a compartment above the part of the spacer bar. Due to this, the rubber can again be pushed inwards more easy. As the glass pane needs a certain thickness of gas barrier, the compartment can not go all the way until under the glass pane. Therefor, another compartment is drawn in this option. This works well according to the 3D print test.

Option eight follows the same principle, but the focus here is to get the hollow section fit in the bar as good as possible in order to press the rubber tightly to the glass pane that is facing the outside.

This is also working.
The following options are experiments with grooves and texture inside the spacer(figure 5.9.2.2) . A sidemark has to be made about the limitations of these experiments.
First of all the choice of the flexible material was limited as the printer has trouble using a too soft and flexible filament. Therefor experimenting with an arrow shape such as figure 5.8.1.3 did not give the most adequate results as the shore (hardness) was higher than desired. Due to this, the arrow shape did not work as it did not fit inside the space. For experimenting with this arrow shape samples obtained from 'Groenrubber rotterdam' were used to gain insight in the functioning. Apart from that, alterations in rigidity were obtained with infill patterns, layer heights, overlap percentage, extrusion percentage and the nozzle size.

It follows that having a groove inside the arm of the pacer bar makes shifting outwards of the rubber extra complicated as the arrow shape of the butyl can nestle in between. Making such a groove gives thus a good result. The proposed design should combine : number 2/3, 7,8 9 and the spacer bar should contain grooves.

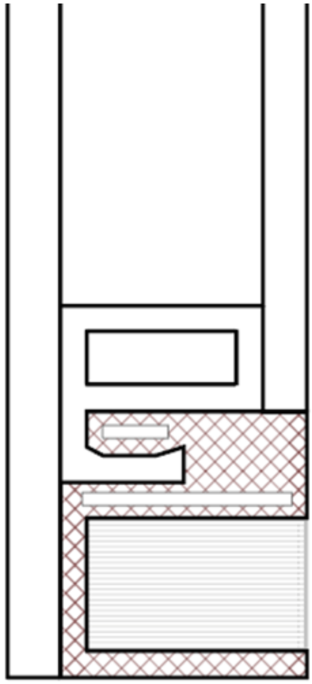


Figure 5.9.2.2: Scheme of the chosen design.(Authors illustration)

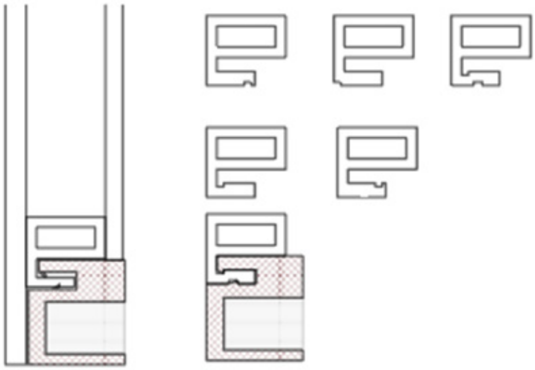


Figure 5.9.2.1: Variants of grooves in the spacer.(Authors illustration)

5.10 Valve options

In order to house a valve inside the spacer bar to pump the argon inside the panel, a system should be chosen. The requirements are obviously a small element since it determines the cavity with of the whole IGU and preferably simple, reliable and without external tap. In this part the basic valves are set out.

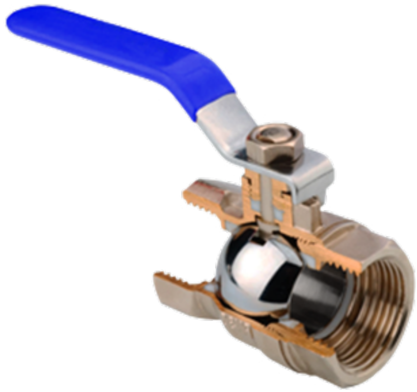
Ball Valve

Ball valves (Figure 5.10.1.1)can partially or completely closes off a liquid or gas flow by the means of a rotating ball with a bore. By rotating the ball 90 degrees on its axis, the medium can pass or not. The ball valve is characterized as reliable, durable and a 90 degree open/close system which makes it good for shut-off applications. A fine flow control is not easy with these sorts of valves unless a v-shaped passage is used but for the application in an IGU this would not be required. However the tap would form an obstacle if this type of valve would be chosen.

Gate valve

A gate valve is also known as a sluice valve and opens by lifting a barrier out of the path of the medium(Figure 5.10.1.2). Gate valves are not recommended for flow control and they are mostly used with larger pipe diameters since they are the simplest to construct than other valve types in large sizes.
But since debris can build-up and the sluice moves up and down it is vulnerable for erosion. Furthermore this system also requires a large space, it is not suitable for

the IGU.



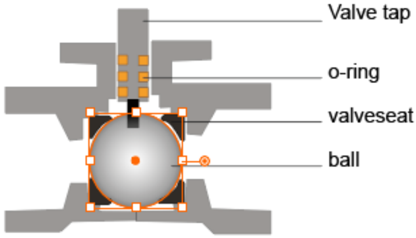


Figure 5.10.1.1: Ball valves //magneetventielshop.nl/kogelkraan-introductie.html1=valve https://www.festo.com

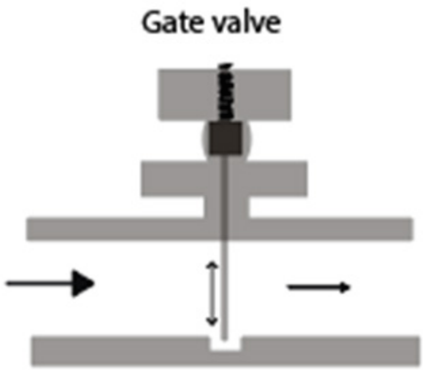


Figure 5.10.1.2: Gate valve

Globe valve

Globe valves can in contrast to a gate valve also regulate flow. It consists of a disk that can totally be removed from the flow path or it can completely close it. It is an excellent shut-off valve(5.10.1.3).
The same principle can be achieved by a magnet valve that can be controlled electrically(5.10.1.4).

Butterfly valve

The butterfly valve is a valve that also can regulate the flow of the medium. The closing system is a disc that can rotate by the hinges that are connected to the operator to control the flow in the body. The principle is comparable with the ball valve but the advantage of a butterfly valve is that it can be used in very big systems.

Also this system is too big for the IGU

Check valve

The check valve is fully automatically opened and closed and there are multiple different designs for the same principle. Check valves are widely used in tyres.

Swing check valve

The first type explained is the swing check valve (5.10.1.5).
The and can also be created from a disc ball . The valve operates when there is flow in the wanted line and gets fully closed when there is no flow. It consists of a valve body, a seat, a disk that is connected to the arm and a pivot pin. If there is pressure on the other side when the gas would like to flow away, the disk will press onto the seat, what prevents the gas to flow out. In some cases, a spring can be used to help to close the valve or a weight on the arm can be add

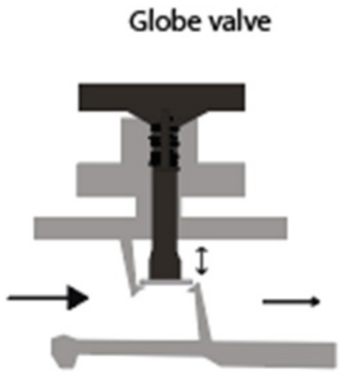


Figure 5.10.1.3: Globe valve based on: https://www.youtube.com/watch?v=NNml3LO7m8I

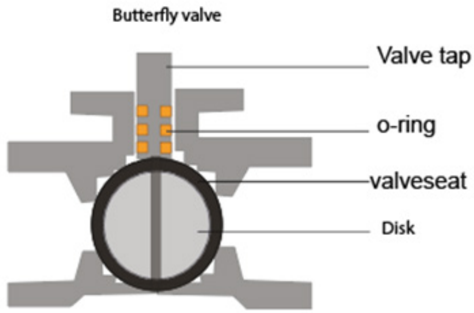


Figure 5.10.1.4: Butterfly valve based on 'Production technology on youtube'

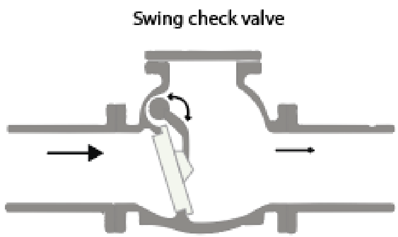


Figure 5.10.1.5: Swing check valve

Ball type and plug type check valve

Ball type and plug type check valves work on the same way and are mostly used when the velocity of the flow is high and are suitable for horizontal of vertical pipelines with upward flow.
When the flow enters from below the seat, the disk or ball is raised from the seat by the pressure of the upward flow while when the flow stops or is reversed the gravity forces its down again.
However it would require a big hole in the spacer bar to place this valve type.

Dual plate check valve

Two halves of the disk move towards each other when a flow comes from the right direction in this way the flow can continue(figure 5.10.1.7). However, when the flow reverses or stops the two half disks closes again at the centreline by resting on the seat.
The use of this system is popular in low-pressure liquid and gaseous services since this is a very lightweight system.

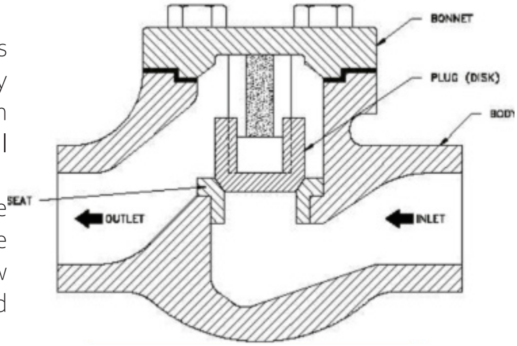


Figure 5.10.1.6: top: Plug type and under ball type check valves. from https://hardhatengineer.com/what-is-check-valves-types-parts/

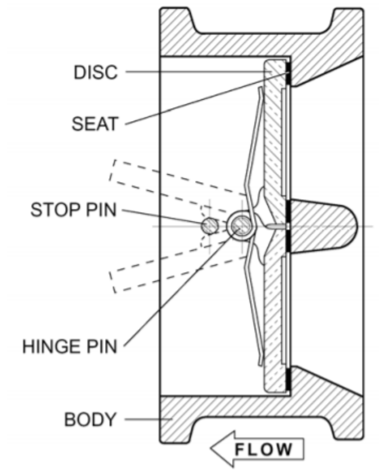


Figure 5.10.1.7:Dual plate check vale from Hardhateengineer.com

Dunlop/ Woods valve

These valves are used for tyres. It consists of a metal tube with a hole at the side where an elastic hose is tightly sided along the tube to seal it. When air is pumped in, the stream pushes the elastic sleeve open and air can flow inside the tyre. By the overpressure inside the tyre, the elastic sleeve is pressed against the metal tube to seal it even better so that no airflow can go the other way.
The Dunlop valve is demountable (5.10.1.8).

Figure 5.10.1.8:Dunlop valves (.sheldonbrown.com)

Blitz valve

Also the Blitz valve is used for bicycles. Less pressure than with a Dunlop valve is needed to pump it up. A ball is placed inside a metal tube with two holes. When there is an overpressure inside the tyre the ball will be pushed back to the seat where it seals off the gap. By pumping air inside the tyre the ball will roll downwards allowing the incoming stream inside the tyre. Just like the Dunlop valve the Blitz valve is demountable(Figure 5.10.1.9).

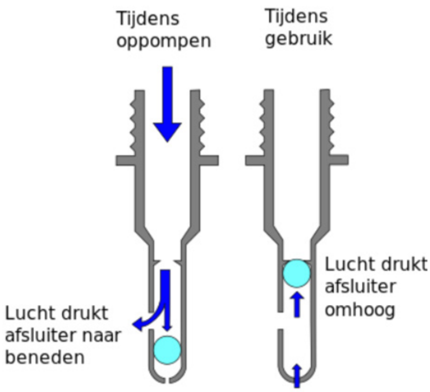


Figure 5.10.1.9: Blitz valve- Tijmen Stam (2006) Wikipedia

Minivalveballs

The balls of these minivalves are made out of hard rubber so keep medium high pressures but because it is softer than steel or plastic ,it is compliant to irregular seat surface's which creates a good working valve component while having a diameter of just 3.0 mm(figure 5.10.1.10).

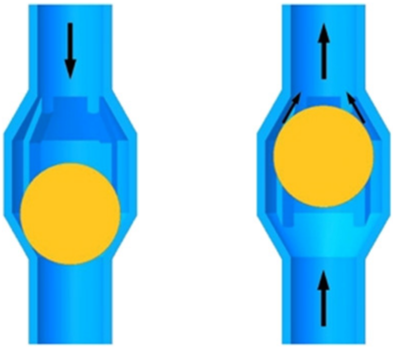


Figure 5.10.1.10:Mini ball valve. www.minivalve.com

Duckbill valves

Duckbill valves are one-piece, elastomeric components, check valves. They have elastomeric lips in the shape of a duckbill which prevents back flow. They are corrosion resistant, wear resistant and as they are made of just one piece in a variety of materials they are very cost effective.
They are available in very small sizes already ranging from 2.0 mm diameter However, they open at very low over pressure

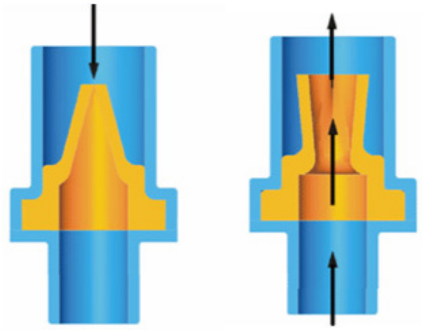


figure5.10.1.11. Duckbill valve http://www.minivalve.com/newsite/index.php/en/by-type/duckbill-valves/how-they-work

Inline check valve

A tiny inline check valve that works for miniature assembly in small spaces as the valve can be made from already 2.5 mm small. It can be made in a cracking range from already 0.04-4 bar as the materials can be adjusted to preference. E.g/ the spring is mostly made from (303) stainless steel while the disc is made from an elastic material or the ball in the second option is made from ceramics.
When a stream is put on the inlet side the disk catches this extra pressure and will move forward in line with the stream. The spring regulates the amount of cracking range and to move the disk back Figure 5.10.1.13 in position afterwards. The second option has the direction of flow reversed in a way that the spring is not under constant load.

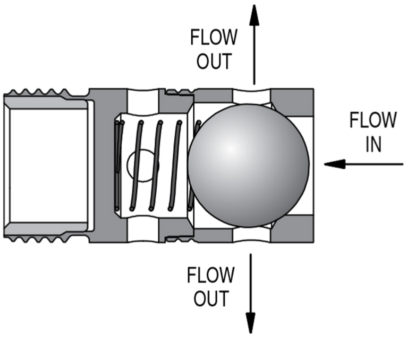


Figure5.10.1.12.https://leeimh.com/products/check-valves/for-installation-into-plastic/2-5mm-diameter-models/2-5mm-check-valve-for-plastic-installation/

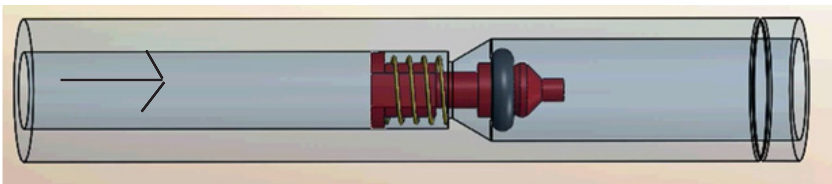


Figure 5.10.1.13: Inline valve https://www.cambridgereactordesign.com/check-valves-connector.html

§ 5.10.1 Evaluation

To be able to compare positive and negative points of the valve types, criteria have been made to evaluate them. The same method as earlier described in this report is used grading for grading the designs.

Diameter: In order to fit the valve into the spacer bar, a maximum diameter to the valve is set.
This diameter is now set to equal or smaller than eight mm since this is the maximum place that is available if the width of the spacer bar supports the optimal cavity width. However, most valve types are either a lot bigger in/under this size or available.

Durable materials/parts:
For the valve it is important to have a durable design that will last for decades. Metals are considered as durable while if the quality of the valve depends on elastomeric materials it is stated as less durable since they last less long. A spring can last long as it is made out of metal, however it can be a fragile part as it is movable therefor a spring is weighted as 'o' as the literature does not provide detailed information over the life span of their springs.
Green (1): It is possible or there are already examples with only durable material / parts on the market.
Yellow(0): A spring is used which may be the weakest part in the construction
Red(-1) : The quality of the valve depends on elastomeric material

Horizontal/Vertical working:
This grading is based on if a valve can be installed with flow in either horizontal as vertical direction. This would not mean not to have a preference direction, but it is just to assure that whenever a window is tilted or by accident rotated for example during transportation, installation or repair this would not form a problem in terms of opening the valve. Opening the valve accidentally can mean argon loss and vapour entering the panel.
Green (1): The window can be tilted and be rotated horizontally without opening the valve.
Yellow (0): The window can be tilted and rotated horizontally to just one side without opening the valve.
Red(-1): By rotating or tilting the window the valve can be opened accidentally.

Easy field replaceable
As the glazing panel is designed for a lifespan of 100 years, it is imaginable that the valve would not be reliable for such a long period. Hence it would be handy if also the valve could be replaced when this is needed. The valve part could for example be screwed in or out of the valve duct that is kept in place inside the spacer bar.
Green (1): It is possible to replace the valve in field.
Red(0): It is not possible to replace the valve without demounting the whole panel

Suitable cracking range:
If a valve is very sensitive to small overpressure it may cause the valve to open when this is unwanted for example when

the temperature chances. The cracking barrier should be made sufficient high but also not too high as then the velocity of the incoming air has to be too high and will cause turbulence inside the cavity. The suitable cracking range of 0.1-0.2 Pa. As the highest

measured air pressure was 1084 hPa (in Agata Russia) while the lowest was 870 hPa. (http://www.meteoschoonebeek.nl/weerextremenwereld(weerextremen, n.d.)
Green (1): It is possible to have a cracking pressure of around +0.1 bar
Red (-1): It is not possible to have a cracking pressure of around +0.1 bar

Many types of valve exist to fit in all sorts of disciplines and functions. As for the design of a window the valve needs to be simple , small and requires only flow in one direction (inwards).Check valves offers this quality as no extern lever is required as it is an automatic system. The swing check valve, ball type and plug type are too big while the dual plate check valve is also unnecessarily complex.
The Blitz/miniball valve and Dunlop valve are simple principles that are also demountable. But since the Dunlop valve uses an elastic hose, it seems less durable than the Blitz/miniball valve would be a suitable solution if it would also be possible to operate this type of valve in a tilted position. The last could be achieved if the materials would be magnetic a possible effect of working with these magnetic materials is the raise of cracking pressure what would make all the gradings positive for this valve. The last evaluated valve is a tiny valve that can be found in microhydraulic systems e.g. the aerospace industry or cartridges. The 'inline' valve is concluded by this evaluation as the only option without any negative grading and can be formed in the desired way. It can work with a disk or a ball together with a spring that controls the cracking range.

As can be seen the form can also be made with grooves at the inlet.

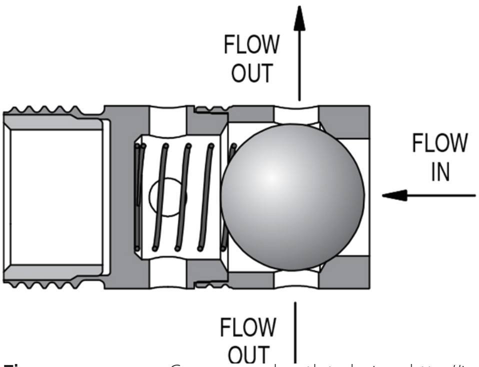


Figure 5.10.1.13. Grooves and outlet choices.http://imh-fr.maier.com/produits/check-valves/plastic/2-5mm-diameter-models/2-5mm-check-valve-with-ceramic-ball/

Aspect	Diameter <8 mm	Durable materials/ parts	Horizontal/ Vertical position	Easy field replacable	Demount-able	Cracking range
Ball valve	-	+	+	-	+	+
Gate valve	-	+	+	-	+	+
Globe valve	-		+	-	-	+
Butterfly valve	-	+	-	-	+	+
Swing check valve	-	+		-	+	+
Plug type check valve	-	+	+	-	+	+
Ball type check valve	-	+		+	+	+
Dual plate check valve	-			+	+	+
Dunlop	+	-	+	-		+
Blitz/mini-valve	+	-	+	+	-	+
Duckbill valve	+	-	+	+	+	-
Inline valve	+	+	+	+	+	+

Table 5.10.1.14.: Evaluation of the valves. (Authors image)

§ 5.10.2

Implementing the valve

Many check valves are only designed to seal bubble tight and not provide a high leak integrity for gas over time. (According to Brik de Ploeg from Lee Company) Especially since the cracking pressure is very low. Reliable valves as proposed for this thesis, are designed for use in the aerospace industry and in term of costs these valves are hundreds of euros each and from a commercial point of view, these valves are not mass produced.

Valve for multiple windows

As an alternative solution on the already proposed idea, a valve could be used for several windows instead of two per one window each. This could reduce the amounts of valves needed significantly as they are in fact just used once per ten years while they are one of the biggest cost factors.
The requirements for the chosen valve does not have to change as the valve now will be used multiple times and still for a very long time, it is better to manufacture it in durable materials such as stainless steel and the cracking range has not changed. Furthermore The benefit of using a spring into a check valve's mechanism is that it eliminates the effect of gravity on the function of the valve. This means that during the (re) manufacturing the valve's vertical orientation is not a critical factor for a check valve to work properly.
Above this, the easy field replaceable and demount ability plays even a larger role now and ¼" (inch) – ½"inch would still be an ideal size concerning the balance of the aesthetics but also easy to work with. The downside to this idea however is the longer installation time as now time has to be invested on installing the valves first instead of just ' plug and pump' the argon inside.
The ideal situation would therefor still be a reliable valve of high quality but made for mass production so it can be affordable but as written by the first line of this text, the gas tightness for a long time span has to be proven first.

Apart from the considerations of the media, pressure/cracking range, temperature, requirements of the seat leakage and the material, the in and outlet connections also can vary with different variants as can be seen in figure 5.10.2.1

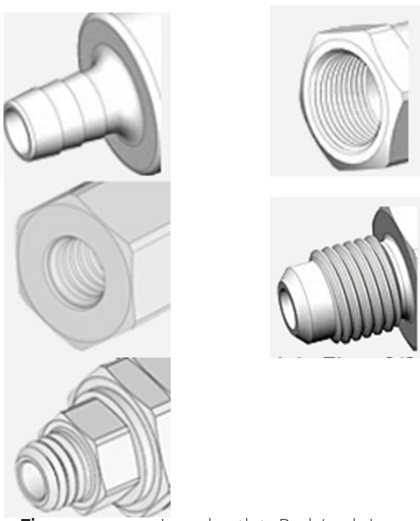


Figure 5.10.2.1: In and outlets Barb/male/female

The Idea is thus to design a valve system that can be placed inside 1 of a range of windows close to each other where the valves are placed to stay. The other windows would make use of plugs instead of the valves.

Description of the working of it: A cylindric metal tube threaded from the inside (figure 5.10.2.1) can be UV glued to the hole of the glass pane.

Then, from the outside, a metal threaded plug will be screwed inside this cylindric metal tube. Also this plug will stay for the lifespan of the panel.

To assure the airtightness , a betaplug will be used in combination with a plug. The front of the metal plug will be interlocking with the back of the outer plug on the same way as can be seen in figure 5.10.2.2

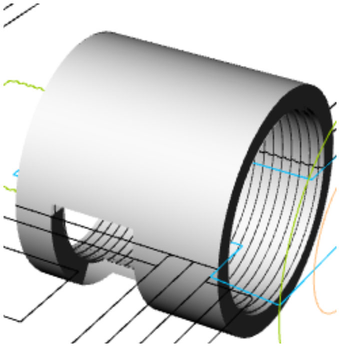


Figure 5.10.2.1.:Cylindric metal tube. (Authors image)

Figure 5.10.2.2.:Hex intersection.

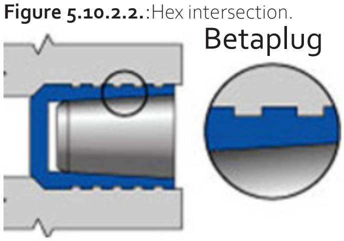


Figure 5.10.2.3.:Betaplug (lee IMH).

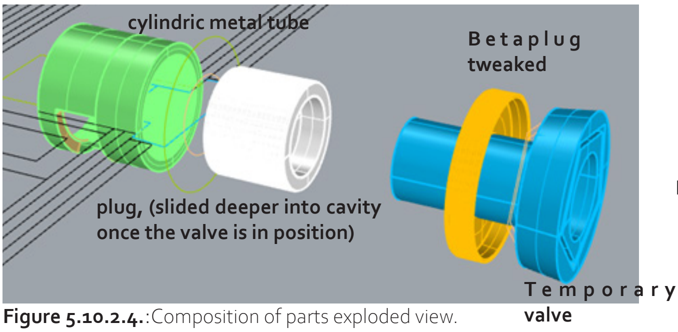


Figure 5.10.2.4.:Composition of parts exploded view.

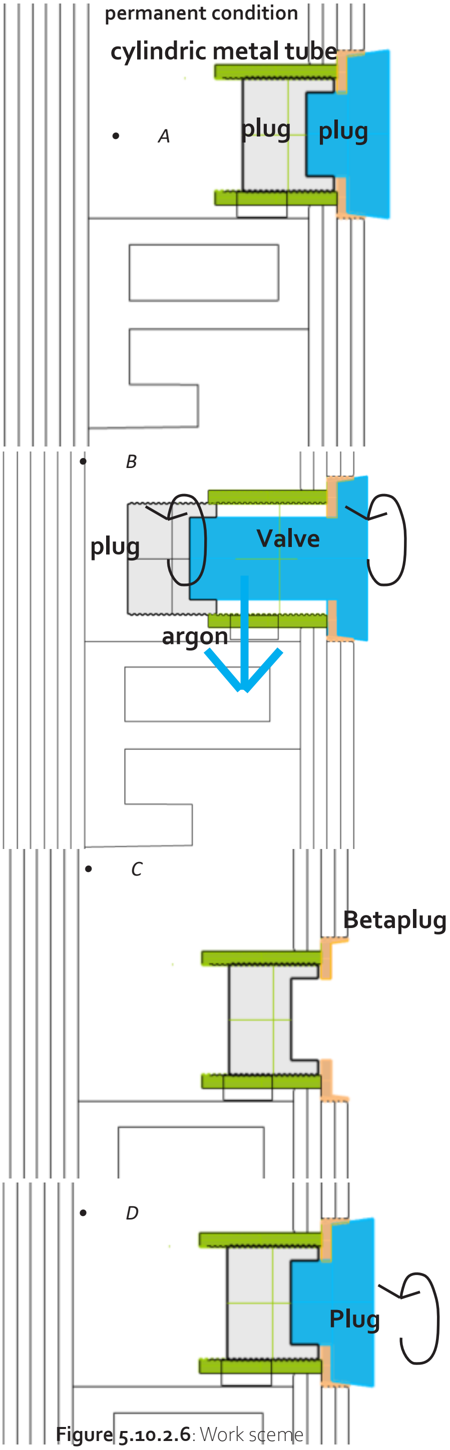


Figure 5.10.2.6: Work sceme

Steps to fill the window with argon

1) The plug is inside the window for the permanent case (A)

2) Unscrew the plug with the tool of figure 5.10.2.4 (C)

3) Screw the valve inside (B)

4) Change the Betaplug (C)

5) Place the plug again. (D)

Figure 5.10.2.5: Hex key

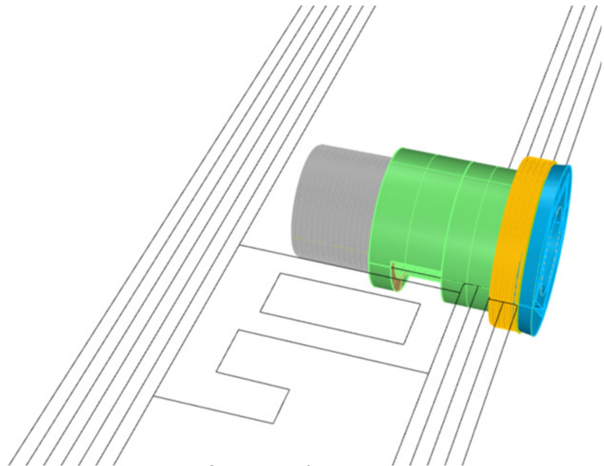


Figure5.10.2.7 :The configuration of the elements in working condition : plug(grey), cylindric metal tube(green), Betaplug (orange) and valve (blue). (Authors image)

Valve with plug

However, as the valve that is supposed to serve several windows, requires lots of installation time, this variant from now on referred to as 'valve with plug' is a combination between the 'valve only' and ' valve for multiple windows'. It does require more elements than the ' valve alone' as this design requires also a cylindric metal tube as the valve needs to be replaceable but also stay in place. As most check valves are only designed to seal bubble tight and not provide a high leak integrity for gas over time. (According to Brik de Ploeg from Lee Company). It would be safe to assume that a valve that functions for a long time-span such as these,should have an extra stop as extra reliability until tests have proven that the special designed valves are gas tight for this long time span and can be mass produced to becomes economically feasible, furthermore these plugs can block the dirt just as the caps on tyres valves.

As can be seen in the figures on the right (Figure 5.10.2.8), The system consists of three elements: the valve with wire that would be UV glued to the glass pane, a cylindric metal tube with wire from the inside where the valve can be screwed in, and finally a butyl plug with grooves based on the Beta-plug but now it is just one solid plug element that will be thrown away after every re-manufacturing and will be replaced.

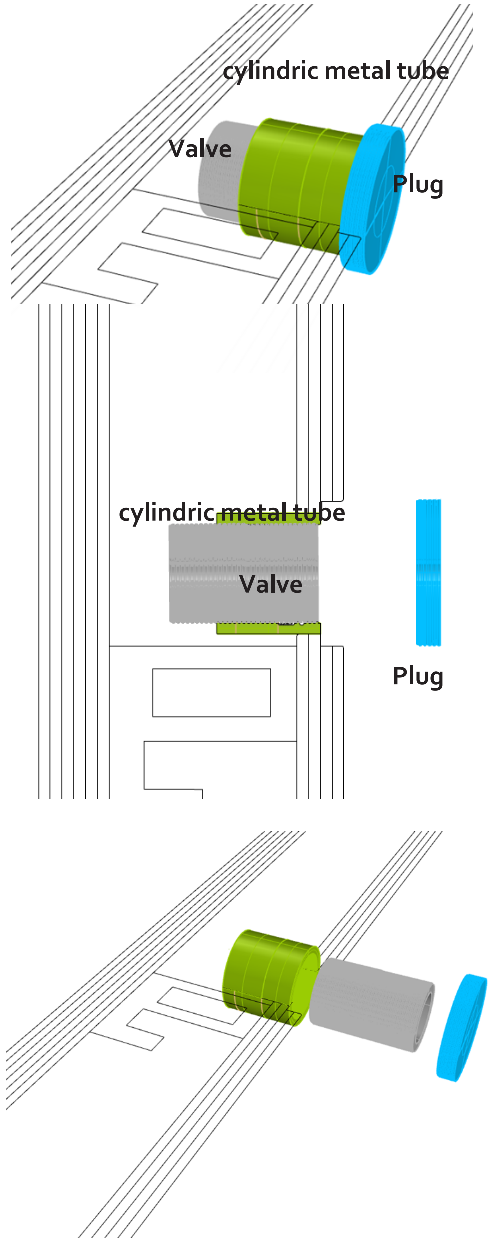


Figure5.10.2.8 :The configuration of the three elements : valve, cylindric metal tube, and plug. (Authors image)

§5.10.3 Comparison

To choose between the three variants a comparison should be made with a short overview of the most important factors.
This is done in table 5.10.3.1 .

	Valve only	Valve for multiple windows	Valve with plug
Cost			
Reliability			
Dust free			
Ease of installation			
Amount of tools needed	Nothing	Hex key	Hex key
Glued connection			
Parts	Valve O-ring	Valve Plug Cylindric metal tube Plug Betaplug	Valve Plug Cylindric metal tube
Throw away	O-ring	Betaplug	Plug

Table 5.10.3.1: Comparison between variants of installing the valves.

For this research the factors: reliability and ease of installation are set to most important.
A glued connection is of course less ideal but as it is the same glue as used for the connections between glass and spacer, it can be removed in the same way.
Ease of installation is important not only because ' time is money' but less time means less hindrance and less actions can mean less mistakes. A valve with plug seems therefor the best option. Even tough these valves are very expensive, mass production will drop these costs significantly.

The overall process of producing a stainless steel valve is like this: The steel bars are cut to size. Driling will make the desired centre parts. A milling machine will ground the valve for a precise tolerances. After this, the parts can be sanded and mixing It with gravel, the valve will be polished. The last part includes testing of the quality of the valve.

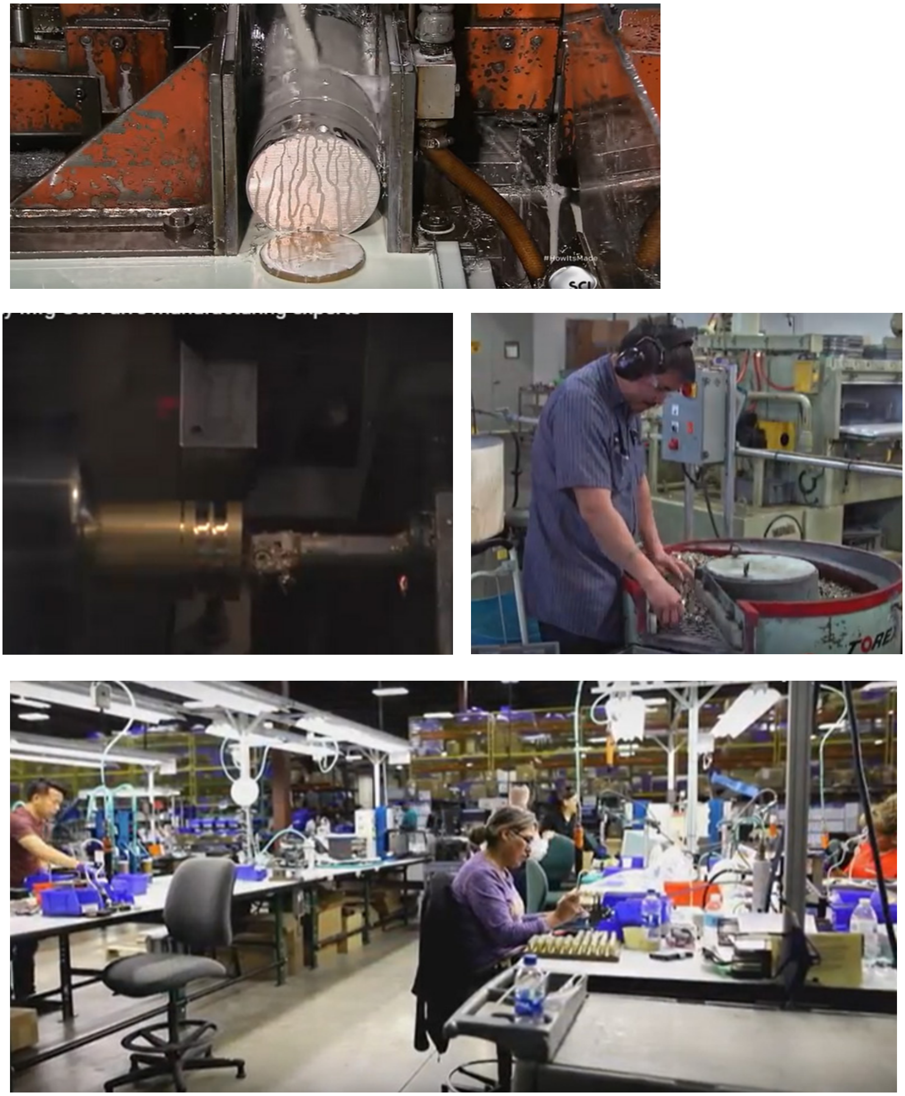


Figure 5.10.3.9: Valve process steps. cutting, milling, polishing, checking (The Specialty MFg Co).

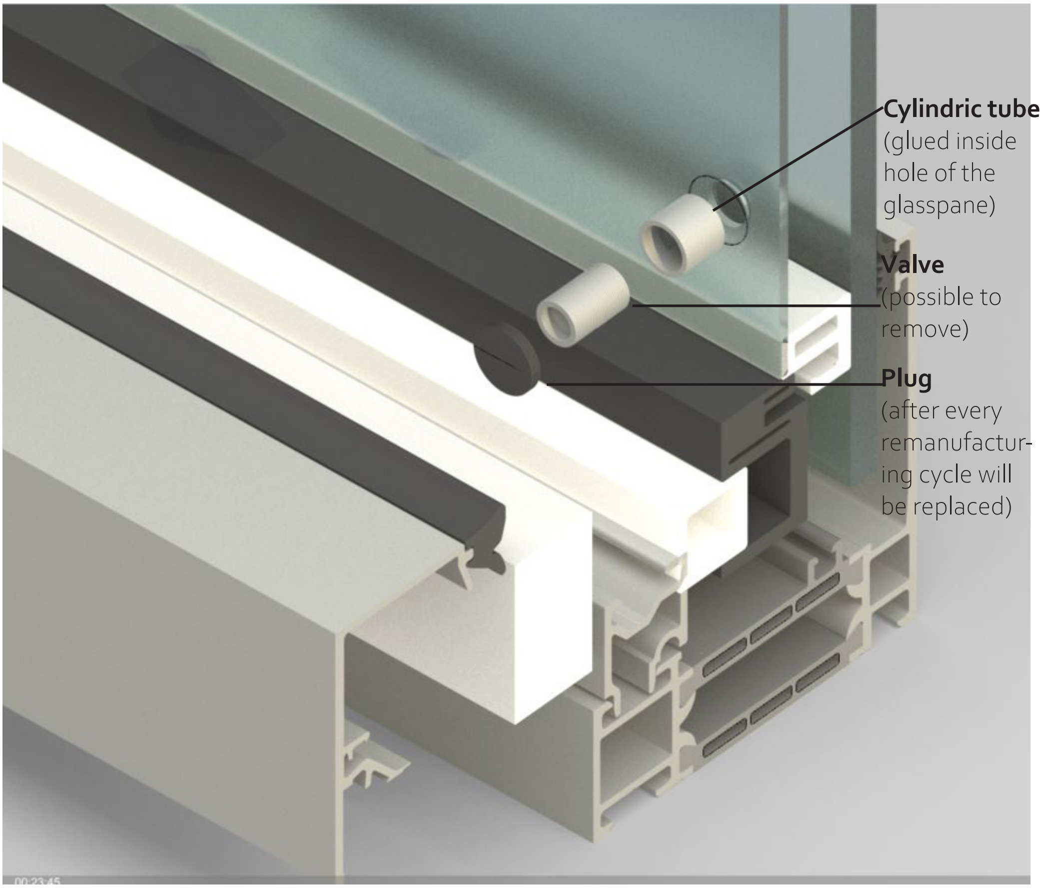


Figure 5.10.3.10: The chosen valve inside the glazing panel

IV

CHAPTER 6
Final design

Content

Calculation- heat flow
Calculation- structural
Buildability
Implementation in existing frames
Production line

6.1 Heat flow calculations

Thermal conductivity is defined as the amount of heat per second passing trough a surface area of 1m2 at a temperature difference of 1 degree kelvin (or also Celcius). As the thermal conductivity of glass is 1.0 W/(mk) it can on its own not count as an insulated element as insulated materials have a thermal conductivity of less than 0.065 W/(mK) (AGC Glass Europe, 2014). However, having dry air or gas trapped between two glass panes, it can now function as insulation as the thermal conductivity of dry air is just 0.025 (W/mK). This reduces the thermal transmittance Ug of the glazing.
At the edge of the IGU not dry air but material is placed. Therefor the edges have a big influence on the heat transmittance of the IGU. In the conducted simulations three materials are being used as parameters: steel, aluminium and fiberglass to see the differences in heat transmittance for both the spacer bar as the hollow section. A hand calculation is being made in the section of the glass before simulating in the program ' Therm 7.7' to verify the retrieved values. Because the materials have difference in strength it also determines the amount of material, varying with thickness and height of the elements and the result is therefore not straightforward. With the retrieved information for heat transmittance and with the height differences of the total package from the edge of the window (retrieved from the static hand calculation) , a weighted decision for the material of the spacer bar and hollow section will be made.
The cost will be of less relevance for this design. In short: A lower heat transmittance is preferable and a smaller window edge is beneficial in terms of view and daylight purposes.

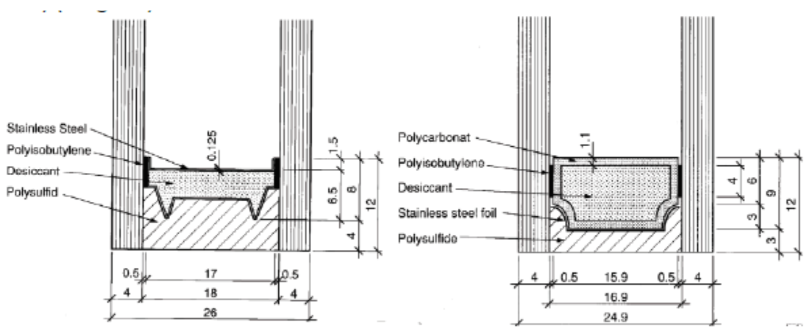


Figure 6.1.0.1:Different spacer bar thickness due to different materials. Lecture notes Building Physics tudelft R.Bokel

§ 6.1.1 Thermal hand calculation

For the calculations the following parameters were used in both excel as in program Therm 7.7. Therm has also pre-defined material properties in its data-base,= but the shown values are from EN ISO 1007-2 Annex A.

Outside temperature= -10 °C
Inside temperature = +21 °C
a (alpha in W/m^2/K) at 263= 25 W/m^2/K
a (alpha in W/m^2/K) at 293= 7.8 W/m^2/K

Floatglass: 1,0 W/m·K
Butyl rubber: 0.24W/m·K
Fiberglass: 0.3 W/m·K
Stainless steel: 17 W/m·K
Silicone: 0.35 W/m·K
Aluminium 160W/m·K
Air(5%)-Argon(95%)Mix is used

For the hand calculations (table 6.1.1.1) only the glass part of the window with-out the edge seal (figure 6.1.1.1) were taken into account. It is meant as a comparison, verification and refer-ence for the computer simulations. The following formulas are used:
r=d/lambda
Rn/Ri*dT=dTn

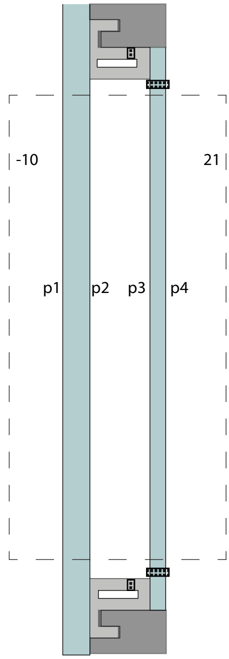


Figure 6.1.1.1: The outline of the thermal hand calculation.

Constructi	thickness (m)	lambda (W/mk	r=d/lambd	Rn/R1*dT=d	T (c)	Position
Air outside					**-10**	outside temp
re			0.04	3.5428571	-6.46	p1
Cavity outs	0.006	1	0.006	0.5314286	-5.93	p2
Cavity insic	0.016		0.17	15.057143	9.13	p3
Room insic	0.004	1	0.004	0.3542857	9.49	p4
ri			0.13			
air inside					**21**	inside temp

Table 6.1.1.1: The the thermal hand calculation.

§ 6.1.2 Therm 7.7 Simulations

To determine the thermal impact of the new remanufacturable IGU design, a comparison has to be made with the current IGU's . Therefore, the current U value of the IGU is calculated and temperatures at several nodes are shown in the figures simulated in Therm 7.7. Figure 6.1.2.1 and figure 6.1.2.2 show an aluminum and steel spacer whereof the temperatures and flux vectors are shown. According to literature the U-value of a window with dimensions of (4-12-4 mm) gives a result of 3,0 W/m²/K ((Linden, Erdtsieck, Kuijpers-van Gaalen, & Zeegers, 2011). Figure 6.1.2.1 shows that the simulated value of the glass part does come close to the one calculated by hand and therefore can be considered as an useful simulation model (inside temperature of 9.2 and 9.49 according to Therm 7.7 and excel respectively). Furthermore, figure 6.1.2.1 shows that most of the heat is transferred to the exterior through the edge and mainly through the spacer bar.

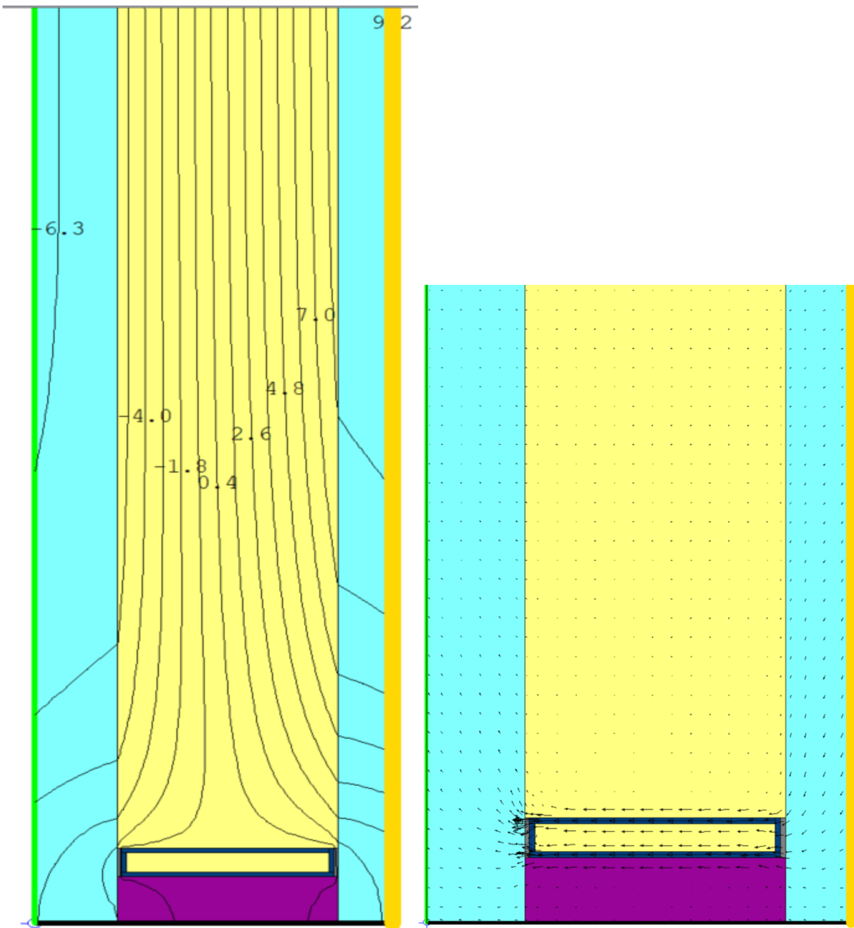


Figure 6.1.2.1: Temperature and flux inside an conventional IGU with al uminium spacer. (Simulated with Therm 7.7)

Conventional Aluminium spacer bar with butyl primary seal and with silicone secondary seal .

Conventional Steel spacer bar With silicone secondary seal and butyl primary seal.

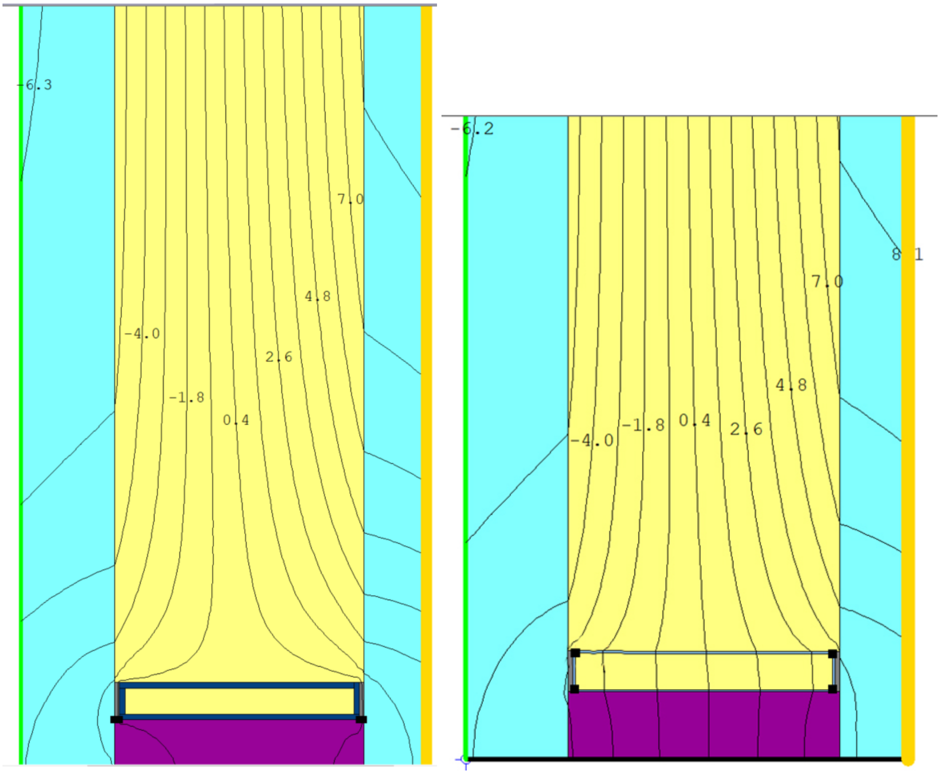


Figure 6.1.2.2: Temperature in conventional IGU with aluminium and steel spacer. (Simulated with Therm 7.7)

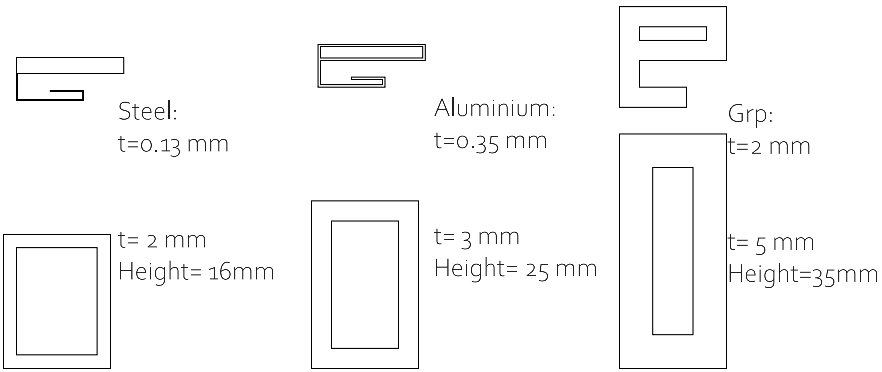


Figure 6.1.2.3: Respectively steel, aluminium and GRP profiles, dimensions of hollow sections by hand calculation and thickness of the spacer bar from literature studies. (Authors image)

Steel spacer bar
Aluminium hollow section

Steel spacer bar
Steel hollow

Steel spacer bar
Grp hollow section

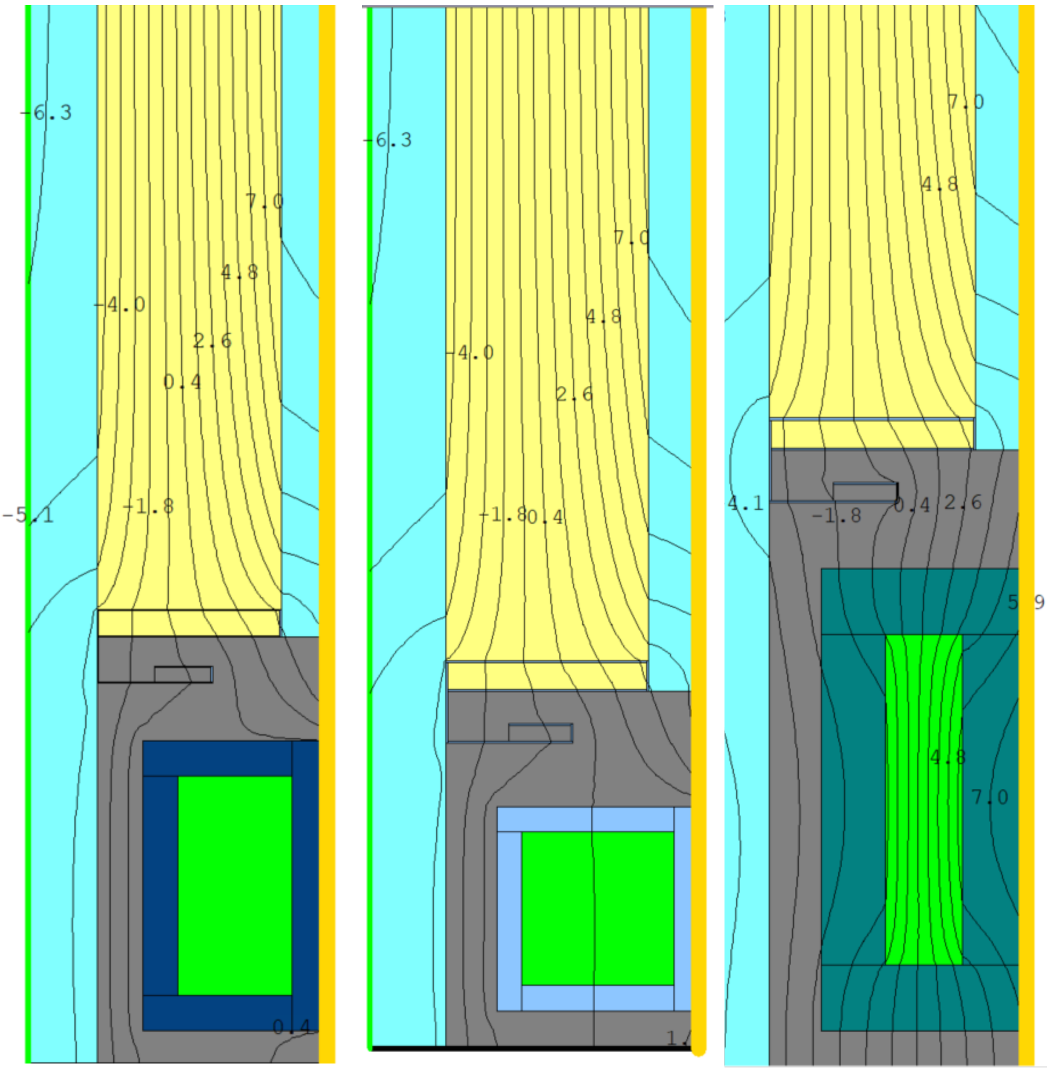


Figure 6.1.2.4: Temperatures with steel spacer bar and different hollow sections. (Simulated with Therm 7.7)

Aluminium spacer bar
Aluminium hollow section

Aluminium spacer bar
Steel hollow section

Aluminium spacer bar
Fiberglass hollow section

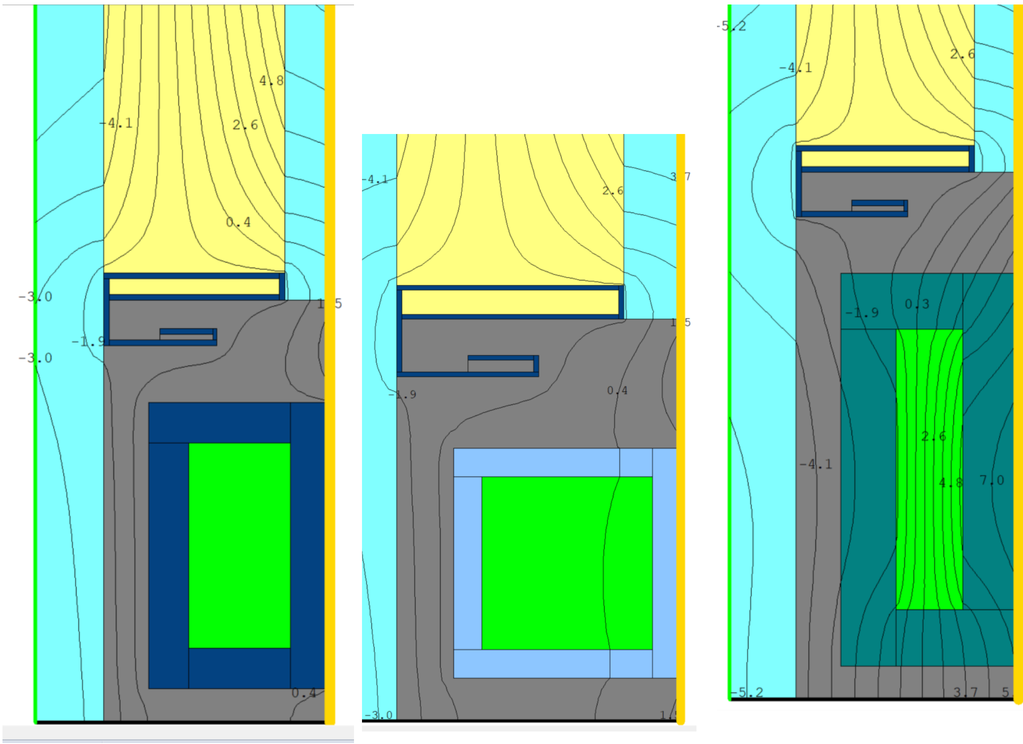


Figure 6.1.2.4: Temperatures with aluminium spacer bar and different hollow sections. (Simulated with Therm 7.7)

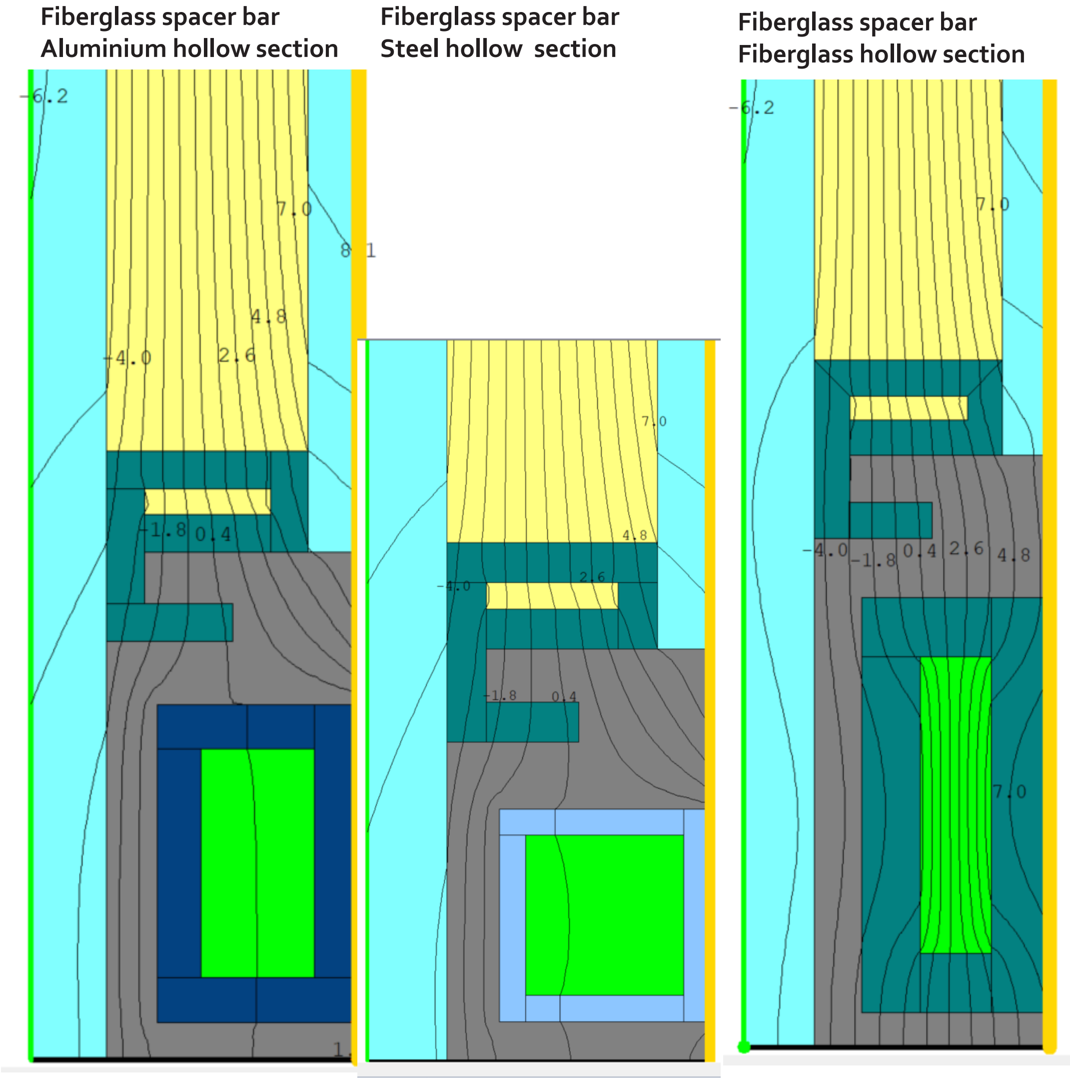


Figure 6.1.2.5: Temperatures with aluminium spacer bar and different hollow sections. (Simulated with Therm 7.7)

§ 6.1.3 Heat flow conclusion

If fiberglass is utilised for both the spacer bar and hollow section the highest thermal values can be achieved. Fiberglass has the best thermal insulating properties from the three materials.
After fiberglass steel is the second choice. Apparently the variant with a steel spacer and fiberglass hollow section is a better choice than the variant with fiberglass spacer bar combined with the steel hollow section.
The ratio between the amount of steel and amount of fiberglass is likely more important than the way they are connected (the butyl forms a thermal break).
Aluminum is the worst of the three materials related to heat transmission, as shown in table 6.1.3.1. Figure 6.1.3.1 shows the simulated heat transfer in the better insulated edge. The heat transfer now is divided. The final chosen fiberglass edge has a comparable U-value to the conventional modeled design (2.97 < 2.98 < 3.0).

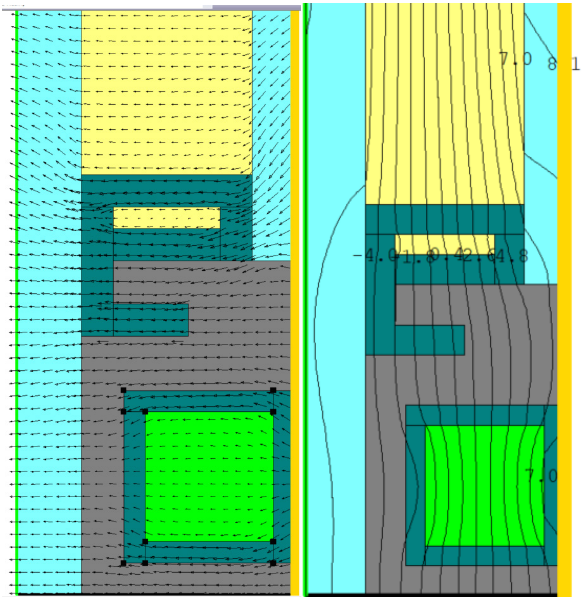


Figure 6.1.3.1: Flux vectors and temperatures of the final design a fiberglass spacer combined with a fiberglass hollow section (16*16). (Simulated with Therm 7.7)

	U value	spacer	Hollow section	U value	error
Base	theoretical			3	
	modeled	Aluminium		2.9952	
	modeled	Steel		2.9656	
		GRP	GRP	3.0037	1.33%
New design		Steel	GRP	3.0258	2.19%
		GRP	Steel	3.0538	1.84%
		Steel	Steel	3.0688	2.50%
		Aluminium	GRP	3.0757	3.17%
		GRP	Aluminium	3.1006	1.83%
		Aluminium	Steel	3.108	3.11%
		Steel	Aluminium	3.115	3.07%
		Aluminium	Aluminium	3.1531	2.96%
Final design		GRP	GRP	2.9801	1.13%

Table 6.1.3.1: U values of the variants. The final design has a comparible value U valueto the conventional steel spacer IGU.hollow section (16*16). (Simulated with Therm 7.7)

6.2 Structural calculations

To estimate the glass thickness and bar height a hand calculation is conducted where after a FEM simulation will give us better insight in the real structural behaviour. This first page will describe all the values that were used for all hand calculations.

Low rise buildings are usually not higher than four elevations. Considering an office building, the height of an elevation for this calculation will be 3.6m. Furthermore, the wind pressure used for the calculations will be conservative. The considered region will be a coastal area chosen from figure 6.2.1. (I).
3.6*m*4=14.4m A height of 15m will be taken for calculation.

The formula for the wind pressure:
P (kN/m^2)=ce*cs*cf*qp(ze)
cs*cd=1 (building is <50 m high) and height/width of building where the width is perpendicular on the wind direction
qp(ze)=qp(15m)=0.96 kN/m^2 . Assuming site coverage (built environment).
we=qp(ze)*cpe
qp(ze)= extreme pressure at height ze. -> 0.96 kN/m^2
ze= reference height -> 15m
cpe= pressure coefficient -> considering cpe1 (for all surfaces smaller than 1m^2)-> cpe,1=-1.4
results in: we=0.96*-1.4=-1.34 kN/m^2 (1340 pa)

Timonshenko rule

b/a	1	1.2	1.5	2	3	4	5
Beta	0.27	0.36	0.474	0.602	0.711	0.74	0.748
Alfa	0.047	0.065	0.089	0.116	0.14	0.147	0.149

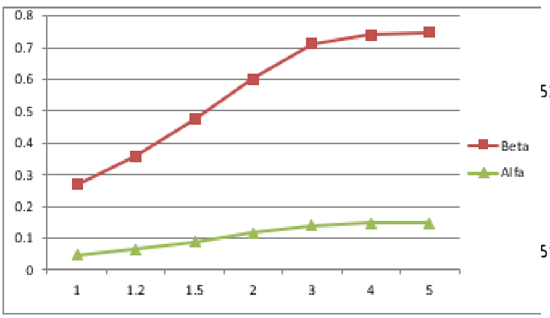


Figure 6.2.2: Timonshenko rule and its value

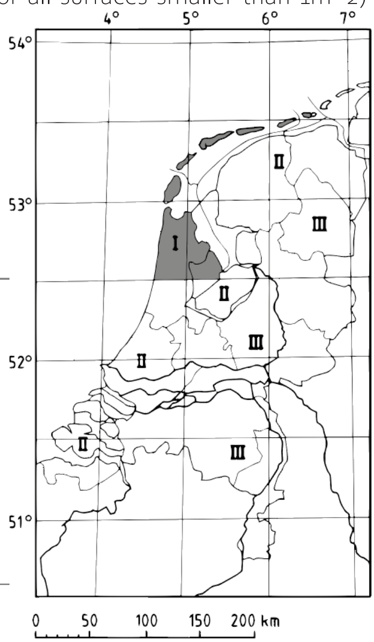


Figure 6.2.1: Coast area based on NEN-EN 1991-1-4

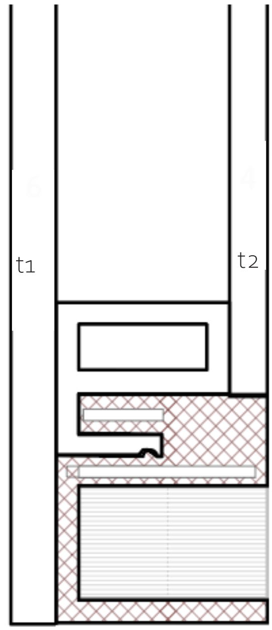
§ 6.2.1 Calculation 1: Estimation of the glass thickness

For a first estimate of the thickness of the glass panes, the rule of Timonshenko (figure 6.2.2) is used for a window with dimensions of 1 m*1 m which is supported on all four sides. The values are:

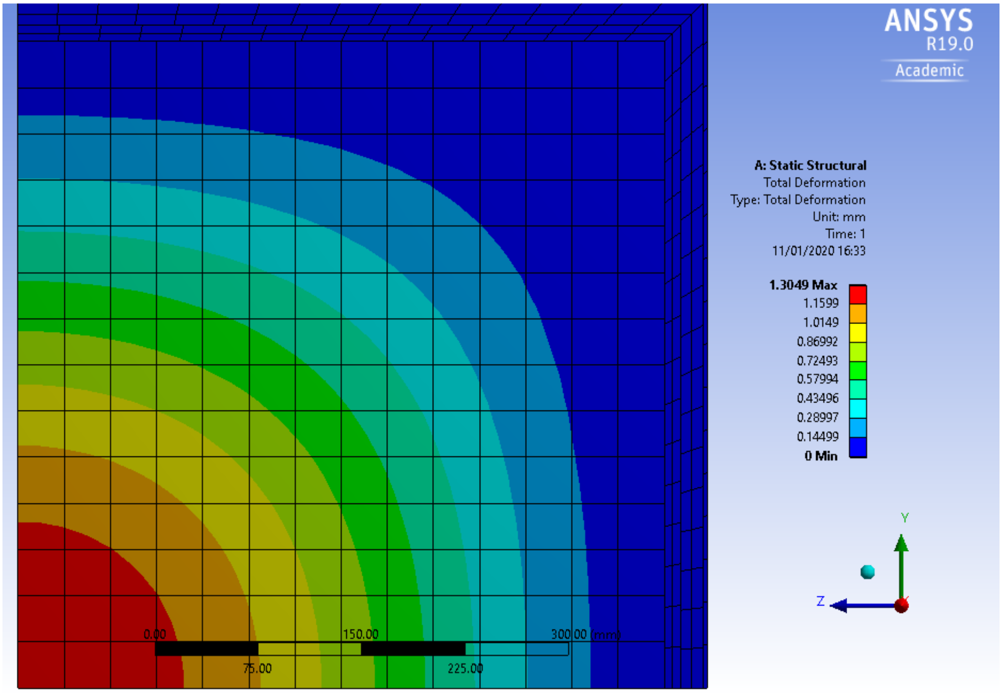
$$Q = \frac{Beta * w * a^2}{t^2} \qquad \delta_1 = \alpha P_1 a^4 / (E\, t_1^3)$$

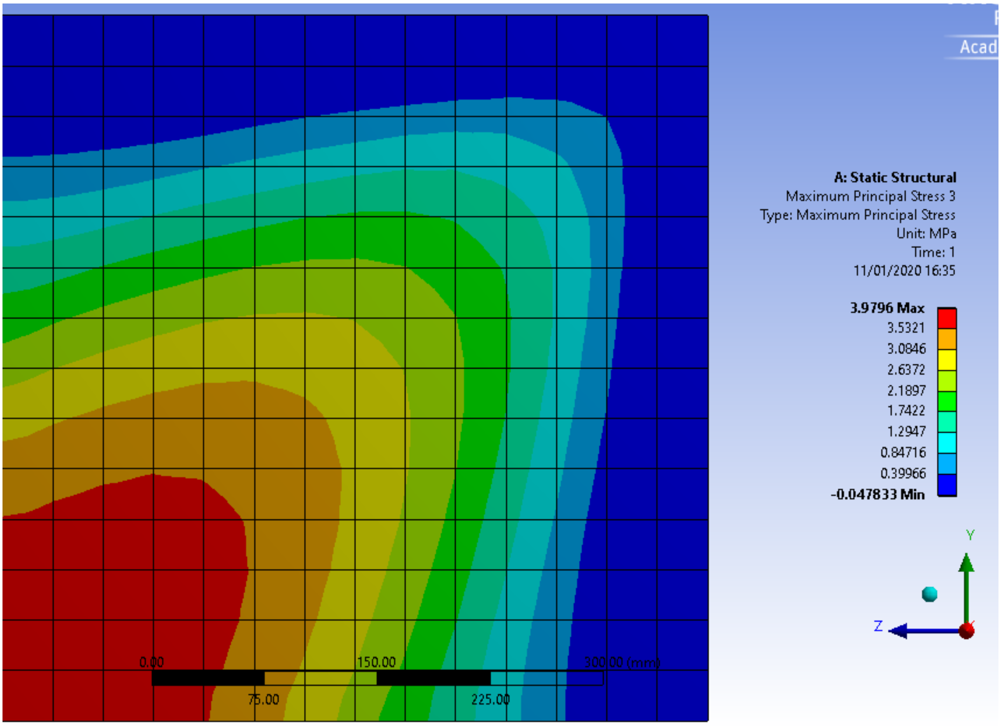
4 sides supported

E	72000	N/mm2
w	1.34	kN/m2
b	1	m
a	1	m
t1	5	mm
t2	4	mm
t3	0	
t4	0	
beta	0.27	
alpha	0.047	
Q=	4.466667	Mpa
deflection	1.199893	mm



The highest stress and deflection occurs at the center of the glass pane if supported on 4 edges. According to the hand calculation the values for pressure and deflection should be 4.47 MPa and 1.2 mm. The estimated thickness and glass type is sufficient when the result is under the 20 Mpa for annealed glass. Also the deflection is under the 5.71 mm as maximal criterion for the formula (1/175*1000).
To simulate the model in Ansys Workbench 19.0, the cavity had to be modeled with a Young's modulus (1E6 Pa, Poisson's ration of 0.4) to have the panes working together. On the next pages the maximum stress found = 4.0 Mpa and the maximum deflection of 1.3 mm. Zhou (2002) gives thus a stress value on the safe side but the deflection is bigger in the FEM model.


ANSYS
R19.0
Academic
A: Static Structural
Total Deformation
Type: Total Deformation
Unit: mm
Time: 1
11/01/2020 16:33
1.3049 Max
1.1599
1.0149
0.86992
0.72493
0.57994
0.43496
0.28997
0.14499
0 Min
Y
Z
0.00
150.00
300.00 (mm)
75.00
225.00


Acad
A: Static Structural
Maximum Principal Stress 3
Type: Maximum Principal Stress
Unit: MPa
Time: 1
11/01/2020 16:35
3.9796 Max
3.5321
3.0846
2.6372
2.1897
1.7422
1.2947
0.84716
0.39966
-0.047833 Min
Y
Z
0.00
150.00
300.00 (mm)
75.00
225.00

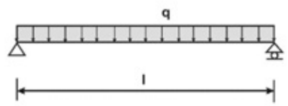
§ 6.2.2 Hand calculation 2: Estimation of the hollow section height

To estimate the dimensions of the hollow section, a hand calculation is conducted with a simplified model: a simply supported beam, which carries the weight of the glass.
The formula used is = M=1/8 q l^2 as the IGU is simply supported

thickness	0.003	m
gamma_g:	2550	kg/m^3
q	0.075	kN/m2*m'
M=	0.009	kNm
E grp=	23000	N/mm^2
Esteel=	210000	N/mm^2
Eal=	71000	N/mm^2

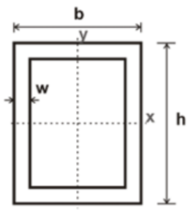
Ligger op 2 steunpunten (draagbalk)

Uitleg



https://www.mile17.nl/ligger.php

Koker - holle rechthoekige doorsnede



Breedte b (mm), buitenkant: 16

Hoogte h (mm), buitenkant: 35

Dikte w (mm): 5

Bereken | Invoer legen

Formules

$$A = bh - (b-2w)(h-2w) \qquad W_x = \frac{bh^3 - (b-2w)(h-2w)^3}{6h} \qquad I_x = \frac{bh^3 - (b-2w)(h-2w)^3}{12}$$

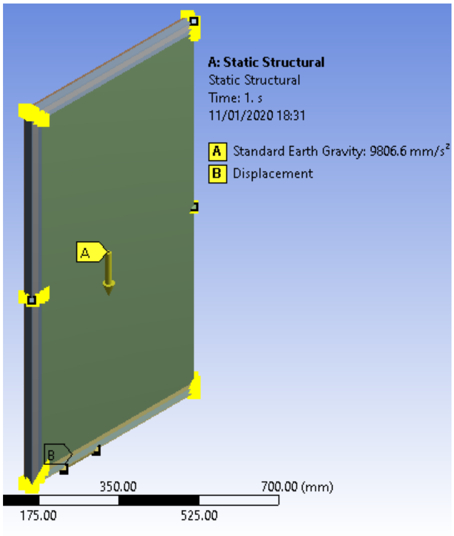
The outcomes are the following, if the sag in the middle of the beam should not be more than 1 mm (which is the difference the gap in the butyl seal can accommodate). The width of the cavity is set to 16 mm for all cases.
The results of the thicknesses and heights for different materials are when set that the priority is to have the height as low as possible:

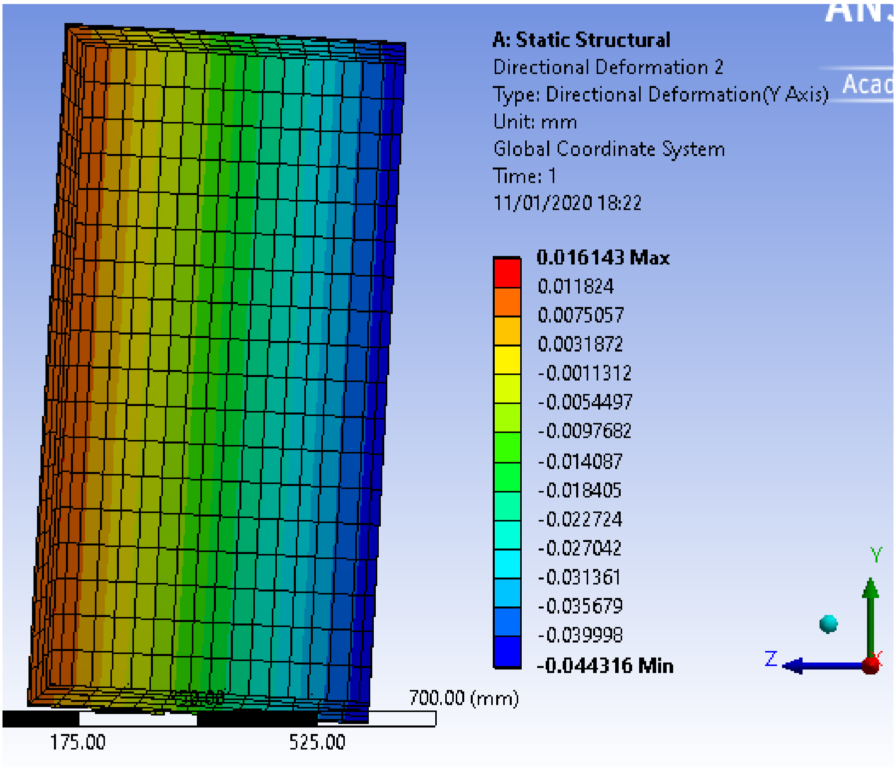
GRP :	height= 35 mm ;	thickness= 5 mm
Aluminium:	height= 25 mm ;	thickness = 3 mm
Steel:	height= 16 mm;	thickness = 2mm

Table 6.6.6.2: The results of dimensions for the hollow sections according to the hand calculation

§ 6.2.3 Simulation 1. The sag of IGU to calculate the hollow section height

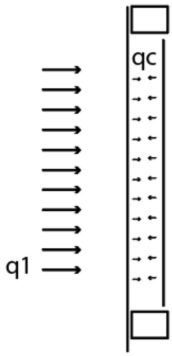
The model in Ansys simulates is more accurate to the 'real' situation, taking into account a frame in contrast to a single bar the for hand calculation. Symmetry is used for modeling. The results of sagging are due to the frame more favourable and shows that the dimensions calculated by hand (table 6.6.6.2 for Aluminium/steel/GRP) is over dimensioned. A frame is stiffer than a single bar. Therefore, the combination of the most favourable thermal material fiberglass can be combined with the small dimensions of the steel hollow section. Even now the sag in the middle of the model is just 0.044 mm but a bar of less than 16 mm would not seem practical. It has to be mentioned that for this thesis no creep has been taken into account.

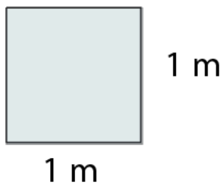




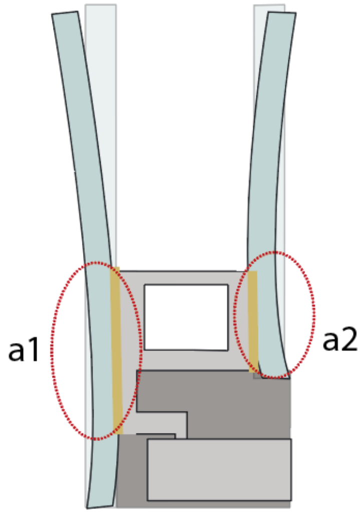
§ 6.2.4 Hand calculation 3
Estimation of the tension on the bonding.

Climate load
pc= inside pressure within the cavity (0.101) N/mm2 (Pa)
pa=outside pressure in summer (0.103) N/mm2 (Pa) (Mepla iso 2017)



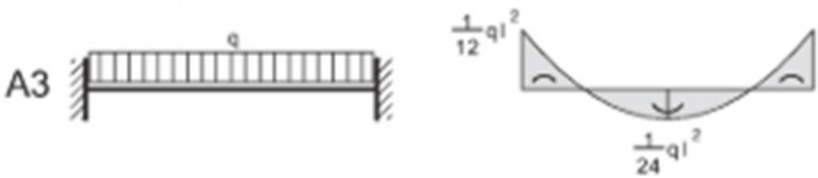


panel size



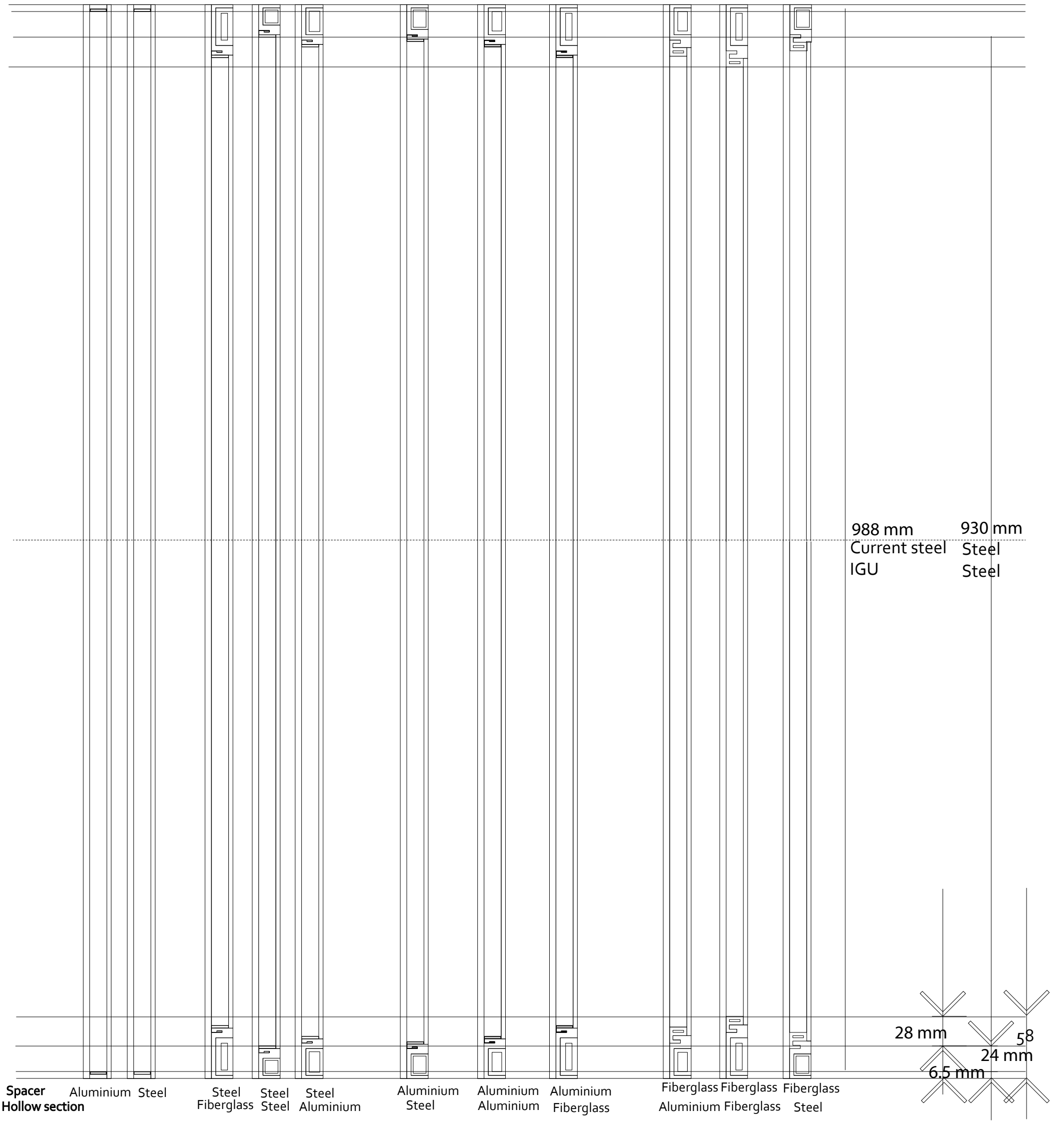
Q1=1.34 kN/m^2
q1=1.34 kN/m (so per meter)
Qc=0,103-0,101 N/mm^2= 0.002 N/mm^2 -> 2kN/m2.
qc=2kN/m2*1m= 2kN/m (so per meter)
qL=qc+q1= 1.34 + 2= 3.34 kN/m
qr=2 -1.34=0.66 kN/m but worst case scenario is 3.34 kN/ m
Ml=1/12*ql*l^2= 1/12*3.34 (kN/m)*1^2(m^2)=0.28kNm

M=F*a ; Q=F/A
a1=15 mm 0.28=Ft1*15E-3 -> Ft1= 18.6 kN/m (per meter)
a2= 8 mm Mr=Ft2*8E-3; ->0.167=Ft2*8E-3 -> Ft2 = 20.8 kN (per meter)
18.6/0.015 -> 1237 kN/m =(1.24MPa) and 18.6/0.008=2319 KN/m -> 2.3MPa
According to the Delo Datasheet, the weakest bonding is 3.0 MPa. But because of the inexact gluing and conditions, fatigue and long life span a large safety factor should be taken into account of more than 3. A bonding strength of 10 Mpa should therefore be the the minimum requirement.



§ 6.2.4 Overview of the different heights due to the different material used: 1m

The three materials steel, aluminium and fiberglass and the combinations are portrayed in the illustration below. From the 1m of glass pane, 988 mm is useful for sight with the conventional window. For the variants the most optimal choice regarding view is the variant Steel-steel -930 mm. The final design however Fiberglass-Fiberglass (16*16)= 922 netto view.



6.3 Implementation

According to the structural and thermal simulation an edge of 16 mm high fiberglass hollow section and a fiberglass spacer would be the outcome of this IGU proposal. When this system is implemented in a standard frame it would not fit into it as shown on the previous page. The current IGU's have an edge of less than 7 mm, while the new circulair edge system needs 39 mm. Schüco already has profiles where the new circulair IGU proposal fits into, but these are not used frequently yet (Figure 6.3.1). The new circulair IGU proposal therefore should ideally be implemented in newly build facades. An intermediate solution of an existing facade frame with a standard used schüco profile is also drawn in combination with a new higher glazing bead which offers an option for a facade that should be renovated. From the exterior of the building the butyl and the spacer bar are noticeable and therefore the architect should be the one to agree with this choice. The literature research points out that it is common to extrude all sort of facade profiles for new or special projects as long as there is demand for it.

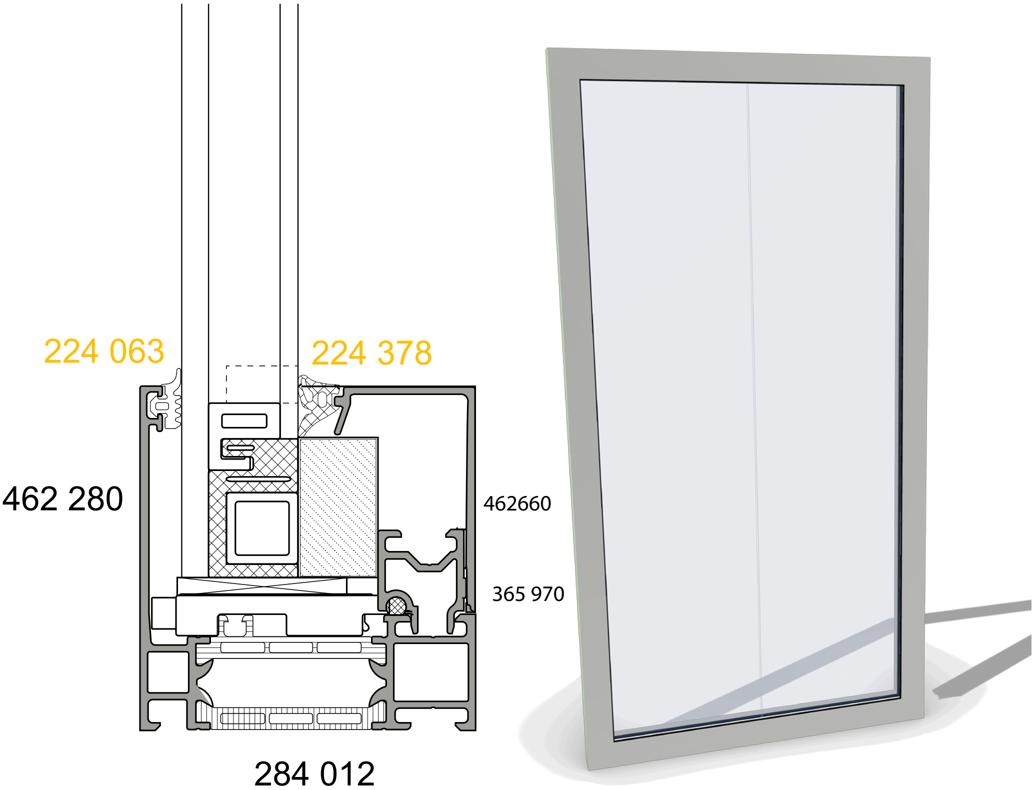
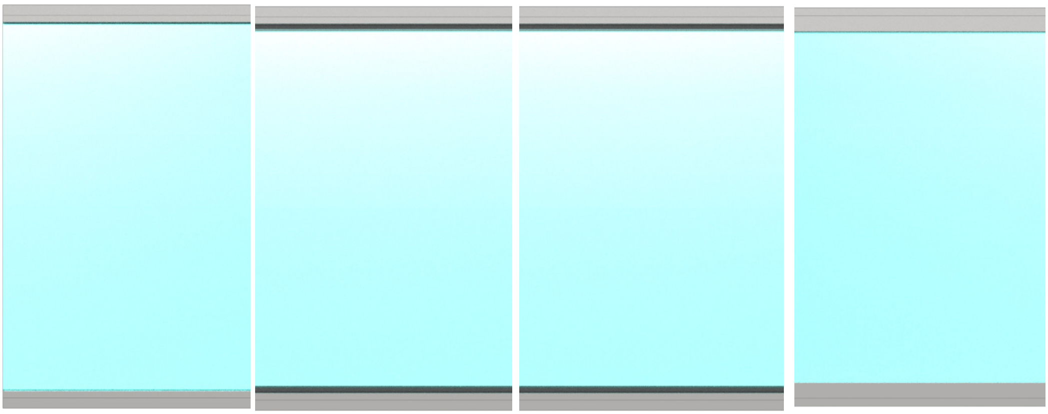
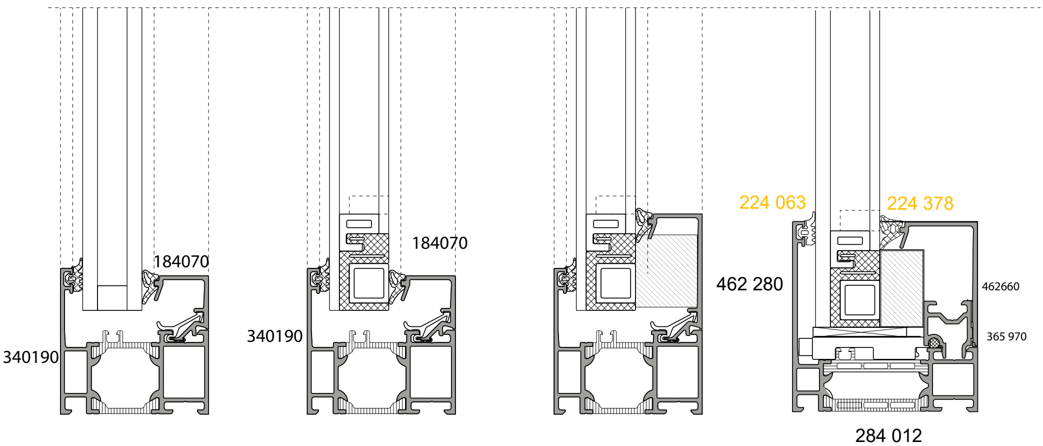


Figure 6.3.1: Detail of how the proposed IGU fits in a (Schuco)frame

Exterior appearance of the facade: conventional IGU and proposed IGU



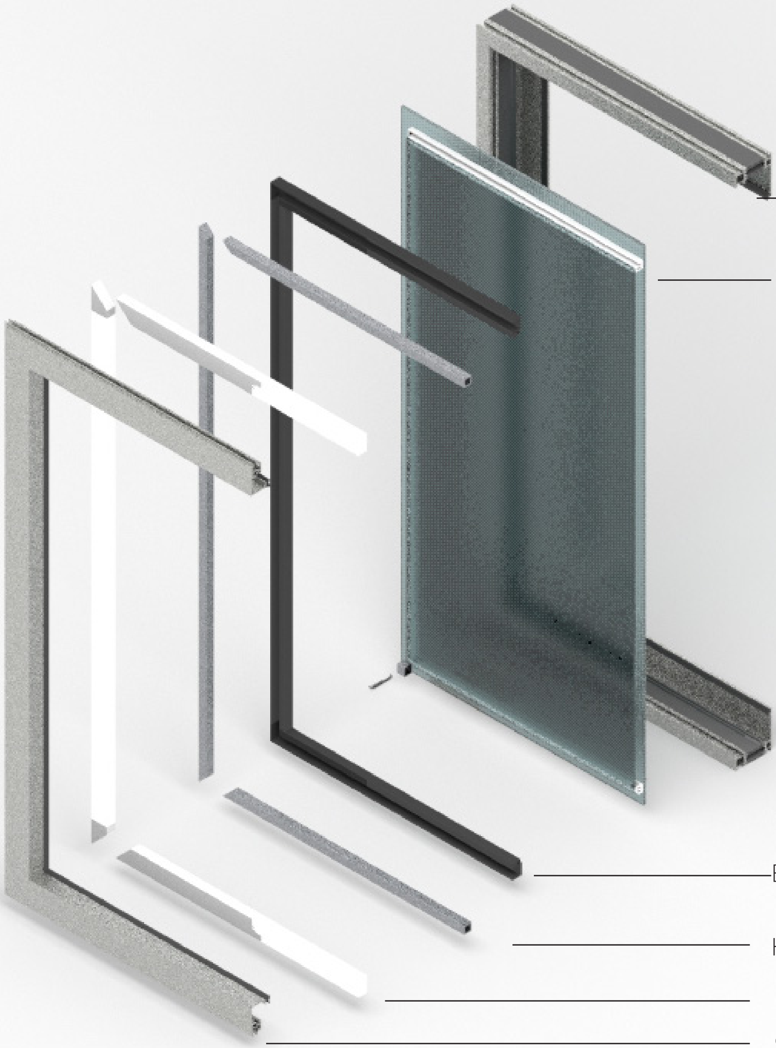


Conventional IGU inside the fixed frame AWS 65.

New remanufacturable IGU inside Fixed frame AWS 65.
This is not a valid solution as can be seen the edge is not well supported

New remanufacturable IGU inside Fixed frame AWS 65. with a higher glazing bead
From the outside you can clearly see the edge of the IGU.

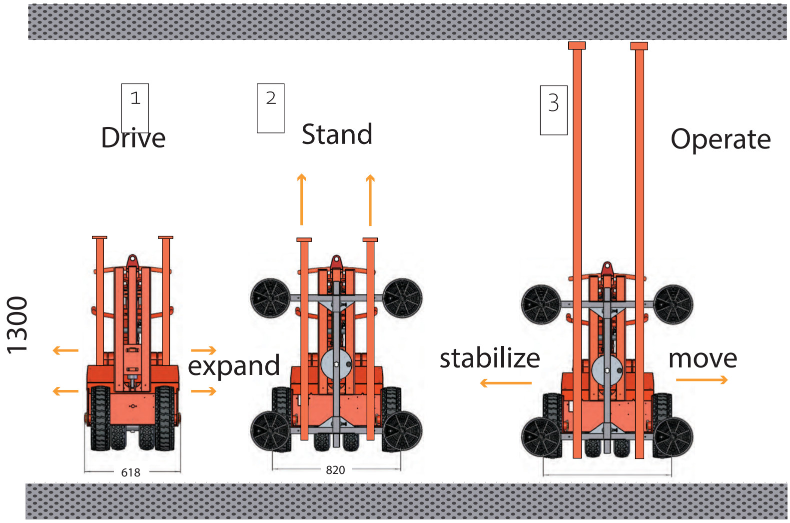
New remanufacturable IGU inside Fixed frame



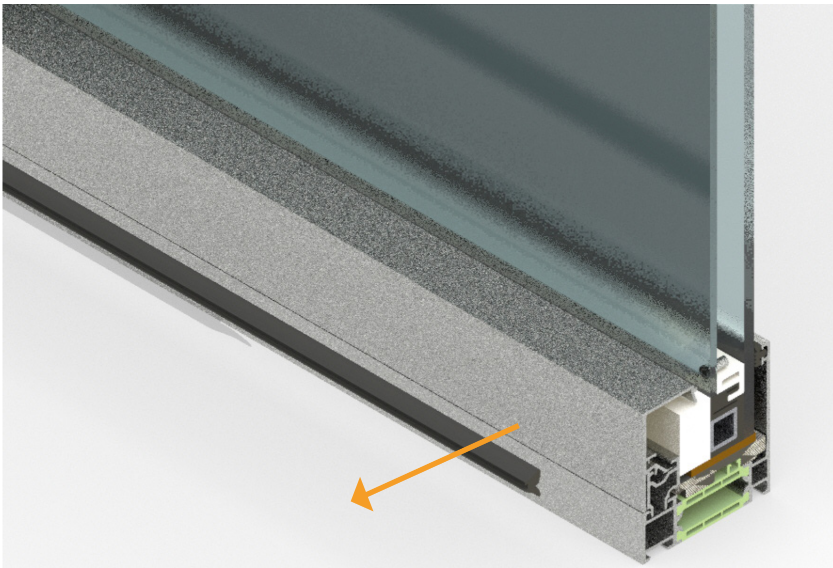
Exploded view of the IGU parts inside a frame

6.4 Buildability: Remanufacturing steps

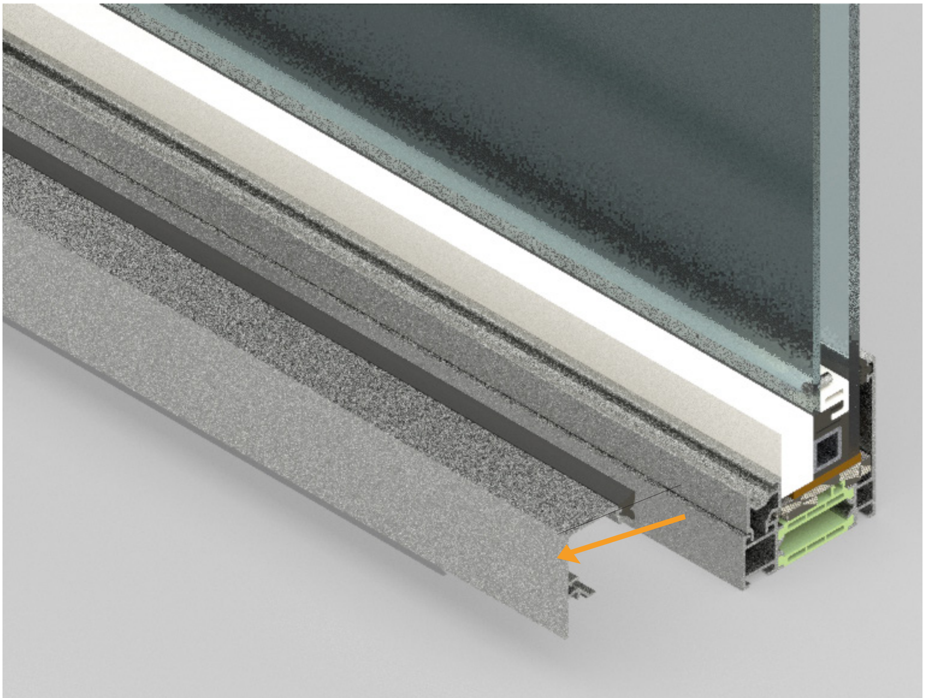
Step 1: First, install the glasslift and let it carry the glazing panel



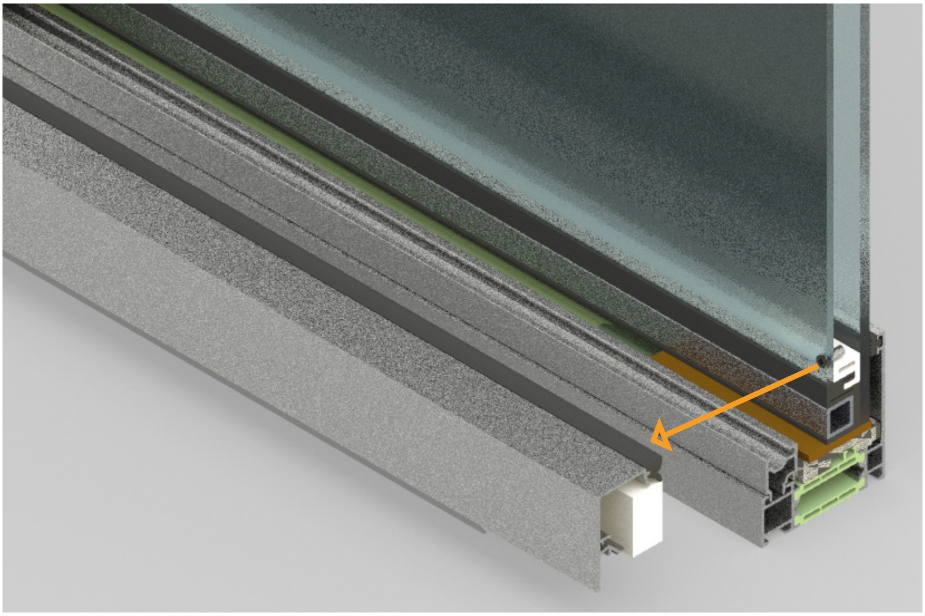
Step 2: Then take away the EPDM gasket



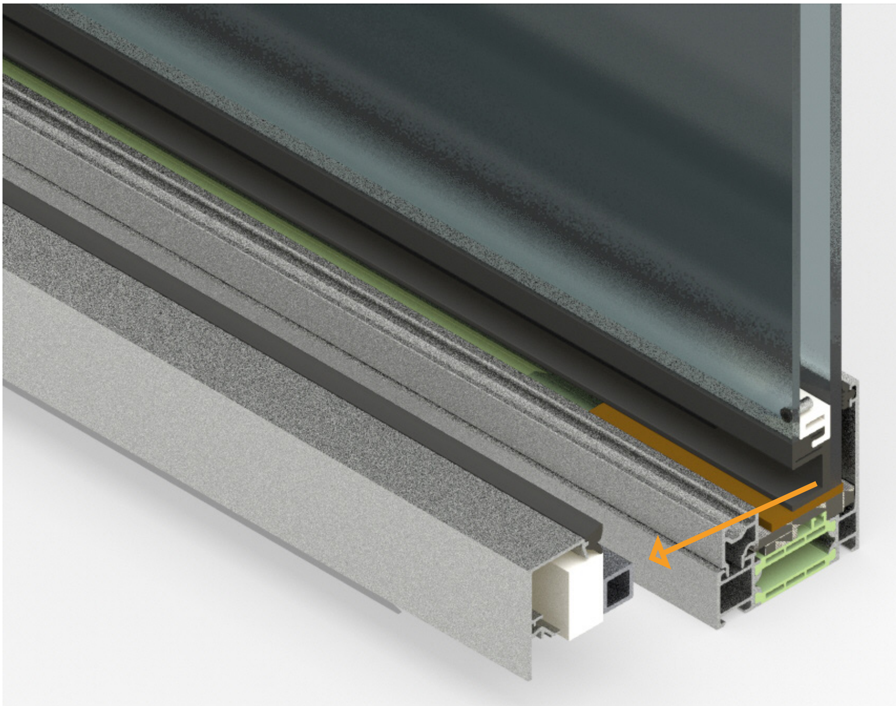
Step 3: Take away the glazing bead



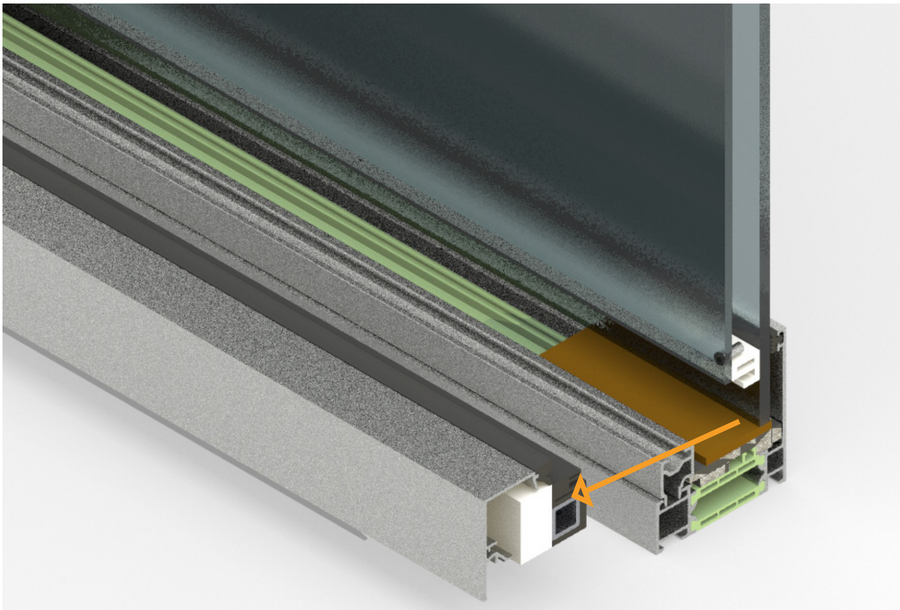
Step 4: Take away the foam block



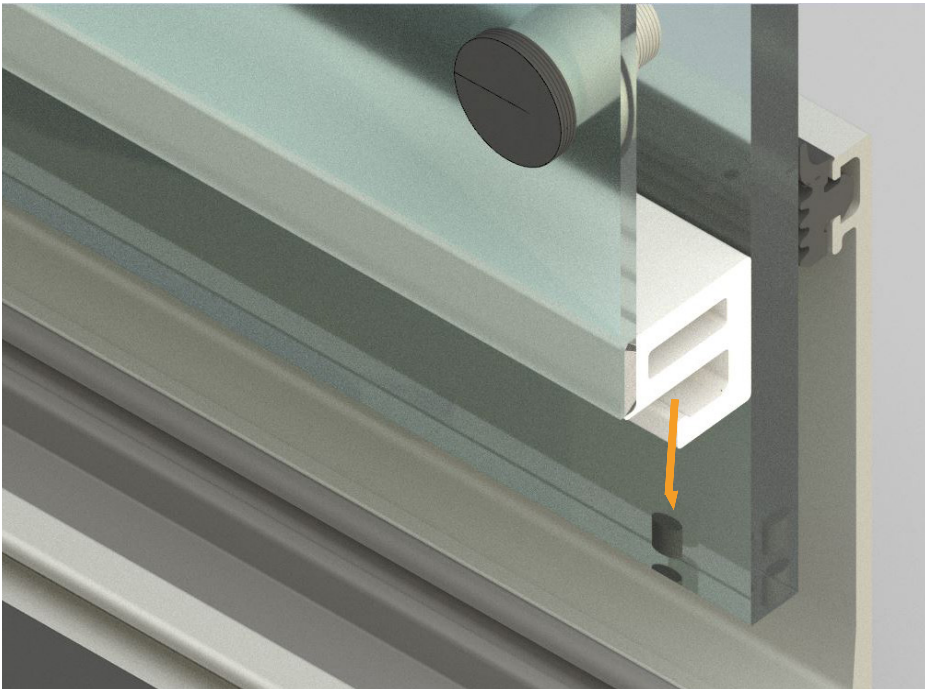
Step 5: Take away the hollow section



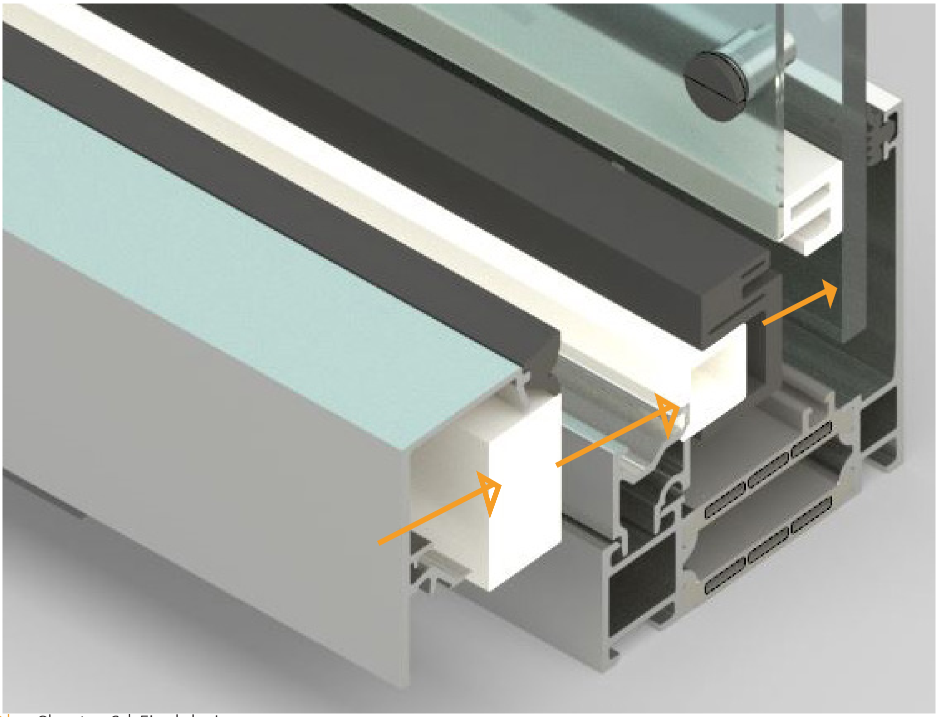
Step 6: Now remove the butyl profile



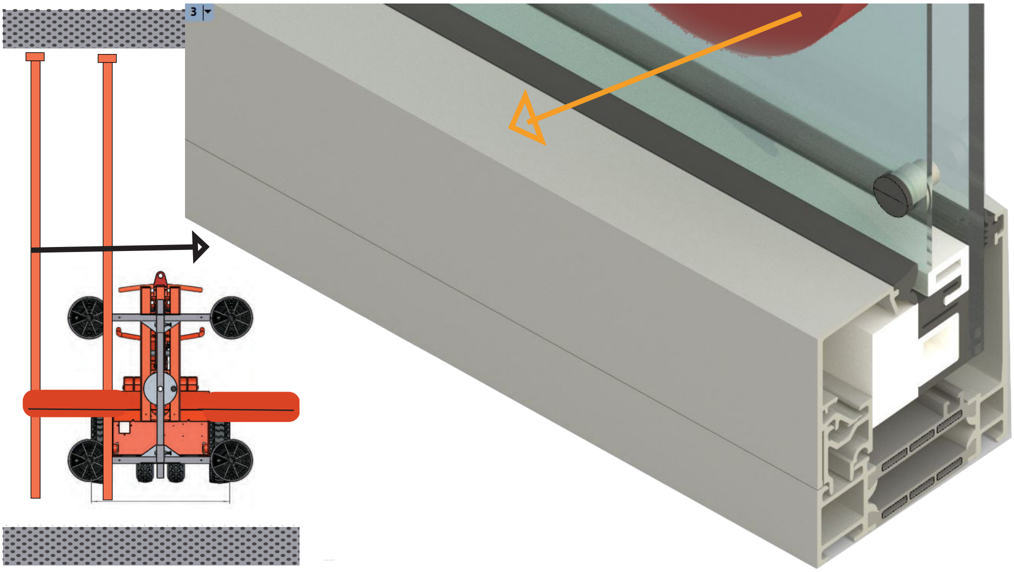
Step 7: Take both plugs out of the spacer bar and fill with desiccant



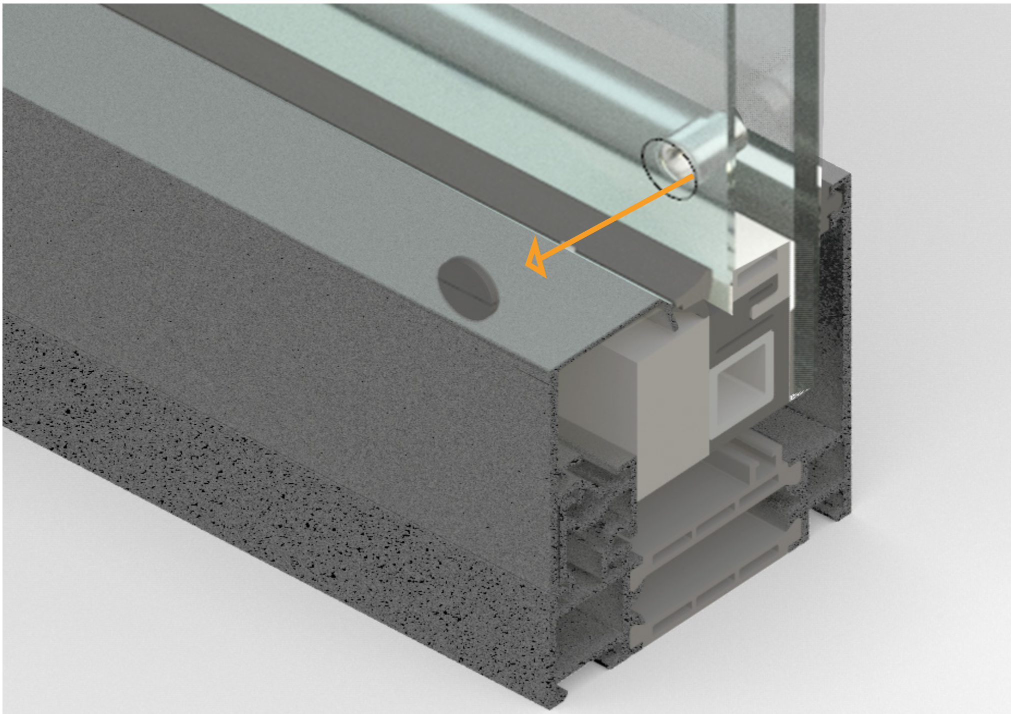
Step 8: Place new butyl profile and re-assemble everything



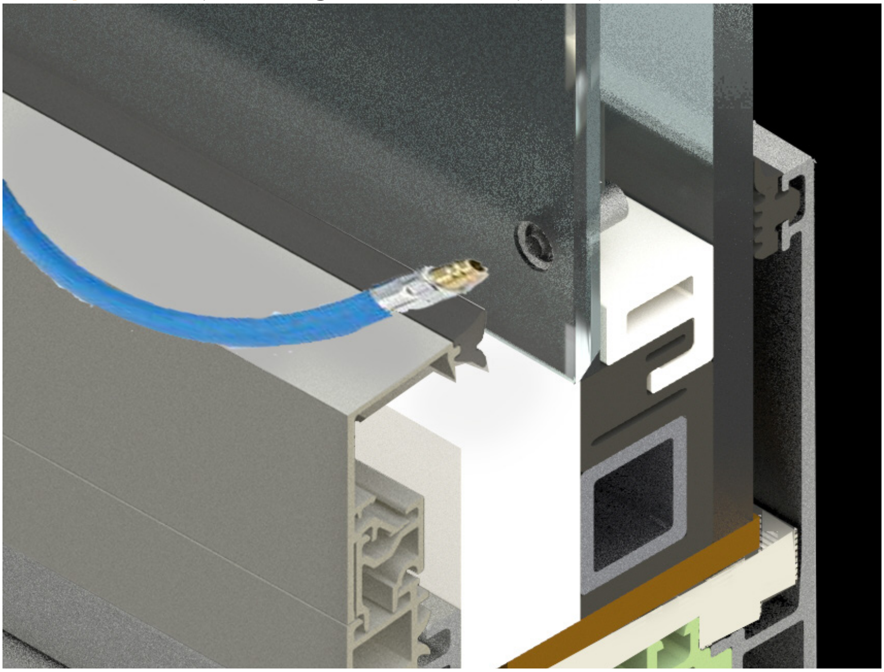
Step 9: Remove the glass lifter (and attach to the next IGU)



Step 10: Open the valve by removing the plug

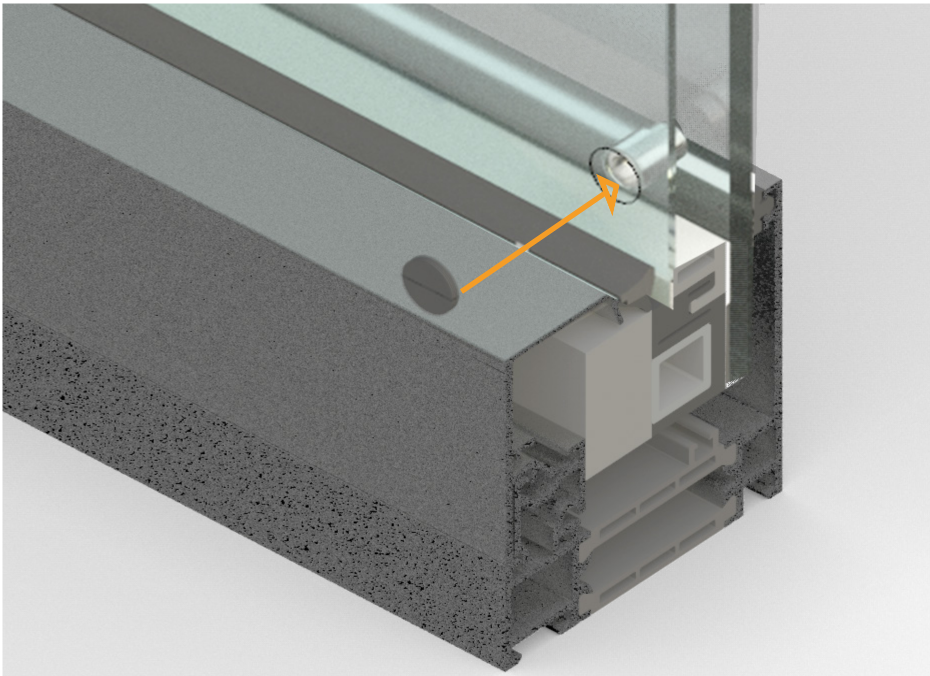


Step 11: Fill up with Argon. (+at the top pump out the air).



Step 12: Measure the Argon percentage at the top side. Appendix 4

Step 13: Place a new plug to protect the valve



In 13 steps, the remanufacturing is finished

Equipment used during manufacturing, installation and remanufacturing:

Assembly:

Materials

-Spacer bar+connectors
-Plugs for spacer bar
-Uv- Glue
-Desiccant
-Hollow sections
-Argon
-Butyl profile

-Valves:
-Plugs for valves
-Cylindric metal tube

Installation:

Equipment

-Glasslift
-Stepladder

Replacement

Materials:

-Argon
-Butyl profile
-Dessicant
-New plugs for the valve
-Pump: to pump the argon gas in and the air out.

Equipment

-Hex key/ hammer
-Glasslift
-Argon Gas filling measuring tool (Sparklike)

Output:
-Butyl profile
-Valve plugs
-Desiccant

6.5 Production line:

In the following scheme, the manufacturer of the IGU is set as the central company. The IGU company should build up a good relationship with his suppliers to know and about the materials of where the parts are made. In this way it keeps control of the selection of durable materials for their own final product. As the suppliers in this scheme offer different products out of different materials, more suppliers than one are involved. Only the hollow section and spacer can be manufactured by the same manufacturer as they are fabricated out of the same material and production process (fiberglass and are both pultruded).

Since the manufacturer of the IGU does not install the product in a frame himself, he will not take full responsibility for possible damage. A contracted remanufacturer could therefore be in this case a facade company like de Groot en Visser, as they can have a service contract with the client and can provide the required service for both the windows as façade elements. In this way they can give feedback to the IGU manufacturer to improve the product based on their perspective as well. Besides these already existing facade companies, also start-up, specialised businesses can find a place in this market. They should have a contract with the IGU manufacturer and maintain a close relationship. Top results can be achieved as both parties will strive for the best performance since they share responsibility in this way.

The in orange hatched boxes illustrated in figure 6.5.0.1 are process steps that are new in relation to the conventional IGU process. The green coloured boxes are conceivable steps that still has to be proven though (applying a metal coating onto the fiberglass spacer e.g. which is explained in appendix A7). The double arrows are transportation/ distribution ways and depending on the position of the box it is a received or distributed product.

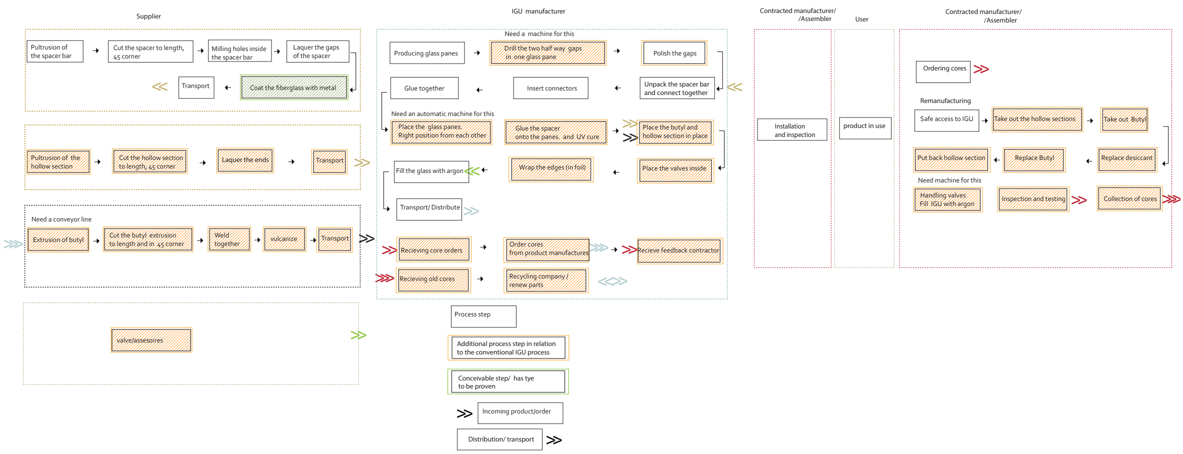
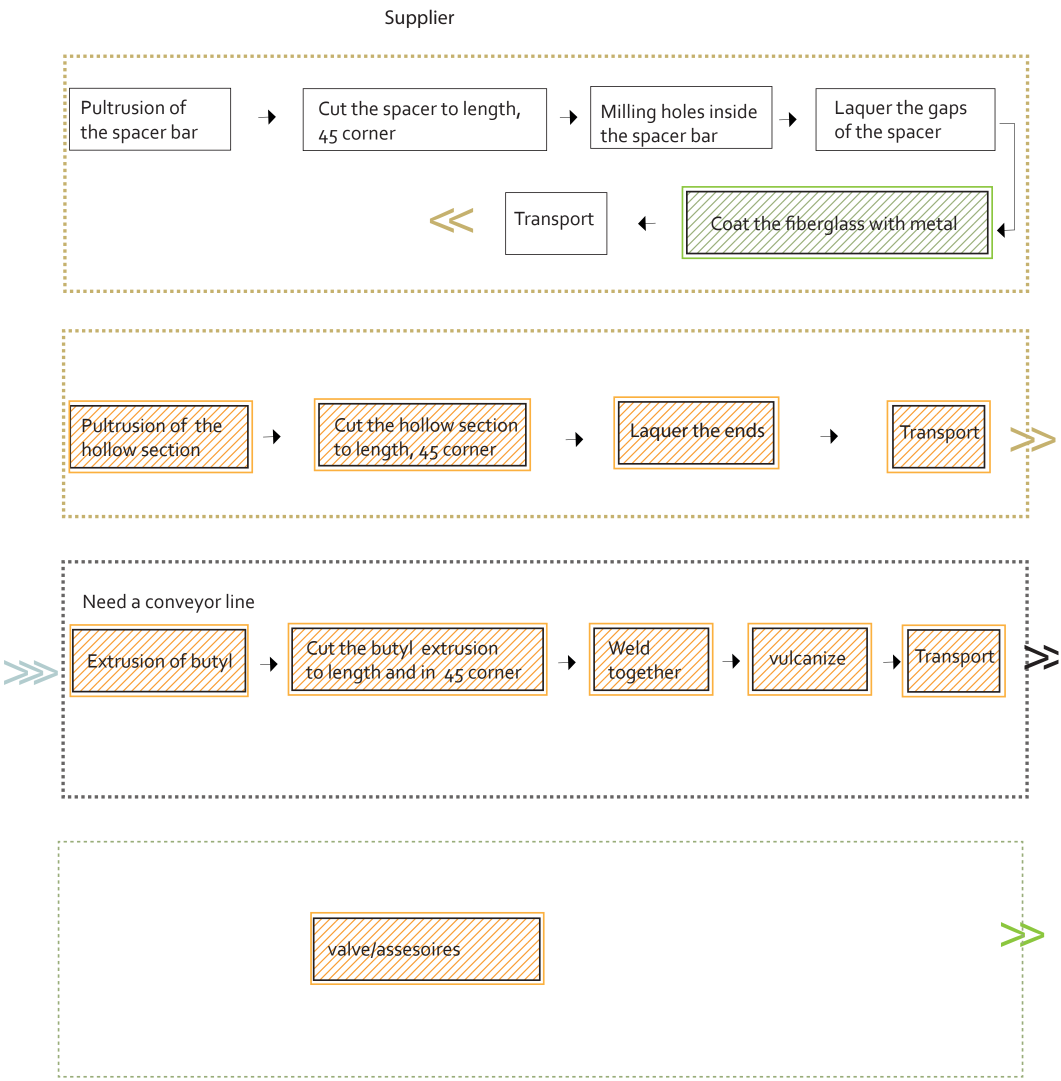
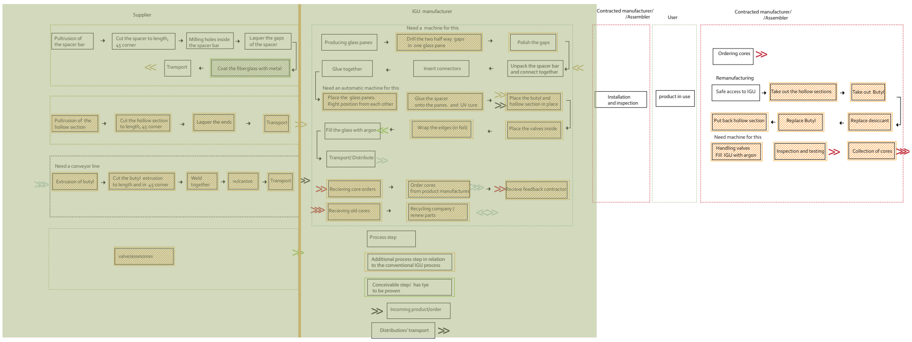
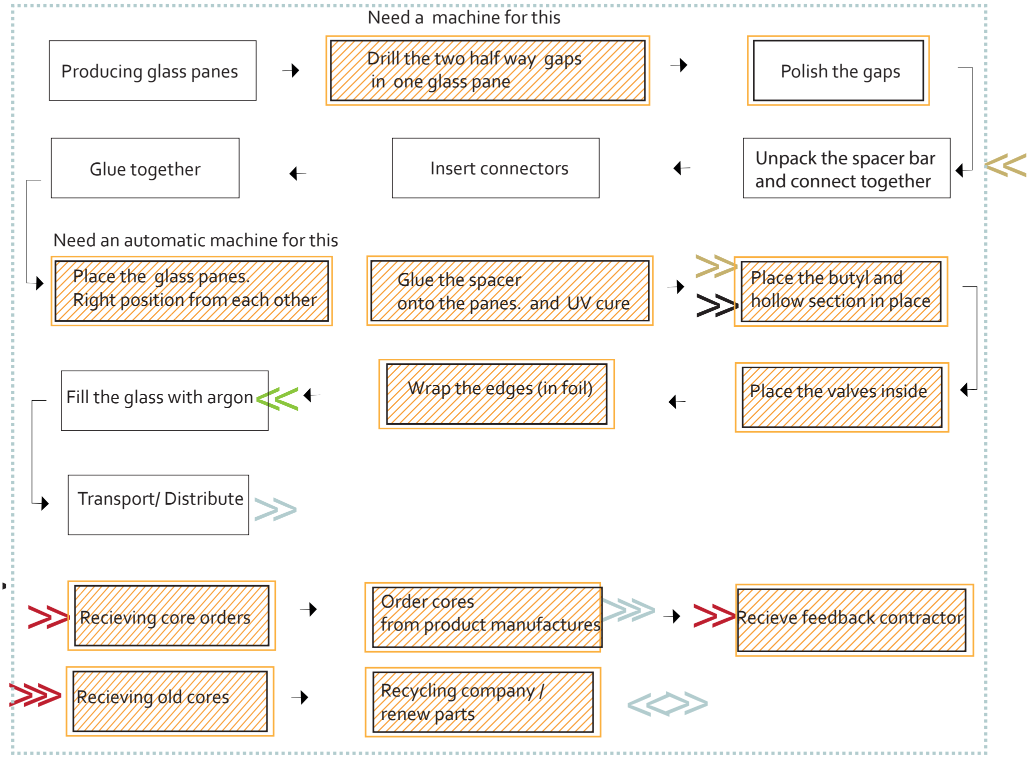


Figure 6.5.0.1: Production line (Authors image)

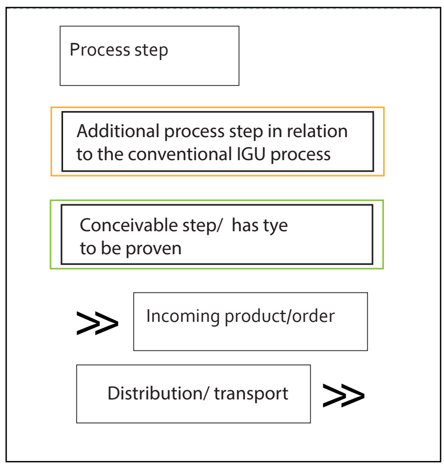

Supplier
Pultrusion of the spacer bar
Cut the spacer to length, 45 corner
Milling holes inside the spacer bar
Laquer the gaps of the spacer
Coat the fiberglass with metal
Transport
Pultrusion of the hollow section
Cut the hollow section to length, 45 corner
Laquer the ends
Transport
Need a conveyor line
Extrusion of butyl
Cut the butyl extrusion to length and in 45 corner
Weld together
vulcanize
Transport
valve/assesoires

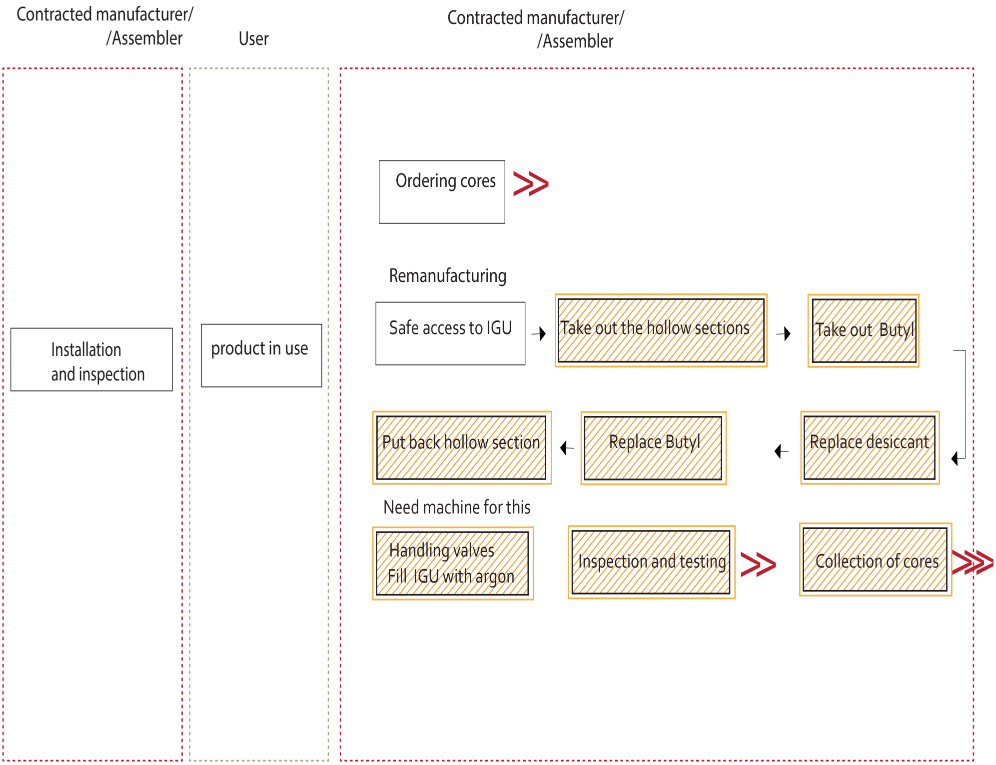


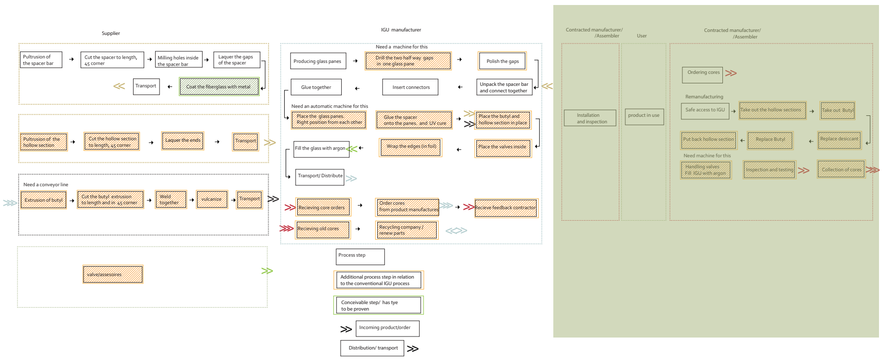
IGU manufacturer



Legend

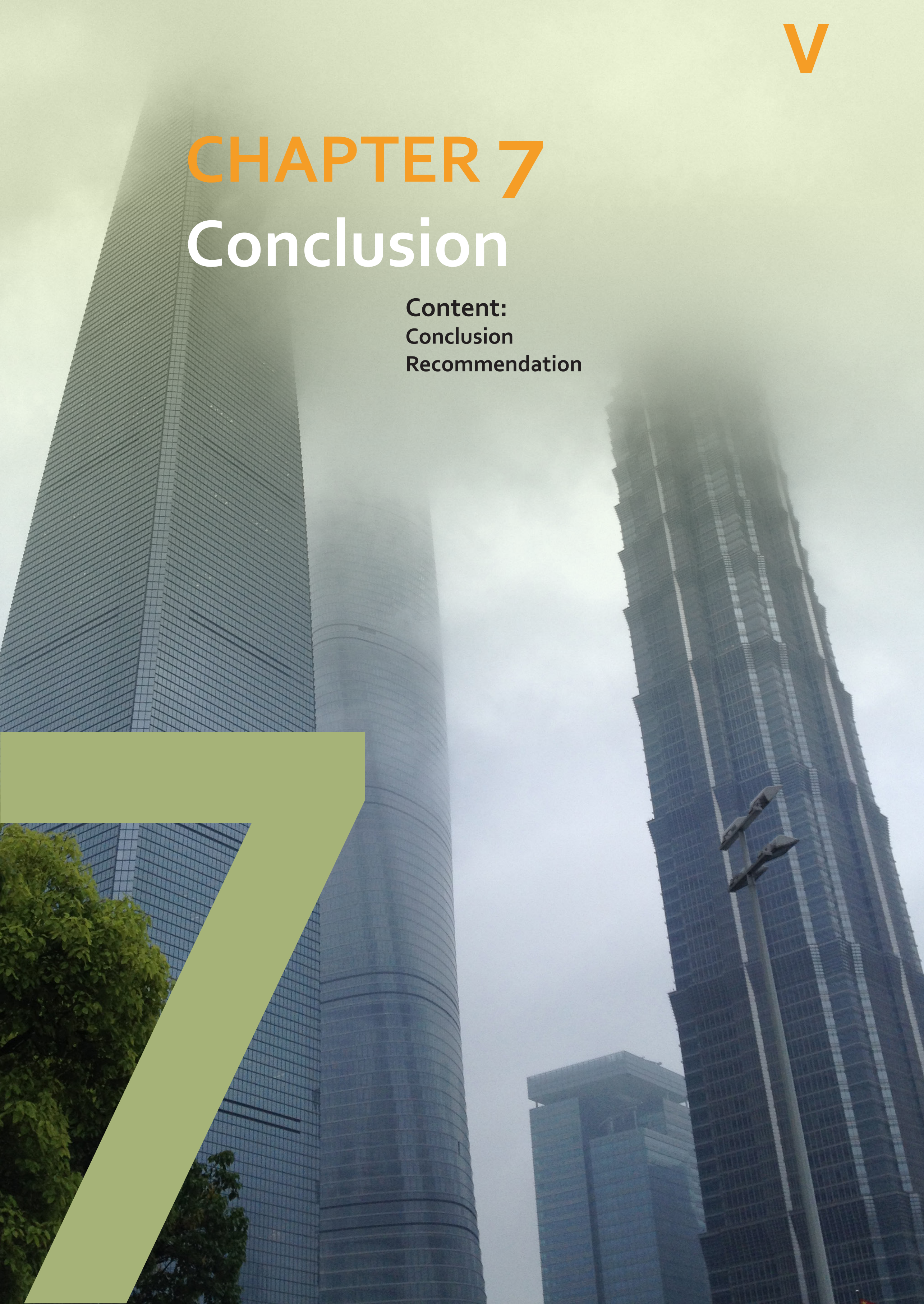



Contracted manufacturer/
/Assembler
User
Contracted manufacturer/
/Assembler
Installation
and inspection
product in use
Ordering cores
Remanufacturing
Safe access to IGU
Take out the hollow sections
Take out Butyl
Put back hollow section
Replace Butyl
Replace desiccant
Need machine for this
Handling valves
Fill IGU with argon
Inspection and testing
Collection of cores



CHAPTER 7
Conclusion

Content:
Conclusion
Recommendation



7.1 Conclusion

The research question: "In what way can the edge seal of the Insulated Glass Unit (IGU) be redesigned for easy and fast re-manufacturing after every ten years in order to achieve a life span of over 100 years, considering low-rise buildings?" is built upon several core words: Insulated Glass Unit , Low rise buildings, Circular economy. These three words are covered by the first three chapters,(the literature part) and every chapters covers a sub research question:
The first chapter about facades was written to create insight of the current situation of the current building stock in terms of façade and window panel principles to answer the question:

What window system is most suitable to start the new design of the IGU and allows easy and fast re-manufacturing?
There are mainly three facade systems. The window system and the curtain wall that can be divided into the unitized systems and stick systems. With both the stick system and unitized systems, the IGU are placed from the exterior of the facade, while the IGU in a window system is placed from the interior. Choosing for an option where the window is installed from the interior would cover a lot of existing low-rise buildings in the Netherlands, while avoiding extern construction differences described by (Ebbert, 2010), such as balconies. Choosing the window system provides the option to leave the IGU in place while at least two educated labourers remanufacture the edges of the IGU. This offers the opportunity to work in a comfortable and controlled environment.
It has to be mentioned that the edges of the remanufacturable IGU design proposed in this thesis, has bigger dimensions than the current IGU edge. This makes the design limited to only higher/bigger existing frames (such as the Schüco 462280 serie) unless it is accepted to see the butyl profile and spacer bar from the outside, in that case just the glazing bead should be higher to give the IGU edges the required stability and reenforcement. In this way also existing frames can accommodate the remanufacturable IGU.
The remanufacturable IGU can also work on unitized systems, where the IGU are placed from the interior with the same ease, they are however more rare. Although placing the windows on the inside of the facade is offering an easy remanufacturing condition, the proposed design is not limited to this and can be placed in any facade type, which includes stick systems. Only wooden window frames are less suitable for this type of windows as removing the glazing bead several time can damage the frame.
A side note to this: If the proposed design would be the new standard, it would be a problem for profile producers to extrude bigger facade elements where this IGU would fit into. The scope of this thesis did not deal with structural glazing (which demand for is in decline in the Netherlands), nor did

it consider fire safety or acoustics behaviour. The second chapter is dedicated to the word "Insulated glass unit" and creates an overview of the current elements of the IGU. Focusing on materials, manufacturing processes and aging factors to answer the question:

What requirements should the new IGU meet to last more than 100 years taking into account every ten years of re-manufacturing?

A big part of the answer is related to the requirements of the edge of the IGU. The sealant, even tough it counts approximately just 1 percent of the total weight of the whole IGU, is responsible for most failures of the panel. When the edge fails, water vapour will get inside the cavity, gas will permeate and as a result the thermal insulation of the IGU will decrease, internal fogging and possible corrosion of the coating will take place and the entire panel can be thrown away.

The edge as a whole should be resistant to working loads, atmospheric pressures fluctuations and wind pressure, extreme temperatures up to 80 degrees Celsius and should be able to resist water, vapor, ozone and UV.

The literature research also went over additional requirements for the glass pane itself. To compensate for a longer lifespan and thus bigger impact risk, the outer pane should have 1 mm extra thickness. This is the order of impact depth of sand abrasion and gravel according to Datsiou and Overend (2017). Furthermore, the glass should have high quality demands for the edge sides. As the edges are important to prevent the initialization of fractures.

The third word circular economy leads to the following sub research question:

What are the distillated tools to redesign a re-manufacturable IGU ?

This question is covered in the last chapter of the literature research part.

In terms of disassembly it is important to think durable, using the right materials for the environment of the product and it is important to think about the connections and finishes.

Standardising the elements is also an important step, as it allows for easy accessible materials needed for remanufacturing or repair. Furthermore, it is important to gather full information about the degradation of the product. This also makes adequate documentation essential.

In order to make the design of the remanufacturable IGU also a circular product, an adequate business model has to be conceived as well. In order to do so certain barriers have to be tackled. On the next page the IGU design is evaluated according to circular design approaches named in the checking boxes.

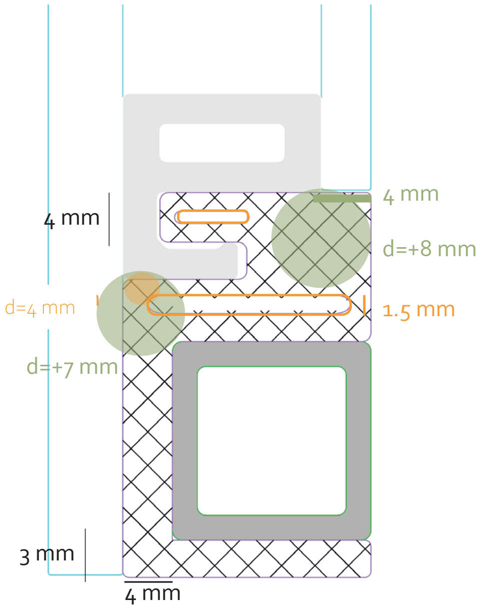
7.2 Evaluation checking box on circularity

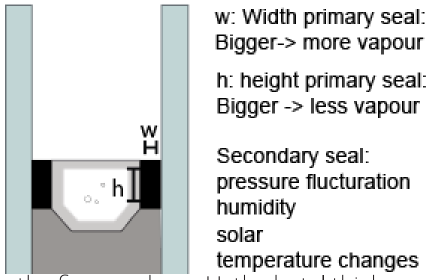
Documentation	• Identify the materials used and in what conditions they are. Also the information on the building manufacturing, along with the assembly and disassembly sequence, should be provided. • A structural way to obtain a diagnostic of the used product to clarify what should be repaired or replaced for remanufacturing.

To meet this documentation requirement it is needed to work with a reliable system that is adaptable to be ' future proof'. Since the glass panes, the spacer bar, but also the valve and hollow section are intended to last for a long life span(>100 years). The information about these parts could be engraved or written on the elements for documentation. The other more temporary parts such as the butyl seal, desiccant and the plug to protect the valve are intended to last for only 10 years and can be replaced with every re-manufacturing or repair cycle. The re-assembler that takes care of the remanufacturing should be a contracted remanufacturer, that should be educated on the necessary skills, information and tools. When the life span of the windows exceed the frame or building a method like working with the material passport and material databases should play a role.

Materials	• Materials should be chosen that could stand multiple life cycles. Materials that might lose strength , become brittle or, are susceptible for wear, can easily corrode, suffer from stain, get discoloured or might later on be banned because of the chemicals should not be used in the design. But also unnecessary parts or layers (such as some coatings) can complicate remanufacturing or can even cause damage to other components in a longer time span because of debris. • Use as few different materials as possible • Add extra materials on surfaces supposed to be machined during remanufacturing. -dimensioning

Design decisions about materials is not always straightforward but mostly a weighted choice. For instance, the PIB seal has been chosen for the reason of the lowest vapour transmission and inert gas permeation, instead of TPE-SEBS, that is theoretically recyclable as it can be melted and reshaped (most companies will however throw it away as much dirt and impurities are added to the material during the life span).
Furthermore, the choice of separating the functions and thus choosing for more elements was done in the case of the elements used for load transfer and gas barrier, which are the butyl seal and the hollow section. This is not in line with the rule of 'use as few different materials as possible' but offers the possibility to keep the hollow section for multiple remanufacture cycles and throw away the butyl layer. The thickness of the PIB is now also 4 mm on one side but the other side is much thicker (7 mm instead of 4) than the conventional design.





In the figures above,H, the butyl thickness, is 4 mm in the conventional design. This is the same for the remanufacturable IGU on interior side , under the condition that the minimal thickness of the inner pane should always more than 4 mm. On the outer pane the minimal thickness of the butyl seal should be more than 4 mm(orange circle) .

Disassembly	• Make demounting as easy as possible to use the same (or the least amount of) tool (s). Screws, snaps, clamps in the same type and size and screws on the same side. • If needed, divide the product into parts or modules. And try to keep all parts that should be replaced at the same remanufacturing period in the same module. Avoid cross-dependence between the modules. • Assembly methods and sequences should be standard • Think ahead for the design: Materials should be chosen that minimize pollution during extraction, processing, usage and recycling. • Use a minimum number of different types of connections and fasteners. • Avoid secondary finishes, adhesives, and coatings

A lot of focus in this design is about the disassembly part. Many elements are clamped and can be taken apart with standard tools. However for removing the valves, special (tiny) equipment should be used. The valve is not supposed to fail in a short time but can be changed when needed. To be able to achieve this however glue had to be used for the cylindrical metal tube. Furthermore, this glue is used to attach the window panels to the spacer bar. The reason for breaking the rule of 'avoid secondary finishes, adhesives and coatings' is that it is undesirable to take apart the glass and spacer bar from each other and it should only be done at the end of its life. After heating the glue to a certain temperature (between 100- 150 degrees Celsius) the adhesive should not longer bond the elements together and can be taken apart. However by making this choice, it limits the possibility to repair and replace just one pane of glass when it gets fractured, but it is not impossible if required. The thesis has left out life cycle analysis for the materials.

Standardizing	• If possible make use of standardized elements, so they would be available over the years and always can be replaced as spare parts are then widely available. • Use a minimum number of components and connections types. • Specialist technologies should be avoided.

The materials in the design have been chosen to be suitable for mass production methods. By using extrusion and pultrusion standardized products can be made. A range of width of the cavity and thus spacer bar should be set. The valves are not dependent on width or height of the window and thus are interchangeable. However, as the IGU does not require specialist technologies, the valves are because of their low cracking range, gas application, dimension and springs more complex to produce than tyre valves, but are comparable to valves used in the aerospace industry and cartridges. If further research is done on how to make the valves also suitable for mass production, the specialist technologies are avoided and the whole product can become much more affordable as then every part can be standardized.

By designing a product for remanufacturing not only the design itself should be thought through but also the barriers such as the business model and process should be taken into account. For the proposal of the new 'remanufactured window' a business model has been considered. Contracted remanufacturing (CR) companies that remanufacture the windows on behalf of the IGU manufacturer could be a strategy that has to be further developed. These CR can be new start-up companies specialized in the IGU refurbishment but can also be implemented within facade companies that have a service contract with their client. It is important that they maintain a close relationship to the IGU manufacturer to enforce the quality of the product during its long lifespan and to keep the heating and cooling loads of buildings as low as possible.

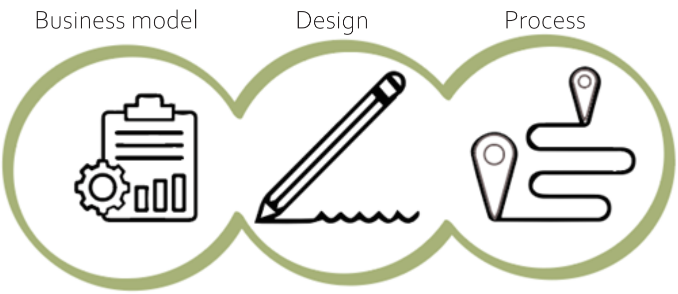


Figure 4.3.1.2: Barriers towards remanufacturing Business model, Design for remanufacturing and process. based on (Vargas, 2019)

7.3 Recommendation

Realisation of the remanufactured IGU will depend on follow-up research in various domains. Recommendations for potential future research is described below:

One of the main limitations of the presented research was time, and therefore, the redesign of this IGU does not cover structural simulations that include creep of the PIB profiles under load, which does occur with this material. It is however an essential detail to know in order to know whether the design of the edge is worth exploring further. For this reason, this point it is included to the recommendation.

For the material choice of this presented research no LCA has been executed it would be interesting to see the economical and.

Production: When talking to valve manufacturers, the valves needed for this IGU would cost above hundred euro each, diving deeper into how the valves can be mass produced would make it a more feasible concept.

The research did not deal with structural glazing and the design proposal can therefore not be used for these applications until further research is performed.

Building physics: Although shortly discussed in the literature part, the design has not acoustically being checked. Furthermore , no scenarios are discussed in case of fire. Conventional windows have the sealant in between the glass slightly protected.

The mock-up model is not tested with gas filling or set under pressure. This is mainly because of the unavailability of the required material and mold to extrude the butyl profile. Trying with silicone did not work at all as many bubbles are trapped inside even after placing it in a vacuum chamber. Also 3D printing with the flexible material would not provide a gas-tight condition. A next step after this thesis therefore will be recommended: Testing the design in a real mock-up with a real butyl profile. To check all the flaws such as gas tightness (over time) since creep will occur.

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APPENDIX

A

Arup (2018)

A.1 Requirements of facades - NEN Norms

Number Theme

1. Statics		
Dead load	NEN-EN 1990 NB	Deflections
Wind	NEN-EN1991-1-4 NB	Windload
Fall through limitation	EN 1991-1	Aluminium construction
Window washer tray	NEN-EN 14019	Impact loading
Special cases (explosion, earthquakes/...)	NEN 2608	Glass construction
Glue connection	NEN3569	Glass/Injury
2. Fire safety	NEN 6069	Testing and classifying
30-60 min	NEN-EN 1364	Fire safety
Fire spreading	NEN-EN 13501/Deerns d.d. 19-12-2017	Fire classes
3. Burglary limitation	NEN 5087, NEN 5096,EN 1627,EN356	Safety
4. Acoustic barrier	NEN 14351-1	Classifying
Intern noise	NEN 5077	measurment method
Flanking sound	NPR 5272	Sound proof building
Sound from outside to inside (traffic)		
5.Wind and water barrier	NEN 2778	Testing pressure
Air gap per m2 or m1 seam	Qv;10 norm	Air passage 10Pa
Testing standard	EN 12207/12152	Class air passage
6. Thermal insulation	EN 12208/12207	Class water passage
Windows, doors and facades	NEN 1068	Rc and Uw values
Closed parts	NEN2778	f-Factor
7. Sun exposure		
ZTA	NEN2057	Daylight opening
LTA	NEN-EN 410	Entry regulation
Thermal barrier glass		
Sunshade /lamellas inside the glass panels		
8. Ventilation		
Grill covering	NEN 1087	Regulation method
Window, scour outlet		
9.Sustainability/durability	NEN 2767	Condition score
EPC,BREEAM, Well/BENG		and Maintenance
10. Surface treatment		
Inside /outside		
11.Dimensions	EN 1090	
Window frames	NEN 2881	Tolerances
(Door) openings	NPR 3685	Tolerances
Tolerances	NEN 1814	Accessability MIVA
12. Escape routes	EN 14451-1	Certification
	EN 179/ EN1125	Locks
13.Assembly and production		
Production control		
Construction site control		
Supply inspection		
14.Drawings		
Maintenance guidance		
Warranty certificates		
Declaration of Performance in short 'DoP'		

Table A.1.1: Qualities and requirements of the Façade system (source: De groot en Visser).

A.2 Requirements for acoustics - NEN Norms

Noise level category	Exterior ambient noise level (dB) (A)	Required Soundinsulation of the exterior components		
		Bedrooms in hosipal wards and sanitariums	Living room, classroom, sleeping areas in hostel	Office spaces
I	Up to 55	35	30	-
II	56-60	35	30	30
III	61-65	40	35	30
IV	66-70	45	40	35
V	71-75	50	45	40
VI	76-80	requirements based on onsite situation	50	45
VII	>80	requirements based on onsite situation	requirements based on onsite situation	50

Table A.2.1: Acoustic requirements per noise level and functions of the room.

A.3

SWISSPACER
The edge of tomorrow.

SWISSPACER – Thermal performance in different window constructions

Spacer bar system	Double glazing				Triple glazing			
	Aluminium	Stainless steel	ADVANCE	ULTIMATE	Aluminium	Stainless steel	ADVANCE	ULTIMATE
WOODEN WINDOWS								
Frame value: U_f = glass value: U_g =	1.4 W/m²K 1.1 W/m²K				1.3 W/m²K 0.7 W/m²K			
Psi value [W/mK]	0.082	0.053	0.039	0.031	0.089	0.054	0.037	0.029
Window, U_w 1 pane [W/m²K]	1.40	1.32	1.29	1.27	1.10	1.02	0.97	0.95
Window, U_w 2 panes [W/m²K]	1.52	1.41	1.36	1.33	1.26	1.13	1.07	1.04
Min. surface temperature* [°C]	4.1	7.3	8.9	9.7	6.0	9.6	11.2	12.1
PVC WINDOWS								
Frame value: U_f = glass value: U_g =	1.2 W/m²K 1.1 W/m²K				1.2 W/m²K 0.7 W/m²K			
Psi value [W/mK]	0.076	0.051	0.039	0.032	0.078	0.050	0.037	0.030
Window, U_w 1 pane [W/m²K]	1.32	1.26	1.23	1.21	1.05	0.98	0.95	0.93
Window, U_w 2 panes [W/m²K]	1.42	1.33	1.28	1.26	1.19	1.08	1.04	1.01
Min. surface temperature* [°C]	5.3	8.3	9.7	10.4	6.7	9.9	11.3	12.0
WOOD-ALUMINIUM WINDOWS								
Frame value: U_f = glass value: U_g =	1.4 W/m²K 1.1 W/m²K				1.4 W/m²K 0.7 W/m²K			
Psi value [W/mK]	0.094	0.059	0.042	0.032	0.100	0.060	0.040	0.030
Window, U_w 1 pane [W/m²K]	1.43	1.34	1.30	1.28	1.17	1.08	1.03	1.000
Window, U_w 2 panes [W/m²K]	1.57	1.44	1.38	1.34	1.35	1.21	1.13	1.100
Min. surface temperature* [°C]	2.2	6.1	7.9	8.8	4.4	8.6	10.5	11.3
ALUMINIUM WINDOWS								
Frame value: U_f = glass value: U_g =	1.6 W/m²K 1.1 W/m²K				1.6 W/m²K 0.7 W/m²K			
Psi valuet [W/mK]	0.110	0.068	0.047	0.036	0.120	0.064	0.042	0.031
Window, U_w 1 pane [W/m²K]	1.54	1.44	1.39	1.36	1.30	1.17	1.12	1.09
Window, U_w 2 panes [W/m²K]	1.72	1.56	1.49	1.45	1.53	1.32	1.25	1.21
Min. surface temperature* [°C]	4.7	8.4	10.0	10.8	6.8	10.6	12.2	12.9

Geometry	Wood	PVC	Wood-Aluminium	Aluminium
Total surface area (1,23 x 1,48 m) A_w in m²	1.82	1.82	1.82	1.82
Frame width bf in mm:	110	117	120	130
Surface area of the frame A_f in m² (1 pane / 2 panes)	0.548/0.686	0.579/0.725	0.593/0.742	0.637/0.796
Length of glass edge l_g in m (1 pane / 2 panes)	4.540/6.840	4.484/6.742	4.460/6.700	4.380/6.560

The equivalent thermal conductivity was calculated according to the ift WA-17/1 guidelines.

The representative Psi values were calculated under the framework conditions defined in the ift WA-08/2 guidelines.

Psi value: linear heat transmission at the edge of the glass [W/mK] according to EN ISO 10077-2:2012-06

* in line with the framework conditions of DIN 4108-3

External temperature: Ta: -10°C
Interior temperature: Ti: +20°C

Looking at the psi values, it seems that warm edge spacer bars can have such a great influence on the heat resistant in the same order of choosing an aluminium frame in contrast to a pvc frame

A.4 Argon measurement

With the device shown in figure A.4.1 the Argon percentage can be measured.
It is known that insulating glass units cannot be filled for 100% with any gas. Most Units therefor have an average above 95% as initial fill (Saint Gobain claims an average of 98 percent). The Ug value for a window is calculated with 90 percent of Argon filling with a tolerance of 5% so with a loss of 1 percent a year, the starting value should be set to at least 94% according to calculations.
There is a device working on plasma emission spectroscopy, created by a high voltage discharge that can measure the gas fill for the igu, this takes measurement time of just 2 seconds. Sparklike Handheld™ is portable, battery operated, and can measure triple and double glazed units, also through coated and laminated glasses.
The measurements have to take place with a dark background and therefor can be best measured at a glazed tube that is connected with the valve on top that sucks the air out (Figure A.4.2).

Figure A.4.2: Argon measuring device to measure will be applied at the top of the window.

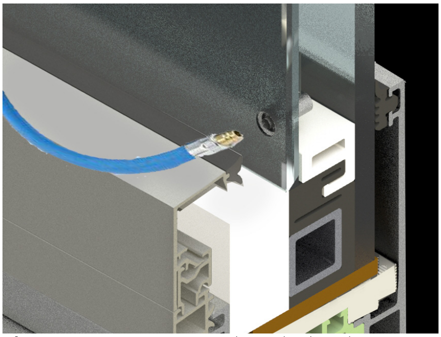


Figure A.4.3: Since Argon has a higher density it it has to fill from the bottom to slowly fill the hole panel

Figure A.4.1: Sparklite handheld device to measure Argon.

O		16 g/mol	
Argon		35 g/mol	
	60 pm	Oxygen radius	60x10-12
	71 pm	argon radius	7 1 × 10-12

Figure A.4.4: Since Argon has a higher and density and bigger radius than oxygen.

A.5 Production cycle of timber pvc and aluminium

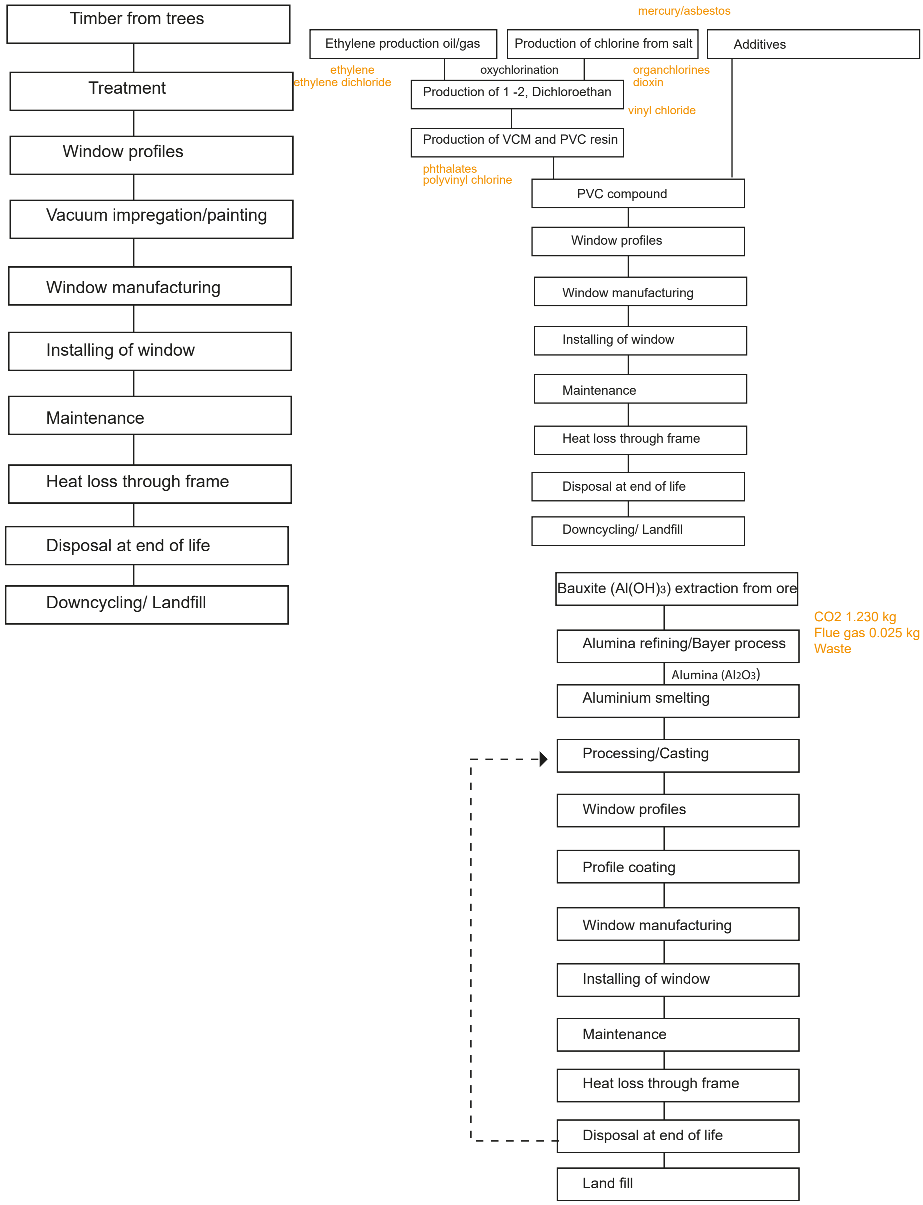


Figure 2.4.2: Production cylcle of timber, Aluminium and PVC

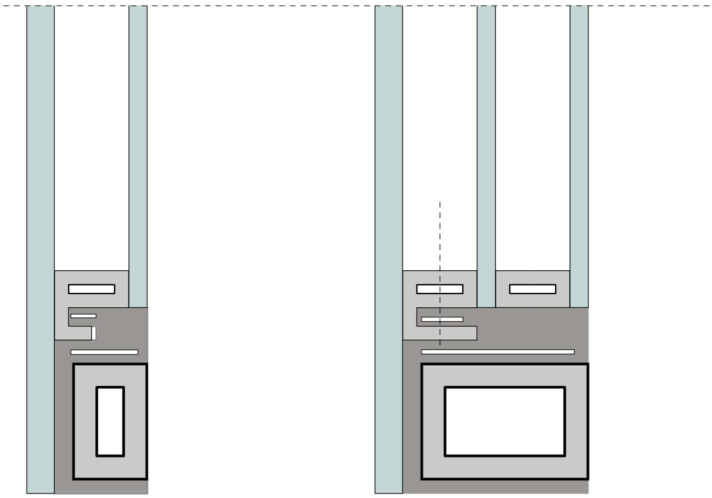
A.6 Delo photobonding adhesive

Photoinitiated-curing acrylates Product group / curing class		UV-curing							
Product code		**GB310**	**GB345**	**GB368**	**PB437**	**4494**	**AD491**	**AD494**	**SD4196**
Application area B = bonding, S = sealing, C = coating		B	B	B	B	B	B	B	B
Color cured product	in 0.1 mm layer thickness	colorless clear	colorless clear	colorless clear	colorless clear	colorless clear	colorless translucen	colorless clear	blue fluorescent
	in 1.0 mm layer thickness	colorless clear	colorless clear	colorless clear	colorless clear	colorless clear	colorless translucen	yellowish clear	blue fluorescent
Viscosity [mPas] at +23 °C, Brookfield	DIN EN 12092	100	1,500	5,700	8,000 thix	20,000 thix	90,000	50,000 thix	47.000 thix
Wavelength range for curing [nm]		← 320 – 400 →		← 320 – 420 →					
Minimum irradiation time [s] DELOLUX 04, DELO Standard 23 at 55 – 60 mW/cm² UVA intensity[1]		20	17	15	6	7	7	14	3
Heat curing time [min] without heating time of components, at +130 °C		–	–	–	–	–	–	–	–
Compression shear strength [MPa] DELO Standard 5 Irradiation and curing conditions: DELOLUX 03 S, layer thickness 0.1 mm; lamp distance approx. 70 mm; UVA intensity[1] 55 – 60 mW/cm² irradiation time 60 s; approx. +23 °C	glass/glass	34	29	23	31	28	25	13	6
	glass/Al	40	27	23	30	25	25	12	6
	glass/PC	4	7	7	14	15	18	13	3
	glass/PMMA	4	–	16	8	4	8	9	3
	PC/Al	–[2]	–[2]	5	9	5	14	10	3
	PC/PC	–[2]	–[2]	6	22	18	28	18	11
	PMMA/PMMA	–[2]	–[2]	15	9	10	12	–	6
Tensile strength [MPa]	DIN EN ISO 527	33	26	20	21	20	20	13	3
Elongation at tear [%]	DIN EN ISO 527	4	40	17	110	160	150	310	340
Young's modulus [MPa]	DIN EN ISO 527	1,600	1,200	900	520	400	400	20	20
Shore hardness	DIN EN ISO 868	D 77	D 70	D 67	D 65	D 62	D 63	D 25	A 68
Glass transition temperature T_g [°C]	rheometer	+120	+77	+102	+114	+100	+100	+48	+44
Average coefficient of linear expansion [ppm/K]	TMA, in temperature range: +25 °C to +140 °C	168	214	236	184	211	180	200	344
Shrinkage [vol. %]	DELO Standard 13	10	7	7	9	9	7.5	7	6.4
Water absorption [weight %]	by the criteria of DIN EN ISO 62 24 h at +23 °C	0.4	0.9	0.5	1.0	1.3	1.0	3	1.4
Special features of product		glass adhesive capillary high-strength	glass-to-metal connections	glass adhesive also for glass-to-plastic connections dry surface	multi-purpose adhesive very fast curing tough-hard	multi-purpose adhesive tough-hard fast curing	multi-purpose adhesive excellent humidity resistance	multi-purpose adhesive steady gap-filling	peel-resistant plastic bondings dry surface tension-

Delo AD491 is chosen for this project, it has a great tensile pressure, can bond between glass but is also multi purpose. Above this it has an excellent moisture resistance and is colourless.

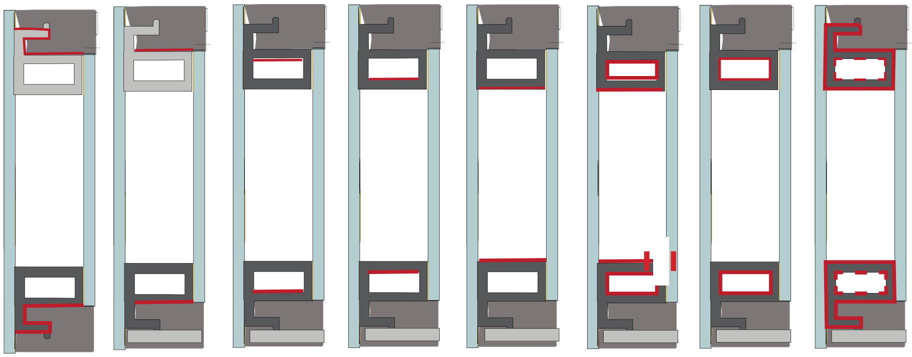
	DELO PHOTOBOND						DELO DUALBOND			
	UV- and light-curing						light- and humidity-curing			UV-/light-/ heat-curing
	4436	4442	44[illegible]	4496	4497	AD414	AD4950	GE4910	AD4930	AD465
	B	B/S	B	B/S	B/S/C	B/S	B/S	B/S	B/S	B/S
	colorless clear	colorless clear	colorless clear	colorless clear	milky	blue fluorescent	colorless clear	colorless clear	colorless clear	red fluorescent
	colorless clear	colorless clear	colorless clear	yellowish clear	milky	blue fluorescent	yellowish clear	yellowish clear	yellowish clear	red fluorescent
	350	650	7,000 thix	17,000 thix	30,000 thix	1,300	36,000	2,000	14,000	24,000
	← 320 – 450 →									320 – 420
	8	60	40	50	15	17	10	10	5	4
	–	–	–	–	–	–	–	–	–	3
	18	4	22	6	19	7	9	7	9	23
	17	4	24	4	19	8	6	6	4	22
	7	5	3	5	10	–	–	–	–	–
	4	3	3	4	3	–	–	–	–	–
	2	2	3	5	4	–	–	–	–	–
	10	6	1	10	12	6	10	–	–	–
	4	2	3	3	7	–	8	–	7	–
	12	3	14	6	11	8	8	6	5	17
	250	300	200	300	200	540	270	315	45	220
	35	–[3)]	250	–[3)]	84	–	45	17	30	320
	D 38	A 30	D 45	A 35	D 40	A 44	A 77	A 62	A 80	D 50
	+57	+18	+74	+21	+52	+28	+70	+70	+65	+100
	247	254	216	239	208	260	217	235	210	204
	10	6	9	6	9	6.3	4.6	5	3	5.6
	0.9	0.6	0.9	0.7	0.9	0.7	2.5	1.3	0.6	1.2
	multi-purpose adhesive fast curing	flexible sealing USP XXIII Class VI approval	glass and glass-to-metal connections USP XXIII Class VI approval	flexible sealing run-resistant	multi-purpose adhesive dry surface	multi-purpose adhesive good flow properties very good sealing properties	multi-purpose adhesive	multi-purpose adhesive highly flexible good flow properties	multi-purpose adhesive flexible	multi-purpose adhesive dry surface build-up of strength in shadowed areas by heat
							← reliable curing in shadowed areas by air humidity →			
							← very fast light fixation →			

A.7 Upgradability



An important aspect of a circulair design is also to prevent waste by designing a product that is not only 'able to' but also is ' worth' making the life span longer. Adaptability is therefor a key word. On this page an illustration of how a double glazed IGU can become triple glazed. To 'upgrade' the panel from 2 to 3 panes, a new butyl profile and hollow section must be made but it always has to be structurally calculated as the IGU now becomes more heavy. When needed, the spacer bar can be extended at the arm so that the butyl stays in place.

A.8 Gas barrier for fiberglass spacer bars



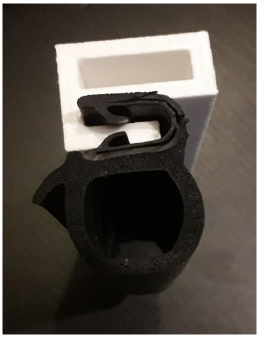
		Allows vapour at left side	Allows vapour on sides	Contact holes dessicant-cavity in the way	Contact holes dessicant-cavity in the way		Allows vapour on sides	
Coating	Fragile for rubber	-	-	-	-	v	-	v
Foils	Fragile for rubber	-	-	-	-	Sight distraction	-	Sight distraction
Al profile	Transferring cold	-	-	-	-	Transferring cold	-	Transferring cold

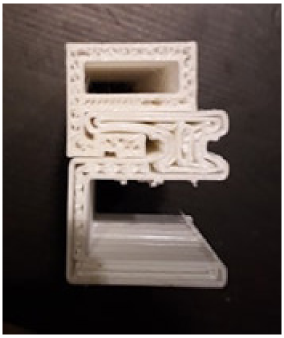
The spacer for the thesis is set to be made out of glassfiber and resin. However, the reason for conventional bars to be fabricated out of metal is the high density and thus low permeability to gas. The way how this is solved for already in use spacer bars that are made out of non-metal is with metallic foils.

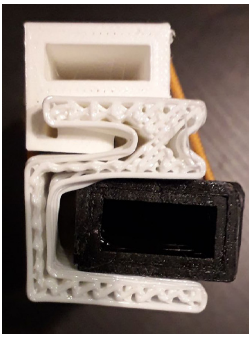
The table and the corresponding figure above is setting out three ways of making a spacer gas tight. Besides an Aluminium profile or patch, also foils or maybe even a coating by laquering or paint can be an option(this last method is however not proven). The red lines in the figures show the place of the metal layer is located. As the form of the designed spacer bar is complex, not every option is possible for all three variants in relation to accessibility. Furthermore, damage can occur to the bottom sides when sliding the butyl profile in and out or because of the desiccant. Sight distraction is imaginable for foils on top of the spacer where it is in sight. According to this table the two most favourable options are with coatings on the inside plus on the top. The whole spacer bar can be immersed ,dipped inside metal paint or coated but this is just a concept and must be further dived into.

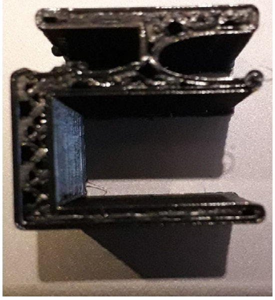
A.9 Photos

Several pictures of some of the printed 3D rubber prints. Different filla-ments, temperatures, infill, forms are used.









Windows are important elements in a building. They protect the interior from the exterior environment regarding weather conditions, noise, security and so on. While they also, in contrast to walls and floors, connect the two, creating links and providing rooms with daylight, fresh air and views in and out of the building.

The most governing element of the window is the insulated glazing unit (IGU). There are many developments concerning coatings to add functions to the glass ,such as solar control or self-cleaning windows but they contain critical materials such as cobalt, copper and titaninum. Added elements such as coatings, foils for laminated glass and the sealant prohibit the IGU from being recyclable, as the prevailing glass industry requires high quality and clean ingredients only. This makes the IGU a finite, single life product resulting in almost 125.000 tonnes of post-consumer glass waste each year in the Netherlands.
The IGU works optimally as an insulating element as long as there is dry (argon) gas inside the glazing panes. However, the life span of current IGUs is just around 15-20 years and is dependent on the butyl seal which is just 1% of the costs and 0.1% of the weight. During its life span the seal starts failing by allowing water molecules inside the cavity. The panel as a result starts building up water vapor and the coating inside will start to corrode, the glass shows fogging and the thermal performance drops down due to outgassing of the panel. In the current design of the IGU no refurbishment is possible, meaning that the glass panes and the spacer will not be re-used, but instead end up as landfill while these materials exceed the life span of the sealant by a large margin (Veer,2016).

This thesis therefore focusses on the possibility of remanufacturing the IGU. The re-designed edge seal system for the IGU makes it easy to remanufacture the IGU on-site. The design utilises a detachable butyl seal that functions as a dry gas and vapor barrier and a hollows section that assures the tightness of the seal. This idea shows the possibility to replace the weakest part of the whole glazing panel every ten years so that the glazing panes which have high stored embodied energy and the spacer bar, which is currently approaching the theoretical value in terms of energy efficiency, both can have a life span of more than 100 years.

The interlocking design of the spacer bar and butyl sealant is a result of a form finding process. A fiberglass hollow section can be slid into the butyl profile to assure the load is transfered to the window system. Furthermore, a check valve type is chosen to fill the cavity again with Argon gas with every remanufacturing cycle.

Keywords: Remanufacture , Window , Service life, Insulated glazing unit, Sealant, Edge seal, Resealable, on-site remanufacturing, interlocking