D1.2 – Concept Design of Eensulate module

WP1

Lead Partner: D'Appolonia

Partner Contributors: UNStudio, Focchi, SAES, All

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Executive Summary

The document collects the main results from the first six months of the Eensulate project and specifically deals with the concept design activities performed within this timeframe.

First, starting from a review of the regulatory and technical requirements and given the outcome of a preliminary market drivers assessment, the design priorities and some key performance indicators have been defined. Then, two different models have been built to be representative of the thermal and mechanical behaviour of the Eensulate module. The thermal model is made as a combination of weighted contribution from the different parts of the module where each contribution is based on WINDOW 7.4 and THERM 7.4 specific analyses. The mechanical model instead is mainly built upon closed form formulations from plates stress theory. The two models are finally used to cyclically explore the design domain in order to converge on the feasible value ranges of the considered design parameters and to consequently inform the development process of the Eensulate glass and Eensulate foam.

A parallel aspect that is investigated within this document concerns the perception of the Eensulate module as assembled in a façade system and its integration with the building. To this aim some long term goals are stated, for instance, in terms of aesthetic and multimedia expectations. Design guidelines are finally discussed addressing both different system and component categories in several application scenarios.

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Abbreviations and Acronyms

[COG] – Center of Glass

[EC] - European Commission

[EOG] – Edge of Glass

[EPDM] - Ethylene Propylene Diene Monomer

[EU] - European Union

[FEA] - Finite Element Analysis

[FEM] - Finite Element Model

[FFL] – Finished Floor Level

[FVM] – Finite Volume Method

[NFRC] – National Fenestration Rating Council

[PVC] - - Polyvinylchloride

[TRL] – Technology Readiness Level

[VIG] - Vacuum Insulated Glass

[WP] – Work Package

1 Introduction

The European Commission has identified building sector as one of the key sectors to achieve 2020 strategy of the EU. The goal of the 2020 strategy is to create conditions for smart, sustainable and inclusive growth. In regards to the building sector, the emphasis has been placed on two key principles – the principle of 'nearly zero-energy building' and the principle of 'cost optimality'. Moreover, European legislators decided that by 31 December 2020, member states must ensure that all new buildings are nearly zero-energy buildings and by 31 December 2018, all new buildings occupied and owned by public authorities must be nearly zero-energy buildings. The developers, bearing in mind these regulations, realized that the building industry in general, and insulation sector in particular, need a game changer.

Curtain walls, i.e. facade modules, which span from floor to ceiling consisting mainly of transparent glass-walled component, have been an integral part of commercial and public building for over a century. Today curtain walls are associated with modern architecture and their popularity is exponentially increasing. However, curtain walls are often criticized for their limited insulation characteristics. For this reason, the developers of Eensulate technology came up with a product, which will reduce unwanted energy losses.

Furthermore, existing buildings, including historical ones, are responsible for up to 60% of energy losses through the envelope. Eensulate modules are suitable for both new and existing buildings and therefore have the capacity to solve the major energy losses through retrofitting of old buildings.

Eensulate will develop up to TRL 7 an affordable (28% reduction of total refurbishment costs) and lightweight (35% weight reduction versus the best performing modules in the market) solution for envelope insulation to bring existing curtain wall buildings to "nearly zero energy" standards, reducing energy bills by at least 20% while complying with the structural limits of the original building structure and national building codes.

Eensulate will develop two key commercial insulating products:

• A **highly insulating mono-component and environmentally friendly spray foam**, **Eensulate foam**, for the cost effective automated manufacturing and insulation of the opaque components of curtain walls as well as for the significant reduction of thermal bridges during installation leading to doubling of the thermal resistance of the whole façade;

• A **lightweight and thin double pane vacuum glass, Eensulate glass**, for the high insulation of the transparent component of curtain walls, manufactured through an innovative low temperature process using polymeric flexible adhesives and distributed getter technology, thus allowing to use both annealed and tempered glass (including laminated safety glass) as well as low emissivity coatings (1% emissivity), not possible with state of the art and emerging vacuum glazing technology. Additionally, a breakthrough multifunctional **thermotunable coating** will allow for dynamic solar gain control as well as anti-fogging and self-cleaning properties.

Based on the above intentions, each of the project participants have a different role to play in the delivery of Eensulate products into the market. This is summarised in picture below.

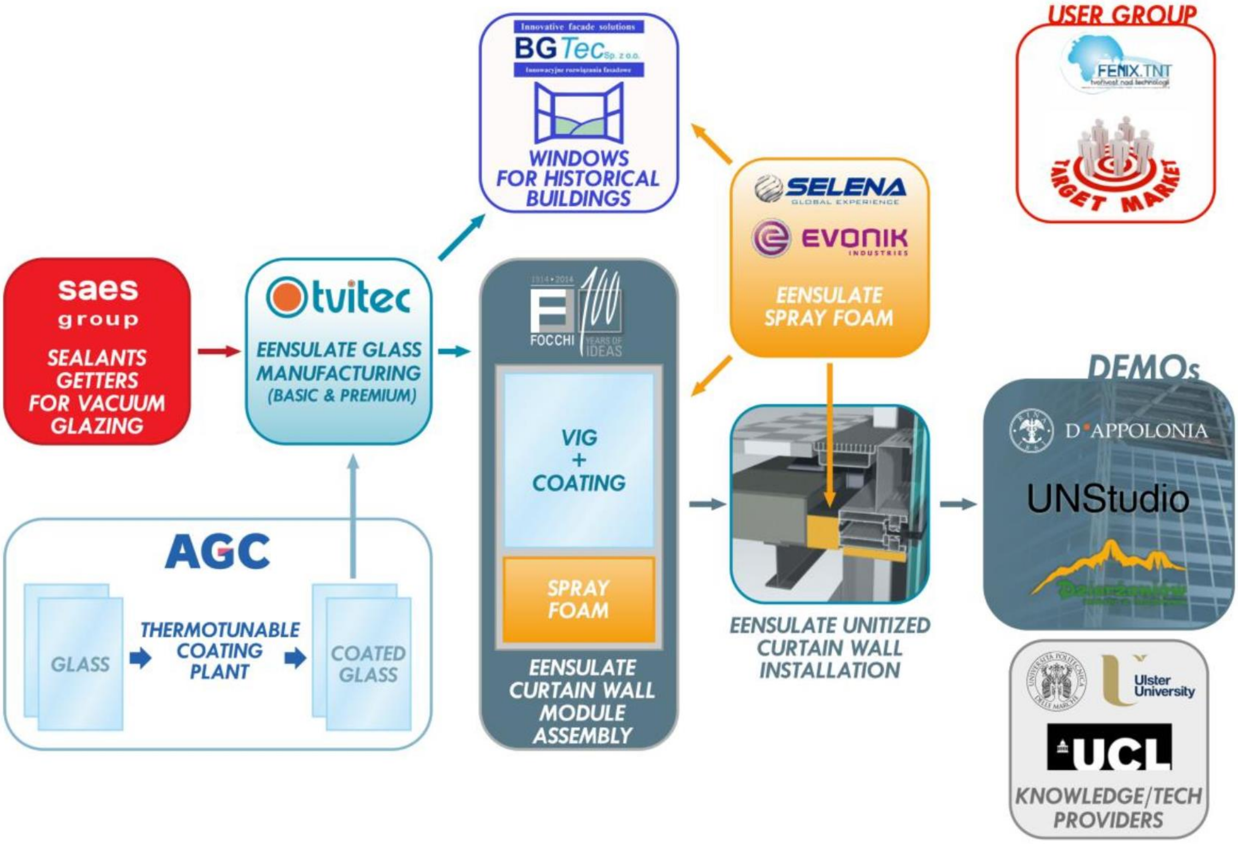


Figure 1-1 – Eensulate value chain.

With this context in mind, this report, “Concept Design of Eensulate module”, is aiming at defining the design options to be further analysed in the next stages of the project development. Specifically, the concept design starts from the findings of the first six months of activities to configure the viable scenarios in order to reach the set target performance and quality of the final product, where a scenario is the combination of values of all the parameters involved in the design of the Eensulate module.

The report is divided into two main sections: section A – performance driven concept design – which is exploring the possible design solutions at the scale of the façade module, focusing on technical and performance aspects, and section B – façade perception and integration with the building – which is devoted to the analysis of the possible design solution at a larger scale, taking into consideration the whole envelope result in terms of aesthetical perception and interface with the building.

PART A: PERFORMANCE DRIVEN CONCEPT DESIGN

2 DESIGN CRITERIA

The Design Criteria are the results of a deep brainstorming that involved the whole Eensulate Consortium starting from the WP1 kick-off meeting in Genoa in October 2016 and have been stated considering the performance goals, the regulatory and market requirements (as previously identified) and the production restraints.

Indeed, the design of the Eensulate module is a complex topic where many aspects are concurring to shape the final solution, such as for instance:

- Performance objectives;
- Safety and quality requirements from standards and regulations;
- Market drivers;
- Production capabilities and economies;

More insight in each of the above aspects is given in the following paragraphs.

2.1 Input from regulatory requirements and market drivers review

According to the analysis of the market and regulatory scenario at European level, as performed in the first three months of the project (see Deliverable 1.1), In Table 2-1 the identified references (main standards and regulations) for each of the performance aspects to be considered for the Eensulate product are reported.

Table 2-1 - Eensulate reference standards and regulations and project objectives.

Topic	Performance aspect	Reference standards	Eensulate project target	Market reference	Comment
Energy	Thermal performance	EN 12631:2012 EN 13947 EN ISO 12567-1; EN ISO 10077 1-2	U-value tot. = 0.4 W/m^2K	U-value tot. = 1.5 W/m2K **	Will always require CE marking
	Radiation properties	EN 410	Solar Factor G = 32%*	Solar Factor G = 67%**	Will always require CE marking
Comfort	Acoustic performance	EN ISO 10140-2 EN ISO 140-3 EN ISO 717-1 UNI EN ISO 10848	Rw = up to 52 db	Rw = 30 ÷ 40 db	Flanking sound transmission will always require CE marking in Scotland and will require CE marking in England and Wales for dwellings
	Surface condensation	EN ISO 13788	-	-	-
	Air tightness	EN 12153 EN 12152	-	-	Not explicitly required in Building Regulations
	Water tightness	EN 12155 EN 12154	-	-	Not explicitly required in Building Regulations but may be CE marked
	Light transmittance	ISO 9050	0.60 ÷ 0.90	0.40 ÷ 80	-
Safety	Wind load resistance	EN 12179 EN 13116	-	-	Will always require CE marking for wind load safety
	Impact resistance	EN 12600 EN 14019	-	-	Not explicitly required in Building Regulations but may be CE marked
	Fire resistance	EN 1364-3 EN 13501-2	-	-	Only requires CE marking if performance required
	Fire reaction	EN 13501-1	-	-	Will always require CE marking
	Burglar Resistance	EN 1627 EN 1630	-	-	-
Products	Curtain wall	EN13830	-	-	-
	Glass	EN 14179-1, EN 14179-2 EN ISO 12543-1 to 6 EN 1279	-	-	-
	Sealant	EN 1279			
	Screws and rivets	UNI 6947, UNI 6955, UNI 9200A	-	-	-

* Eensulate basic.

** Pilkington Spacia.

The preliminary assessment of the main market drivers for the project has instead provided the results summarized in Table 2-2.

Table 2-2 - Eensulate responses to market drivers.

Market Driver	Assessment	Eensulate
Energy efficiency (A steady growth in demand for energy efficient products)	→ Eensulate presents close to 50% improvements in U-value compared to the currently best performing curtain wall → Energy savings above 200 W/m^2 → Doubling R-value compared to the currently best performing curtain wall	✓
Technology Innovation (developing innovative product)	→ Eensulate is referred as a market game-changer → Superior properties while keeping costs low → Innovation might be noted through combination of vacuum glass and insulation spray foam, which together improves U value, R-value and reduces costs	✓
Varying sectors applicability (public, commercial, residential sectors)	→ Eensulate is suitable for public, commercial, and residential buildings	✓
Unitized curtain wall (becoming the preferred type of curtain wall)	→ Eensulate answers the high demand for unitized curtain walls	✓
Environmentally friendly product (willingness to invest in such products)	→ Considering the Global Warming Potential reduction possibilities of the entire life cycle, Eensulate reaches a value of 16.0kg CO_2-eqv./m^2a, which is 40% better then best performing facades → Eensulate expects the prevention of heat escaping, energy wasting, and CO_2 emissions. → Recyclability of aluminium → Recyclability of flat glass	✓
EU financial contribution (through Structural and Operation Funds, the EU can assist with financing of the product)	→ Considering the state of art of EU structural and operational funds, Eensulate is expected to fulfil the criteria as a suitable component of nearly zero energy buildings. Nearly zero energy buildings, currently, can be financed through the funds	Expected
Legislation and regulation (EU legislation pushes for green building, among others through building of nearly zero energy buildings)	→ Considering Eensulate a component of nearly zero energy buildings, EU requires all new buildings to be nearly zero energy buildings by December 2020.	✓
Cost Effectiveness (Price is the top priority of the customer for choosing a product)	→ In average, 100 euro/m^2 of curtain wall saved → The use of spray foam for the manufacturing of the spandrel component will reduce its overall manufacturing cost by 25% → Easy fit of the Eensulate components with the existing building structure reduce the need for costly adaptation of interfaces such as roof offsets, which can exceed 75euro/m^2 → 25% of maintenance costs reduction	✓

Market Driver	Assessment	Eensulate
Improved Quality (Quality is the second most important priority of the customer for choosing a product)	→ Lifespan of at least 20 years → The Eensulate products deal with disaster resistance and cracking prevention	✓
Green Project (Architects have noted the customers' demand for green projects)	→ Examining the energy efficiency of the product and a contribution to nearly zero energy buildings, Eensulate can be seen as a green product suitable for green projects	✓
Fit for Retrofitting (Old buildings tent to be energy ineffective, and are responsible for major energy losses, authorities push for reconstructions to fix this issue)	→ Eensulate is suitable for retrofitting of building with already existing structures for curtain walls. Other buildings must be further prepared to hang a curtain wall on them.	✓
Reduced Weight (construction companies desire lighter materials)	→ Average curtain wall currently weights approximately 70kg/m^2, Eensulate aims to reach weight of 45kg/m^2. → Due to its reduced weight, installation becomes easier, cheaper, and faster	✓
Reduced Depth (clients gain additional usable area)	→ Compared to state of the art IGU based glass curtain walls the depth of the Eensulate system will area back to the building.	✓
Size and colour variations (designers prefer comfortable variety of sizes and colours, which allows them free hand in creation of new designs)	→ Developers promise that Eensulate will come in different shapes; colour demands are yet to be specified.	n/a
Worldwide demand for curtain walls (possible demand for Eensulate license)	→ China and UAE demand for curtain walls is rapidly growing → Selling licenses to produce Eensulate curtain wall	✓

2.2 Production restraints

Besides the regulatory and market aspects, Eensulate design needs to consider also those restraints coming from the production processes and facilities. Some of these restraints are dependant of the specific solution considered (e.g. glass type), some other restraints are related to the current production cycle, and some others again are due to limitations in the achievable precision or, more generically speaking, production tolerances.

To better understand the impact of all the different aspects, at first the foreseen production cycle is illustrated and commented in Table 2-3, considering both the case of an annealed glass and a fully tempered glass type.

Table 2-3 – PRODUCTION FLOW – differences between annealing and tempering process.

Steps are marked with:		x needed		(x) optional	- not needed	
	#	STEP	T [°C]	Duration	ANNEALED	TEMPERED
@AGC	A)	Float			x	x
	B)	Coating* – if required			(x)	(x)
@TIVITEC	1)	Cut of Jumbo Glass Pane			x	x
	2)	Removal of low-e coating *(required if coating is present)*			(x)	(x)
	3)	Drill/edgework[1]			(x)	x
	4)	Tempering	630÷700	10÷15 minutes	-	x
	5)	Heat Soak Test (HST)	290±20	2÷4 hours	-	x
	6)	Pillar positioning			x	x
	7)	Application of sealant and getter	<290 (<200)		x	x
	8)	Pumping out of the air		Hours (the longer the better)[2]	x	x
	9)	Laminating (S.o.A.) – if required			(x)	(x)

*90% of today available coatings in the market can be tempered (max around 10 min @ 600°C).

Then, depending on the glass type, a first set of restraints and associated parameters are summarized in the table below:

[1] Drilling of annealed glass is possible even later if required.

[2] Pump time depends on several factors but in general the longer, the better (hours)

Table 2-4 – Production aspects for annealed and toughened glass types.

Production aspect	Annealed glass	Toughened glass
General glass flatness	Flat	At the centre of the glass pane it is expected to have a deviation from flatness of about 0.06 mm on average (worst condition of 0.12÷0.13 mm)
Edge DIP	Flat	For tempered glass, in the last 200 mm of the pane, due to the rulers configuration, an edge DIP of 0.2÷0.3 mm has to be expected
Removal of low-e coating	The internal glass pane is supposed to be supplied complete of the low-e coating for the subsequent VIG formation. Low-e coating must then be removed from the edges where getter and sealant are to be placed. Currently this happens as a mechanical abrasion process which, however, reduces the smoothness of the glass surface and therefore might affect the adhesion and air-permeability among materials.	
Drilling	Not possible to drill an annealed glass since it may trigger breakages (it might be possible with ultrasonic drilling tools but it takes hours)	possible
Glass dimensions	No restrictions.	Minimum dimension is 400 mm.
Glass thickness	No restrictions.	Minimum thickness for 1 pane is 4 mm
Coating	Coating oven is 10m wide and 200 m long therefore it is not easy to maintain control all over the process.	

The tempering process lasts << 1 hour (10-15 minutes is a standard time for tempering and generally no problems appear during this process); if temperature is reduced, the time can be increased; however, to reach the performances required for a tempered glass, the temperature cannot be less than 650 °C.

The process of removing the coating from the edges (where the sealant and the getter are planned to be placed) before to temper will be necessary to ensure the best adhesion of sealant and getter to the pure glass, mainly because of the uncertainties which affect the reaction of the coatings material with heat (coating resist until 650 °C).

2.3 Design priorities and key performance indicators

Main project performance indicators (KPIs) are summarized in the table below as well as design targets.

Table 2-5 – Key Performance Indicators.

KPI	U-value tot.	Solar Factor G	Light transmittance	Acoustic performance R_w	Weight
Eensulate target	0.4 W/m^{2}K	32% w/o solar control*	0.60 ÷ 0.90*	up to 52 db*	45 kg/m^2

* Not addressed at this stage of design.

Moreover, for the vision glass a double glass pane design with silver magnetosputtered low-e coatings will be investigated with a theoretical target U value of 0.3 W/m^{2}K, enabled by the intended material and process innovations. Making use of the OCN spray foam at different levels (i.e. spandrel, framing system, sub-structure), the aim is also to reduce up to 50% the thermal energy flows due to thermal bridges. Although the frame represent a critical element in fenestration components when heat losses are concerned, its development is instead out of the scope of design at the moment. Since there are several material and technology innovations which are emerging like extruded polymers as well as improvement on thermally broken aluminium frames, the intention here is to use components (frame, structural silicones, gaskets, spacers, etc.) already existing on the market.

2.4 Eensulate Glass

2.4.1 Annealed vs Tempered glass

The first element that influence the achievable performance of the Eensulate product is the choice of the glass type. Basically two different types of glass are considered: annealed and tempered (thermally toughened). A basic comparison of these two types is presented in the table below.

Table 2-6 – Properties of annealed and tempered glass types.

PROPERTIES OF GLASS TYPE	
ANNEALED	**TEMPERED**
Flat	Has divergences from flatness so pillars may move
	More strength for the same thickness
Cheaper	Naturally satisfy certain safety requirements (it breaks in small pieces)
Might be good for samples to test the distributed getter approach[3]	Suggested solution for bigger glasses (façades)

A third glass type that presents a behaviour in between the annealed and tempered glass is called heat-strengthened. Heat Strengthened glass panes allow higher mechanical stress but cannot be considered as safety panes, if not laminated. A picture of the fracture behaviour of the three mentioned glass types is reported below.

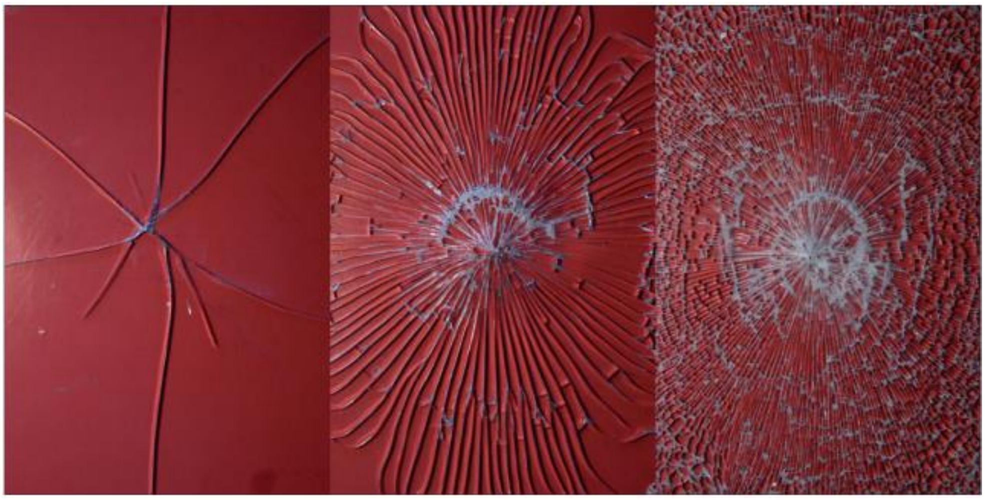


Figure 2-1 – Annealed glass failure (left), heat-strengthened glass failure (centre), and fully tempered glass failure (right).

Although some limitations are evident, most of VIGs currently present in the market are made of heat strengthened glass panes.

[3] In theory also to test the sealing, even if the different glass process might affect sealant adhesion

2.4.2 Aspects related to the application field

Depending on the application field, some more constraints to design may arise. Considering the two main envisaged applications for the Eensulate products, i.e. unitized curtain walls and windows in historical buildings, the following table make explicit some of the additional aspects that have to be kept in mind during the design process.

Table 2-7 – Requirements of Eensulate glass depending on application.

REQUIREMENTS OF Eensulate GLASS DEPENDING ON APPLICATION	
FAÇADE	WINDOW
Naked edge may delaminate therefore tempering of the external pane is suggested (probably necessary) To be defined with local laws.	For windows generally safety requirements are not so stringent. Usually windows are made of annealed glass according to the best and cheaper production process. To define the feasibility and the warranty of an annealed pane with the hole for vacuum pump during production.
If below 0.5 ÷1m from floor level the glass must be tempered or laminated or both for safety reasons	
Framing as slim as possible	Thicker framing solutions are acceptable

2.4.3 Sealant curing process

All the considered sealing processes are happening at temperature <200°C.

If tempered solution is selected and therefore the HST is mandatory, in theory the max temperature for the sealing process might be raised to < 290 °C (as long as it could happen with a similar time-frame/rate of change).

Table 2-8 – Considered sealing processes

	Curable formulation (room temperature dispensed)		Extrudable formulation
	Thermal curing	UV curing	Hot melt
Description	Needed locally (edges) but globally is also ok (in theory it can be used e the same oven as for the tempering/ pumping process[4])	UV lamp that moves along the edges is not suitable for large samples, simultaneous exposure of all the edge is required (linear UV lamps)	Solid material melted at max 250 °C depending on the organic matrix
Max T [°C]	200-250°C	Ambient temperature	250 ° C
Duration	Dynamic process (oven) time: 30 – 120 min	Very fast (minutes)	30-60 min for the lamination process
Drawbacks	Thermal stability during pumping step to be evaluated.	It depends on glass transmittance which is often function of the glass thickness (e.g. 8mm glass pane -> 50% transmittance)	Thermal treatment for lamination is required (it could be the same treatment of the pumping process). Tmax to be evaluated.

During the curing process it is not necessary to have a pump for the vacuum

The influence of glass deformations in the curing methods needs to be analysed very accurately.

[4] To be checked

2.5 Eensulate foam

Foam is only in contact with the spandrel panel, which is constituted by a normal glass (s(not a VIG). The volume that is expected to be filled, according to the EENSULATE module dimensions, is 0.15÷0.18 m^3 (i.e. a space of 1m x 1 m x 0.15÷0.18 m). The foam should have adhesion with the spandrel glass because it can be useful in case the glass breaks. Selena is currently working on some adjustments to the composition of the OCF (formulation must be liquid in order to fill the spandrel through a hole) and the fire resistance class shall be maintained in the required range.

In parallel with the development of the one component foam Selena is manufacturing an innovative bi component foam with features actually not available on the market, but fully compliant with fire requirements for materials and construction elements. The bi component foam has the same density of the OCF, but is characterized by lower lambda values and better fire resistance properties.

The idea would be to maintain the use of the OCF as a thermal sealant at the interface between curtain wall and substructures, to be implemented directly in construction sites thanks to pressurized spray cans, and to use the bi component foam at industrial scale, thus entailing a reduction of time and costs of the production processes thanks to the use of a dedicated industrial equipment to fill in the spandrel instead of multiple spray cans).

The key point is the identification of the standard to be used for the fire performance.

Acoustic performances of the foam have to be considered.

Lambda of foam is around 0.032 for the spandrel.

2.6 Complementary components

Besides the two key enabling technologies – i.e. the VIG and the OCN foam – and the corresponding main components – i.e. vision and spandrel of the unitized curtain wall module – other elements concur to the final performance of the Eensulate system, such as framing system, anchoring system, gaskets, etc.

These elements are not going to be specifically developed in the project but it is important to be aware of the existing solutions that could fit with the project goal.

For the time being, according to the purpose of the current phase of design, only the framing system and the gaskets have been considered and discussed hereafter.

2.6.1 Framing system

Concerning the curtain wall systems, to date it is possible to identify the following main kinds of products on the market:

- **Stick system**

  "Stick" curtain wall systems assume that a grid of vertical (mullions) and horizontal elements (transoms) has to be installed prior to assembling glazing units and spandrel panels. The joints between two adjacent panes of glass can therefore be sealed only by on-site application of wet sealant, working from the outer side of the façade. Which entails the following drawbacks:

    - Long installation times
    - High installation costs
    - Seal quality depends mostly on site conditions

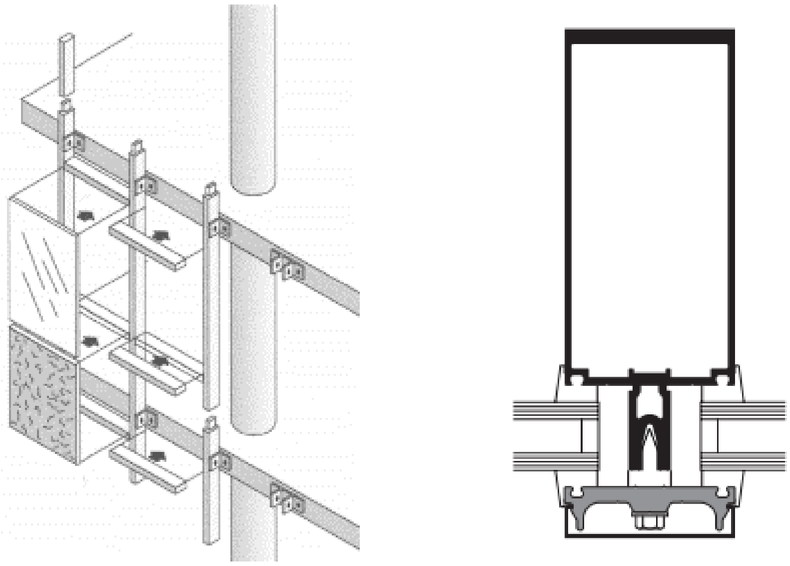


Figure 2-2 – Curtain wall – Stick system

In detail, it is possible to identify the following types of stick systems:

- <u>Grid and panel curtain wall</u> (semi-unitized system)
  Panels are prefabricated in factory where glass units are fastened to the frames by means of structural sealant. Then, the panels have to be brought to the site and fixed on the grid

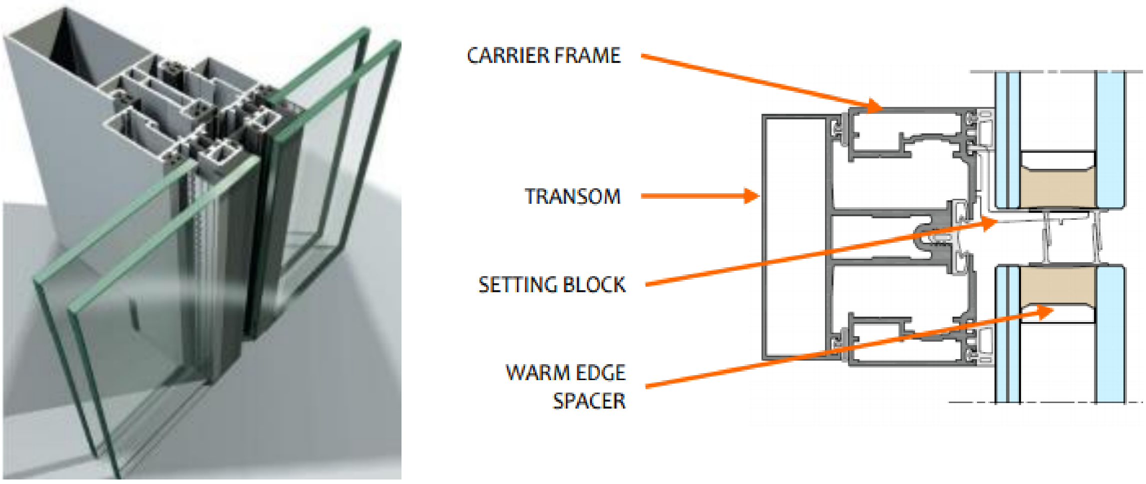


Figure 2-3 – Grid and panel curtain wall – representative vertical section

- <u>Capped system curtain walling</u>
  Glazing panes and opaque elements are to be fixed to the grid using aluminium profiles directly screwed to mullions and transoms.

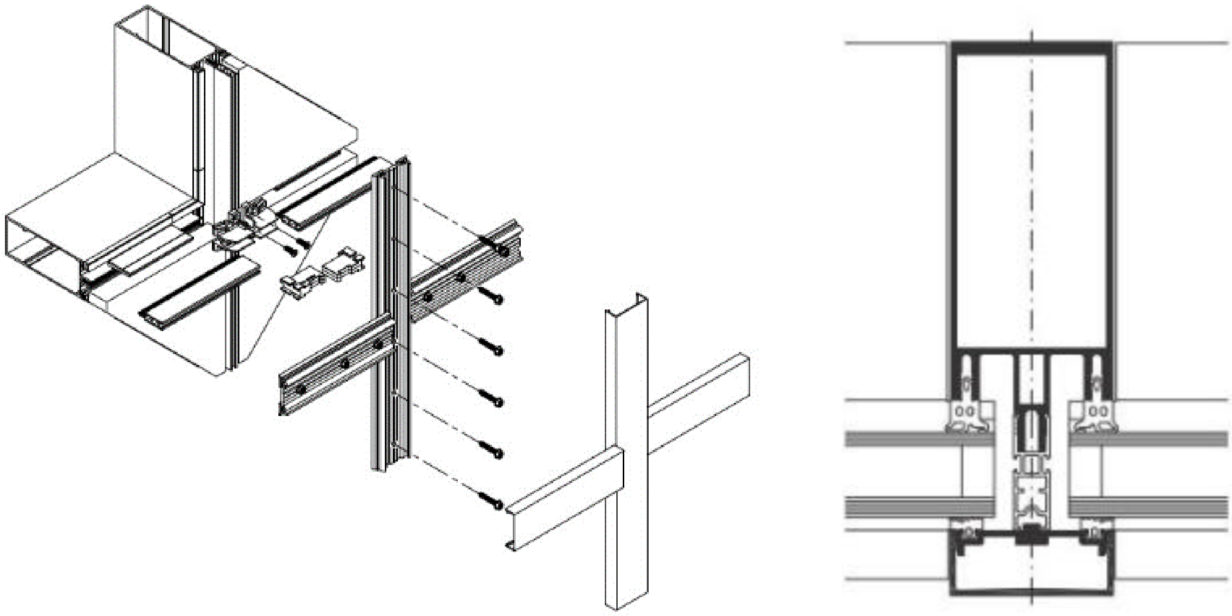


Figure 2-4 – Capped system curtain walling – representative horizontal section

- Stick toggle system
  The system is similar to that already seen above (capped system), but in this case the element which is to be screwed to transoms and mullions, the toggle, applies pressure through the gaskets on the inner glass pane, instead of on the outer one.
  This allows to avoid using any external profile so as to obtain the aesthetic appearance of a SSG façade

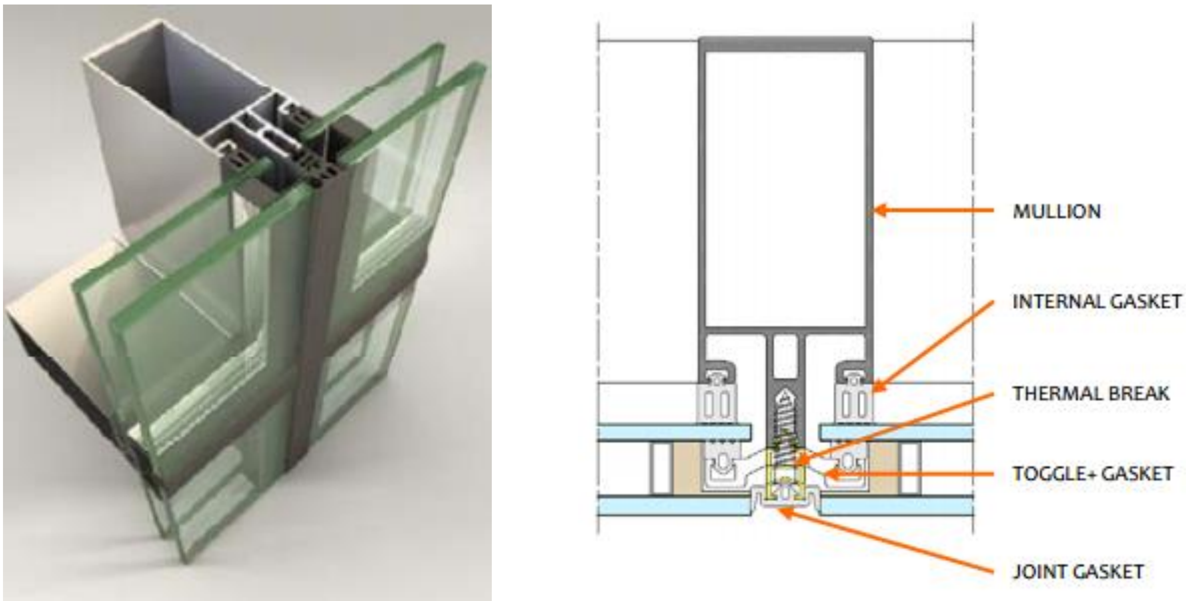


Figure 2-5 - Stick toggle system - representative horizontal section

- **Unitized system**

Unitized curtain walls are composed of structural units that are fully pre-fabricated in factory, and then transported and fitted to the buildings. Usually the units cover the clearance between two consecutive floors, hanging from brackets already fixed along the edge of the upper floor slab. In order to provide weather tightness, open grooves and overlapping gaskets are planned along the perimeter of the units so as to form drainage channels along the edge of such units. On-site application of wet sealants is thereby avoided.

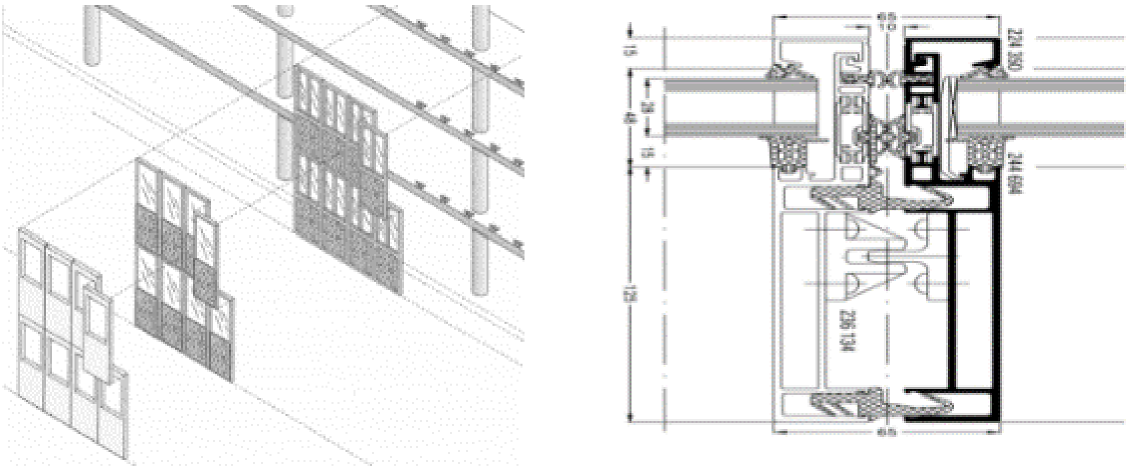


Figure 2-6 – Curtain wall – Unitized system

It is possible to distinguish between the following two types of unitized systems:

- Mechanically fastened system
  The glass system is mechanically captured in gaskets by means of an exterior frame that is thermally isolated from the internal one.

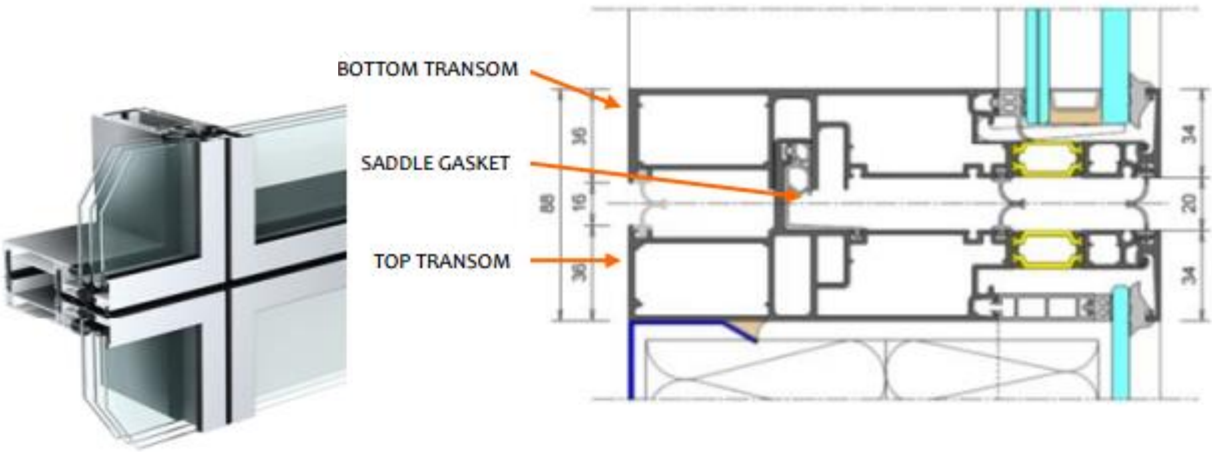


Figure 2-7 - Mechanically fastened system - representative vertical section

- Structural glazed with gasket weather-sealant
  The glass system is fixed to the frame using structural silicone and has dry gasket all around the perimeter of the unit

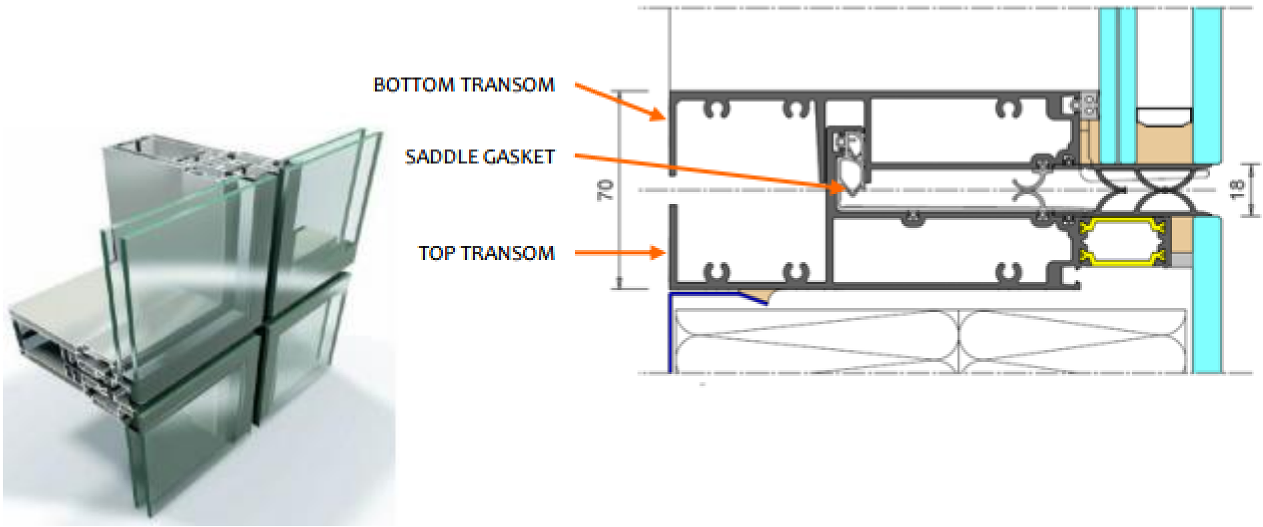


Figure 2-8 - Structurally glazed system - representative vertical section

2.6.2 Gaskets

Gaskets are necessary in order to avoid air leakage and water penetration, distribute and absorb loads and allow relative movements.

A wide range of material is available to fulfil the tasks that have to be performed by gaskets and are selected for their ability to work at extremes of temperature (Figure 2-9), retain their shape, resist weathering and resist tearing.

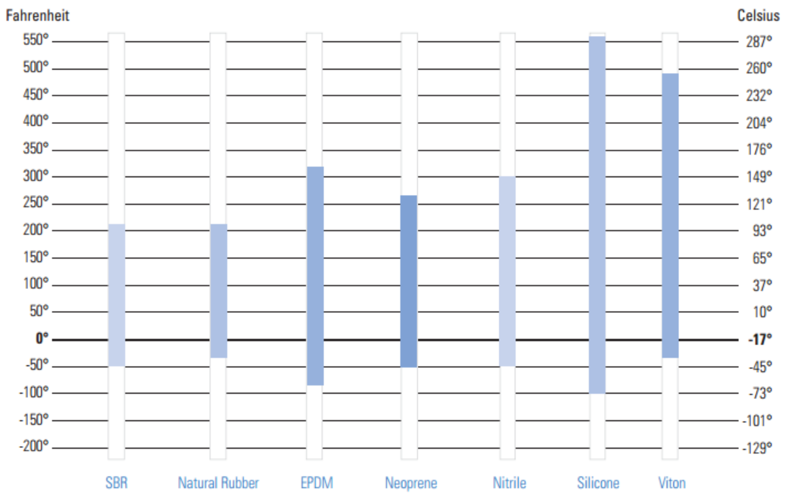


Figure 2-9 – Service temperature of elastomers

Another important parameter which of course influence the choice of the material is the cost. In this sense Figure 2-10 provides a comparison between the most commonly used materials.

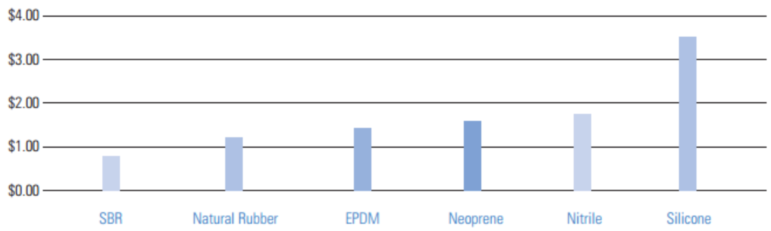


Figure 2-10 – Relative material cost comparison

This said, however, for the reasons set out below, EPDM gaskets are the most widely used sealing technique nowadays.

- Reliable sealing of media over a long period of time.
- Outstanding sealing properties in extreme weather conditions and excellent temperature stability (–40° to +150°C) in cold climate.
- If compared to gaskets made from other materials, EPDM gaskets are extremely resistant to wear, ageing, weather influences, ozone and UV-light.
- EPDM gaskets are color-stable and leave no stains on PVC window frames.

Regardless of their material, gaskets can be also categorized in several ways:

- **Type of seal**
  A weather-strip is a gasket which have to prevent water entering a joint and should be located on the exposed side of the joint
  A draught strip is meant to prevent the passage of air through the joint and is normally located at the back of the joint
- **Method of fixing**
  The following method are employed:
  - Push-in gaskets are designed to be fitted into a groove in the mounting surface, prior to the formation of the joint

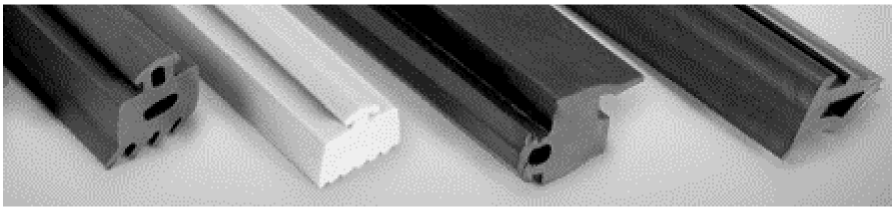


Figure 2-11 - Different types of push-in gaskets

  - Drive-in or wedge gaskets are designed to be forced into the gap between the mounting surface and contact surface, usually as the last stage in sealing the joint. A drive-in gasket can usually be removed by pulling it from the joint, although it may be manufactured with a rigid strip that makes this difficult

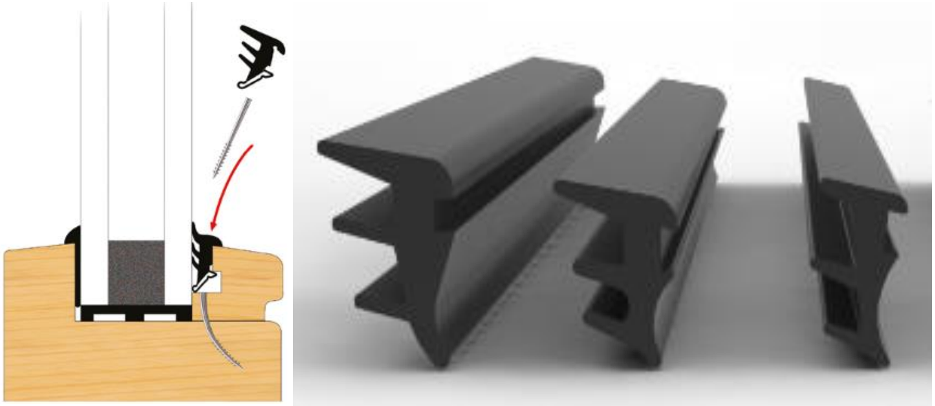


Figure 2-12 - Samples of wedge gaskets

- <u>Slide-in gaskets</u> are designed to slide into a groove on the mounting surface, but must be installed from the end of the groove. A slide-in gasket can usually only be removed by sliding it out from the end of the groove

- **Principle of operation**
  Most gaskets form a seal as a result of compression of the bulk material but some gaskets form a seal by deflection, either of a cantilevered arm or a hollow tube and others work by wiping contact with minimal deflection

3 MODELLING STRATEGY

Keeping in mind the goal, which is defining the concept of the Eensulate module, i.e. a 60% vision glass unitized curtain wall module, the modelling strategy adopted in this first stage of the project is briefly illustrated hereafter.

The first element of this strategy is the **willing to perform a wide investigation of the design domain** in order to end up with several viable solutions, i.e. solutions that satisfy the scientific and technological objectives of the project. As a consequence, this means that many scenarios have to be modelled and analysed. Moreover, to comply with the defined set of design criteria and to develop viable solutions, the design parameters should be tested through different kind of analyses.

Due to the heterogeneity of parameters that concur to the feasibility of the design solution, the second element is the **need to correlate different kind of analysis results as well as the relative parameters variations**.

Starting from these considerations, it was decided to perform only two types of simplified analyses which allow to investigate the parameters considered the most critical in the development process, namely the U-value of the whole Eensulate module (main project target – $U_{tot} \leq 0.4$ W/m^{2}K) and the stress/displacement level in the Eensulate glass (feasibility check).

These analyses are based on two basic models: a thermal model and a mechanical model. The thermal model is investigated first to get the range of variations of the design parameters that allow to reach the target U-value for the Eensulate module. The structural analyses are then run using the restricted set of value ranges for the same design parameters and will check for safe solutions in this pool.

The two models are then made analytically or by means of 2D finite elements (FE) when analytical approaches are not available. This approach implies to accept a certain level of approximation in the results but allows to keep low the calculation time such that the two models could be eventually linked in a unique optimization process. A flow chart of the modelling strategy is shown in Figure 3-1.

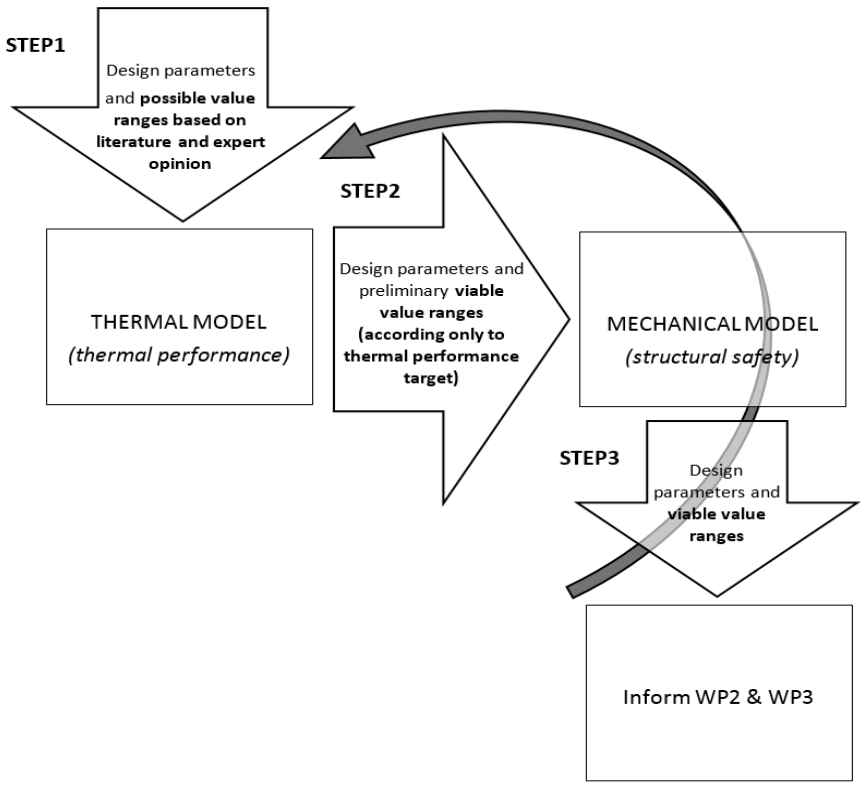


Figure 3-1 – Flow chart of the modelling strategy for the concept design stage.

3.1 Module geometry

The geometry of the Eensulate module to be considered in the analyses is of course related to the design process. Being at the beginning of the design process, parameters can vary quite consistently and some hypotheses are therefore needed in order to define an initial set-up.

To this aim, in the figure below are reported the target module dimensions.

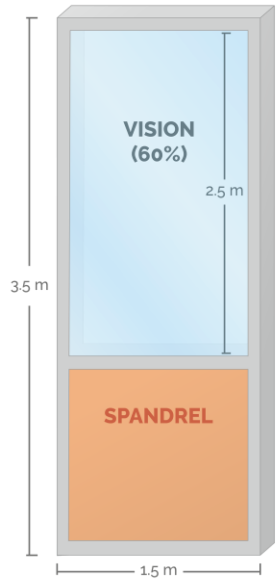


Figure 3-2 – Eensulate curtain wall module – dimensions.

Then, according to the considerations expressed in Chapter 2 of this document, a hypothesis for the dimensions/dimension ranges to be initially considered for the Eensulate glass section is made in Figure 3-3.

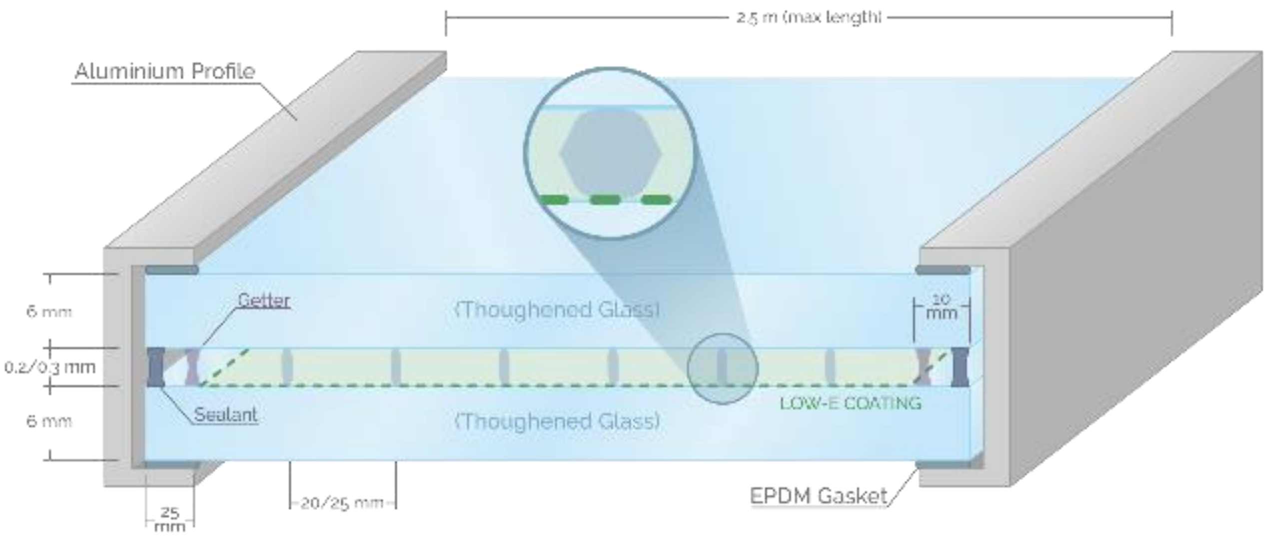


Figure 3-3 – Eensulate glass section – dimensions.

4 PRELIMINARY THERMAL MODEL

Although the presence of point thermal bridges would suggest the use of a three-dimensional finite volume method, capable of evaluating in detail the heat-flux distribution through pillars, vacuum gap and the plates of glass, it is demonstrated that the thermal performance of vacuum glazing predicted by the 2-D models is in good agreement with the 3D-FEM approximations [2]

Specifically, studies by R. Hart and C. Curcija [3] show that:

- *In the center-of-the-glass (COG), a simple analytical evaluation match 3D FEM approximations within 2.3% of total thermal transmittance.*
- *Complexities of EOG heat flow does not allow for a simple analytical model but the 2D FEM models, where the pillar and vacuum space are replaced with an effective solid, produces similar total thermal transmittance approximations, within 1.3% of 3D FVM.*
- *Concerns regarding EOG length and localized pillar conductance are shown to have little impact on total performance and therefore can be neglected in 2D FEM*

Therefore, according to the modelling strategy at this stage of design, it has been chosen to investigate the thermal behavior of the EENSULATE curtain wall modules using 2D Finite Element Modelling

4.1 Workflow

In order to evaluate the thermal transmittance of curtain wall structures, BS EN 12631 (2012) and ANSI/NFRC 100 (2014) are the reference standards in Europe and America. They both describe overall system U-value calculation methods based on area weighting the U-values of different components. We have consequently chosen to follow the same approach.

1. U value - Center of the Glass U_{COG}
   The U-value calculation, carried out in agreement with ANSI/NFRC 100 (2014), has been predicted using WINDOW 7.4 and THERM 7.4, the state-of-the-art computer software developed at Lawrence Berkeley National Laboratory. In particular WINDOW 7.4.6 has been used to define the VIG properties (vacuum pressure and thickness, pillars radius and spacing) and calculate the U-values at the center-of-glazing.

2. Choice of the frame system (unitized cells).
   The frame has only been designed to define a realistic scenario and investigate the behavior of edges of glass and spandrel, though neither the study nor the optimization of the frame have been our aim at this stage of the research.
   Standard method of mechanically capturing the glass system in EPDM gaskets where the exterior mechanical restraint is thermally isolated from the interior frame has been chosen.

3. U value – Edge of the glass (U_{EOG}), Frame (U_F) and Spandrel (U_S)
   Then, after having designed the frame of the unitized curtain wall, the glazing system was imported in THERM 7.4.3. The following elements have been analyzed:
   - The mullion (Figure 4-2 - Joint A)
   - The transom (Figure 4-2 – Joint B)

   At this stage, for simplicity, Joint B is also considered representative of the transom above the glazing. On the other hand, regarding the spandrel, it has been decided to overlook the effects of the mullion so as to focus on the link between the glass system and the spandrel.

4. U value – Unitized cell (U_t)
   Once obtained the partial U-value for each of the main cross-section of the proposed system, the overall U-value has to be calculated by area weighing these U-values following the equation shown below taken from THERM 6.3/WINDOW 6.3 National Fenestration Rating Council Simulation Manual (Lawrence Berkley National Laboratory, 2011) [4]

$$U_t = \frac{[\Sigma(U_f A_f) + \Sigma(U_d A_d) + \Sigma(U_e A_e) + \Sigma(U_{de} A_{de}) + \Sigma(U_c A_c)]}{A_{pf}} \quad (1)$$

Where:

U_t	= Total product U-factor, W/m²-ºK , (Btu/hr-ft²-ºF).
A_{pf}	= Projected fenestration product area, m² (ft²).
U_f	= Frame U-factor, W/m²-ºK , (Btu/hr-ft²-ºF).
A_f	= Frame area, m² (ft²).
U_d	= Divider U-factor, W/m²-ºK , (Btu/hr-ft²-ºF).
A_d	= Divider area, m² (ft²).
U_e	= Edge-of-glazing U-factor, W/m²-ºK , (Btu/hr-ft²-ºF).
A_e	= Edge-of-glazing area, m² (ft²).
U_{de}	= Edge-of-divider U-factor, W/m²-ºK , (Btu/hr-ft²-ºF).
A_{de}	= Edge-of-divider Area, m² (ft²).
U_c	= Center-of-glazing U-factor, W/m²-ºK , (Btu/hr-ft²-ºF).
A_c	= Center-of-glazing area in ft² (m²).

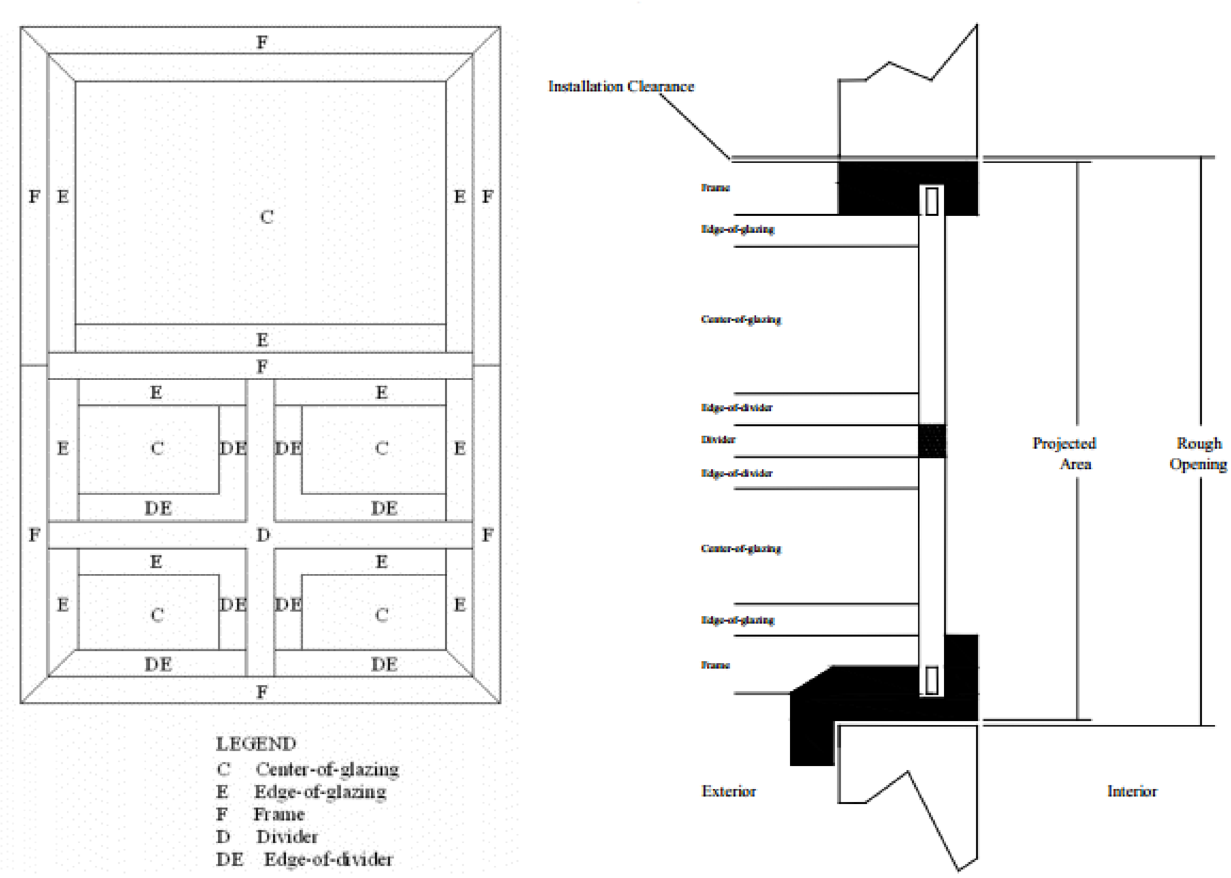


Figure 4-1 - ANSI/NFRC 100 (2014) – Fenestration product schematic. Vertical elevation and vertical section [5]

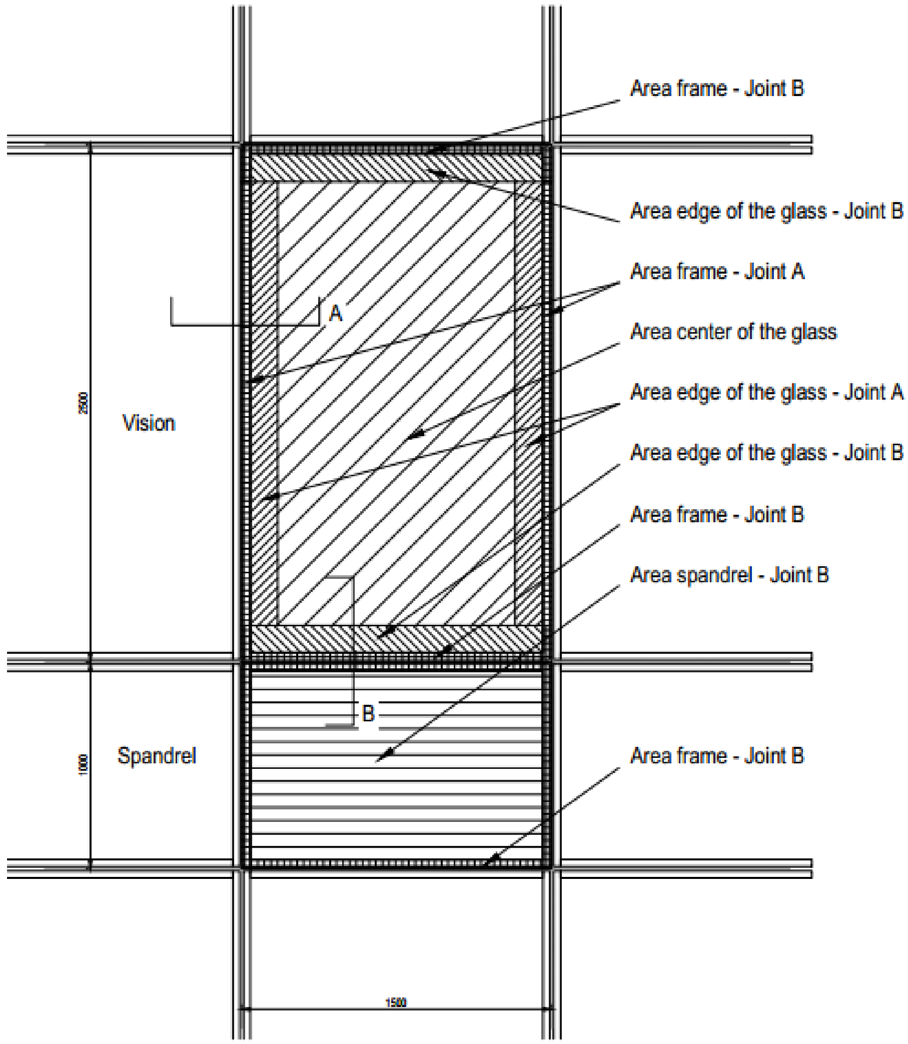


Figure 4-2 – Area of influence. Vertical elevation

With reference to the particular system being considered (Figure 4-2) the equation to be used to evaluate the overall U value becomes:

$$U_t = \frac{\sum(U_{F-A} \cdot A_{F-A}) + \sum(U_{EOG-A} \cdot A_{EOG-A}) + \sum(U_{F-B} \cdot A_{F-B}) + \sum(U_{EOG-B} \cdot A_{EOG-B}) + U_S \cdot A_S + U_{COG} \cdot A_{COG}}{A_t} \quad (2)$$

Where:

- U_{COG} U Center-of-the-glass as calculated in the paragraph 4.3
- U_{EOG-A} U Edge-of-the-glass of the mullion (Joint A) as calculated in the paragraph 4.4
- U_{F-A} U Frame of the mullion (Joint A) as calculated in the paragraph 4.4
- U_{EOG-B} U Edge-of-the-glass of the transom (Joint B) as calculated in the paragraph 4.54.4
- U_{F-B} U Frame of the transom (Joint B) as calculated in the paragraph 4.5
- U_S Average U value of the spandrel calculated in the paragraph 4.5

4.2 Input modelling for simulation

This paragraph is devoted to provide the input data that have been used during the analysis. Concerning the Vacuum Insulated Glazing, the geometric data are listed in the Table 4-1, whereas the meaningful thermal characteristics are shown in Table 4-2

Table 4-1 – Model dimension VIG

Parameter	Variable	Base (mm)	Min (mm)	Max (mm)
Pillar radius	R	0.2	0.2	0.4
Pillar spacing	S	25	20	50
Pillar to edge of glass	Not taken into account at this stage			
Edge seal thickness	W	10	5	35
Vacuum gap	H	0.2	0.2	0.3

Table 4-2 – Conductivity and Emissivity VIG

Parameter	Conductivity (W/m K)			Emissivity		
	Base	min	max	Base	min	max
Inner glass	1	-	-	(1) 0.84	-	-
				(2) 0.01	0.01	0.03
Outer glass	1	-	-	(1) 0.84	-	-
				(2) 0.84	-	-
Pillars	>16	16	290	-	-	-
Edge seal	1	0	100	-	-	-
Getter	Not taken into account at this stage					
Gaskets	0.25 (Ethylene Propylene Diene Monomer – EPDM)					

The conditions assumed are NFRC standardized environmental conditions for U-factor calculations for product ratings and are listed in Table 4-3

Table 4-3 – Environmental Conditions for NFRC Simulations for U-factor calculations

Variable	Assumed values
Outdoor temperature	-18 °C
Indoor temperature	21 ° C
Wind speed	5.5 m/s
Wind Direction	Windward
Direct Solar	0 W/mq
Sky Temperature	-18 °C
Sky Emissivity	1.00

Figure 4-3 and Figure 4-4 represent the main cross sections of the frame system chosen, whose component and their thermal characteristics are listed in Table 4-4

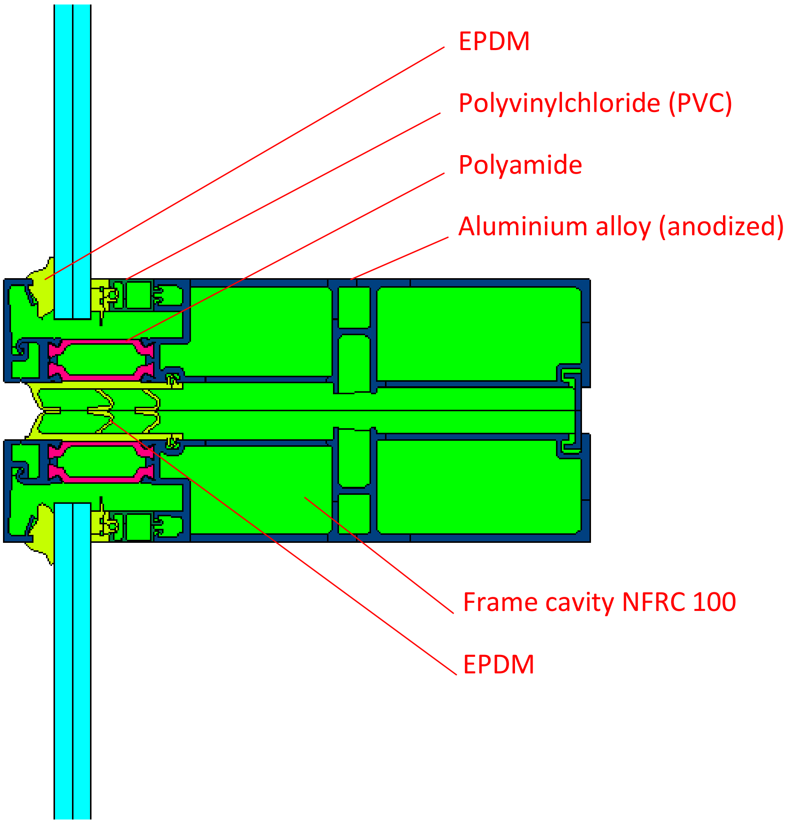


Figure 4-3 - Section of the mullion modelled in THERM. VIG is mechanically fixed with aluminium cap

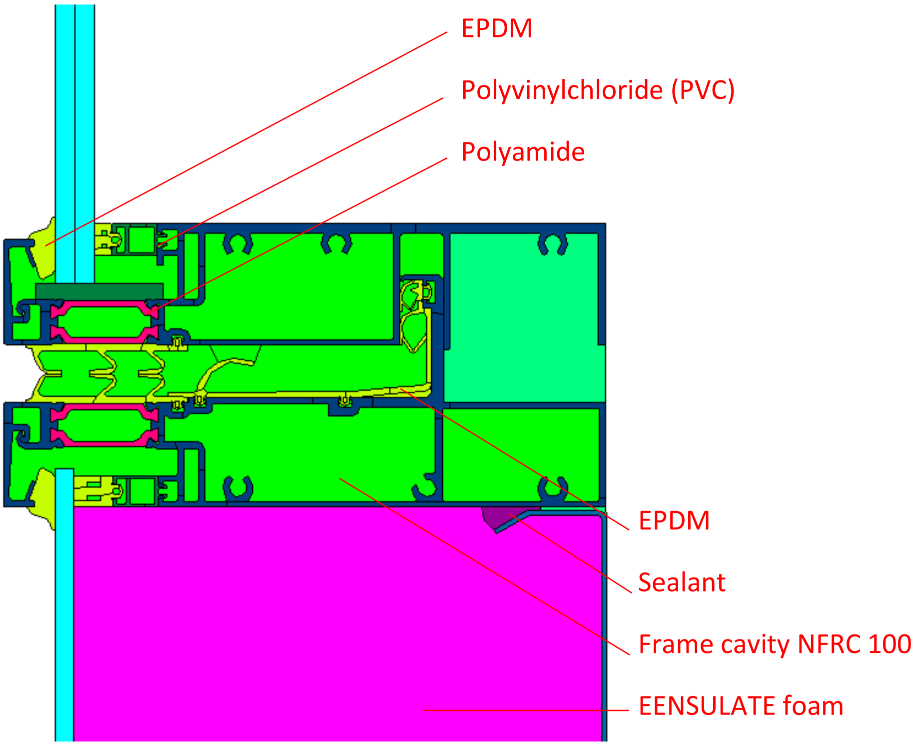


Figure 4-4 - Section of the transom modelled in THERM. VIG is mechanically fixed with aluminium cap

Table 4-4 – Material properties as modelled in THERM

Material	Component	Conductivity (W/m K)	Emissivity
Aluminium alloy (anodised)	Frame	160	0.90
Ethylene propylene diene monomer	Gasket	0.25	0.90
Polyamide (nylon)	Thermal break	0.25	0.90
Polyvinylchloride (PVC) – Vinyl rigid	Frame/Thermal break	0.17	0.90
Cavities modelled as Frame cavity NFRC 100 or Frame cavity Slightly Ventilated NFRC 100			
Silicone	Adhesive, sealant	0.35	0.90
EENSULATE foam	Spandrel	0.032	0.9
IGU imported from WINDOW with the characteristics defined in Table 4-1 and Table 4-2 ($U_{COG,1}$ = 0.271, $U_{COG,2}$ = 0.304)			

4.3 Centre of the Glass

As already stated in the introductory paragraph, Center-Of-the-Glass calculations, as well as sensitivity analysis, have been performed by using WINDOW 7.4. Nevertheless, in order to better understand the behavior of the vacuum gap and to verify the results obtained from WINDOW, U_{COG} factor of VIG has also been calculated analytically as a function of the surface resistances, glass resistance, and the vacuum gap resistance. Collins (1991) [6] and Corruccini (1959) [7] give the fundamental equations presented below (3)

$$U = \frac{1}{R_0 + 2R_{glass} + R_{gap} + R_i} \tag{3}$$

Where:

R_o = Exterior surface resistance [m²K/W];

R_i = Interior surface resistance [m²K/W];

R_{glass} = Glass pane resistance [m²K/W];

R_{gap} = Vacuum gap resistance [m²K/W];

The glass pane resistance of course depends on glass thickness and conductivity.

$$R_{glass} = \frac{t_{glass}}{k_{glass}} \tag{4}$$

Where:

t_{gl} = Glass thickness [m];

k_{gl} = Glass conductivity [W/m K];

Instead, vacuum gap resistance is function of the low-pressure gap conductance, the radiation conductance between glass panes, and the conductance of the support pillars between glass panes.

$$R_{gap} = \frac{1}{C_{cond} + C_{rad} + C_{pa}} \tag{5}$$

$$C_{cond} = \left[\frac{\alpha_1\alpha_2}{\alpha_2 + \alpha_1(1-\alpha_2)}\right].\left[\frac{\gamma+1}{\gamma-1}\right].\left[\frac{R}{4\pi.M.(T_{1c}+T_{2c})}\right]^{1/2}.P \tag{6}$$

$$C_{rad} = \frac{\sigma}{\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_2}-1}.\left[\frac{T_1^4 - T_2^4}{T_1 - T_2}\right] \tag{7}$$

$$C_{pa} = \frac{2.k_{gl}.a}{l^2.\left(1+\frac{2.k_{gl}.h}{k_p.\pi.a}\right)} \tag{8}$$

Where:

- C_{cond} Conductance of low pressure gas between glass panes [W/m2K];
- C_{rad} Radiation conductance between glass panes [W/m2.K];
- C_{pa} Conductance of pillar array between glass panes [W/m2.K];
- α_1, α_2 Accommodation coefficients of the gas molecules
- γ Specific heat ratio
- R Universal gas constant R = 8314,462175 J/mol-K;
- M Molecular weight M_{air} = 28.97 g/mol;
- T_{1c} , T_{2c} Exterior and interior temperature [K];
- P Gas pressure [N/m2];
- σ Stefan-Boltzmann constant 5.67e-8 [W/m2.K4]
- ε_1 e ε_2 Emissivity of the first and the second facing glass surface [-];
- T_1 e T_2 Temperature of the first and the second facing glass surface [K];
- a Pillar radius [m];
- h Pillar height [m];
- k_p Pillar conductivity [W/m-K];
- l Pillar spacing [m].

It should be noted that when the pillars conductivity is far higher than the conductivity of the glass pane, agreeing with L. Hart and C. Curcija [3] , the ratio of conductivities in the denominator of (8) tends to zero and, therefore, can be simplified as follows

$$C_{pa} = \frac{2.k_{gl}.a}{l^2.} \quad (9)$$

WINDOW appears to apply the same simplification and, when entering data, does not allow to choose neither pillars material, nor pillars height.

However, if it were possible to use material with thermal conductivity equal to or lesser than 1 W/m K, the conductance of pillars array thus calculated would be overly overstated and would lead to a significant overestimation of the U values of the center of the glass.

The tables and the graphs that follow summarize the results obtained by varying (a) pillars radius (table 4-4) and (b) pillars spacing (table 4-5)

a. Table 4-5 and Figure 4-5 show how UCOG values vary by varying pillars radius between 0.15 mm and 0.35 mm, for different emissivity values of surface 3 and a fixed pillars spacing value of 25 mm

Table 4-5 - Ug COG changing ‘pillars radius’ and inner glass (surface 3) emissivity. Pillars spacing=25 mm

Setting	emissivity Pillars radius	U_g e = 0.01	U_g e = 0.02	U_g e = 0.03	Average variation from A01
A01	0.15	0.542	0.579	0.615	0%
A02	0.2	0.667	0.702	0.736	21.33%
A03	0.25	0.786	0.819	0.852	41.67%
A04	0.3	0.899	0.931	0.962	61.03%
A05	0.35	1.007	1.037	1.067	79.46%

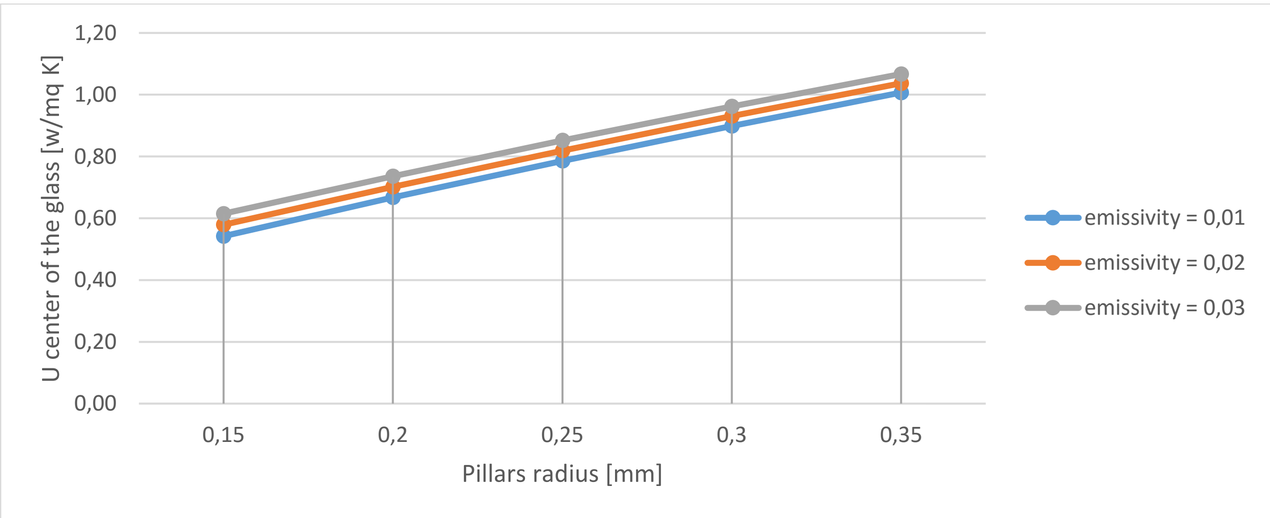


Figure 4-5 – Ug COG changing ‘pillars radius’ and inner glass (surface 3) emissivity. Pillars spacing=25 mm.

b. Table 4-6 and Figure 4-6 show how U_{COG} values vary by varying pillars spacing between 20 mm and 50 mm for different emissivity values of surface 3 and a fixed pillars radius equal to 0.2 mm

Table 4-6 - Ug COG changing 'pillars spacing' and inner glass (surface 3) emissivity. Pillars radius=0.2 mm

Setting	emissivity	U_g	U_g	U_g	Average variation from B01
	Pillars spacing	e = 0.01	e = 0.02	e = 0.03	
B01	20	0.927	0.958	0.988	-0%
B02	25	0.667	0.702	0.736	-26.76%
B03	30	0.513	0.551	0.587	-42.58%
B04	35	0.416	0.455	0.493	-52.58%
B05	40	0.350	0.390	0.429	-59.37%
B06	45	**0.304**	0.345	0.385	-64.08%
B07	50	**0.271**	0.312	0.353	-67.49%

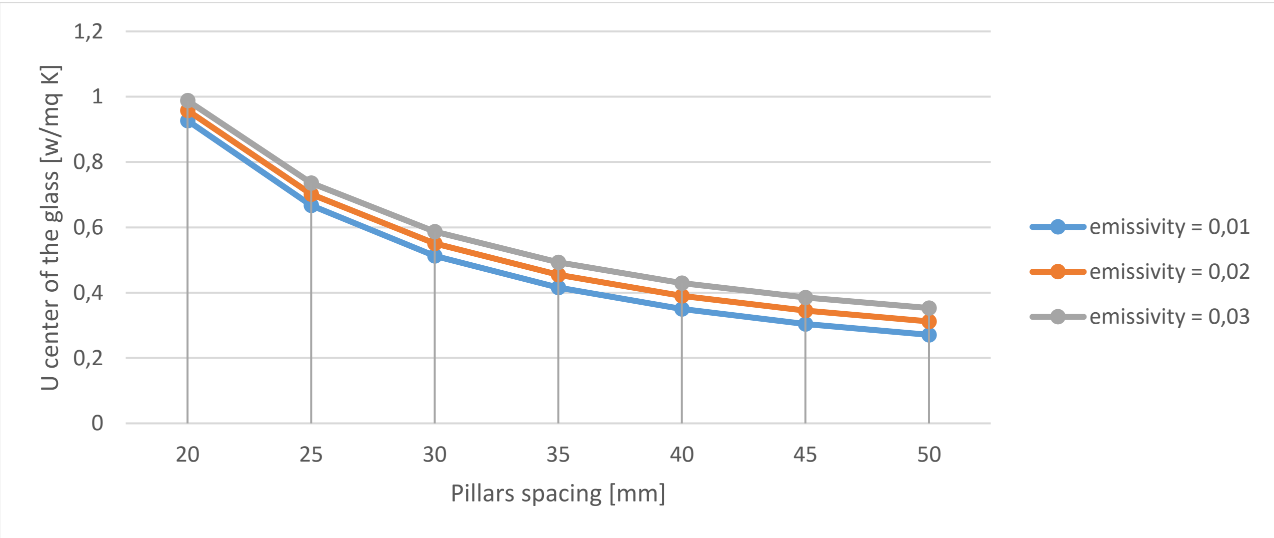


Figure 4-6 - Ug COG changing 'pillars spacing' and inner glass (surface 3) emissivity. Pillars radius=0.2 mm

The glazing systems which would allow us to achieve the target set for the Center of the glass are those having pillars spacing higher than 45 mm and pillars radius not greater than 0.2 mm.

It is also noteworthy that, if compared with the results analytically calculated using glass as pillars material, the overestimation of U_{COG} is about 20%.

4.4 Joint A –The mullion

First of all, it has been necessary to understand which could have been the right length of the edge of the glass, hence, after having drawn the detail of the frame shown in the following figure, it has been imported in THERM a sample of glazing system characterized by:

- Pillars radius: 0.2 mm
- Pillars spacing: 25 mm
- Emissivity coating: 0.01
- Edge seal thickness:10 mm

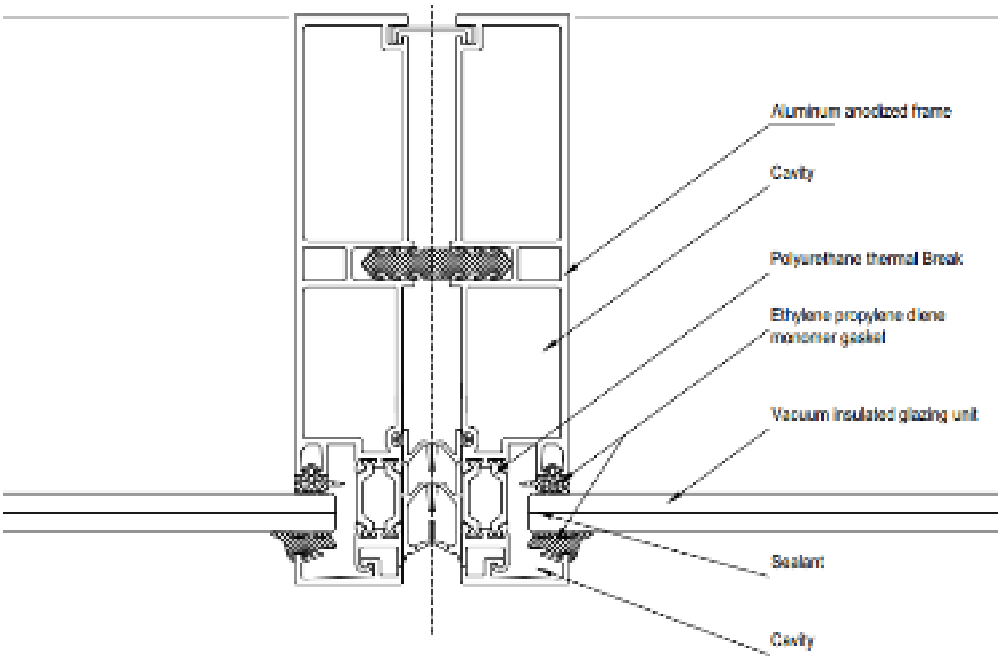


Figure 4-7 – Section of the mullion. VIG is mechanically fixed with aluminium cap

In addition, silicone conductivity has been set equal to 0.35 [W/mK] as sealant. This assumption has allowed to determine the penetration length of the EOG effects into the VIG unit so as not to underestimate the area where the U-edge will be applied.

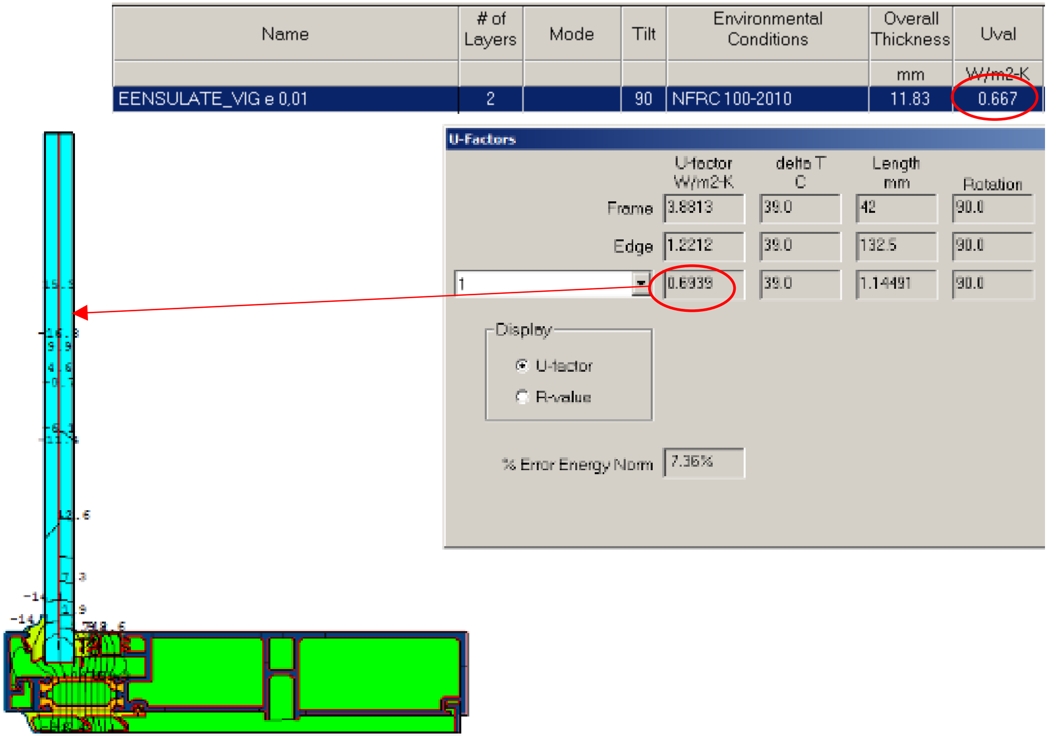


Figure 4-8 – Preliminary analysis carried out to assess the penetration length of the EOG effects into the VIG unit

The results show that after approximately 145 mm from the edge of the glass, and 132.5 mm from the gasket, the difference between the U factor and the transmittance evaluated at the center of glass becomes less than 5%. This length is longer than what would be expected for a standard double pane glass (63.5 mm) because the high insulation effect of the vacuum forces the heat flux direction to be almost parallel to the glass plane.

Considering this specific configuration, the heat flux analysis shows the sealant as the weakest point.

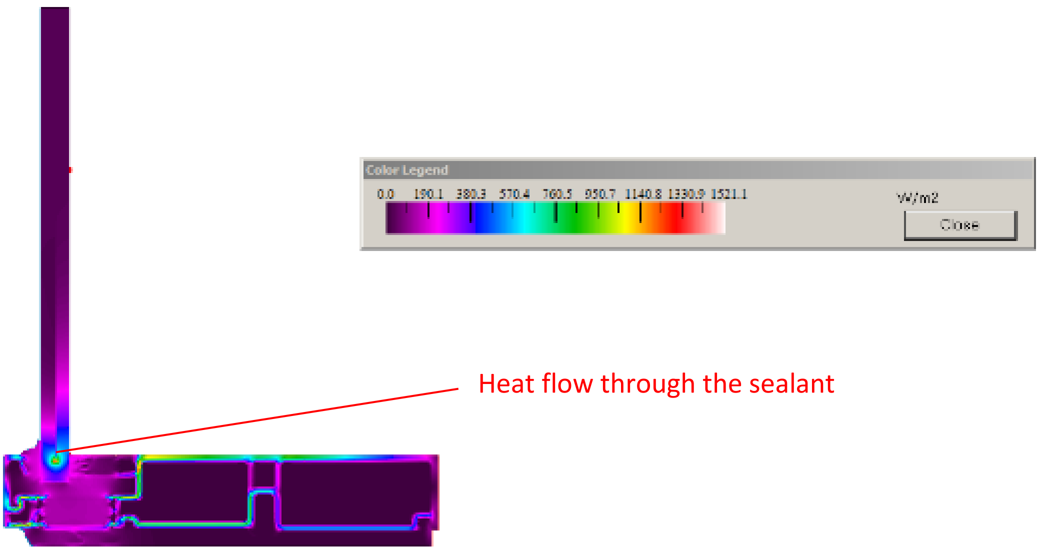
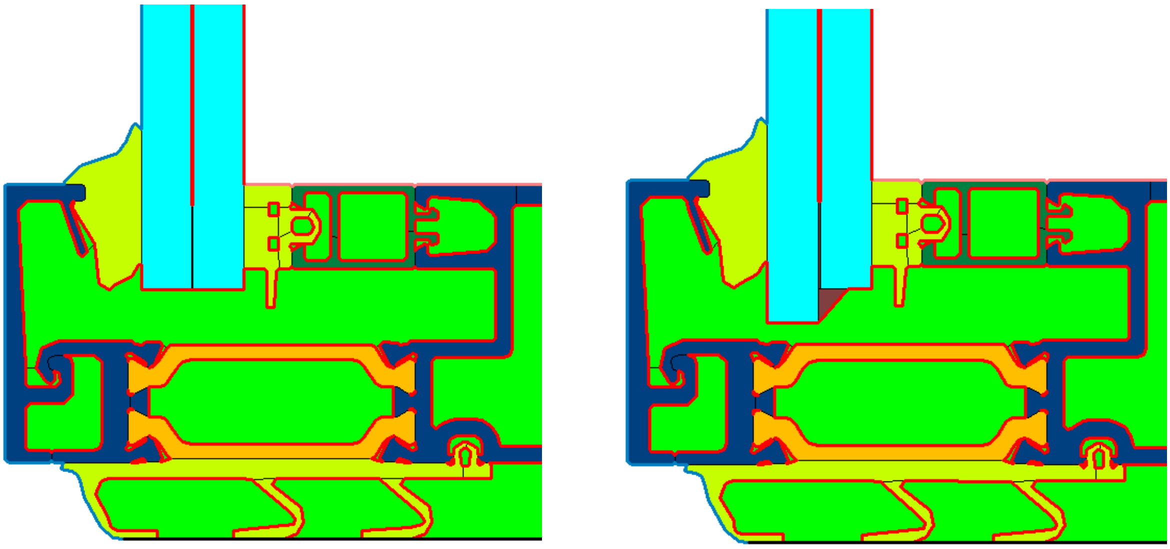


Figure 4-9 - Preliminary analysis carried out to assess the penetration length of the EOG effects into the VIG unit. Heat flow evaluation

The next step has been to examine how the edge of the glass behaves changing the conductivity of the sealant and the joint configuration, for a constant value of the sealant length equal to 10 mm.

In order to analyze the sensitivity to changes in variables it has been studied how the heat flow varies in the two configurations showed below, and using as glazing system the following VIG (table 4-6) among those investigated previously, which are those that would allow to achieve the target set for the Center of the glass.



Configuration 01 Configuration 02

Figure 4-10 – Configurations that will be considered. In the second, the inner pane is 5 mm shorter than the outer one

Table 4-7 – Combinations that will be considered

Setting	Configuration	Pillars spacing mm	Pillars radious mm	emissivity	U center of the glass W/mq K
B 06	C 01	45	0.2	0.01	0.304
B 07	C 01	50	0.2	0.01	0.271
B 06	C 02	45	0.2	0.01	0.304
B 07	C 02	50	0.2	0.01	0.271

The tables and the figures that follow summarize the results of the sensitivity analysis and show that, with the kind of frame system chosen (which involves EPDM gaskets), the conductivity of the sealant become less meaningful when increase up to 0.1 W/m K and negligible for values above 0.5 W/m K (in agreement with [16]). Furthermore, the configuration 2 appears to behave only slightly better than configuration 1. However, even in the worst-case scenario, the U edge remains below 0.968 W/mq K.

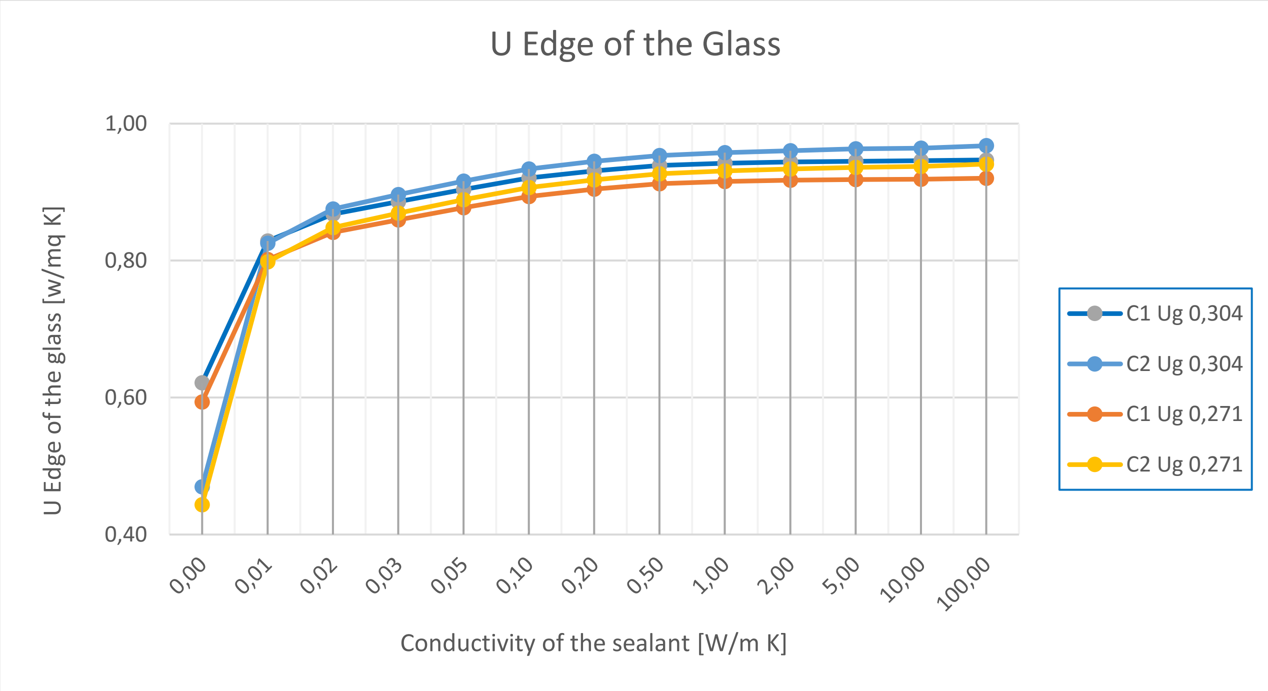


Figure 4-11 – U edge-of-the-glass values for different values of sealant conductivity

Table 4-8 – U edge-of-the-glass values for different values of sealant conductivity. Values that could be achieved by means of commercial sealants (conductivity between 0.5 and 2 W/ m K) are highlighted in bold.

Sealant conductivity W/m K	U Edge of the glass – W/mq K			
	C 01 – Uc 0,304	C 02 –Uc 0,304	C 01 – Uc 0,271	C 02 – Uc 0,271
0.00	0.622	0.470	0.594	0.444
0.01	0.829	0.826	0.802	0.798
0.02	0.868	0.875	0.841	0.848
0.05	0.904	0.916	0.877	0.889
0.10	0.921	0.934	0.894	0.907
0.50	**0.939**	**0.954**	**0.912**	**0.927**
1.00	**0.942**	**0.958**	**0.915**	**0.931**
2.00	**0.944**	**0.961**	**0.917**	**0.934**

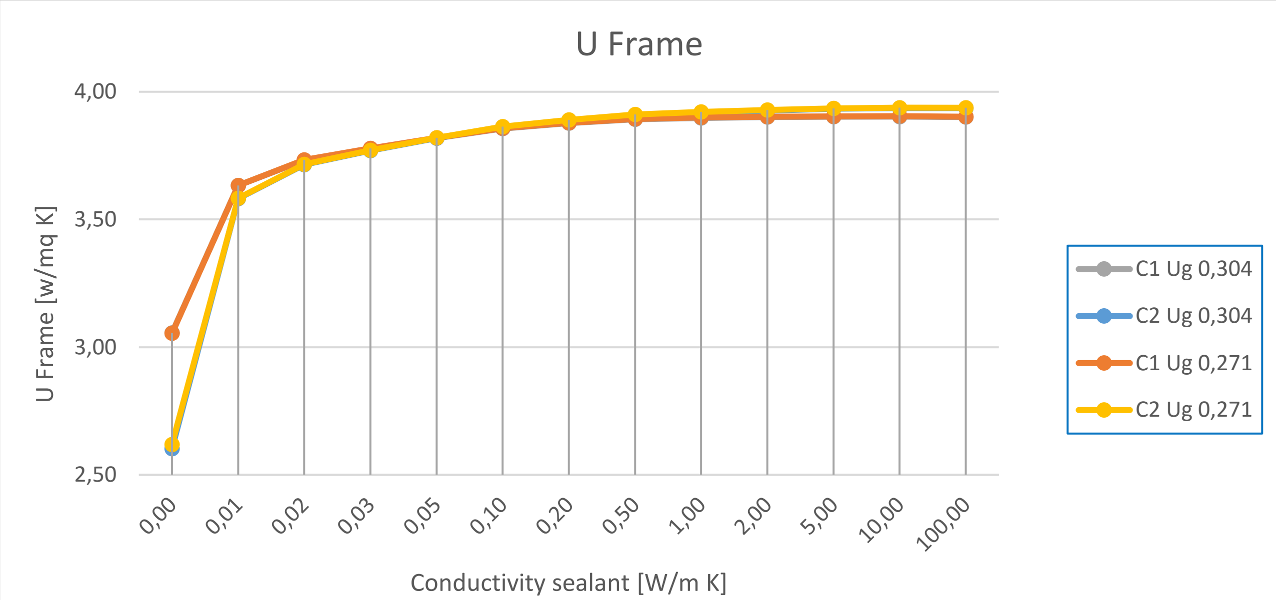


Figure 4-12 – U frame values for different values of sealant conductivity

Table 4-9 - U frame values for different values of sealant conductivity. Values that could be achieved by means of commercial sealants (conductivity between 0.5 and 2 W/ m K) are highlighted in bold.

Sealant conductivity W/m K	U Frame – W/mq K			
	C 01 – Uc 0,304	C 02 –Uc 0,304	C 01 – Uc 0,271	C 02 – Uc 0,271
0.00	3.056	2.603	3.054	2.619
0.01	3.633	3.582	3.633	3.583
0.02	3.732	3.715	3.734	3.716
0.05	3.819	3.819	3.820	3.820
0.10	3.856	3.862	3.857	3.864
0.50	**3.892**	**3.909**	**3.894**	**3.911**
1.00	**3.898**	**3.919**	**3.899**	**3.921**
2.00	**3.901**	**3.927**	**3.902**	**3.928**
5.00	3.903	3.933	3.904	3.935

Once understood how the heat flow varies changing the sealant conductivity in both configurations, let's look at what happens when the free variable is the length of the sealant. In this case, it has been examined the behavior of the joint for a constant value of the sealant conductivity equal to 1 W/m K. Configurations and characteristics of the glazing systems are the same as those chosen in the previous case.

Tables and figures that follow summarize the results of the analysis and show that U edge-of-glass values follow a linear development whose gradient appears to increase slightly when the sealant extends over the length (15 - 20 mm) that which would enable the sealant to keep within the width of the frame.

Table 4-10 - U edge-of-the-glass values for different sealant lengths-

Sealant length mm	U Edge of the glass – W/mq K			
	C 01 – Uc 0,304	C 02 –Uc 0,304	C 01 – Uc 0,271	C 02 – Uc 0,271
5.0	0.831	0.880	0.804	0.853
7.5	0.885	0.930	0.858	0.903
10.0	0.942	0.958	0.915	0.931
12.5	1.003	1.047	0.976	1.021
15.0	1.070	1.115	1.037	1.088
17.5	1.170	1.184	1.144	1.158
20.0	1.213	1.259	1.187	1.233
25.0	1.360	1.410	1.334	1.384
30.0	1.506	1.559	1.480	1.533
35.0	1.702	1.710	1.676	1.684

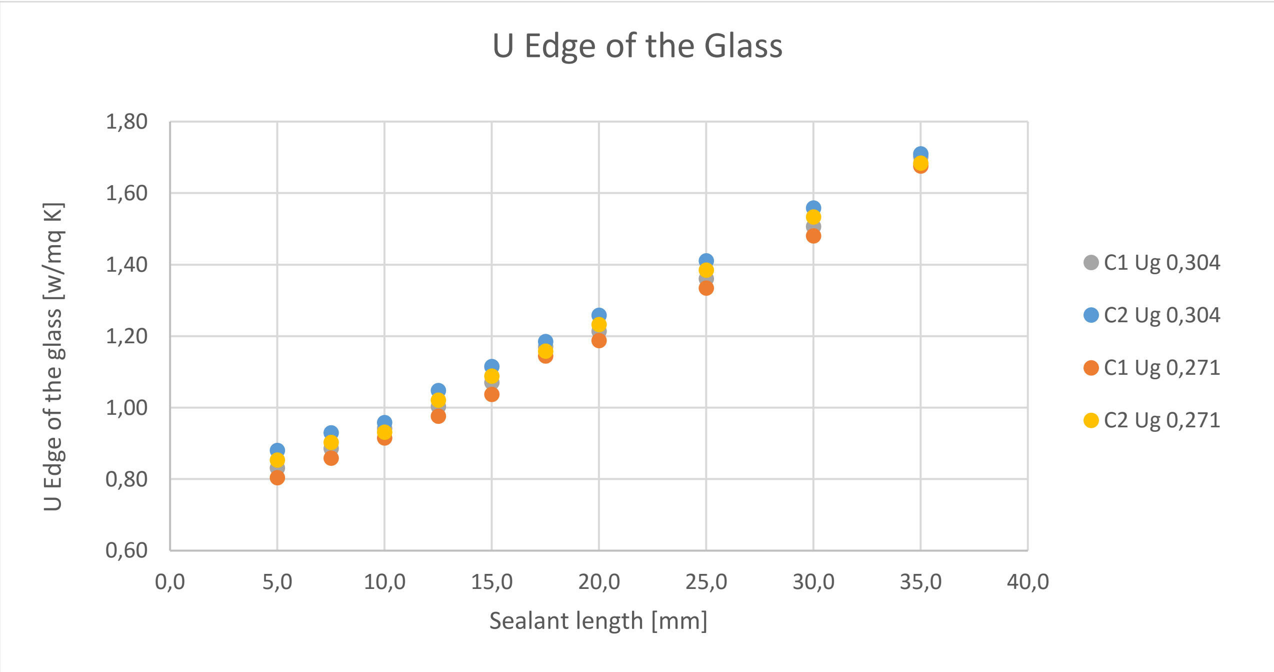


Figure 4-13 – U edge-of-the-glass values for different sealant lengths

On the other hand, with regard to the U-frame values, the opposite happens. When the sealant length exceeds 15 -20 mm, U frame values almost stop growing.

However, in the case being considered, also in order to meet the architectural requirements, the maximum acceptable value of sealant length should be 20 mm. Therefore, when the time comes to calculate the overall U value, only the U values associated with sealant lengths between 10 mm and 20 mm should be taken into account.

As an additional indication from the analyses still regarding the sealant, it would seem more logical to focus on minimizing length than on achieving lower values of conductivity.

Table 4-11 – U frame values for different sealant lengths

Sealant length mm	U frame – W/mq K			
	C 01 – Uc 0,304	C 02 –Uc 0,304	C 01 – Uc 0,271	C 02 – Uc 0,271
5.0	3.701	3.775	3.702	3.776
7.5	3.812	3.867	3.813	3.868
10.0	3.898	3.919	3.899	3.921
12.5	3.962	4.004	3.963	4.006
15.0	4.008	4.046	4.003	4.048
17.5	4.047	4.075	4.050	4.078
20.0	4.064	4.097	4.067	4.099
25.0	4.095	4.126	4.098	4.129
30.0	4.114	4.143	4.117	4.145
35.0	4.132	4.153	4.135	4.156

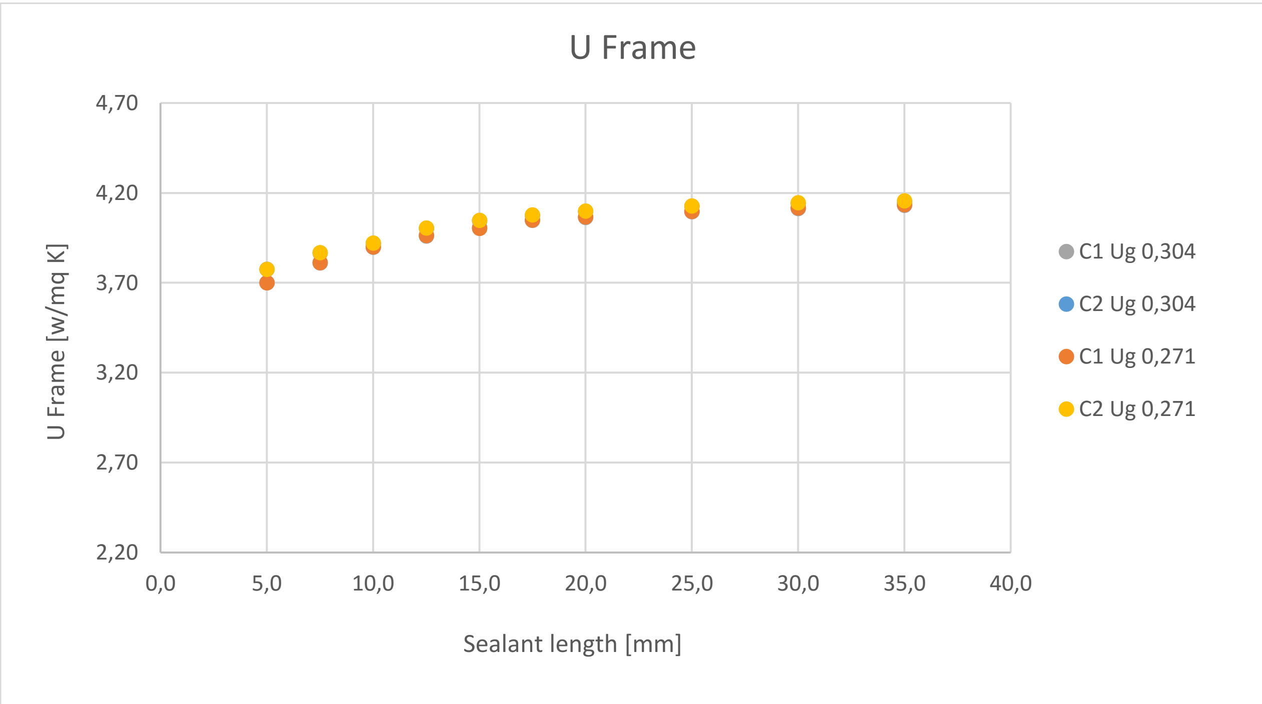


Figure 4-14 - U frame values for different sealant lengths

In addition, in order to obtain an ideal U overall value for the chosen frame, an evaluation has been carried out under the following conditions:

- U cog equal to 0.271 and configuration 2 have been considered
- Sealant conductivity tending to vacuum conductivity
- Length of the sealant equal to 10 mm
- All the cavities are filled with EENSULATE foam

The results are shown in the table below.

Table 4-12 – U frame and U EOG values of the ideal situation

U frame - W / mq K	U edge of the glass - W / mq K
1.660	0.343

4.5 Joint B –The transom

Although the section in the center of the spandrel, designed with a 165 [mm] thickness of foam insulation, using the equation (10) would allow to reach the theoretical value of approximately 0.19 W/mq K, the results of the heat flux analysis (Figure 4-15) show that the effect of the thermal bridge on the overall section compels us to apply a weighted average normal value to the area of the spandrel.

$$U = \frac{1}{R_0 + R_{glass} + R_{foam} + R_i} \qquad (10)$$

Where:

- R_0 exterior surface resistance [m2K/W];
- R_i interior surface resistance [m2K/W];
- R_{glass} glass pane resistance [m2K/W];
- R_{foam} foam resistance [m2K/W].

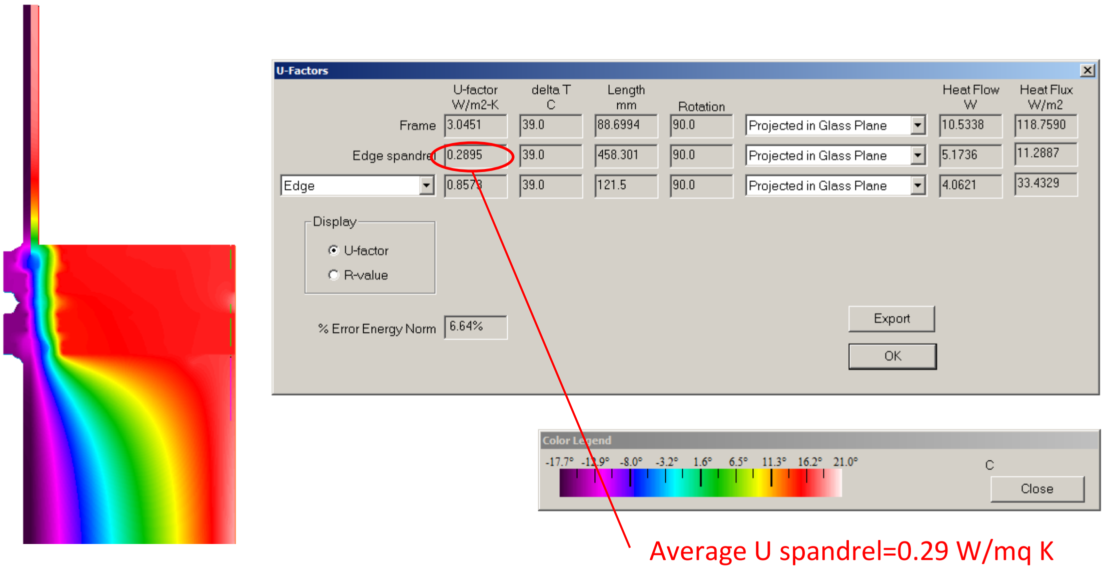


Figure 4-15 - Preliminary analysis carried out to assess the penetration length of the Frame effects into the spandrel

Figure 4-15 and Figure 4-16 show the results for a value of sealant conductivity equal to 1 W/mK. In this case the average U value to be applied on the area should be 0.29 W/mq K. Sealant, also in this situation, is the weakest point of the frame.

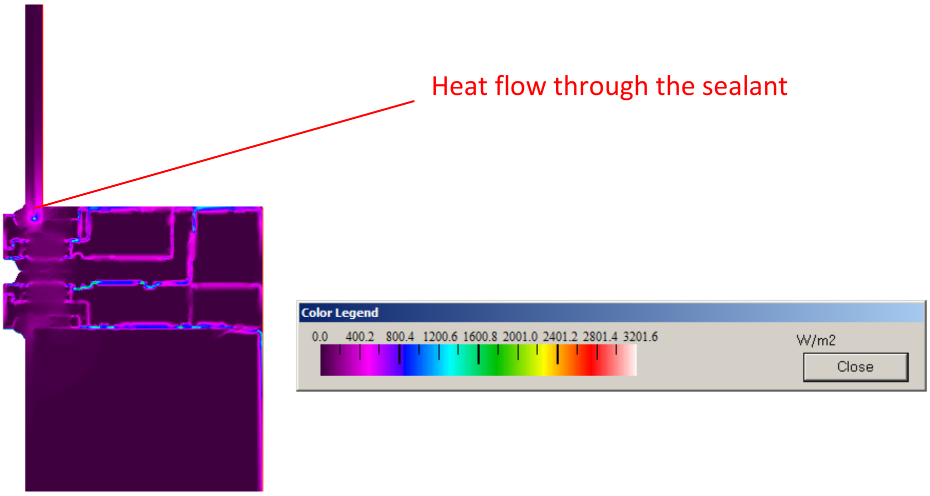


Figure 4-16 - Preliminary analysis carried out to assess the penetration length of the Frame effects into the spandrel. Heat flow evaluation

However, as in the previous case, in order to analyze the influence of the thermal bridge around the perimeter on the spandrel behavior, the first step has been to define a frame.

Using the type of frame system already chosen (with EPDM gaskets) and the glazing system previously shown in table 4-6, we have studied how varying the sealant length affects the behavior of the thermal bridge and therefore the local values of:

- U Spandrel
- U Edge of the glass
- U Frame

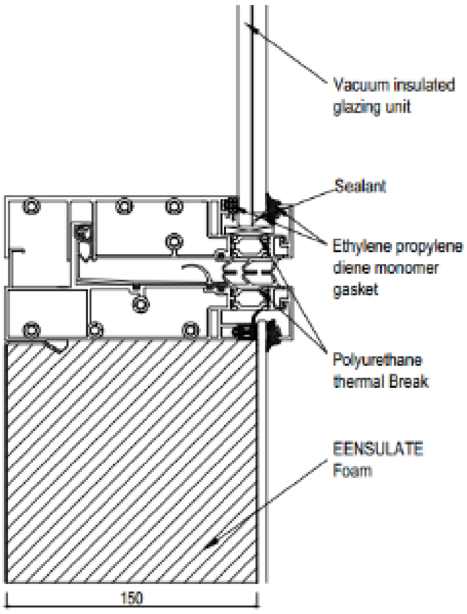


Figure 4-17 - Section of the mullion. VIG is mechanically fixed with aluminium cap

Once again, a distinction has been made between the two configurations indicated in Figure 4-10.

In view of the above, presuming changes in conductivity value of sealant, within the range of values that could be achieved (between 0,5 and 2 W/m K), don't cause the joint to behave differently, during the analysis we have set the sealant conductivity equal to 1 W/m K

Tables and figures that follow summarize the results of the analysis and show that the same considerations developed in the previous section, relating U frame and U edge-of-the-glass, also apply to the present case.

Table 4-13 - U edge-of-the-glass values for different sealant lengths.

Sealant length mm	U Edge of the glass – W/mq K			
	C 01 – Uc 0,304	C 02 –Uc 0,304	C 01 – Uc 0,271	C 02 – Uc 0,271
5.0	0.789	0.887	0.762	0.854
10.0	0.886	0.998	0.859	0.971
15.0	0.995	1.128	0.968	1.102
20.0	1.129	1.271	1.103	1.245
30.0	1.431	1.569	1.405	1.542

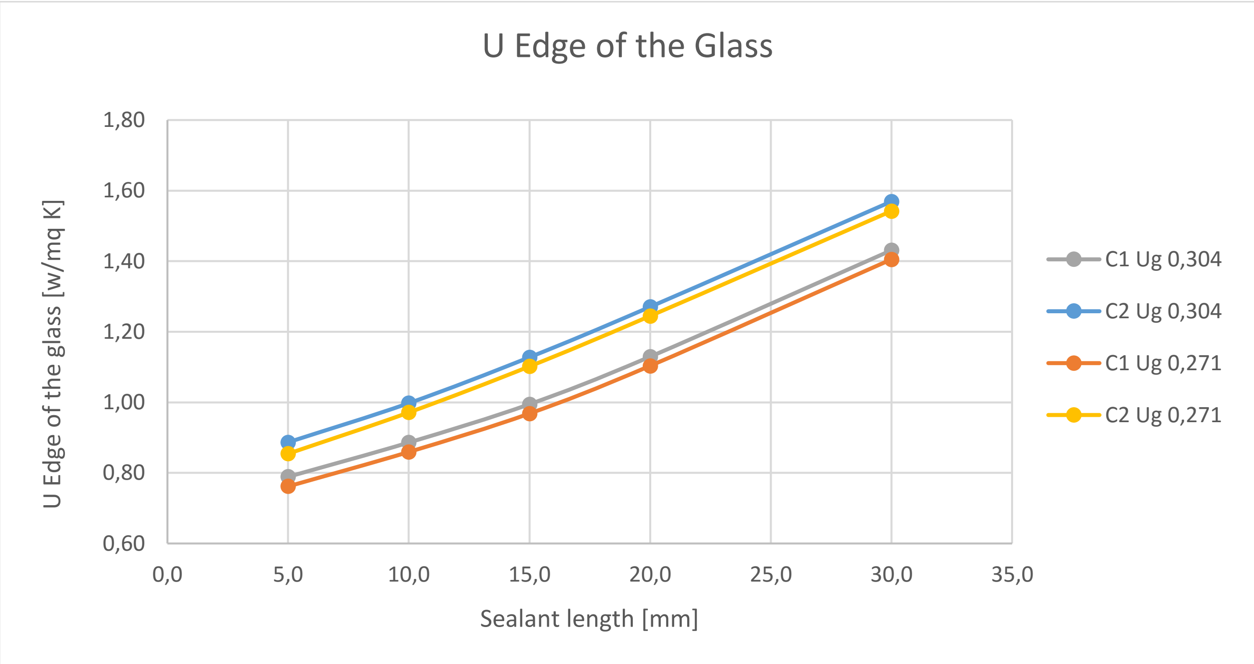


Figure 4-18 - U edge-of-the-glass values for different sealant lengths

Table 4-14-- U frame values for different sealant lengths.

Sealant length mm	U frame – W/mq K			
	C 01 – Uc 0,304	C 02 –Uc 0,304	C 01 – Uc 0,271	C 02 – Uc 0,271
5.0	2.855	2.951	2.858	2.935
10.0	2.950	3.002	2.953	3.005
15.0	3.037	3.037	3.040	3.040
20.0	3.065	3.049	3.068	3.052
30.0	3.083	3.045	3.087	3.048

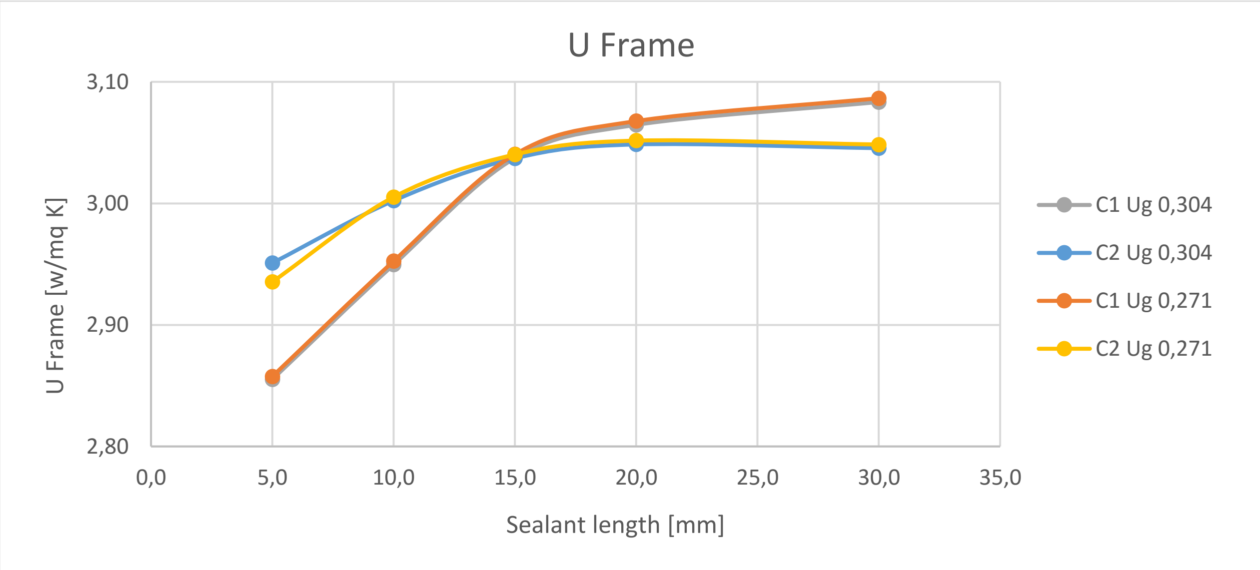


Figure 4-19 – U frame values for different sealant lengths

As expected, the sealant length is much less influencing the U value of the spandrel compared to the impact on U frame and U edge-of-the-glass. In fact, as it is shown in the graph and the table below, the difference between the maximum and minimum values is almost negligible (<5%).

Table 4-15 – average U spandrel values for different sealant lengths.

Sealant length mm	U average spandrel – W/mq K			
	C 01 – Uc 0,304	C 02 –Uc 0,304	C 01 – Uc 0,271	C 02 – Uc 0,271
5.0	0.280	0.284	0.280	0.282
10.0	0.283	0.286	0.283	0.285
15.0	0.287	0.288	0.287	0.288
20.0	0.289	0.290	0.289	0.290
30.0	0.293	0.293	0.293	0.293

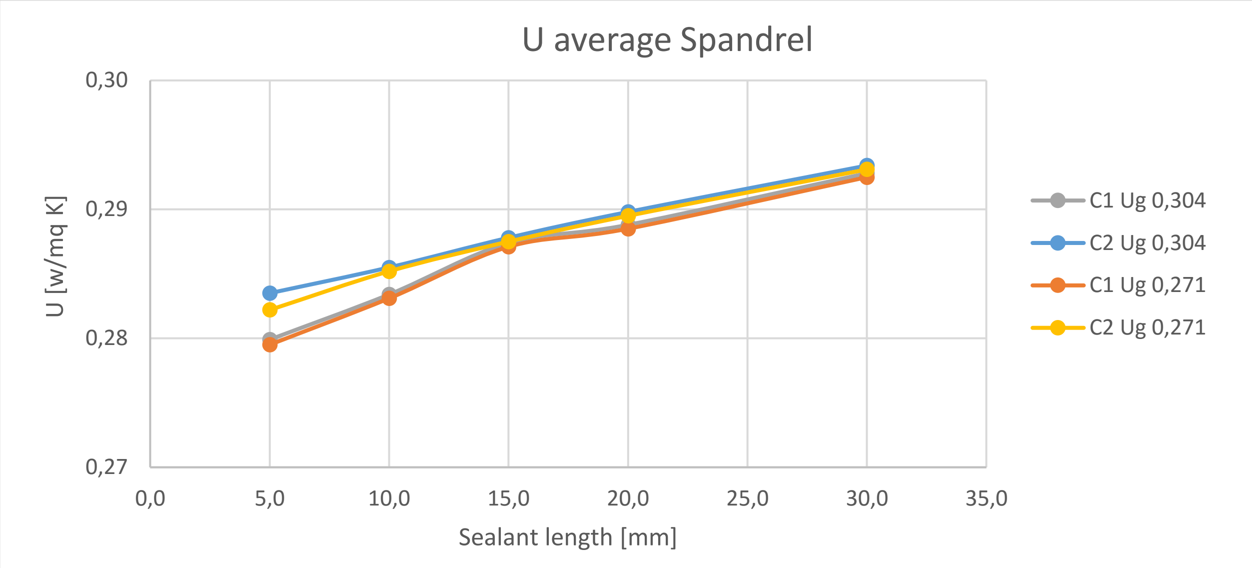


Figure 4-20 - average U spandrel values for different sealant lengths

In closing, for the same purpose already stated at the end of the previous section, to obtain an ideal overall U value for the chosen frame, an evaluation has been carried out under the following conditions:

- U cog equal to 0.271 and configuration 2 have been considered
- Sealant conductivity tending to vacuum conductivity
- Length of the sealant equal to 10 mm
- All the cavities are filled with EENSULATE foam

The results are shown in the following table

Table 4-16 - U frame, U EOG and average U spandrel values of the ideal situation

U frame **W / mq K**	**U edge of the glass** **W / mq K**	**U average spandrel** **W / mq K**
1.825	0.328	0.237

4.6 Performance of the entire system

All that remains is to evaluate the overall U-value by applying the U-values already calculated to their respective areas, in accordance with the scheme shown in Figure 4-2.

Keeping in line with what is stated in 4.1, Table 4-17 and Table 4-18 provide the values of the areas specified in Figure 4-2 which have to be used to evaluate the overall U factor.

Table 4-17 – Vision. Areas and associated U values

VISION		
Name selected area	**U value to be applied**	**Area - mq**
Area COG	U COG	2.4712
Area EOG mullion	U EOG Joint A	0.5690
Area frame mullion	U frame Joint A	0.2026
Area EOG transom	U EOG Joint B	0.3752
Area frame transom	U frame Joint B	0.1320

Table 4-18 - Spandrel. Areas and associated U values

SPANDREL		
Name selected area	**U value to be applied**	**Area value - mq**
Area spandrel	Average U spandrel	1.2914
Area frame transom	U frame Joint B	0.1320
Area frame mullion	U frame Joint B	0.0766

The table and the graph below summarize the results of U overall values calculated using expression (2) obtained by analogy with equation (1) taken from THERM 6.3/WINDOW 6.3 National Fenestration Rating Council Simulation Manual and ANSI/NFRC 100 (2014)

Table 4-19 - Overall U values for different sealant lengths

Sealant length mm	Overall U values – W/mq K			
	C 01 – Uc 0,304	C 02 –Uc 0,304	C 01 – Uc 0,271	C 02 – Uc 0,271
5.0	0.686	0.709	0.666	0.687
10.0	0.720	0.734	0.700	0.714
15.0	0.753	0.768	0.731	0.748
20.0	0.782	0.797	0.762	0.777
30.0	0.839	0.854	0.819	0.834

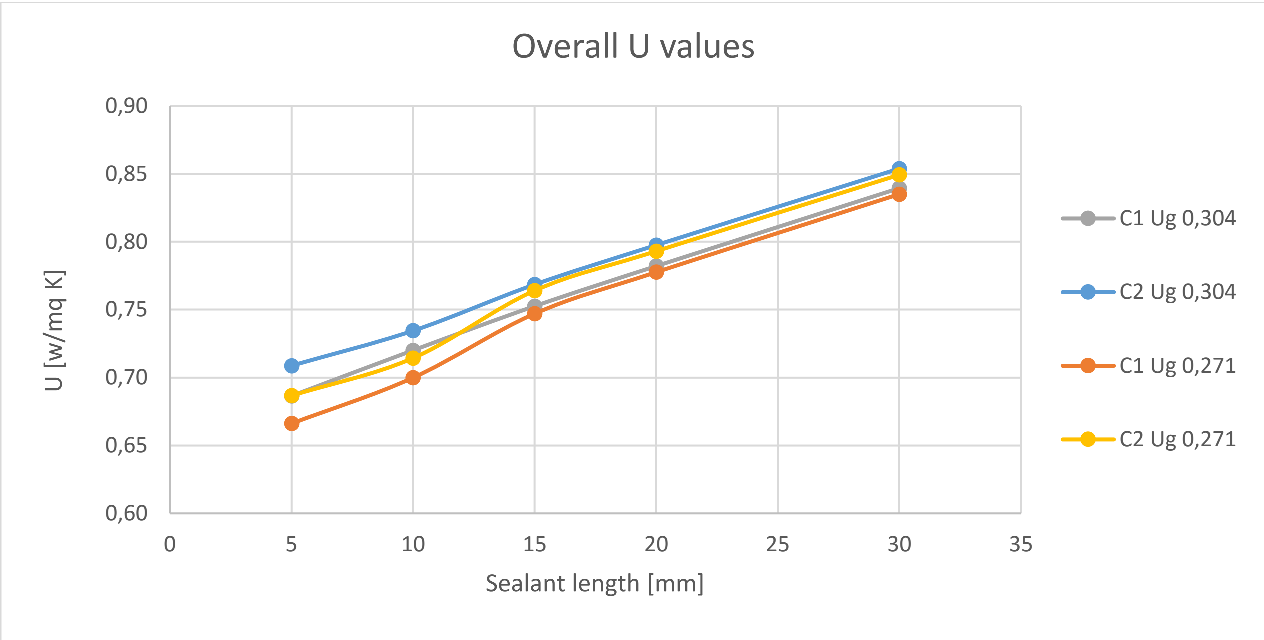
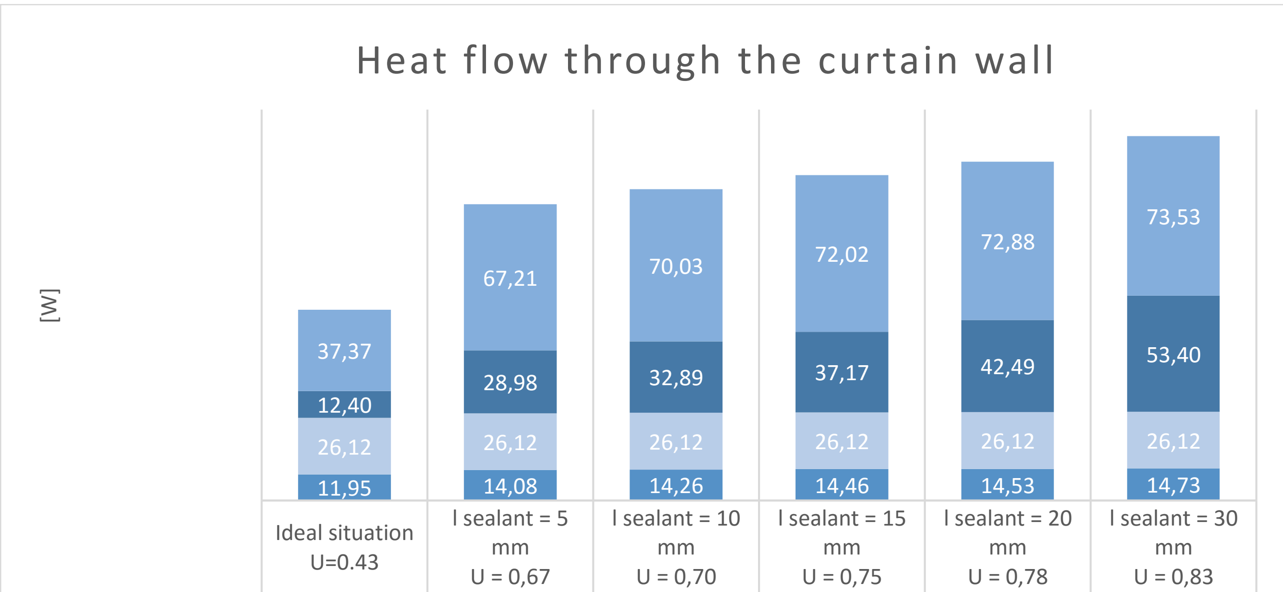


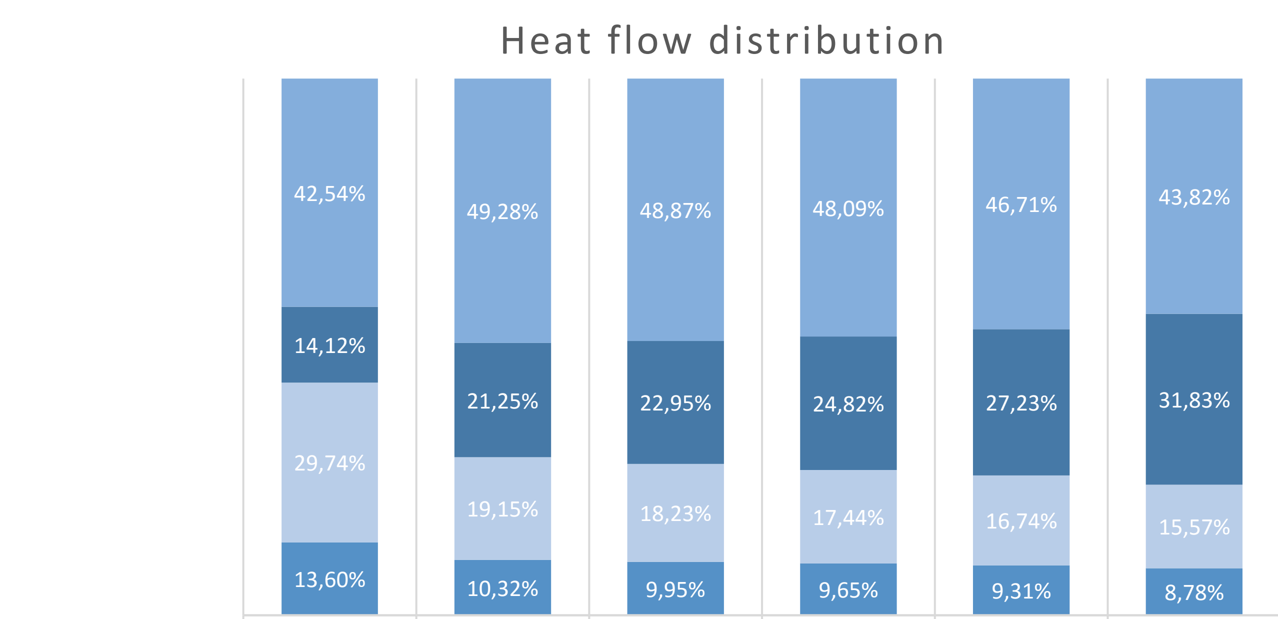
Figure 4-21 - Overall U values for different sealant lengths

In summary, the first step of the research has been to define Vacuum Insulated Glazings which have allowed to meet the requirement for the U_{COG} value. Than it has been defined an unitized curtain wall, where VIG and spandrel were fixed to the unit frame by means of a continuous external aluminum glazing bead, whose behavior has been analyzed varying both thermal and geometric characteristics of the sealant.



	Ideal situation U=0.43	l sealant = 5 mm U = 0,67	l sealant = 10 mm U = 0,70	l sealant = 15 mm U = 0,75	l sealant = 20 mm U = 0,78	l sealant = 30 mm U = 0,83
Frame	37,37	67,21	70,03	72,02	72,88	73,53
Edge of glass	12,40	28,98	32,89	37,17	42,49	53,40
Center of the glass	26,12	26,12	26,12	26,12	26,12	26,12
Spandrel	11,95	14,08	14,26	14,46	14,53	14,73

Figure 4-22 – Heat flow through the curtain wall for different sealant lengths. The contributions for each element have been highlighted.



	Ideal situation U=0.43	l sealant = 5 mm U = 0,67	l sealant = 10 mm U = 0,70	l sealant = 15 mm U = 0,75	l sealant = 20 mm U = 0,78	l sealant = 30 mm U = 0,83
Frame	42,54%	49,28%	48,87%	48,09%	46,71%	43,82%
Edge of the glass	14,12%	21,25%	22,95%	24,82%	27,23%	31,83%
Center of the glass	29,74%	19,15%	18,23%	17,44%	16,74%	15,57%
Spandrel	13,60%	10,32%	9,95%	9,65%	9,31%	8,78%

Figure 4-23 - Heat flow distribution for different sealant lengths. Comparison between the flow through each system and the flow through its elements

The results are presented in Figure 4-21. Although the target overall value for the whole module is ideally achievable (U_t = 0.43 W/ mq K, calculated applying the partial value indicated in Table 4-12 and Table 4-16), the research shows that the U overall value that could be achieved with realistic values of sealant length and conductivity, and with the currently assumed layout (i.e. commercial framing system, joint configurations) is within a range of 0.7 to 0.8 W/ mq K.

In order to converge towards the ideal situation, some considerations can be made starting from the chart represented in Figure 4-22 which compares the heat flow of the ideal situation to those calculated for different sealant lengths. Looking at the contribution of each element, it leads to the conclusion that, in order to achieve the overall U value of 0.43 W/mK, heat flow through Frame and Edge of the glass have to be reduced by more than half (by two-thirds in case of sealant length higher than 20 mm). In other words, this means that different design solutions which allow for an improved joint between the frame and the VIG are needed.

On the other hand, from chart of Figure 4-23 it clearly emerges that the impact of the Center of the glass accounts for only between 15 and 20 % of the overall heat flow. This entails that it is not possible to achieve significant overall improvement by improving the performance of the glazing unit.

5 PRELIMINARY MECHANICAL MODEL

The present Section is devoted to the development of a preliminary mechanical model which is representative of the vision part only of the curtain-wall module. This limitation is functional to the objectives of this concept design phase as stated in chapter 2.6.

The modelling of the vision glazing component is first discussed and considerations on the key parameters involved in the determination of the glass structural behaviour as well as their relationship/connections are provided.

After that, a design approach derived from the latest introduced norms and standards is proposed and a set of analyses are performed to investigate the feasibility of different settings.

5.1 Glass mechanical properties

Glasses are **brittle** materials (Figure 5-1). As a result, their fracture behaviour is usually determined by environmental factors and not by the inherent strength of the bonds forming the vitreous network. The fracture strength of glasses varies with prior surface treatment, chemical environment, and the method used to measure the strength. As brittle materials, glasses are also quite susceptible to failure due to thermal shock.

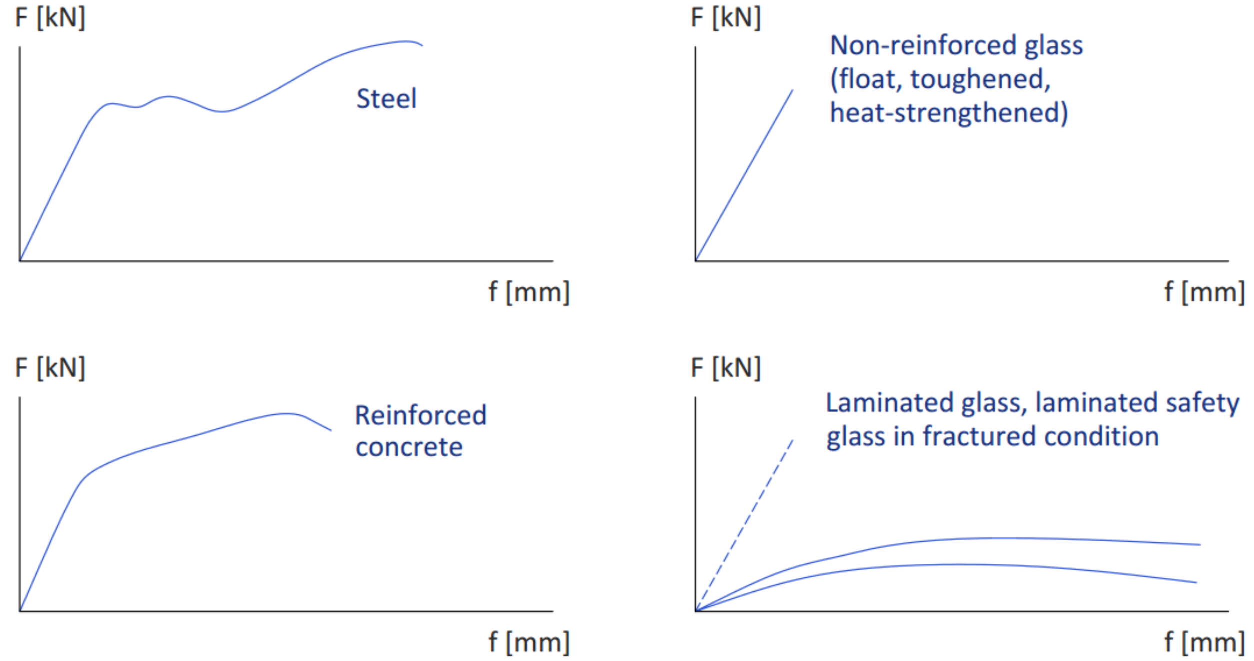


Figure 5-1 – Strain behaviour of construction materials in the non-linear zone.

Other mechanical properties of glasses are inherent to the material. The elastic modulus, *E*, is determined by the individual bonds in the material and by the structure of the network. The hardness of glasses is a function of the strength of individual bonds and the density of packing of the atoms in the structure.

Examples of this variability of mechanical parameters depending on the specific chemical composition of the glass are reported in the following table.

Table 5-1 – Toughness, Young's modulus and surface energy values for different glasses (Aben and Guillemet, 1993; Barton and Guillemet, 2005).

Glass	K_c (MPa m$^{1/2}$)	E (GPa)	ζ (J m^{-2})
Silica	0.74 ÷ 0.81	73	0.65
Soda-lime-silica	0.72 ÷ 0.82	70 ÷ 74	0.4 ÷ 1.0
Borosilicate	0.75 ÷ 0.82	64 ÷ 89	0.63
Aluminosilicate	0.85 ÷ 0.96	83 ÷ 91	0.63
Lead-silicate	0.62 ÷ 0.73	58 ÷ 65	0.44

(a) Native surface. Considering that $G_c = K_c^2/E$ is the energy release on fracture, one finds with E = 70 GPa and K = 0.7 MPa m$^{1/2}$, $G_c = 7\,Jm^{-2}$, that is, one order of magnitude larger than the actual value. This discrepancy is attributed to the rearrangement (relaxation) of the surface after breakage. Another reason might be the dissipation of energy in the plastic zone confined at the crack tip.

According to prEN 16612, mechanical and physical properties of glass needed for calculation, such as Young's modulus E, the Poisson number μ and the density ρ, can be obtained from the following product standards:

Table 5-2 – Glass standards

Product Standard	Short description
EN 572-1	Basic soda-lime silicate glass
EN 1748-1-1	Basic borosilicate glass
EN 1748-2-1	Basic glass ceramics
EN 1863-1	Heat strengthened glass
EN 12150-1	Thermally toughened soda lime silicate safety glass
EN 12337-1	Chemically strengthened glass
EN ISO 12543-1	Laminated glass and laminated safety glass
EN 13024-1	Thermally toughened borosilicate safety glass
EN 14178-1	Basis alkaline earth silicate glass
EN 14179-1	Heat soaked thermally toughened soda lime silicate safety glass
EN 14321-1	Thermally toughened alkaline earth silicate safety glass

When no distinction between the various differences in mechanical and physical properties can be taken into account, or when it is not necessary, the following values (for soda-lime-silicate glass) are suggested to be used for all glass types:

Glass density ρ = 2500 kg/m^3

Young's modulus E = 70000 MPa

Poisson number μ = 2.2

Thermal expansion factor = 9×10^{-6} K^{-1} - in the range 20 ÷ 300 °C

The above values have been then used to make the first set-up of the mechanical model, whereas the previously mentioned variability ranges will be eventually considered in order to perform sensitivity analyses in the following design stages.

5.1.1 Fracture strength

The fracture strengths of glasses are usually far less than their theoretical strengths. Fracture strength can only be described in terms of a distribution function, and does not exhibit a single value characteristic of a given glass composition. The reduction in strength is attributed to surface flaws which severely weaken the glass. Orowan proposed that the stress necessary to break a bond is determined by the energy necessary to create two new surfaces due to the fracture. The Orowan stress, σ_m, is given by the expression:

$$\sigma_m = \sqrt{\frac{E\gamma}{r_o}} \tag{11}$$

where y is the fracture surface energy, which has a value in the range of 2 to 4 J m^{-2}. If we substitute values of E = 70 GPa, y = 3 J m^{-2}, and r_o= 0.2 nm into this expression, we obtain a theoretical strength of 32 GPa for a typical silicate glass. Since the terms in this expression are all relatively independent of glass composition, we thus predict that glasses should have strengths in the range of 1 to 100 GPa, regardless of composition.

The strengths calculated using Eq. 11 are orders of magnitude greater than those found in practical applications of bulk glasses. This reduction of strength is attributed to the presence of flaws in the surface of the glass. These flaws act as stress concentrators, increasing the local stresses to levels exceeding the theoretical strength and causing fracture of the glass. Griffith treated this problem in detail and derived the expression:

$$\sigma_{mf} = \sqrt{\frac{2E\gamma}{\pi c^*}} \tag{12}$$

where σ_f is the failure stress and c* is the critical crack length for crack growth, Attainment of the critical crack length is only a necessary condition for crack growth. It is also necessary for the stress at the crack tip to exceed the theoretical strength of the material before the crack will grow spontaneously. Since Griffith flaws typically have curvatures approaching atomic dimensions at their tips, Orowan argues that any applied stress sufficient to exceed the Griffith criterion will also exceed the theoretical strength of the material, and that the Griffith criterion is usually sufficient to cause fracture.

The elastic modulus and the fracture surface energy are relatively small functions of glass composition. Flaws, which are introduced by external factors, are not intrinsic to the material. Flaw lengths are determined by prior treatment of the surface and can vary over several orders of magnitude. It follows that **the inherent strength of a glass is usually of little importance in determining the practical strength. The hardness of a glass can influence the practical strength through its influence on the resistance to flaw formation, i.e., scratch resistance**.

5.1.2 Fatigue

The strength of glasses usually decreases with time under normal ambient conditions. This effect, known as *static fatigue*, is due to interaction of the glass with the surrounding atmosphere, resulting in crack growth under constant load. One also finds that a higher failure strength is observed when the load is increased rapidly than when it is increased slowly. Since this effect is observed under conditions of changing load, it is often called *dynamic fatigue*.

5.1.3 Thermal expansion behaviour

The thermal expansion curve for a glass yields three important pieces of information:

- the thermal expansion coefficient;
- the glass transformation temperature;
- the dilatometric softening temperature.

The thermal expansion coefficient indicates the relation between the volume of a glass and its temperature. The glass transformation temperature indicates the onset of viscoelastic behaviour, while the dilatometric softening temperature indicates the onset of flow under a modest load. Each of these properties is a strong function of glass composition. Lesser effects are due to changes in thermal history or the heating rate used during the measurement. The morphology of a sample has, at best, only a very small effect on the thermal expansion coefficient for phase separated glasses, while the glass transformation and dilatometric softening temperatures are strongly affected by phase separation. Crystallization of a glass can also significantly alter the thermal expansion behaviour of a glass.

5.2 Sealant mechanical properties

Contrary to the glass, the sealant material behaviour could be non-linear and is highly influenced by aspects like the operating temperature and load conditions (duration).

At the current stage of design, sealant mechanical properties are neglected and, according to the problem at hand and to the imposed boundary conditions, the VIG is modelled as a unique glass pane of once (no coupled) /twice (perfectly coupled) the thickness of each glass pane.

5.3 Construction details

Like most building materials, glass elements can only be produced, delivered to site in prefabricated form and installed in situ in limited sizes. On site the glass elements are either individually fixed to a loadbearing construction or they are joined together to form a coherent, self-supporting structure. In doing so, the glass elements must be connected in such a way that the filtering or sealing functions are properly fulfilled. Owing to the transparency of the material, the discontinuity at joints is particularly noticeable; all conduction details demand the utmost care.

Transfer of stress

Fixings for glass and load-carrying connections between glass elements introduce forces into either the edge or the body of the glass. In order **to avoid excessive stress peaks**, a certain minimum size of stress transfer zone is always essential. Local stress peaks, which occur as a result of unintentional contact with other components or twisting at the supports, must be avoided at all costs in glass construction. The mechanisms for transferring stresses in glass elements and the associated typical failure modes are explained below.

Only compressive forces acting perpendicular to the contact face may be transmitted via contact. A prestressed contact face accommodates external tensile forces up to the point of neutralization of the prestress.

The contact faces must be of such a size that the stresses occurring in the zone of stress transfer remain sufficiently low. With hard bearings (glass-steel or glass-glass contact) or when movements and constructional or geometric imperfections have to be absorbed, an intervening elastic pad is necessary.

A contact fixing can only fail if the materials in contact themselves fail as a result of the compressive load or if the contact faces are displaced in relation to each other as a result of vibrations or severe deformation, e.g. if a bent pane slips out of Its glazing bead.

Friction

Forces in a glass element can be transferred by way of friction, i.e. the mechanical interlocking of the microscopic surface imperfections of both contact faces. Besides the mechanical interlock, adhesive forces also occur at the contact face. The relationship between the axial force present and the thrust/shear force which may be transmitted to the glass element by way of friction is roughly linear. As glass cannot be placed directly on steel, the elasticity and fatigue strength of the intervening cushion are crucial to the quality of the friction joint. Intervening buffers may be made from soft metals (pure aluminum, soft- annealed). fiber-reinforced plastics (sealing materials from apparatus engineering) or natural materials processed to a limited extent (cork, leather, cardboard). All these materials must remain permanently within the elastic zone of the stress-strain curve when in use.

5.4 Norms, standards and other technical references

The main references in terms of standards and regulations for the design of glass panes are reported below:

- IStructE. Structural use of glass in buildings. [8]
- pr EN 16612:2013. Glass in building – Design of glass panes – Part 1: General basis of design. [9]
- pr EN 13474-1:1999. Glass in building – Design of glass panes – Part 1: General basis of design. [10]
- BS 6180:2011. Barriers in and about buildings – Code of practice. [11]
- CWCT TU14, Technical update on Load combinations [12]
- CNR-DT 210/2013, Istruzioni per la Progettazione, l'Esecuzione ed il Controllo di Costruzioni con Elementi Strutturali di Vetro. [13]
- JRC 2014. Guidance for European Structural Design of Glass Components. [14]

5.5 Loads

In order to carry on realistic analyses, a set of loads is described hereafter according to an hypothetical scenario.

5.5.1 Vacuum induced load (V)

Equivalent pressure, v_p $= +101.325\ kN/m^2$ *(1 atm)*

5.5.2 Wind load (W)

Net pressure, w_p $= +1.5\ kN/m^2$

Net suction, w_s $= -2.1\ kN/m^2$

5.5.3 Imposed/live load (L)

i. Residential areas:

Line load, $q_{Ih,k}$ *= 0.74 kN/m* *- applied at a height of 1.1m above FFL*

Point load, $Q_{Ih,k}$ *= 0.5 kN* *- applied within a height of 1.1m above FFL*

Infill load, $w_{Ih,k}$ *= 1.0 kN/m²* *- applied within the infill height of 1.1m above FFL*

ii. Retail and general assembly areas:

Line load, $q_{Ih,k}$ *= 1.5 kN/m* *- applied at a height of 1.1m above FFL*

Point load, $Q_{Ih,k}$ *= 1.5 kN* *- applied within a height of 1.1m above FFL*

Infill load, $w_{Ih,k}$ *= 1.5 kN/m²* *- applied within the infill height of 1.1m above FFL*

5.5.4 Maintenance load (M)

Manual maintainance on walls:

Point load, $Q_{Ih,k}$ *= 0.5 kN* *- applied on square of 100mm sides*

5.5.5 Climatic load (C)

Climatic loads as a result of temperature, atmospheric pressure and altitude difference is checked in accordance with prEN 13474-1 under the following hypotheses:

i. Glass production

$H_{production}$ *=+216.0 m* *- above sea level*

ii. Construction site

Highest altitude of glass installation,

H_{site} *=+140.0 m* *- above sea level*

Table 5-3 – Internal actions of insulating glass units.

Summer	Temperature difference, ΔT [°C]	+ 27
	Pressure difference, Δp_{met} [kN/m^2]	- 3.0
	Altitude difference, ΔH [m] = +216 - 0	+ 216
Winter	Temperature difference, ΔT [°C]	-27
	Pressure difference, Δp_{met} [kN/m^2]	+6.0
	Altitude difference, ΔH [m] = 0 - 140	- 140

5.6 Design Approach

IStructE's "Structural use of glass in buildings" 2nd edition and the draft European standard for determination of the load resistance of glass panes prEN 16612 are used as guidance for the following glass structural calculations.

Design criterion : $\sigma_d \leq f_{g,d}$

5.6.1 Glass design stress (σ_d)

Analysis of glass panes gives principal stresses to be factored by the partial factors below.

i. Partial factors

Variable action, γ_Q = 1.2 *- for glass used as infills for façade / curtain wall*

Climatic action, $\psi_0 \cdot \gamma_Q$ = 1.0 *- accompanying variable load to leading wind or imposed load*

5.6.2 Glass design strength ($f_{g,d}$)

i. Annealed glass

Design bending strength, $f_{g,d}$ $= k_{mod} \cdot k_{sp} \cdot f_{g;k} / \gamma_{M;A}$

Characteristic bending strength, $f_{g;k}$ *- see table below*

Load duration factor, k_{mod} *- see table below*

Glass surface profile factor, k_{sp} = 1.0 *- float glass*

Material partial factor, $\gamma_{M;A}$ = 1.6 *- annealed glass*

ii. Prestressed surface glass

Design bending strength, $f_{g,d}$ $= k_{mod} \cdot k_{sp} \cdot f_{g;k} / \gamma_{M;A} + k_v (f_{b;k} - f_{g;k}) / \gamma_{M;v}$

Characteristic bending strength, $f_{b;k}$ *- see table below*

Strengthening factor, k_v = 0.6 *- used either for horizontal or vertical toughening*

Material partial factor, $\gamma_{M;v}$ = 1.2 *- prestressed surface*

Table 5-4 – Allowable stress for vertical glazing infill panel.

Float glass types	Bending Strength [$f_{g,k}$, $f_{b,k}$]	Design Strength [N/mm^2]	
		Wind load* $k_{mod} = 0.74$ (W) $f_{g,d}$	Imposed load only $k_{mod} = 0.89$ (L) $f_{g,d}$
Annealed monolithic	45	20.8	25.0
Heat-strengthened	70	33.3	37.5
Thermally toughened	120	58.3	62.5
Enamelled heat-strengthened	45	20.8	25.0
Enamelled thermally toughened	75	35.8	40.0

Note: *Wind load only or load combination involving wind load.

5.7 Stress analyses

The purpose of the stress analyses performed at this stage is to explore those combinations of design parameter values that could lead to safe solutions. To make this possible in an efficient way, some simplifications are applied to the problem. Indeed, interest is in directing the next steps of design more than providing fully accurate solutions.

5.7.1 Analysis settings

The analyses have been performed mainly by means of analytical calculations since closed form solutions exist for the investigated static schemes. Some additional 2D FE analyses using the Sap2000 Advanced solver[5] have been performed on a case by case basis.

Accepting the approximation error, in order to take advantage of closed form solutions, some simplifications have been introduced in terms of boundary conditions. Specifically, restraints against displacement in the Y direction (perpendicular to glass plane) have been placed along the edges of the glass pane to simulate the framing system.

Simplifications have been also made in terms of considered load patterns; namely only vacuum and wind loads have been considered at this stage.

Materials and load combinations have been assumed according to the previously defined design approach.

Then, two different models have been made for the calculation of the wind induced stress and the vacuum induced stress. The specificities of these two models are further discussed in the next paragraphs.

5.7.2 Wind induced stress

Wind induced stress are supposed to be independent of the pillars distribution and have been calculated according to the Annex B of EN 16612.

The analysis is considering a two glass panes separated by the vacuum cavity and coupled through the sealant at the glass edges, as represented in Figure 3-3. In the model, the coupling of the two panes has been represented through a unique glass section of twice the thickness of the single pane.

As analysis scenarios, the combinations derived from three glass thickness options – i.e. 3, 4 and 6 mm – and different glass dimension options – i.e. 600x1500 mm, 600x2000 mm, 600x2500 mm, 1000x1500 mm, 1000x2000 mm, 1000x2500 mm, 1500x1500 mm, 1500x2000 mm and 1500x2500 mm have been considered.

The following tables show the main results from the performed analyses.

Table 5-5 – Wind induced max displacement (w_{max} [mm]) on different glass panes (thickness and dimensions in mm).

w_{max}	600*1500	600*2000	600*2500	1000*1500	1000*2000	1000*2500	1500*1500	1500*2000	1500*2500
3	3.9456	4.3560	4.5054	12.6587	16.8082	20.5029	20.5056	27.6700	34.6598
4	1.7002	1.8559	1.9095	7.6061	10.0317	11.7914	14.2361	19.7012	24.7880
6	0.5050	0.5505	0.5661	2.5997	3.4053	3.8743	6.4839	9.9261	12.7458

deflection limit =min(50; (shorter dimension/65))

600*1500	600*2000	600*2500	1000*1500	1000*2000	1000*2500	1500*1500	1500*2000	1500*2500
9.23	9.23	9.23	15.38	15.38	15.38	23.08	23.08	23.08

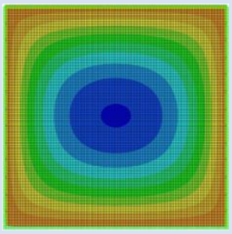
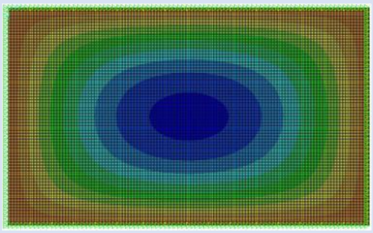
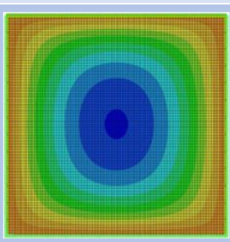
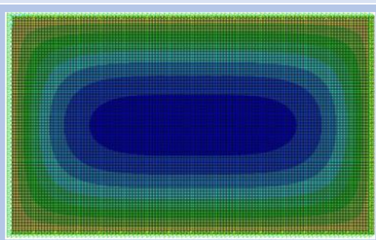
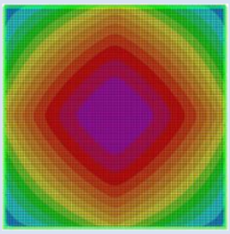
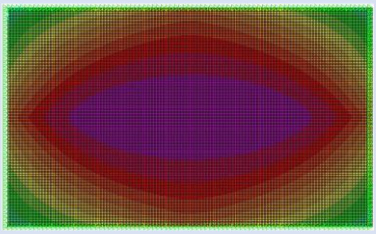
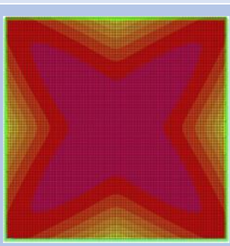
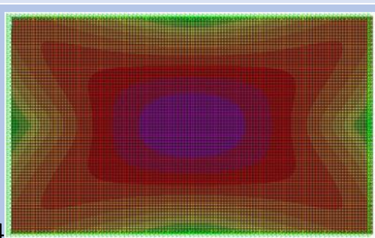
[5] www.csi-italia.eu

Table 5-6 – Wind induced maximum stress (σ_{max} [MPa]) on different glass panes (thickness and dimensions in mm).

σ_{max}	600*1500	600*2000	600*2500	1000*1500	1000*2000	1000*2500	1500*1500	1500*2000	1500*2500
3	23.90	25.90	26.61	31.94	39.59	47.42	32.51	41.11	49.54
4	13.57	14.64	15.01	24.82	31.23	35.57	25.97	30.92	35.82
6	6.04	6.51	6.67	11.81	14.96	16.73	14.83	22.03	27.23

In order to give also a visual results of the stress distribution, the following table shows some results from a FE analysis.

Table 5-7 – Wind induced stress for 6 mm thick glass pane of dimension 1.5m x 1.5m and 1.5m x 2.5m

	Glass pane 1.5m x 1.5m	Glass pane 1.5m x 2.5m
Displacement [mm]	Uy= 7 mm = a/214 <a/65	Uy= 14.8 mm =a/101<a/65
Mx [kNm]	 Mx max =0.364 kNm	 Mx max =0.705 kNm
My [kNm]	 My max =0.364 kNm	 My max =0.340 kNm
σmax [MPa]	 σmax =17.4 MPa	 σmax =14.3 MPa
σmin [MPa]	 σmin =-17.4 MPa	4  σmin =-29.2 MPa

Project		Number	Sheet No
EENSULATE		**16-047 TI**	**1/1**
Area of Project			Revision
Simply supported rectangular plate			**Rev.0**
Element Description			Prepared by / date
Maximum stress and deflection - uniform load			**SID / 28-02-2017**
According to EN16612 ANNEX B			Checked by / date
			SID / 28-02-2017

1. DIMENSION			
Dimension a (shorter)	a=	1500	[mm]
Dimension b (longer)	b=	2500	[mm]
Aspect ratio	λ=a/b	0.6	[-]
Thickness	h=	12	[mm]
2. MATERIAL			
Young Modulus	E=	70000	[Mpa]
Poisson ratio	ν=	0.22	[-]
3. LOAD			
Load	Fd=	3.6	[kN/m2]
Load	Fd=	0.0036	[Mpa]
Non dimensional load	p*=	2.180	[-]

4. CALCULATION OF STRESS

The coefficients given in the following formulas are valid for Poisson number in range 0.20 to 0.24

$$\sigma_{max} = k_1 \frac{A}{h^2} F_d$$

where

$$k_1 = \frac{1}{4\left[\frac{1}{z_2^2} + \frac{p^{*2}}{\left(z_3^2 + (z_4 p^*)^2\right)}\right]^{0.5}}$$

$$z_2 = 24\lambda\left[0.0447 + 0.0803\left(1 - \exp\left(-1.17\left(\frac{1}{\lambda} - 1\right)^{1.073}\right)\right)\right]$$

$$z_3 = 4.5\left(\frac{1}{\lambda} - 1\right)^2 + 4.5$$

$$z_4 = 0.585 - 0.05\left(\frac{1}{\lambda} - 1\right)$$

Coefficient z2	z2=	1.258	[-]
Coefficient z3	z3=	6.500	[-]
Coefficient z4	z4=	0.552	[-]
Coefficient k1	k1=	0.2904	[-]
Maximum stress at the center of the plate	**σmax=**	**27.23**	**[Mpa]**

4. CALCULATION OF DEFLECTION

The coefficients given in the following formulas are valid for Poisson number in range 0.20 to 0.24

$$w_{max} = k_4 \frac{A^2}{h^3} \frac{F_d}{E}$$

where

$$k_4 = \frac{\left[\frac{\left(\left(\frac{1}{z_1^4} + 4p^{*2}\right)^{0.5} - \frac{1}{z_1^2}\right)}{2}\right]^{0.5}}{16p^*}$$

$$z_1 = 192\left(1 - \mu^2\right)\lambda^2\left[0.00406 + 0.00896\left(1 - \exp\left(-1.123\left(\frac{1}{\lambda} - 1\right)^{1.097}\right)\right)\right]$$

Note: For p*=0, $k_4 = \frac{z_1}{16}$

Coefficient z1	z1=	0.569	[-]
Coefficient k4	k4=	0.0305	[-]
Allowable deflection	Wadm=	23.08	[mm]
Maximum deflection at the center of the plate	**Wmax=**	**12.75**	**[mm]**

Figure 5-2 – Example of calculation sheet for wind induced max stress and displacement according to EN 16612.

5.7.3 Vacuum induced stress

The analysis is considering two glass panes separated by the vacuum cavity and coupled through the sealant at the glass edges, as represented in Figure 3-3. In the model, the coupling of the two panes has been neglected and the thickness of a single pane has been considered as the calculation section.

Pillars have been modelled as restraints against displacement in the Y direction (perpendicular to glass plane).

The adopted static scheme is then that of a plate supported by a rows of equivalent columns and a closed form solution is available according to Timoshenko [15] . A diameter of 0.5 mm for the pillars has been assumed for the calculation of the resultant stress at the supports. The results of the analyses for different glass pane thickness and different spacing of the pillars are reported in the following tables.

Table 5-8 – Vacuum induced maximum deflection at the centre of the plate.

w,center [mm]		distance between pillars [mm]		
		20	**40**	**50**
thickness [mm]	**3**	0.00139	0.00911	0.02223
	4	0.00059	0.00384	0.00938
	6	0.00017	0.00114	0.00278

Table 5-9 – Vacuum induced maximum stress at the centre of the plate.

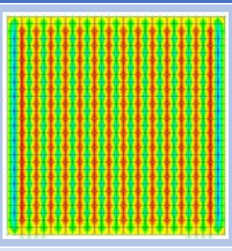
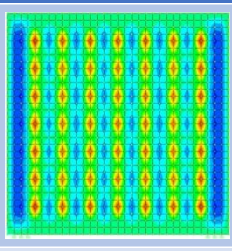
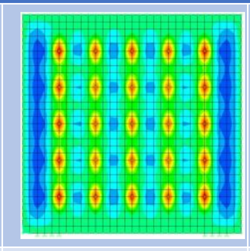
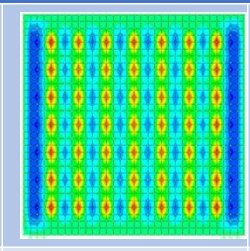
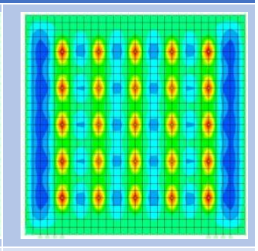
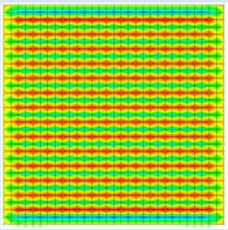
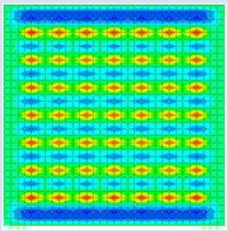
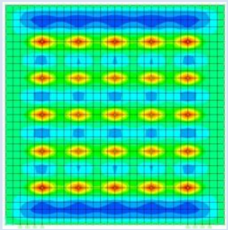
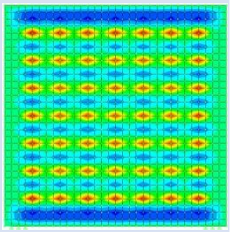
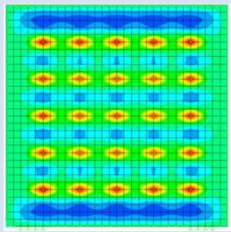
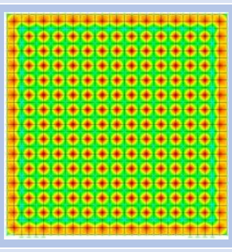
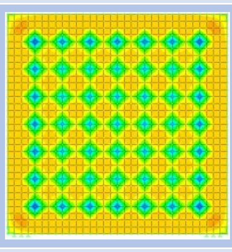
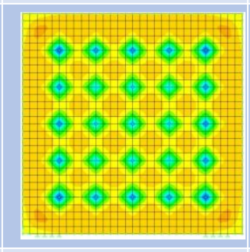
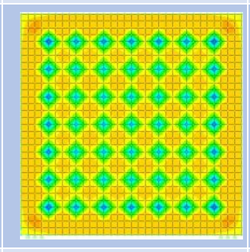
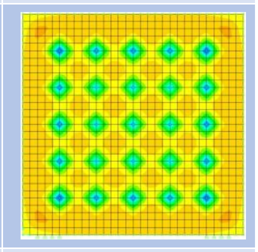
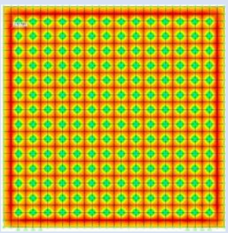
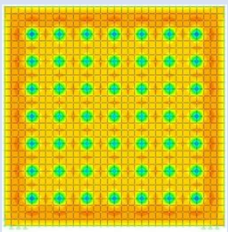
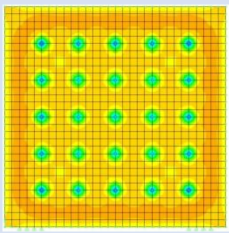
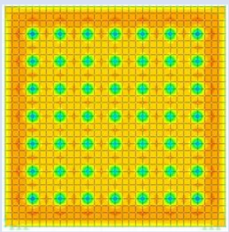
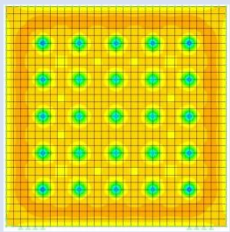
σmax,center [Mpa]		distance between pillars [mm]		
		20	**40**	**50**
thickness [mm]	**3**	1.40	3.58	5.59
	4	0.79	2.01	3.14
	6	0.35	0.89	1.40

Table 5-10 – Vacuum induced maximum stress at the supports (pillars).

σmax,pillar [Mpa]		distance between pillars [mm]		
		25	**40**	**50**
thickness [mm]	**3**	4.873	14.618	24.429
	4	2.741	8.223	13.741
	6	1.218	3.654	6.107

Some FE analyses have been also performed in parallel to provide a visual outcome of the stress distribution around the pillars for a 300x300 mm glass pane. Stress maps are reported in Table 5-11; numerical results are instead omitted since the mesh density is not enough to provide significant values.

Table 5-11 – Vacuum induced stress – visual results for glass pane 300 x 300 mm.

	Thickness 3mm i=20mm	Thickness 4mm i=37.5mm	Thickness 4mm i=50mm	Thickness 6mm i=37.5mm	Thickness 6mm i=50mm
Moment x [kNm]					
Moment y [kNm]					
σmax [MPa]					
σmain [MPa]					

Project	Number	Sheet No
EENSULATE	16-047 TI	1/2
Area of Project		Revision
Plate Supported by Row of Equivalent Columns		Rev.0
Element Description		Prepared by / date
Maximum Moment and deflection - uniform load According to "Theory of Plates and Shells" by Timoshenko		SID / 28-02-2017
		Checked by / date
		SID / 28-02-2017

1. DIMENSION

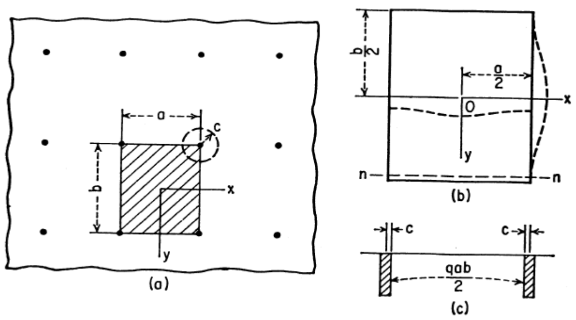
Dimension a (shorter)	a=	50	[mm]
Dimension b (longer)	b=	50	[mm]
Thickness	s=	6	[mm]
Radius of column	c=	0.25	[mm]
Aspect ratio	b/a=	1	[-]

2. MATERIAL

Young Modulus	E=	70000	[Mpa]
D=(E*s^3)/(12*(1-ν^2))	D=	1324085.8	[-]
Poisson ratio	ν=	0.22	[-]

3. LOAD

Load	q=	101.325	[kN/m2]
Load	q=	0.101325	[Mpa]



4. CALCULATION OF DEFLECTION AND MOMENT AT THE CENTER OF THE PLATE

The coefficients given in the following tables are valid for Poisson number equal to 0.2

b/a	α	β	β1
1	0.00581	0.0331	0.0331
1.1	0.00487	0.0231	0.0352
1.2	0.00428	0.021	0.0363
1.3	0.00387	0.0175	0.0375
1.4	0.00358	0.0149	0.0384
1.5	0.00337	0.0131	0.0387
1.6	0.00328	0.01232	0.03918
1.7	0.00319	0.01154	0.03966
1.8	0.0031	0.01076	0.04014
1.9	0.00301	0.00998	0.04062
2	0.00292	0.0092	0.0411
infinite	0.0026	0.0083	0.0417

		α	β	β1
(b/a)min=	1.0	0.00581	0.0331	0.0331
(b/a)max=	1.0	0.00581	0.0331	0.0331

α (b/a)	0.00581
β (b/a)	0.03310
β1 (b/a)	0.03310

$$w = \alpha \frac{qb^4}{D} \qquad M_x = \beta q b^2 \qquad M_y = \beta_1 q b^2$$

Deflection at the center of the plate	w=	**0.00278**	**[mm]**
Maximum moment x at the center of the plate	Mx=	**8.385**	**[Nmm]**
Maximum moment y at the center of the plate	My=	**8.385**	**[Nmm]**

Figure 5-3 – Example of calculation sheet for vacuum induced max stress and displacement according to plate theory – part 1.

Project	Number	Sheet No
EENSULATE	16-047 TI	2/2
Area of Project		Revision
Plate Supported by Row of Equivalent Columns		Rev.0
Element Description		Prepared by / date
Maximum Moment and deflection - uniform load		SID / 28-02-2017
According to "Theory of Plates and Shells" by Timoshenko		Checked by / date
		SID / 28-02-2017

5. CALCULATION OF MOMENT AT SUPPORTS

The values of Mx and My at the supports are given by the following formulas

$$(M_x)_{x=a/2, y=b/2} = -\frac{qab}{4\pi}\left[(1+\nu)\log\frac{a}{c} - (\alpha + \beta\nu)\right]$$

$$(M_y)_{x=a/2, y=b/2} = -\frac{qab}{4\pi}\left[(1+\nu)\log\frac{a}{c} - (\beta + \alpha\nu)\right]$$

in which α and β are coefficient given for several value of ratio *b/a* by the following table

b/a	α	β
1	0.811	0.811
1.1	0.822	0.698
1.2	0.829	0.588
1.3	0.833	0.481
1.4	0.835	0.374
1.5	0.836	0.268
1.6	0.8364	0.1632
1.7	0.8368	0.0584
1.8	0.8372	-0.0464
1.9	0.8376	-0.1512
2	0.838	-0.256

		α	β
(b/a)min=	1.0	0.811	0.811
(b/a)max=	1.0	0.811	0.811

α (b/a)	0.811
β (b/a)	0.811

Moment Mx at support	Mx=	**-36.644 [Nmm]**
Moment My at support	My=	**-36.644 [Nmm]**

6. CALCULATION OF STRESS

6.1. stress at the center of plate

Flexural modulus	W=	6 mm3/mm
Maximum stress in x direction	**σ1=**	1.397 **[Mpa]**
Maximum stress in y direction	**σ2=**	1.397 **[Mpa]**
Maximum stress	**σmax=**	**1.397** [Mpa]

6.2. stress at the support

Flexural modulus	W=	6 mm3/mm
Maximum stress in x direction	**σ1=**	-6.107 **[Mpa]**
Maximum stress in y direction	**σ2=**	-6.107 **[Mpa]**
Maximum stress	**σmax=**	**-6.107** [Mpa]

Figure 5-4 – Example of calculation sheet for vacuum induced max stress and displacement according to plate theory – part 2.

5.7.4 Combination of actions

Under the assumption of a linear behavior of the glass material, by combining the actions derived from each of the previous models according to chapter 5.6, the resulting stresses reported in the following tables are found. Table values are differently colored depending on which type of glass can be considered for the design (i.e. which design stress threshold has been passed according to Table 5-4): green – all type of glass can be considered, yellow – annealed glass type doesn't satisfy the strength requirements, orange – only thermally toughened glass type could satisfy the strength requirements; red – not feasible design setting.

Table 5-12 – Combined tress [MPa] with pillars spacing @ 25 mm.

σmax	600*1500	600*2000	600*2500	1000*1500	1000*2000	1000*2500	1500*1500	1500*2000	1500*2500
3	33.55	35.96	36.80	43.20	52.38	61.78	43.89	54.20	64.32
4	19.03	20.31	20.75	32.53	40.22	45.42	33.91	39.84	45.72
6	8.46	9.03	9.23	15.39	19.17	21.30	19.02	27.65	33.89

Table 5-13 – Combined tress [MPa] with pillars spacing @ 40 mm.

σmax	600*1500	600*2000	600*2500	1000*1500	1000*2000	1000*2500	1500*1500	1500*2000	1500*2500
3	43.30	45.70	46.55	52.94	62.13	71.52	53.63	63.95	74.06
4	24.51	25.80	26.23	38.01	45.70	50.91	39.39	45.32	51.20
6	10.90	11.47	11.66	17.82	21.61	23.73	21.45	30.08	36.33

Table 5-14 – Combined tress [MPa] with pillars spacing @50 mm.

σmax	600*1500	600*2000	600*2500	1000*1500	1000*2000	1000*2500	1500*1500	1500*2000	1500*2500
3	53.11	55.51	56.36	62.75	71.94	81.34	63.44	73.76	83.88
4	30.03	31.31	31.75	43.53	51.22	56.42	44.91	50.84	56.72
6	13.35	13.92	14.11	20.28	24.06	26.19	23.91	32.54	38.78

As already stated, the results are not to be intended as accurate safety assessments since several simplifications have been assumed and only part of the possible load patterns have been considered. Moreover, having 3 mm thick thermally toughened glass is not considered a realistic option.

However, keeping in mind the scope of the analyses, the tables above suggest that 40 to 50 mm spacing of the pillars with thermally toughened glass could be a feasible solution considering a 4/6 mm thick pane.

In fact, up to 6 mm thick pane, the weight to square meter ratio of the Eensulate module can be kept under 45 kg/m^2 as illustrated in the table below.

Table 5-15 – Estimated weight of the Eensulate module.

Total area	**5.25**	**m²**				
	Density [kg/mc]	Thickness [m]	Volume [m3]	Weight [kg]	Linear weight [kg/m]	
VIG	2500	0.012	0.045	112.5		
OCN Foam	20	0.15	0.225	4.5		
Frame (Aluminum)	2700			79.11	6.88	
Spandrel (glass)	2500	0.006	0.009	22.5		
Spandrel (metal)	2900	0.003	0.0045	13.05		
Total weight				**231.66**		
Weight/m²				**44.13**	kg/m²	< 45

On the other hand, the 25 mm pillars spacing case is just reported as a reference of available solutions in the market since it does not allow to reach the thermal performance target as already commented in chapter 4.

5.8 Shear force at glass edges

As a preliminary estimation of the shear strength required by the sealant in order to accommodate the different dilatations of the glass panes induced by internal-external temperature difference, a rough calculation has been made under the following hypotheses:

- Thermal expansion factor (α) = 9×10^{-6} K^{-1} - in the range 20 ÷ 300 °C
- Maximum dimension of the glass pane (d_{max}) = 2.5 m
- Minimum dimension of the glass pane (d_{min}) = 1.5 m
- Temperature difference (ΔT) = 50 °C
- Young modulus of the sealant (E_{seal})
- Glass panes can freely dilate in all directions

Therefore, since the expected maximum relative displacement between the two glass pane is calculated as:

$$\delta = \frac{\alpha \times d_{max} \times \Delta T}{2}$$

this leads to δ = 1.125 mm.

The shear action on the sealant is then calculated as:

$$V = \delta \times E_{seal}/d_{min}$$

For an assumed $E_{seal} = 1750$ N/mm², the shear value would be $V = 1.31$ kN/m

PART B: FAÇADE PERCEPTION AND INTEGRATION WITH BUILDING

6 Vision for the future of a curtain wall system

In order to provide suitable design solution for the curtain wall system it is necessary to match the future functional needs as well as the aesthetical tastes of the architects, developers and users. In order to achieve the needs of clients and users in the near future, one should look at the not yet achievable goals inherent in state of the art facades and fabrication technologies today. For this concept document those aspects of the state of the art have been divided into 5 topics:

- Optimization of complex systems
- Pure transparency
- Interactive modulation
- Light and Media
- Energy Harvesting

While the Eensulate system will not achieve all of these goals, it is worthwhile to understand how the project will be a step down the path toward the facades of the future.

6.1 Long Term Goals of Curtain Wall Systems

Curtain wall system development is a relatively complex and time consuming process, therefore a long term strategy with stretch goals is required to show the direction for the advancements of the Eensulate project and the development of curtain wall systems in general. Below we will go through these goals laid out above.

6.1.1 Optimization of complex systems

State of the art façade systems are increasingly multifunctional, with more systems implemented in them than ever before. Therefore it is necessary to fully control the integrity and appearance of those systems. With an understanding of the processes and combinations of systems a more efficient design can be achieved. One may be required to have interior and exterior blinds or shading, solar control, double skins, security, operable windows, opaque panels and other components possible in the current market. It is no longer acceptable to aggregate these components with taking into account their implicit redundancies and possibilities for integration.

Figure 6-1 – This 3d printed and structurally optimized node (2015), from Arup, demonstrates the surprising results of integration in a complex system.

6.1.2 Pure transparency

The main reason for the curtain wall development was to create the feeling of openness to the outside and bring in light to deep spaces, which creates a better quality working and living environment. The recent trend of glass facades is to reduce the mullions size and visibility, and to highlight those effects in an elegant manner. Clearly, the complex systems mentioned above do not allow this level of transparency. Nonetheless, this level of transparency is still demanded by clients and end users. Thus the desire for 'Pure Transparency' requires the most efficient integration of complex systems. In order to achieve these seemingly contradictory goals, one must work below the level of visibility. It is in this combination of systems at the micro and nano level that the Eensulate takes the possibilities of facades several steps into the future.

Figure 6-2 – Apple store, 5th Avenue, NY, USA, by Bohlin Cywinski Jackson

6.1.3 Interaction

One of the most difficult and simultaneously important hurdles for the improved comfort and efficiency of façades is the ability to control their performance in a continuous and interactive way. Whether it is the shading system integrated in a façade that allows users to manually control the light on their desk or the thermal active coating to adjust the proper radiant heat vs. light transmission through different seasons, in the future the dynamic quality of a façade system will determine its acceptance in the market. As stated in other Eensulate deliverables the curtain wall façade renovation market is growing as early curtain wall installations are ending their warranty and viability lifetimes.

Figure 6-3 – In the future direct interaction, either manually or automatically, will be required for the modulation of façade performance.

While the basic structure and fabrication of curtain walls has not changed since their inception several decades ago, the materials that systems that can be integrated into them has grown exponentially. Mechanical shading systems, smart coatings and adjustable ventilation systems are just some of these possibilities that allow interaction and don't require a whole sale adjustment to the building structure in order to implement them. The Eensulate project aims precisely at this market with the inclusion of the moth-eyed nanostrutural coating.

In order for efficiency and comfort to be durable, interaction will also be required with building systems. Mechanical ventilation, electrical, low voltage and even plumbing systems should be integrated for the optimum performance of future facades.

6.1.4 Light and Media

Figure 6-4 – Galleria Centercity, Cheonan, Korea, by UNStudio

Light and media always provide the possibility for interaction. This might be at the level of interacting with the activity of a city, providing space for advertisement and information or providing lights for traffic and pedestrians. Lighting will be integrated in façade systems, which allow buildings to communicate with the environment and light its surroundings. A more seamless connection with city infrastructure will mean more efficient energy and communication networks.

Media content is already used in many commercial buildings in cities where space is at a premium. We imagine that this will continue, and increase, allowing buildings to not only communicate advertisements and entertainment, but also to communicate their energy and health status. At the smaller scale front doors, entrance lobbies and foyers will integrate media from the facades above into their content.

6.1.5 Energy harvesting

Figure 6-5 – Wind turbine farm

Energy use and production will be a primary barrier and driver for facades of the future. To offset the cost and power of light and media light and media as discussed above, facades will be required to produce their own energy. It will also further the communication between buildings and the built environment around them as buildings begin to give energy back to the grid.

6.2 The goals and vision of Eensulate project

Figure 6-6 – The placement of Eensulate project within curtain wall properties to understand how it will play into the future of façade development.

Further development of the system will answer where the Eensulate project is located within the trajectory of the future of curtain wall. It is a strong step in the direction of pure transparency and the optimization of complex systems toward a multifunctional integrated façade.

7 Design guidelines for Eensulate

The Eensulate system should be flexible enough in design to be applied to various building typologies and functions. The more geometric possibilities can be achieved by the modules the greater the possibilities of application can be obtained by the system.

7.1 System categories

3 system categories have been presumed. They relate to various wall types and building functions.

7.1.1 System category 1 – Transparent and multi-functional

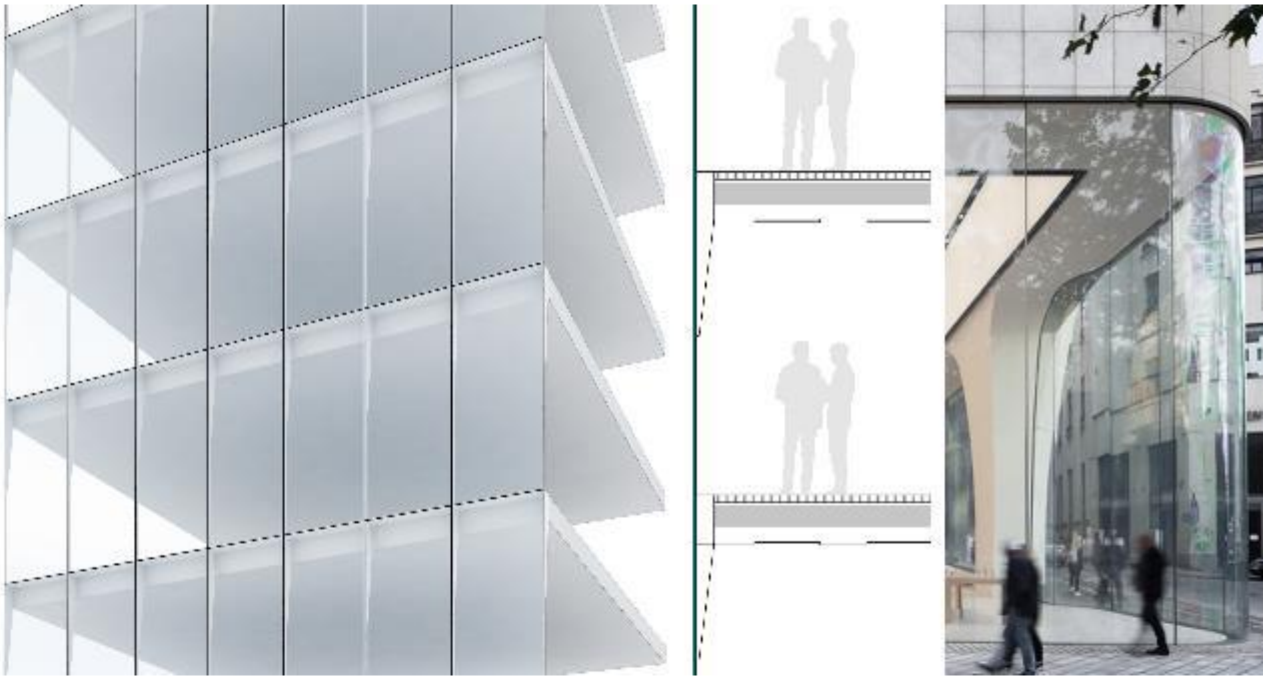


Figure 7-1 – System category 1 perception

Façade parameters	Frame parameters	Glass parameters
1. High transparency 2. All-weather responsiveness	1. Heating (bottom transom heating system) 2. Cooling (top transom ventilation system) 3. Ventilation (through frame) 4. Insulation (at spandrel)	1. Light transmittance 0.90 2. Thermal insulation U=0.4W/m²K (vig) 3. Safety (laminated glass) 4. Acoustic performance up to Rw=52db 5. Solar gain control (thermotunable coating) 6. Shading (Low-E coating) 7. Self-cleaning and anti-fogging (nanocoating) 8. Energy renewal (PV cells) 9. Light and media display

7.1.2 System category 2 – Modern curtain wall retrofitting

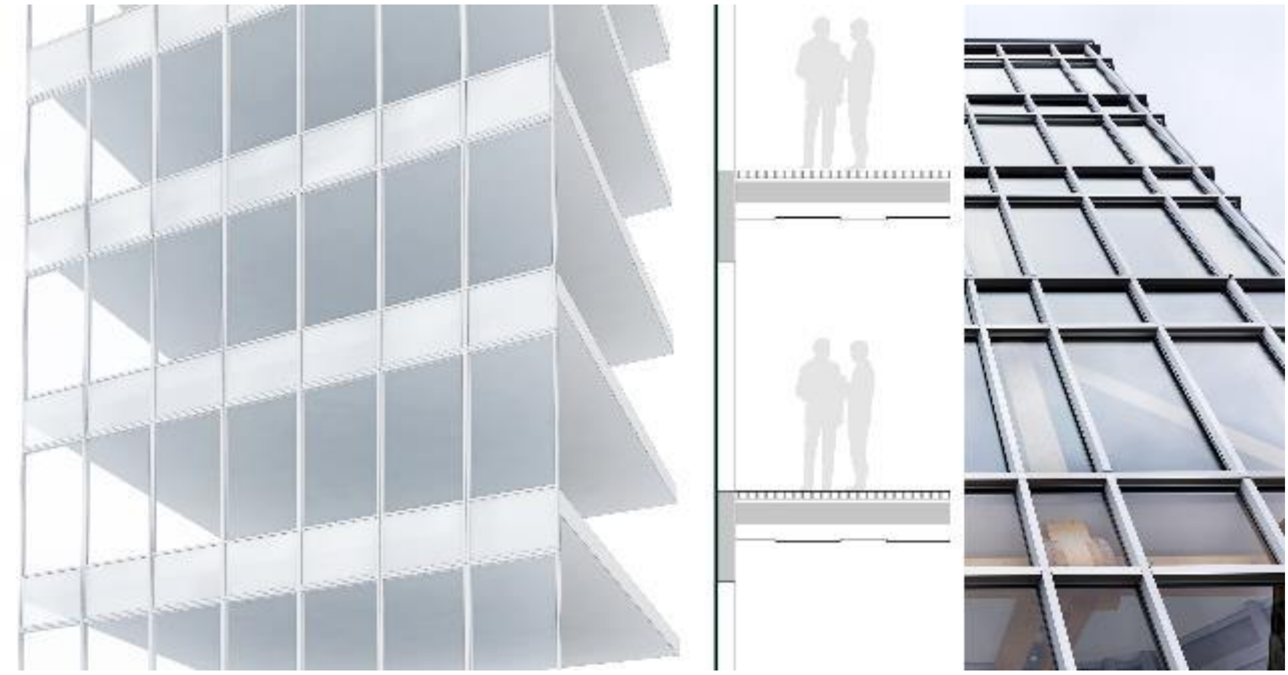


Figure 7-2 – System category 2 perception

Façade parameters	Frame parameters	Glass parameters
1. Increased transparency 2. Improved performance	1. Ventilation (operable window or through frame) 2. Insulating (at spandrel)	1. Light transmittance 0.90 2. Thermal insulation U=0.4W/m²K 3. Safety (laminated glass) 4. Acoustic performance up to Rw=52db 5. Solar gain control (thermotunable coating) 6. Shading (Low-E coating) 7. Self-cleaning (nanocoating)

7.1.3 System category 3 – Window retrofitting

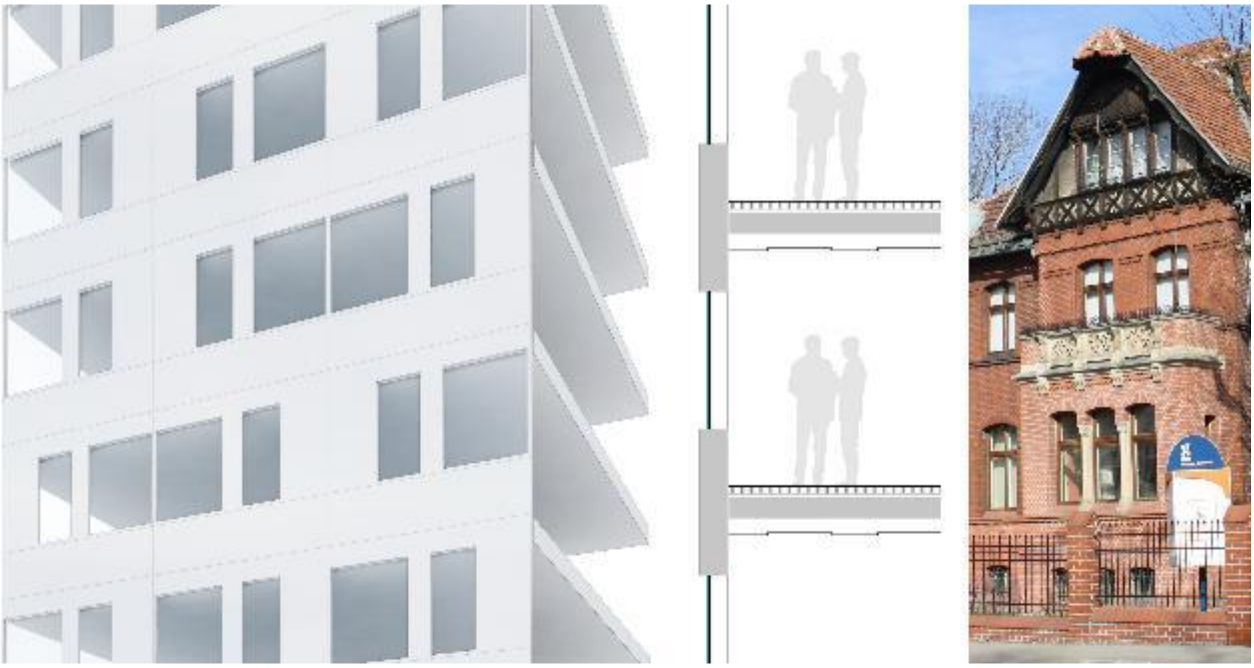


Figure 7-3 – System category 3 perception

Façade parameters	Frame parameters	Glass parameters
1. Preserve intended aesthetics 2. Improved performance	1. Ventilation (operable window or through frame) 2. Insulating (at spandrel)	1. Light transmittance 0.90 2. Thermal insulation U=0.4W/m²K (vig) 3. Safety (laminated glass) 4. Acoustic performance up to Rw=52db 5. Solar gain control (thermotunable coating) 6. Shading (Low-E coating) 7. Self-cleaning and anti-fogging (nanocoating)

7.2 System components

According to technical features of the system, the frame, pillars and spandrel can be extracted as separate elements. The variable appearance of those system components relates to the system categories. The concept and detail design of the components should be accomplished taking into consideration their feasibility and influence on the perception of the façade.

7.2.1 Frame

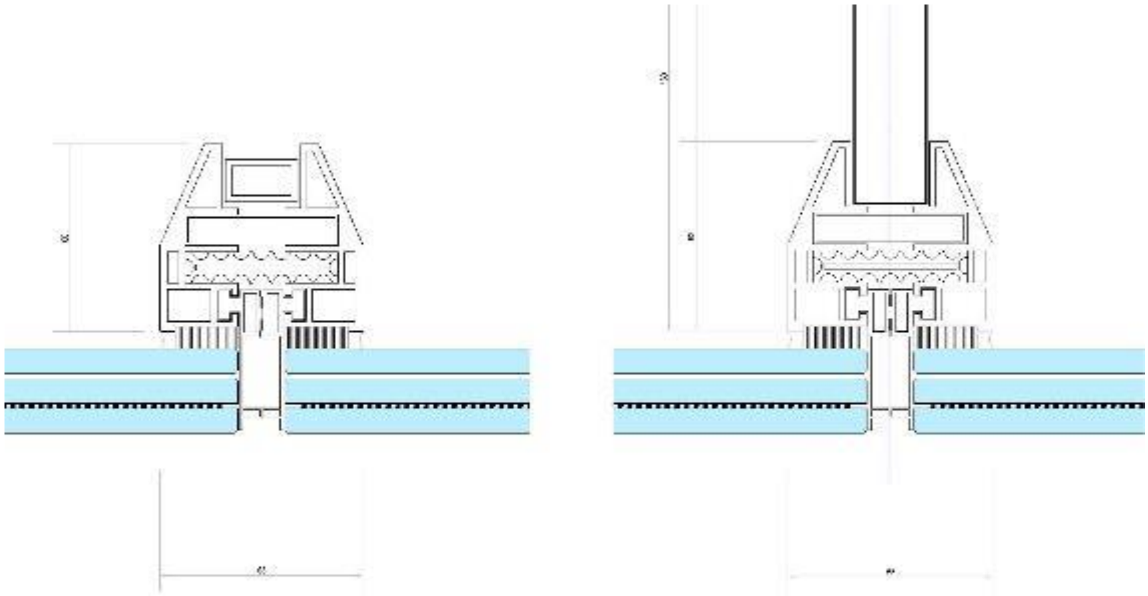


Figure 7-4 – System category 1 detail. Structural silicon connection with variable depth of profile as necessary from structural modelling.

Various frame detail designs should be considered to match different system categories. By reducing the mullion elements in front of the glass it is possible to achieve the impression of pure transparent glass envelope (7.1.2).

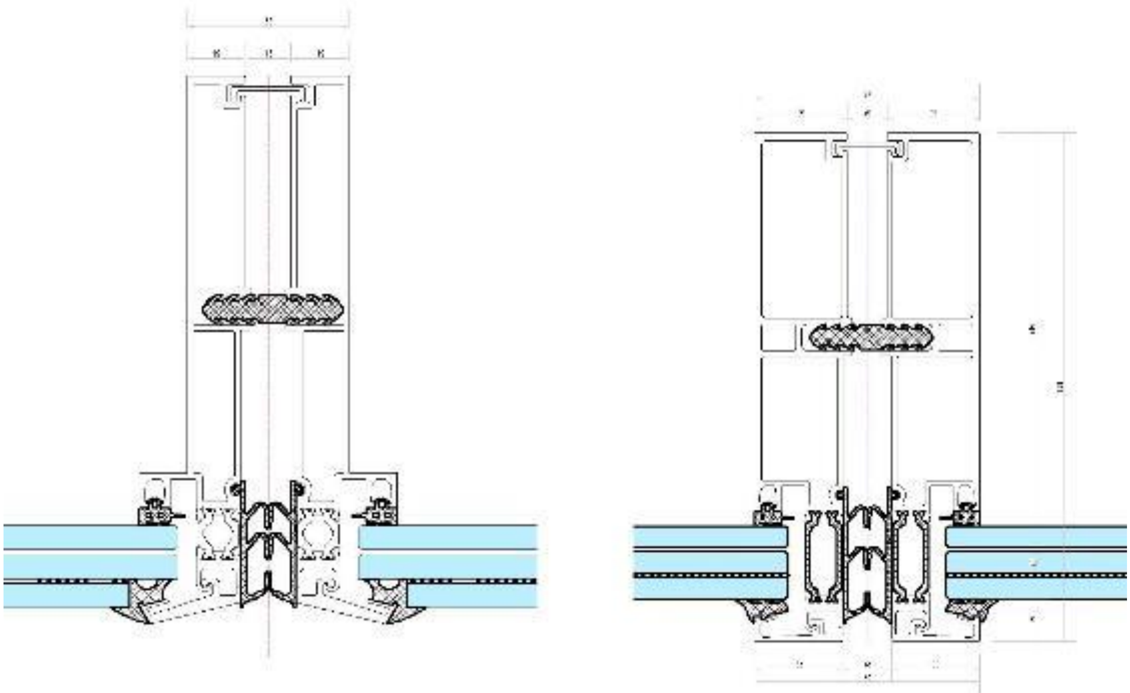


Figure 7-5 – System category 2 detail. 2 options for mechanically fixed VIG with aluminium cap.

Window details will be developed further for specific demo cases in Deliverable 1.4

The window retrofitting (7.1.3) frame system should allow for:

- Often very thin mullions
- Operable units
- Variable frame materials like wood, steel and aluminium.
- Arched, curved or circular shapes
- Small glass pieces

-

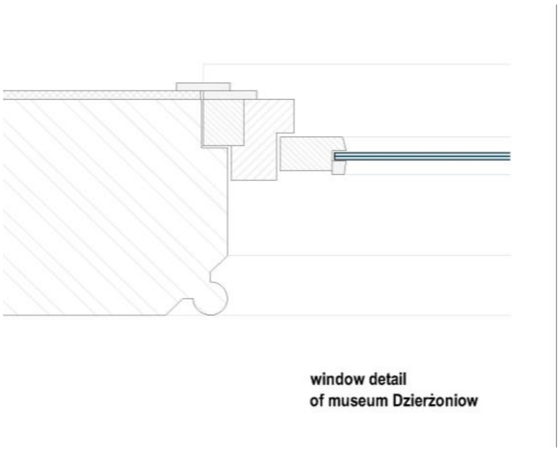


Figure 7-6 - Assumed detail of the museum in Dzierzoniow Poland

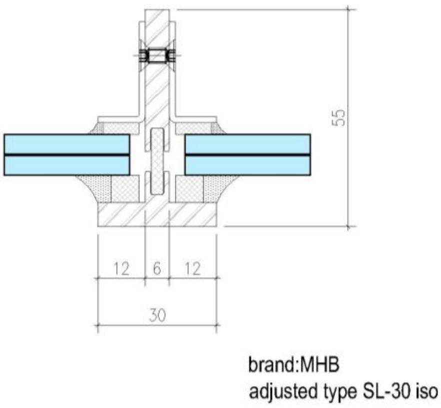


Figure 7-7 - Detail of a possible steel mullion which can be used in the facade of the pavillion Zonnestraal Hilversum Holland

7.2.2 Pillar layout

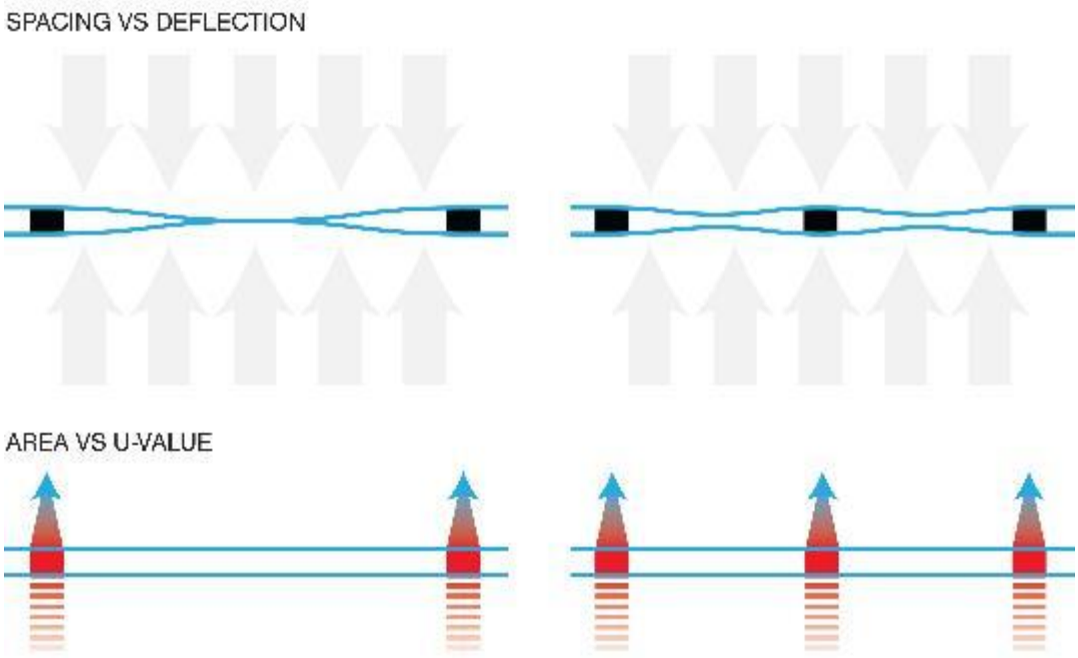


Figure 7-8 – Pillars location guidelines

The spacing of the pillars should be an optimum between the fabrication possibilities, the glass deflection and the U-value.

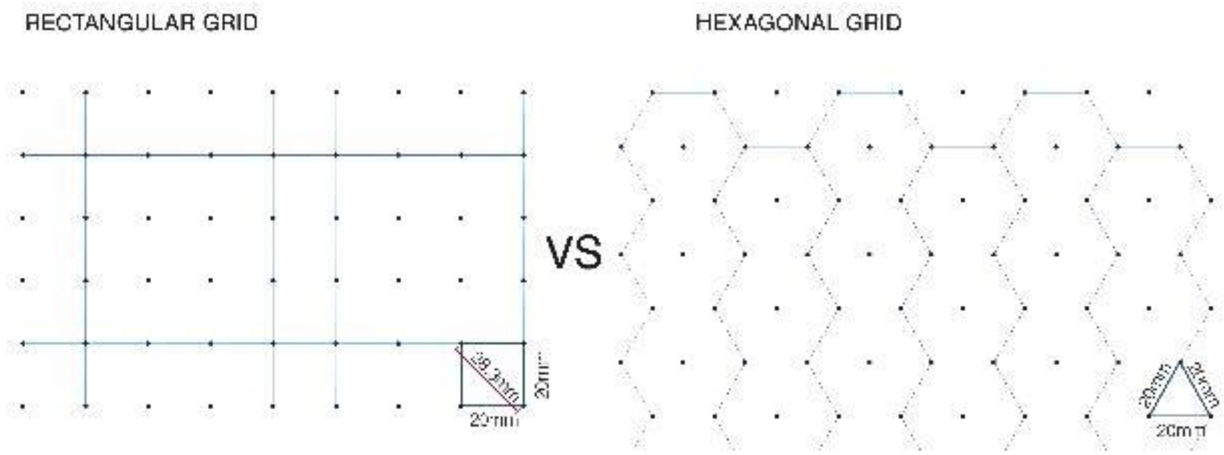


Figure 7-9 – Pillar grid efficiency diagram

In terms of the relation of spacing between U-Value and glass deflection the hexagonal grid is more efficient than the typically used rectangular grid, because it provides a constant distance between the pillars. Therefore the same spacing quality can be achieved with less pillars usage. Which reduce the overall spacer area, therefore reducing the relative U-value. The Pillar layout design relates to thermal efficiency and close perception of the façade. The spacers might influence the view from the inside of the building and can create interesting for the designer.

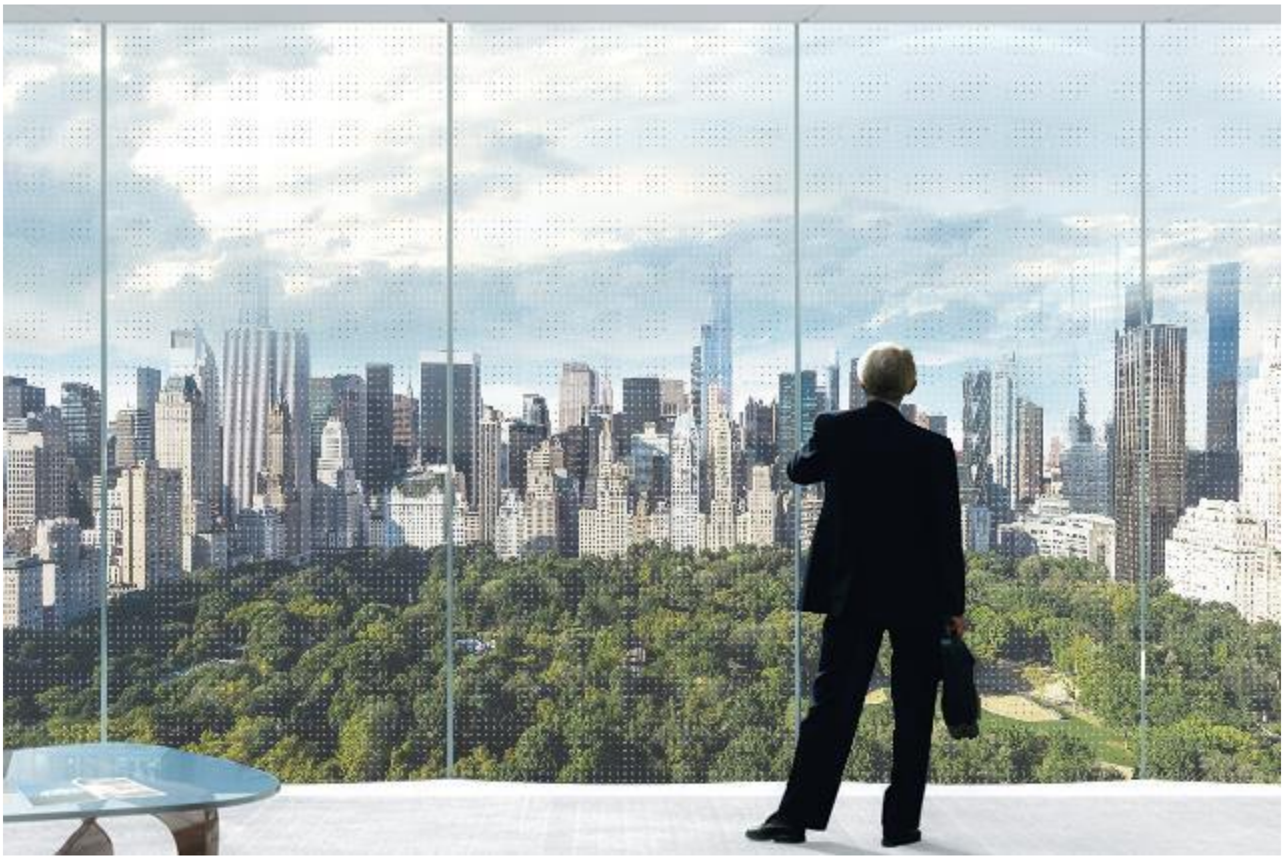


Figure 7-10 - Rectangular grid pillar perception

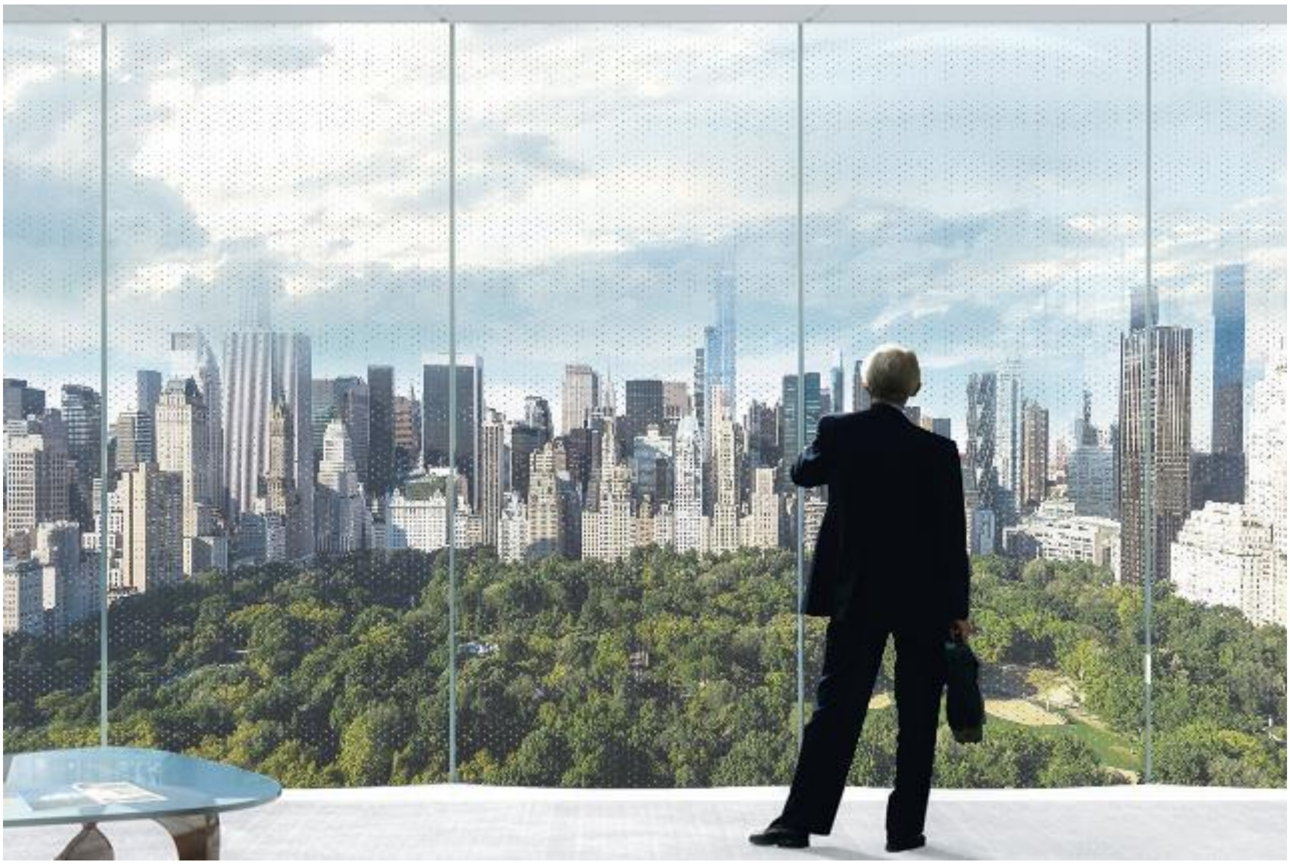


Figure 7-11 – Hexagonal grid pillar perception

Figure 7-12 – Gradient grid pillar perception

Figure 7-13 – Irregular grid pillar perception

7.2.3 Spandrel

Design of the spandrel detail component should allow for straight forward and low cost possibility of various materials and geometries. The designer using the system should be able to choose among a diverse selection of material types. Below are several common examples.

Figure 7-14 – Usage of ceramics in façade design

Figure 7-15 – Usage of aluminium in façade design

Figure 7-16 – Usage of composite in façade design

Figure 7-17 – Usage of concrete in façade design

Figure 7-18 – Usage of ceramics in façade design

Figure 7-19 – Usage of glass spandrel in façade design

Figure 7-20 – Usage of dichroic foil glas in façade design

Figure 7-21 – Usage of stone in façade design

8 Conclusions

After the first six months of the project, a first screening of the design domain has been made limiting the target to the achievement of the desired U-value for the whole Eensulate module and to the compliance with basic structural safety requirements. The initial set-up of the analyses has then considered parameters and value ranges from literature review and expert opinions.

Starting from these considerations, the results from the current design stage can lead to the following main conclusions:

- To make possible to reach the target U-value for the whole Eensulate module (0.4 W/m^2K), the spacing of the grid of pillars should be more than 40 mm and new frame-VIG joint configurations need to be investigated;
- The influence of the pillars radius on the U-value has to be further investigated;
- To converge as to the target U-value for the whole Eensulate module, it is necessary to investigate new different geometries of the frame as well as new frame-VIG joint configurations, for instance considering a system where the glazed panels are fixed to the unit frame by means of a structural silicone joint, with the purpose to minimize the heat flow through frame and edge of the glass as much as possible.
- Due to the minimum possible spacing between the pillars that allows to reach the target U-value of 0.4 W/m^2K, thermally toughened glass is the only possible solution;
- Although more complete calculations have to be developed, it appears feasible to consider thermally toughened glass of 4 mm thickness as the lightest possible solution;
- In the next stage of design, ad hoc Finite Element Models will have to be developed to investigate new specific layout and detail solutions, i.e. cases where no closed form analytical solutions exist.
- In the next stage of design, fire and thermal actions have to be deeper analyzed.

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