T.U. DELFT UNIVERSITY, FACULTY OF ARCHITECTURE, DEPARTMENT OF BUILDING TECHNOLOGY

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>> RESEARCH REPORT

RESEARCH ON THE DEVELOPMENT OF A 'GLASS FIBER REINFORCED POLYESTER' (GRP) FAÇADE WITH INTEGRATED OPERABLE GRP WINDOW FRAMES

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"In the future there will be few construction needs that plastics and advanced resins cannot meet", Prof. Jan Brouwer (architect), 1992

The use of plastics in construction industry started in around 1930's and since then a rapid increase of plastic applications for building components has been observed. The materialization of the buildings has recently seen a move away from other traditional construction materials, such us concrete and brick towards new products. Plastic formed the key factor of this change as it became the choice of new architects and builders that were interested in expoiting the new posibilities of this material.

In around 1990's 4.89 million tonnes of plastics (20 per cent of the total amount of plastics used) were required by the building construction sector. Up to then the total volume of plastics used was still small compared to other materials, and the most common building applications were pipings, windows, roofing and flooring covers, ducting and insulation sheets.

Nowadays the use of plastic in buildings has been dramatically increased while new advanced plastic composites and resins have led to the production of more economical and environmentally friendly final products that can also meet the advanced structural, functional and aesthetical requirements of the building industry.

Architects now take advantage of the high performance benefits of this new-age materials, which are now used in more applications such us facades, furniture and other building equipments. As a result, the consumption of plastics in the year of 2011 reached the peak of 47 million tonnes, with the building and constuction sector being the second largest market of plastic materials after packaging.

The increase in the demand and use of plastics in facade industry in combination with the lack of knowledge on this recently developed field and my personal interest in this particular group of materials gave me the spark to deal with plastics for my graduation thesis. This research will study the use of a particular plastic composite material which is widely used in facade applications, the **Glass Fiber Reinforced Polymer** (GRP).

In this thesis I will seek the possibilities of designing a **GRP facade with integrated operable windows**. The potentials of creating a highly integrated facade made out of only two main materials (Glass Fiber Reinforced Polymer and Glass) will be analyzed and the possible advantages or disadvantages of such a product in relation to other conventional solutions will be explored.

Aim of this research is to provide the knowledge and the directions that need to be followed in order to change the way in which GRP facades are designed, manufactured and installed. The ultimate goal is to optimize the way they perform as a building's envelope. In the course of this research, both aesthetical and technical aspects will be taken into consideration.

Kunsthaus in Graz (Austria) was built using an organic shape with a skin made of translucent, blue, acrylic-glass panels. (source: http://humanandnatural.com/img-kunsthaus-graz-1431.htm)

2.1_ RESEARCH ON THE MATERIAL – GLASS FIBER REINFORCED PLASTIC (GRP)

2.1.1_ HISTORY OF THE MATERIAL

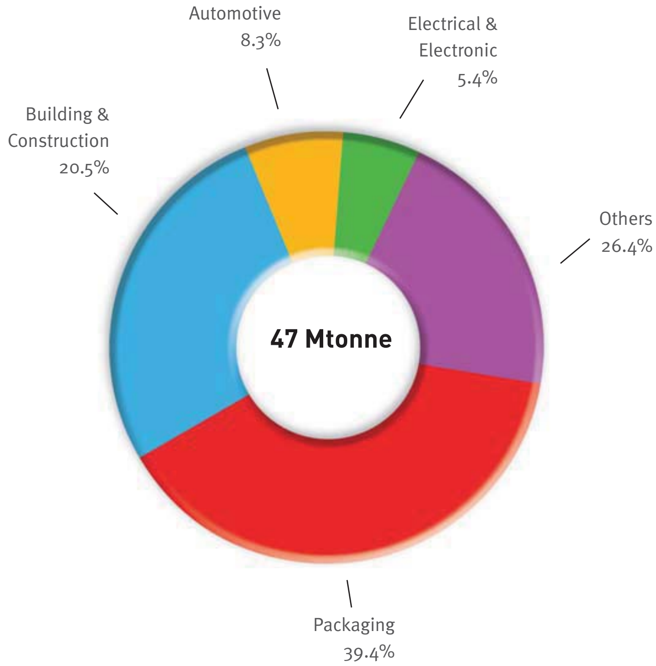
The starting point of the use of GRP dates back at the early 1930's when Slayter and Thomas patented the production of glass fibers. However the first applications can be found in the early 40's in structural aerospace parts, where high strength and light weight was of major importance. The history of the use of Glass Fiber Reinforced Plastics continued during the Second World War, when "rapid progress was made with the manufacture of the first radomes to house electronic radar equipment"[1].

In construction industry the use of GRP's started twenty years later in the 1960's. This was the time when the industry markets showed an increased interest in glass fiber / polyester composite products. The first two major structures that played an important role in the development of GRP materials for construction were the dome structure in Benghazi, erected in 1968 and the roof structure at Dubai airport built in 1972.

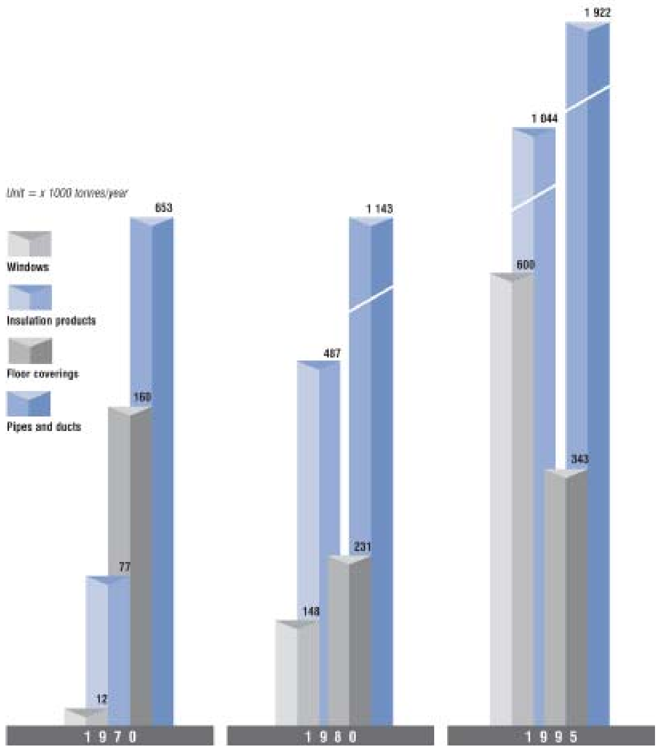
The 1980's and early 1990's saw a variety of structural engineering and architectural applications of GRP materials and a sharp rise in more commercial products made out of reinforced plastics. The increased demand and production led to "reduction in cost, to more comprehensive knowledge of the fundamental properties of composites, which has enabled more specific uses and has reduced safety factors to realistic levels, and to the numerous advantages of GRP's as compared to conventional materials such as concrete and steel"[2].

Over the same time period, the Neste Corporation (Finland) designs and constructs an experimental house built almost entirely by polymers and composites in an attempt to show that these materials can "achieve results that are competitive with traditional materials and are aesthetically, functionally and technically sound"[3].

In the years following, developments achieved in polymer resins, fibre reinforcements and production techniques led to increasing use of GRP materials in construction industry which is responsible for over 20% of the total amount for plastics that is nowadays produced.



European Plastics Demand by Segment 2011 (source: Plastics Europe Market Research Group_PEMRG)



Increase in plastics consumption in building and construction products from 1970-1995, Western Europe (source: Plastics, A material of choice in building and construction)

[1]Goeran Pohl (Editor), Textiles, Polymers and Composites for Buildings, September 28, 2010, Woodhead Publishing Series in Textiles
[2]Goeran Pohl (Editor), Textiles, Polymers and Composites for Buildings, September 28, 2010, Woodhead Publishing Series in Textiles
[3]Guneri Akovali (Editor), Polymers in Construction, 2005, Rapra Technology Limited

2.1.2_ A SHORT INTRODUCTION TO GLASS FIBER REINFORCED PLASTICS

For the complete understanding of the GRP material, its properties and potentials, a short introduction should be made. At first the material itself will be explored. Its constituents and the way they are composed as well as the production techniques used will be analyzed. Finally the possible products of it will be categorized.

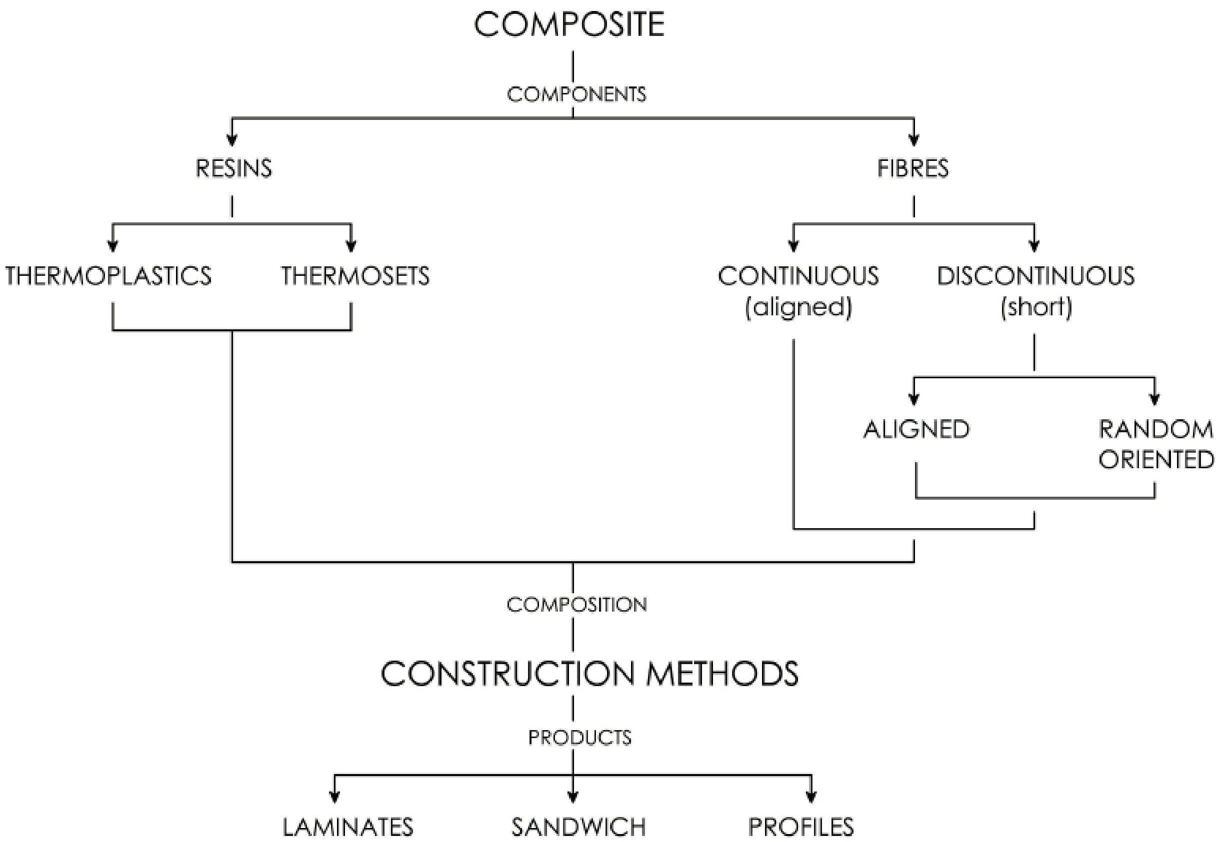
Glass Fiber Reinforced Plastic (GRP) or else Fiberglass is an artificially produced composite material made of a polymer matrix (resin) reinforced by glass fibers. The two different materials exhibit significant different physical and chemical properties but when combined together they result to a very strong and rigid material.

The matrix material surrounds and supports the reinforcement by maintaining its relative position while the reinforcement imparts their special mechanical and physical properties to enhance the properties of the final product. In this way, the matrix which is a relatively tough but weak material is reinforced by the fibers which can mechanically enhance the strength and elasticity of the polymer.

More specifically the plastic resins are "strong in compressive loading and relatively weak in tensile strength while the glass fibers are very strong in tension but tend not to resist compression" . The combination of these two materials and properties leads to the development of a new material (GRP) that can resist both compressive and tensile forces.

The different properties of the component materials of fiberglass, as well as the different ways with which these materials are combined together, can lead to the production of various types of GRP materials that can meet almost any requirements of the consumer market regarding the strength or stiffness of the final product. Furthermore, the different manufacturing processes can enable endless possibilities concerning the sizes and shapes of these products. As a result we may assume that Glass Fiber Reinforced Polymers show great potential and can be used in a vast variety of applications.

Towards a more complete understanding of fiberglass, the diagram below shows the aspects that need to be further analyzed and the steps and decisions that need to be made in order for a group of raw materials to be turned into composite.



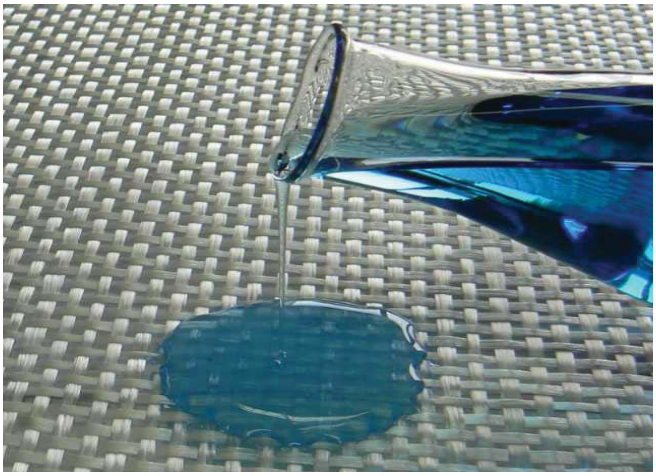
[4]Erhard, Gunter. Designing with Plastics, Trans. Martin Thompson, Munich: Hanser Publishers, 2006

2.1.3_ FIBERGLASS COMPONENTS

Fiberglass is produced by a combination of different materials. A polymer resin is always combined with a reinforcement material while other strengthening and hardening materials as well as core materials such as wood or foam can be added. The two main components of fiberglass (resin and glass fibers) and their properties are more thoroughly analyzed below.

POLYMER MATRIX (RESIN) TYPES

Usually the polymer matrix component of a fiberglass material consists of at least two parts, the substrate and the polymer. The polymers are normally categorized according to their physical properties as thermoplastics, thermosetting and elastomeric. The resin types analyzed below are the ones used for the production of fiber glass: the thermoplastics and thermoset resins.



Liquid system resin (source: http://www.5m.cz/en/epoxy-resins-1/)

THERMOPLASTICS

Thermoplastics, also known as thermo-softening plastics are polymers that become pliable or moldable when they reach a specific temperature but they turn solid again when they are cooled down. This process is reversible which means that it can be repeated without the polymers to lose their initial properties. They can be remolded and thus they can be easily recycled, as their polymer chain does not degrade when there are heated up.

Polyester and vinyl ester resins are the most widely thermoplastic materials used, while other examples of thermoplastics include polyethylene, polystyrene and poly (ethylene terephthalate).

A. Polyester resin (UPE):
Polyester resins have good combination of chemical, electrical and mechanical properties. The maximum recommended operating temperature is 80°C for the basic grade polyesters but this can be modified. They can also be modified so that they can be flame-retardant of self-extinguishing. (www.exelcomposites.com).

Their main disadvantage is that they are UV sensitive, they tend to degrade over the years and they acquire a yellowish tint. This is the main reason why their applications are relatively restricted. They are often used for sports equipment as well as for industrial, transportation and marine products. At the constructions field they are mainly used for the production of Glass fiber profiles.

The properties of polyester resins are described in the following table:

	Unit	Structure = UCU	Structure = U
Typical glass content	[%-vol]	55-58 %	58-65 %
Tensile strength	[Mpa]	600-900	1000-1200
Tensile modulus	[Gpa]	38-42	42-45
Flexural strength	[Mpa]	700-1000	1000-1300
Flexural modulus	[Gpa]	35-40	40-43
Coefficient of thermal expansion	[10-6/K]	9-11	6-8
Density	[kg/dm3]	1.9-2.0	1.9-2.0
Structure: U = unidirectional, C = Cross-wound			

B. Vinylester resin (VE):
Vinylester resins combine the best features of polyester resins and thermosets. They show good strength and

chemical resistance properties in acids and alkalis environments, especially in high temperatures and they can operate in a temperature of maximum 90-150°C. What is more, they have good electrical and thermal insulation properties. (www.exelcomposites.com).

The vinylester tends to have a purplish tint, and is more transparent than the polyester resin. In terms of degradation it performs better than other thermoplastics and it is more resistant over time.

THERMOSETS

Thermosets, also known as thermosetting plastics are polymer materials that cannot be remolded after curing. They are usually liquid materials before curing and after they are heated up and reach a specific temperature they become permanently hard and they can no longer be melted back to a liquid form. This means that these kinds of polymers cannot be recycled.

Thermosets are generally harder and stronger than thermoplastics and for this reason "they are mainly used far more than other matrices in advanced composite materials for structural aerospace applications. Although they are generally sensitive to moisture… they present superior properties to polyesters in resisting moisture and other environmental influences." [5]

Bismaleide resins (BMIs), Polyimide and Epoxies are some of the thermosets, but the epoxy resin is the most commonly used thermoset.

Epoxy resin (EPO):
Epoxy resin is a two-part resin system used when high strength, low shrinkage and low brittleness are required. It performs better that almost every thermoplastic resin and it is almost transparent when cured. The toughness of the resin can be different in each application and it can be controlled by the amount and type of additives that are mixed with the resin.

Due to its optimal mechanical properties ans easy processing it is mainly used in aerospace industry as a structural matrix or even structural glue. It shows high corrosion resistance and is affected less by water and heat compared to other resins. The main disadvantages of resins are the relatively high cost and the long curing period.

OTHER RESINS

Apart from the most commonly used resins, such as polyester, vinylester and epoxy, there is also a wide range of resin systems available for every application. There are resins used for very high temperatures, fire retardant systems or systems used for extremely aggressive environments.

RESIN COMPARISON TABLE

At the table below the main types of resins are compared in terms of cost, strength, chemical and electrical properties.

	Polyester	Vinylester	Epoxy	Other
Cost	1	2	3	4
Strength	2	2	1	2
Chemicals	2	1	1	2
Electrical	2	2	1	1-3
Legend: 1= superior | 2= excellent | 3 = good				

TEXTILE GLASS FIBERS TYPES

Textile glass fibers are the most commonly used reinforcing fibers for matrix composites. They are basically made by a combination of SiO_2, Al_2O_3, B_2O_3, CaO, or MgO in powder form. "This mixture is heated up at 1,600C and liquid glass is formed. The liquid is passed through microfine bushings and simultaneously cooled to produce glass fibre filaments from 5-24μm in diameter. The filaments are drawn together into a strand (closely associated) or roving (loosely associated), and coated with a "size" to provide filament cohesion and protect the glass from abrasion"[6] .

Textile glass fibers (source: photo by the author)

There are different types of glass fibers. The most common ones are made of

- A Soda- lime glass
- E Electrical type (Borosilicate)
- C Chemical resistant type
- AR Alkali resistant type
- S High performance type

The E-glass is the less expensive glass type which is broadly used in reinforced plastics industry. The S-glass is higher tensile strength and higher modulus than E-glass, but on the other hand it is also quite expensive.

[5]M.J.L. van Tooren / J. Sinke / H.E.N. Bersee, Composites: Materials, Structures & Manufacturing Processes, May 1993, Delft University of Technology
[6] SP systems, Guide to composites

GLASS FIBERS PROPERTIES TABLE

At the table below, the different properties of the various types of glass fibers are displayed.

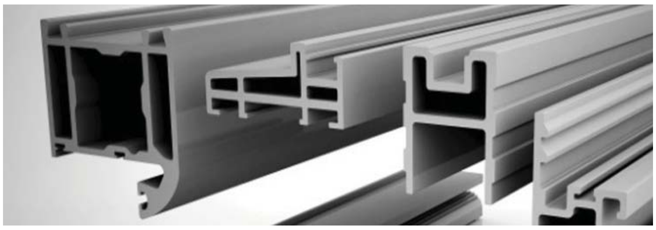
Properties	E-glass	AR-glass	S-glass
Tensile strength (GPa)	3.5	3.5	4.6
Modulus (GPa)	73.5	175	86.8
Elongation (%)	4.8	2	5.4
Density (g/cc)	2.57	2.68	2.46
Refractive Index	1.547	1.561	-
Coefficient of thermal expansion (107/0c)	50-52.0	75.0	23-27.0
Dielectric Constant RT, 1010Hz	6.1-6.3	-	5.0-5.1

(source: Moin S. Khan, Glass Fiber Composites, Properties of Glass Fiber, Manufacturing of Glass Fiber, Applications of Composite Glass Fiber)

2.1.4_COMPOSITION OF THE MATERIAL

The strength and elasticity of the composed product (GRP) depends mainly on its constituent materials. The mechanical properties of the chosen resin and fibres, the percentage of their volume, the fibers' length and orientation influence the mechanical properties of the end material.

In this way we can have almost endless possibilities of Glass fiber reinforced polymers having different properties according to the requirements and needs of every application.



Pultruted GRP profiles (source: http://www.exelcomposites.com/en-us/english/home.aspx) // GRP laminates (source: http://www.exelcomposites.com/en-us/english/products/laminates.aspx)

2.1.5_ CONSTRUCTION METHODS FOR GRP COMPOSITES

The shape, size and level of details that can be achieved with GRPs depend on the construction methods used. These also influence the final appearance of the product. At present there are more than twenty molding methods widely used. These can be divided in two categories (open molding and close molding) and include:

OPEN MOLDING
- HAND LAY-UP
- SPRAY LAY-UP
- CONTINUOYS LAMINATION
- PULTRUSION

CLOSED MOLDING
- COMPRESSION MOLDING
- INJECTION MOLDING
- VACUUM BAG MOLDING
- FILAMENT WINDING
- VACUUM ASSISTED RESIN TRANSFER MOLDING
- AUTOCLAVE CURING
- RESIN TRANSFER MOLDING
- AUTOMATIC LAY-UP

HAND LAY-UP

Characteristics and application:

Hand lay-up is the simplest, oldest and most widely used open molding method of producing fiberglass. It is a manual, low volume and labor intensive fabrication process that is basically used for large diameter structures that cannot be produced with automated methods (boat hulls), custom elements with asymmetric shapes that are needed in small batches, or even when a bonding between two or more modules is required.

The production of small batches is made by foam molds which are cheap but can be easily damaged after several times of use. This is the reason why foam molds are only used for small batches. On the other hand when large batches are needed, FRP molds are used as they are characterized by better durability.

The hand lay-up method also enables the production of composite GRP structures with foam cores.

Production:

At first a release agent in the form of a wax, or liquid is applied to the chosen mold so that it can allow a careful and damage-less removal of the final product. Pieces of chopped glass, glass fiber rovings or woven glass mat impregnated with resin are then manually placed in the open mold and conform to its shape. Subsequently a resin is applied on and between the glass mat by rollers or brushes. This procedure is repeated until the product reaches the required thickness. The glass mat is then rolled and sometimes squeegees and rollers are used in order to ensure that the reinforcement is perfectly wet-out and all the trapped air bubbles are removed.

"In some cases, the work is covered with plastic sheets and vacuum is drawn on the work to remove air bubbles and press the fiberglass to the shape of the mold"[7]. In this way, due to the negative pressure applied, many irregularities of the shape of the element can be prevented while in the meanwhile the production speed is also increased due to faster curing of the resin.

Hand lay-up (source: http://www.precisioneering.com/glossary_laminating_methods.htm)

Curing and finishing:

The maximum fiber content that can be achieved is 45% and the resin used for this method is usually a polyester, vinyl or epoxy. Most commonly, room temperature curing resins are used. "Curing is initiated by a catalyst in the resin system which hardens the fiber reinforced resin composite without external heat."[8] This means that the whole procedure of forming the GRP element should be relatively short in time before the resin starts to cure. In cases were more time is needed, high temperature resins are used and an oven in required for the hardening of the material. During the process additives can be applied to the resin.

Due to the use of a release agent applied on the mold, the face of the element that is attached to the mold forms a smooth surface while the other face is rougher. The quality also of the whole product can vary because this production technique is based on the skills of the operator and can thus display large irregularities and differences.

SPRAY LAY-UP

Characteristics and application:

Spray lay-up presents many similarities with the hand lay-up process as it is also a simple and relatively economical technique of producing glass fiber in an open mold. As the hand lay-up operation, this production technique is manual and requires low-cost tooling as well as low cost material systems. What is more it is suitable for the fabrication of large components with a complex geometry but without high structural requirements.

The main difference of this technique with the hand lay-up is based on the way the resin and glass fibers are applied to the mold. In this case, the resin and reinforcement materials that are sprayed onto the mold "may be applied separately or simultaneously 'chopped' in a combined stream from a chopper gun. Workers roll out the spray-up to compact the laminate. Wood, foam or other core material may then be added, and a secondary spray-up layer imbeds the core between the laminates. The part is then cured, cooled and removed from the reusable mold."[9] Vertical laminates is also possible to be made.

The applications of spray lay-up are usually small or medium in volume and mostly include track camper shells, tub and shower stalls, swimming pools, storage tanks, ducts and air handling equipments.

Production:

The production procedure of spray lay-up is quite similar with that of hand lay-up. At first a release agent is applied to allow a clean removal of the material after the completion of the treatment. Subsequently a gel coat-

[7] http://en.wikipedia.org/wiki/Fiberglass
[8] http://www. Engineershandbook.com/MfgMethods/
[9] http://en.wikipedia.org/wiki/Fiberglass_spray_lay-up_process

ing is added in order to ensure a high surface quality of the final product. This is left to cure and harden for about two hours before the chopped fibers (mostly glass fiber rovings) and resin are placed in the mold. Then a spray gun impels the mixture of the reinforcement and resin on the first hardener surface. When thicker laminates are required, the mixture is left to cure and the same procedure of spraying is repeated. The trapped air in the laminate is removed with a roller.

Spray lay-up (source: http://www.precisioneering.com/glossary_laminating_methods.htm)

Curing and finishing:

In most cases temperature curing resins are used. Catalysts added in the mixture of the glass fiber and resin allows the hardening of the composite without external heat. Otherwise the laminate is cured in an oven. The finishing of the product is almost the same with that of the hand lay-up process. The surface attached to the mold is smooth due to the release agent, while the other one is relatively rough.

What is more, this method makes the control of the orientation of the glass fibres impossible and creates also large differentiations on the thickness of the final product as this mostly depends on the operator's skills.

PULTRUSION

Characteristics and application:

Pultrusion is a manufacturing method of producing continuous and great-length GRP structural elements. The word describes the procedure during which the fibers are pulled through a resin and into a heated die. The pulling method can be made by either a hand over hand or a continuous roller method.
Pultruded products are stronger than structural steel, are 20-25% the weight of steel and 70% the weight of aluminum. They are easily transported and handled and easy in installation. Their main application is window framing.

Production and curing:

Raw materials include a liquid resin mixture (containing resin, fillers and specialized additives) and reinforcing fibers. The process involves pulling these raw materials (rather than pushing as is the case in extrusion) through a heated steel forming die using a continuous pulling device. The reinforcement materials are in continuous forms such as rolls of fiberglass mat or doffs of fiberglass roving. As the reinforcements are saturated with the resin mixture ("wet-out") in the resin impregnator and pulled through the die, the gelation (or hardening) of the resin is initiated by the heat from the die and a rigid, cured profile is formed that corresponds to the shape of the die.
(source:http://www.precisioneering.com/glossary_laminating_methods.htm)

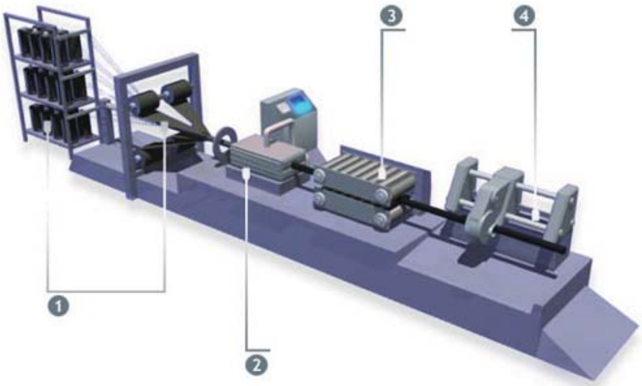


Diagram of the pultrusion process / 1.Reinforcement, 2.Pultrusion die, 3. Pulling unit, 4. Sawing unit (source: http://www.exelcomposites.com/en-us/english/composites/manufacturingtechnologies/pultrusion.aspx)

Among all the existing manufacturing processes, manual and spray lay-up are the simplest and oldest methods. They are labor intensive but do not demand expensive tooling, that's why they are widely used. The pultrusion process is the most suitable process for manufacturing high-detailed and high-strength profiles while vacuum based techniques are mostly used when accuracy is required when producing large batch sizes. (The most commonly used vacuum based processes are described later on).

2.2_ RESEARCH ON GRP FACADES

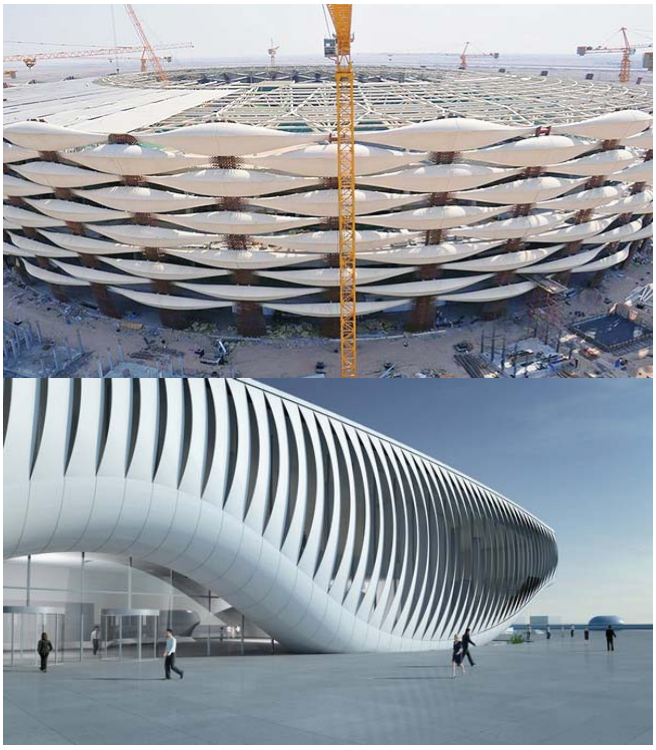
2.2.1_ GRP APPLICATIONS FOR FACADES

As it was mentioned above, there are many different applications of GRP materials in facades. Primary structural elements, load bearing sandwich panels (SWP), infill panels, rebars, pultruded profiles, are only some of them.

This research thesis will focus on the study of GRP buildind envelopes that consist of sandwich panels and will try to manage a high degree of integration of pultruded GRP profiles and the sandwich facade panels.

For this reason a first research on facades that are, or are about to be built out of GRPs is necessery. Over the last years, a few projects have been designed, making use of the free form possibilities and great properties of GRP. Especially in the Netherlands, there has been noticed a rapid increase in the use of this material for the building's envelopes.

Some examples of buildings made by GRPs are the Windesheim Academy in Zwolle (Netherlands), the One-Ocean Thematic Pavillion EXPO 2012 in Yeosu (South Korea), the City Office in Utrecht (Netherlands), the Sozawe building in Groningen and the Hilton Hotel in Schiphol (Netherlands). The last three projects are currently under construction.



Basrah Main Stadium Construction made by GRP facade panels (source: http://www.thorntontomasetti.com/blog/post/22-Basrah-Main-Stadium-Construction-Timeline) // Thematic Pavillion EXPO 2012 in Yeosu, South Korea (source: http://www10.aeccafe.com/blogs/arch-showcase/2011/07/09/thematic-pavilion-expo-2012-in-yeosu-south-korea-by-soma/)

GRP facade element for RAK Gateway. THe prototype panel built by PCT, measures 8x4m and is one of the approximately 1000 required to clad the entire building. (source: http://www.pct.ae/composites_projects.php?project=18)

2.2.2_ CASE STUDIES

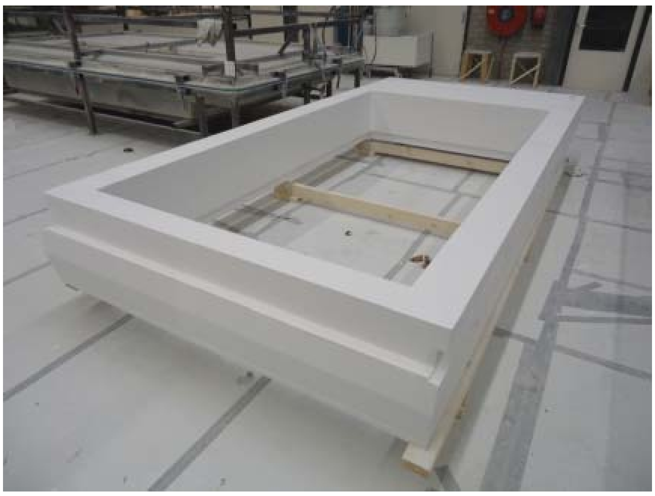
Sozawe builiding in Groningen (Sociale Zaken en Werk):
The Sozawe building designed by Meyer and Van Schooten Architecten is a 17,000 sqm office building that houses the department of Social Services and Employment. It is an eco-friendly building that offers office spaces, large interior public spaces and parking places.

SoZaWe building in Groningen, Netherlands. Still under construction (source: http://cubeme.com/blog/2009/11/23/sozawe-eco-friendly-office-by-nl-architects/)

The facade of this building is designed to be built out of large GRP sandwich panels. The choice of the use of GRP in facade in combination with glass, gives a light weight and frienfly appearence to the building and creates the impression of an inviting and transparent environment with plenty of daylight.

Apart from the green balconies, roof gardens and sedum roofs, the architects' choice for using Glass Fiber Reinforced Polymers at the facades, gives a sustainable character to the building.

The building's envelope consists of nine main different facade elements that are designed, copied and combined in order to create the design of the overall facade. The windows of the building (operable) are supported to the GRP elements by aluminium frames. The elements are currently under construction by the company Polux BV by Vacuum Assisted Resin Transfer Molding (VARTM).



Facade element under construction in Polux BV (source: photo by the author)

City office in Utrecht:
The City offce building (Stadskantoor) in Utrecht, designed by the architect Dirk Jan Postel, is a 90meters buiding that consists of concrete cores and a steel structure and is raised from ground level.

Because of the large spans and the manu voids, the steel structure has been chosen to make the building as 'light' as possible and the choice of using GRP as the material for the building's envelope has also helped in creating a light weight appearence.

The facade's elements have been already manufactured and they are currently installed at the building. They consist of GRP sandwich panels with aluminum window frames to support the operable windows of the building. The elements have been manufactured by Polux BV by Vacuum Assisted Resin Transfer Molding (VARTM)

Stadskantoor building in Utrecht, Netherlands. Still under construction (source: http://www.bouwenmetstaal.nl/index.php?page= projectbeschrijving-stadskantoor-utrecht)

OneOcean Thematic Pavillion EXPO 2012 in Yeosu (South Korea):
The Theme Pavilion designed by soma architecture from Vienna, Austria, is one of the central buildings of the Expo 2012 in Yeosu, South Korea. The main entrance and the side overlooking the expo site are characterized by a moving media façade, which draws attention on the Expo's theme The Living Ocean and Coast.

"The basis for the development of the biomimetic façade was the analysis of natural movement principles found in the flora world. The use of glass-fiber reinforced plastics (GRP), which combine high tensile strength with low bending stiffness, allowed large reversible elastic deformations and thus enabled a completely new interpretation of convertible structures" [10].

The aesthetical result of the building expresses the idea of creating a seamless surface of 108 lamellas which changes its form through soft movements with a conceptually simple logic motion.

Thematic pavillion EXPO 2012 in Yeosu, South Korea. Realized project (source: http://www10.aeccafe.com/blogs/arch-showcase/2011/07/09/thematic-pavilion-expo-2012-in-yeosu-south-korea-by-soma/)

Windesheim Academy in Zwolle:
Broekbakema Architecten was the architectural office in Rotterdam that designed this innovative facade fot the Windescheim College of Higher Education in Zwolle. The building houses many different functions and it consists of two wings separated by a central atrium.

The facade of the building consists of triagle sandwich elements of Glass Fiber Reinforced Polymer and triangle glass planes and reminds of lattice vectors in a vertical direction.

The GRP elements are made by the company Holland composite and the whole facade consists of only two different molds. Each mold is 12 meters long and 3.6 meters wide and the facade is built by these two different molds that are stacked upon each other, in order to create the facade's full height of 24 meters.

The facade is completely self-supporting and relies only in vertical direction against the floors, so as to stand the wind pressure. The whole weight of it is supported by the vertical posts. The manufacturing process followed by Holland Composite was Vacuum injection.

Christelijke Hogeschool Windesheim in Zwolle, Netherlands. Realised project (source: http://lenco-montage.nl/en/referenties/Montage-Project-christelijke-hogeschool-windesheim-zwolle.htm)

Hilton Hotel in Schiphol:
The new Hilton Hotel in Schiphol housing 433 guest rooms is designed by the Dutch architectural office, Mecanoo. The new cube-shaped building, which will feature rounded edges and a diamond-shaped façade with diagonal lines, has been designed to become a new airport landmark.

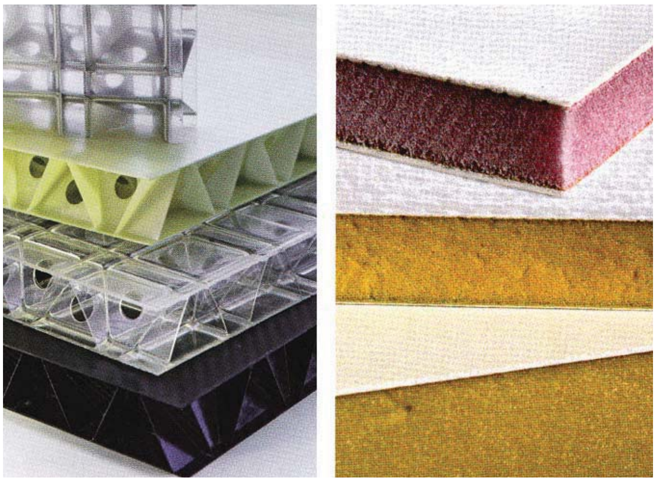
The facade of the building consists of GRP sandwich elements of diamond shape (5.4widthx3.6hheight) with a small curve and glass planes with aluminum window frames supporting the operable windows. The construction of the building has already started while it i expected to open in 2015. The manufacturing of the GRP sandwich panels will be made by Polux BV by Vacuum Assisted Resin Transfer Molding (VARTM).

The Hilton Hotel in Schiphol, Netherlands. Still under construction (source: http://www.e-architect.co.uk/hotel_buildings.php)

[10] Knippers Helbig_ Advanced Engineering, Opening of the Expo 2012 in Yeosu, South Korea Theme Pavilion "One Ocean" and GS Caltex Company pavilion

2.2.3 _ ANALYSIS OF CURRENT WAY OF PRODUCING GRP FACADES – GRP SANDWICH PANELS

As seen above, the common practice for the use of GRP materials in building envelopes is the sandwich panel. It consists of a sandwich structure that combines the exterior facing layer, the insulation layer and the interior layer in one piece, providing high mechanical strength, rigidity and high thermal insulation properties.



Thermoplastic // Thermoset + foam (source: Plastics in architecture and construction)

The main advantages of GRP sandwich panels are:

- High strenght
- High stifness
- Very low weight (light structure)
- Possibility of 3d shapes

This chapter will focus on the way that GRP facades are currently made. Aim is to fully understand the way they perform, they ways they can be manufactured and installed and the ways they can be combined with glass in a facade application.

WHAT A GRP SANDWICH PANEL IS

A GRP sandwich panel is a special form of a laminated composite comprising a combination of different materials that are bonded to each other so as to utilize the properties of each separate component to the structural advantage of the whole assembly.

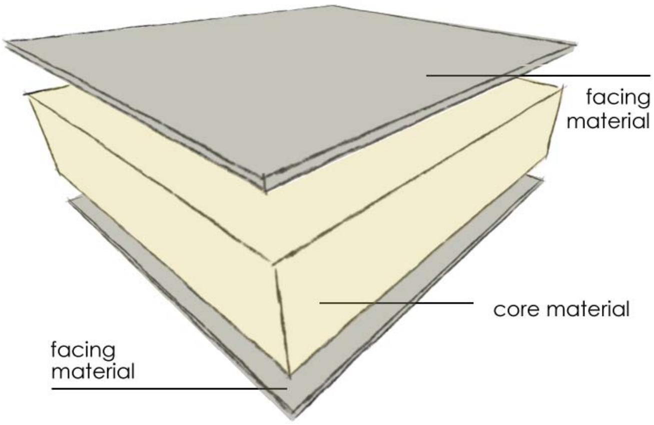
Typically a GRP sandwich panel consists of three main parts; two thin, stiff and strong faces made by a Glass Fiber Reinforced Polymer material, separated by a thick, light and weaker core which is most commonly foam, wood or honeycomb. The faces are bonded to the core to obtain a load transfer between the components.

The design principle of a sandwich composite is based on an I-beam, which is an efficient structural shape because as much as possible of the material is placed in the flanges situated farthest from the center of bending or neutral axis. Only enough material is left in the connecting web to make the flanges act in concert and to resist shear and buckling loads. In a sandwich, the faces take the place of the flanges and the core takes the place of the web. The difference is that the core of a sandwich is of a different material from the faces and it is spread out as a continuous support for the faces rather than concentrated in narrow web.

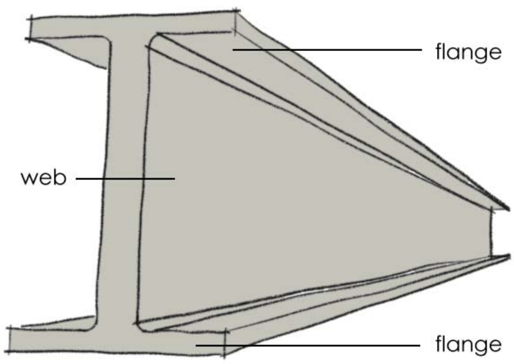
The faces act together to form an efficient stress couple or resisting moment counteracting the external bending moment. The core resists shear and stabilize the faces against buckling or wrinkling.

The primary advantage of a GRP sandwich panel is very high stiffness-to-weight and high bending strength-to-weight ratio. The sandwich enhances the flexural rigidity of the structure without adding substantial weight. Sandwich structures have in several applications shown to have fatigue strength, acoustical insulation and additional thermal insulation.

(Information taken by http://www.angelfire.com/ma/ameyavaidya/F_sandwch3.htm)



3d sketch of a GRP sandwich panel in section



3d sketch of an I-beam illustrating the basic principles that a GRP sandwich panel is designed with.

CONSTITUENT MATERIALS OF GRP SANDWICH PANELS AND MATERIAL PROPERTIES

The constituent materials of GRP sandwich panels can be divided in two main categories, the facing and the core materials. There can be many variations and combinations of facing and core materials that can lead to different sandwich panels that can have different properties. At this chapter only the most commonly used materials for the production of a GRP sandwich panel will be analysed.

FACING MATERIALS:

The material used for the facing of the GRP sandwich panel is a polymer (usually polyester) reinforced by glass fibers (GRP). The properties of the facing material have been thouroughly analysed above (chapter Glass Fiber Reinforced Plastics).

The properties of GRP materials that are of primary interest for facing materials are :

- High stiffness giving high flexural rigidity
- High tensile and compressive strength
- Impact resistance
- Surface finish
- Environmental resistance
- Wear resistance

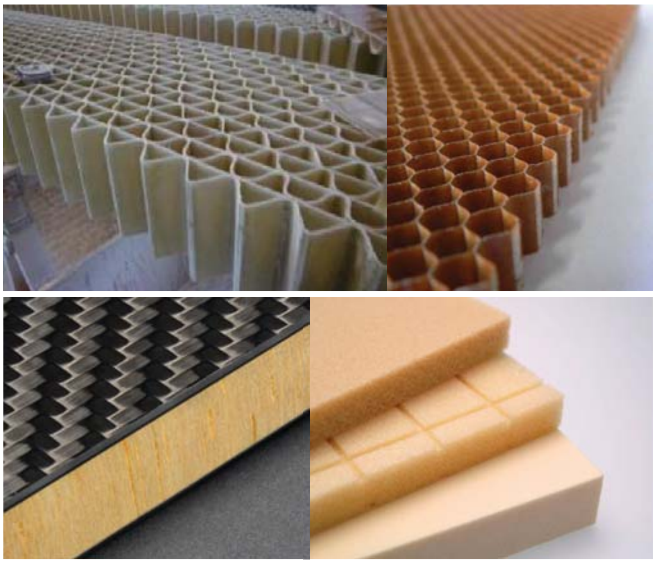
CORE MATERIALS:

The core materials should possess low density in order to add as little as possible to the total weight of the sandwich construction. Other functions of the sandwich such as thermal and acoustical insulation depends mainly in the core material and its thickness.

The properties of primary interest for the core are:

- Density
- Shear modulus
- Shear strength
- Stiffness perpendicular to the faces
- Thermal insulation
- Acoustical insulation

The cores used in load carrying sandwich constructions can be divided into four main groups; corrugated, honeycomb, balsa wood and foams. The most commonly used group for architectural and facade applications is foam as it provides great thermal insulation properties.



Corrugated (source: http://www.fhwa.dot.gov/bridge/frp/deck15.cfm) // Honeycomb (source: http://www.5m.cz/en/composite-sandwiches/) // Balsa wood (source: http://www.kaskus.co.id/post/000000000000000754338077) // Foam (source: http://www.gurit.com/corecell-structural-core.aspx)

PVC foam as core material (source: http://www.nauticexpo.com/prod/cel-components-srl/core-materials-pvc-foams-34324-257560.html)

MANUFACTURING OF GRP SANDWICH PANELS

There are many different manufacturing processes which can be used for the production of a GRP sandwich panel. These can be pultrusion, high temperature resin infusion, vacuum assisted resin transfer molding, vacuum injection, etc.

According to the GRP facades built – or under construction in the Netherlands that are mentioned at a previous chapter, two are the main production techniques that are most commonly used for facade applications and they are both liquid molding processes; the vacuum assisted resin transfer molding(VARTM) and the vacuum injection molding.

Liquid molding has recently become very famous due to its capability of producing geometrically complex structures in an economical fashion, without creating an unhealthy work environment since the processes are closed molds. During this process, the reinforcement is first placed in the mold whereupon the liquid resin is infused into the reinforcement fabric through a difference in pressure.

VACUUM ASSISTED RESIN TRANSFER MOLDING (VARTM)

VARTM is a single sided molding process where the dry preform (reinforcement or coring materials) is placed into the mold, a cover (or a vacuum bag) is placed over the top to form a vacuum-tight seal. A distribution medium (a mesh) is used and laid on top of the top release fabric to help maintain an even distribution of resin and facilitate the flow of resin through the thickness of the panel.

Closed mold production technique of a GRP sandwich element in Polux BV. (source: photo by the author)

The low viscosity resin typically enters the preform through resin distribution and vacuum distribution lines with the aid of vacuum. In VARTM process, the flow of resin occurs in plane as well as in the transverse directions to the preform. The permeability of the preform, fiber architecture and fabric crimp have an influence on the wetting of the fabric.

MATERIALS OPTIONS:

- Resins: Any resin with low viscosity, e.g. epoxy, polyester, vinylester
- Fibers: Any woven or stitched into a fabric form
- Cores: Any core type except honeycombs
- VARTM TECHNOLOGY BENEFITS:
- Applicable to larger, less complex and lower volume part production of composite parts
- Simple and low cost tooling
- On site manufacturing and reparing are practical
- High fiber volume panel achievable

The material used for the distribution of the resin // Foam core material (source: photo by the author)

VARTM PROS AND CONS:

+ Low void content
+ Low One-sided tooling cost
+ Large-scale structural parts
+ Design flexibility for complex shapes
- Labor intensive
- High production cost
- Limit with room temperature curing
- Difficulty with epoxy due to its high viscosity

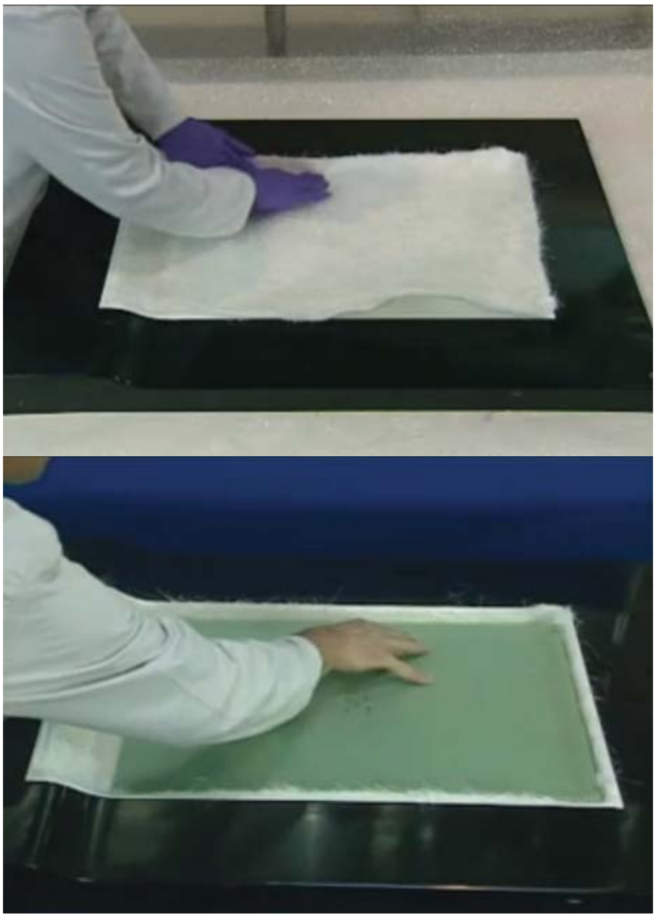
Closed mold during the fabrication of a GRP sandwich element in Polux BV. The resin is let for one day in the mold to cure. After that the element is ready. (source: photo by the author)

(Information on Vacuum assisted resin transfer molding is taken by http://www.precisioneering.com/glossary_laminating_methods.htm)

VACUUM INJECTION MOLDING

The basic principle of vaccum injection is to inject resin through dry reinforcement placed between a rigid air-tight mold and a flexible film. It employs a one-sided mold, often a marginally modified version of wet lay-up mold, covered by a vacuum bag.

Reinforcement and core materials are placed into a gel coated mold, normally by hand. Inserts and fasteners can be also easily added. After everything is placed in order, a vacuum bag is added on top and the resin is introduced into the mold. The vacuum bag provides the force that drives the impregnation of the reinforecement materials.



The reinforcement and core material is placed in a mold. (source: http://www.youtube.com/watch?v=xVErb2-bnuw)

The resin is often heated to lower the viscosity and thus facilitate impregnation. The resin infusion is stopped when the resin font has reached all the ventilation holes in the mold and the resin starts to leak out.

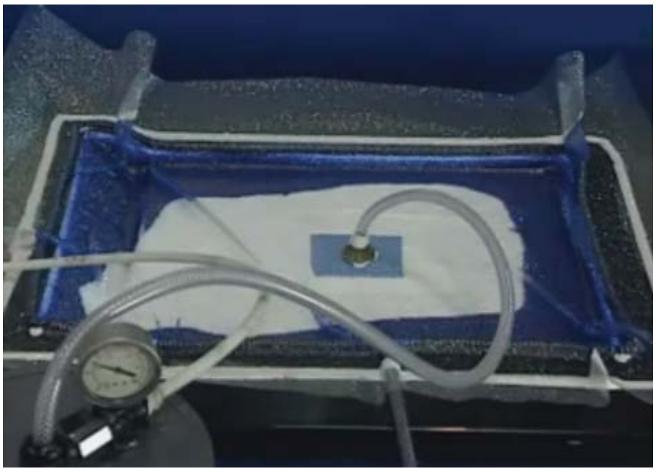
MATERIALS OPTIONS:

- Resins: Conventional preformulated resins, similar to those used in the wet lay-up processes are used
- Fibers: Any woven or stitched into a fabric form

VIM PROS AND CONS:

+ High production output rates
+ Inserts within the mold and fillers can be used for added strength
+ Close tolerances on small intricate parts are possible
+ Typically requires very little post-production work – ejected parts usually have a very finished look
+ Very little waste – all scrap can be reground to be re-used
+ Full automation is possible
+ Relatively low cost per part
- Extremely high start-up costs
- Requires a great deal of engineering time
- Long time frames necessary to fabricate tooling, making to time-to-market a major drawback

(Information taken by http://www.e-tplastics.com/blog/what-are-the-differences-between-vacuum-forming-and-injection-molding/)



The resin is introduced in the mold and the vacuum assists the impregnation of the reinforcement material. (source: http://www.youtube.com/watch?v=xVErb2-bnuw)

2.3_ RESEARCH ON INTEGRATION/CURRENT CONSTRUCTION METHODS OF GRP FACADES

Except from the manufacturing of the GRP sandwich panels, another challenging step towards the completion of a GRP façade element is its connection with the façade's window frames. Until nowadays, there are two ways developed and realized in buildings that allow the connection of glass windows with composite panels. Both ways have advantages and disadvantages.

These two different construction methods will be further explained below by analyzing one existing example from each category.

2.3.1_ ALUMINIUM WINDOW FRAMES

This method has been realized in almost every GRP façade. Some examples are the SoZaWe Building in Groningen, the City Hall in Utrecht and the Hilton Hotel in Schiphol.

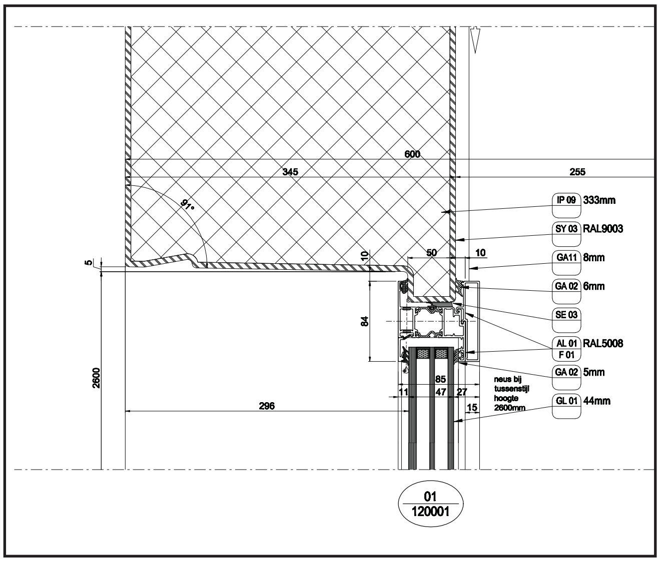
According to this method the window panes are supported by traditional aluminum frames which are mounted onto the GRP sandwich panels.

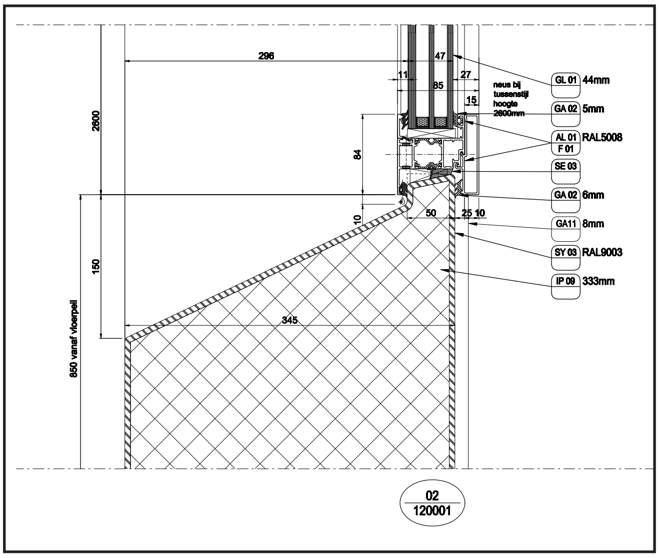
The frame is mounted the same way it is done in traditional facades of for instance brick. During the manufacturing of the GRP panels a special space for the aluminum frame is left. This has exactly the same size with the frame that needs to be attached to the panel. After the panel is finished, the aluminum frame is bolted onto it. An adhesive is also added to ensure the façade's water tightness.

The main advantage of this method is that it allows having operable windows on a façade.

The aluminum frames provide an easy and well-tested solution for façade manufacturers but when combined with GRP materials they present some drawbacks. GRP façade units if well designed they have very high thermal insulation properties, better than those of aluminum frames. Thus, the combination of these two materials ruins the overall thermal performance of the façade.

Aluminum frame bolted onto the GRP element (source: photo by the author)





Details of the connection of the GRP element and the aluminum frame that supports a non operable window. (source: Dgmr)

2.3.2_ GLUED WINDOW PLANES

This method is a relatively new and experimental construction method as it has only been used for the construction of Windesheim project's façade. This façade is an exemption as according to it, the glass panes are directly glued onto the GRP framework without the need of any frames.

Installation of GRP facade in Windesheim, Zwolle. (source: http://www.trebbe.nl/actueel.aspx?id=160&archief=2009)

During the manufacturing of the GRP panels a special space for the installation of the glass is left. After the panel is finished, glass plane is directly glued onto the GRP panel. The glue ensures the façade's water tightness.

In this case the façade comprises of only two materials, the GRP material and the glass, which present quite similar thermal insulation properties. Thus, the thermal performance of the overall façade is better. However this construction method shows other disadvantages. The most important one is that it does not allow the construction of operable windows, as these are totally glued to the panels. Moreover, the durability of the whole façade depends on the durability of the insulation glass that forms the windows.

Interior view of the facade of Windesheim, Zwolle. (source: http://www.solico.nl/projects/architecture/windesheim.html)

2.3.3_ OTHER POSSIBILITIES

In an attempt to achieve having operable windows in a façade without using aluminum frames, several kinds of pultruded GRP window frames have been developed. These seem to perform better in terms of thermal insulation if compared to aluminum ones.

However, there is still not a large scale architectural application or a façade system developed that takes advantage of them. The reason is that being a relatively new product, they still cannot be compared with aluminum products in terms of cost and there is still a lack of knowledge or uncertainty in the way they should be applied on a façade.

An interview with the director of Polux BV, Jack Smith revealed that the main reason for the industries of not using GRP window frames is that the construction companies feel a lot more comfortable when dealing with a well-tested material such as aluminum and they are not so willing to experiment with new materials that can cause changes in their currently used production techniques.
But which could be the advantages of integrating GRP pultruded profiles in a composite façade?

2.3.4_ ADVANTAGES OF AN INTEGRATED GRP FACADE

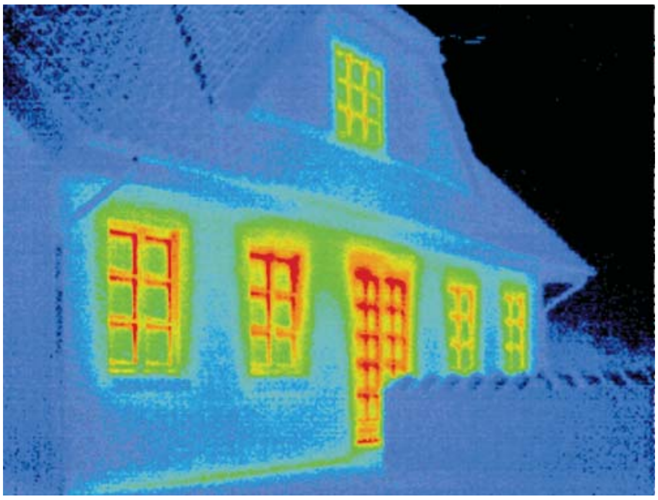
"I had noticed how much the cost of the façade really represent in the aggregate square meter price in a building. So I thought if we could reduce the cost without compromising the architecture – perhaps on the contrary – we might be able to build better houses for the same money.
Moreover, most façade design is quite old-fashioned, and not very sustainable, because aluminum plays as large a role, and aluminum is rather energy intensive to produce. Therefore, it seemed an idea to explore the option of using fiberglass instead." (Bo Boje Larsen, Partner at 3XN Architects)

When aluminum and GRP profiles are compared as a solution for integrating windows in a façade, there are a lot of aspects that need to be researched. It is sure that there is no material that performs best and that both materials analyzed below present advantages and disadvantages. The goal is to determine whether a technology shift in the way we produce facades can be feasible and which are the benefits and possible drawbacks from this change. Can a new façade system be produced which enhances the insulation performance of window frames and sills while creates an aesthetically pleasing, high strength and low cost and maintenance product?

The main issues that need to be addressed when investigationg the possibility of a new material are mentioned below. The properties of GRP's are compared with those of the aluminum and the possibilities andbenefits of integrating GRP profiles into GRP facade systems are explored.

BETTER THERMAL INSULATION PROPERTIES

Looking at the thermographic image below, we can observe that the highest heat loss (red) takes place through the window frames. "It is estimated than more than one third of the energy used to heat buildings is lost through windows and doors"[11].



This thermographic image reveals that the highest heat loss (red) takes place through the window frames. It is estimated that more than one third of the energy used to heat buildings is lost through windows and doors. (source: http://www.reinforcedplastics.com/view/6654/composite-window-frames-reduce-heating-bills/)

HEAT LOSS FROM BUILDINGS //SOME EXTRA FACTS[12]

- Home heating – not electricity as is widely believed – is the biggest item on the domestic energy budget
- Approximately 40% of the energy consumption is used to heat buildings
- Despite intensive research into developing window glass with improved insulating characteristics, heat loss through window frames and sills remains high even with modern windows
- Windows account for more than one third of domestic heat loss

The need to reduce the buildings' heating costs led to the search of new products. GRP products appear to show a strong advantage in this filed, as they perform better than other aluminum products. According to a research conducted by the Danish University Aalborg, the heat loss of a building "can be more than halved by using modern GRP windows". This can be achieved because:

- The GRP materials when designed and detailed well can prodide ultra slim frames and sills that can be aesthetically pleasing and permit the entry of more daylight during a day. This can lead to more sun coming into the building, contributing to the increase of gains of passive solar energy.

[11] http://www.reinforcedplastics.com/view/6654/composite-window-frames-reduce-heating-bills/
[12] These facts come from a research conducted by Arup, Permasteelisa, Fiberline, 3XN Architects, Make Architects, Art Andersen and Cabot. The research's title is "The Integrated Building Envelope" and presents the development of a pre-fabricated modular facade system based on composites

- The thermal conductivity of GRP is relatively similar with that of the glass. On the other hand the aluminum or steel present cosnsiderably higher thermal conductivity values, which means that GRP performs better in a facade in terms of thermal insulation if compared with aluminum or steel.

- The integration GRP frames into the GRP facade panels can further decrease the heat losses of a builidng as the structure is more compact without many weak connection points that can act as thermal bridges.

- The coefficient of thermal expansion of a GRP profile is similar to that of the glass in the window. This means that GRP windows generally perform better because they are better air and water-tight. Aluminium on the other hand expands linearly 2.5 times as much as fibreglass.

The table below shows the different values of typical material properties of different materials including aluminum and composite.

Property	Unit	Composite	PVC	Aluminium	Steel	Wood
Thermal conductivity	W/m°K	0.3	0.2	160-250	45-55	0.11-0.16
Linear thermal expansion	‘10 E-6/°	10	60	24	12	4
Density	g/cm3	1.8	1.4	2.7	7.85	0.4-0.7
Elastic Modulus	GPa	23	3	70	210	9-13
Tensile Strength	MPa	240	50	240	250	50-100

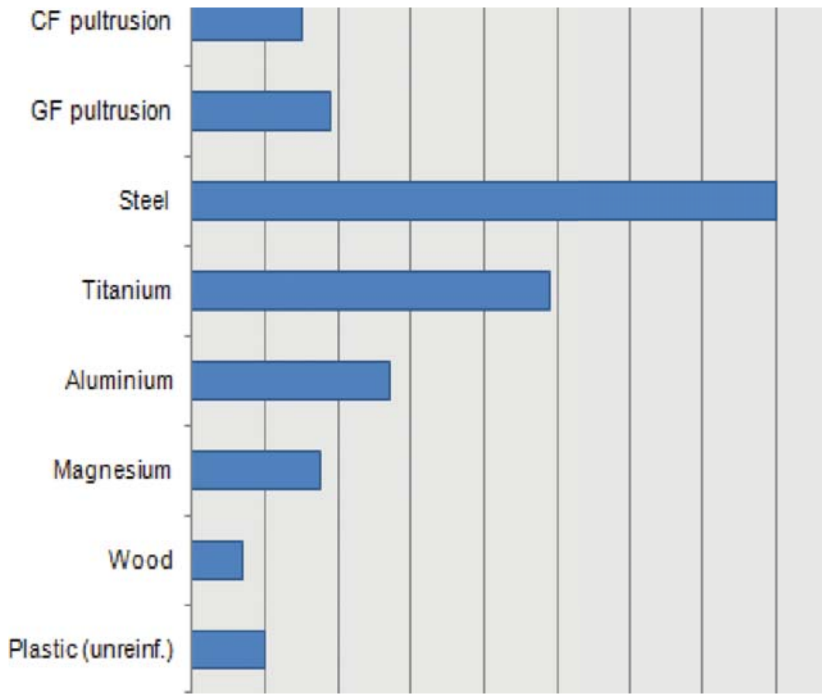
(source: http://www.exelcomposites.com/)

REDUCED WEIGHT

When designing light-weight structures, GRP materials are considered more suitable than steel or aluminum as they provide equivalent performance for considerably less weight. They weigh up to 80% less than steel and 30% less than aluminum.

The table on the right shows the differences in density between various materials including GRP and aluminum. (source: http://www.exelcomposites.com/)

What is more, weight saving can also be achieved by structural integration. Integrated facades require less elements and less material in order to get built. Therefore, an integrated GRP façade weight less than a simple (non-integrated) GRP façade and even less than an aluminum one.



FIRE SAFETY

GRP is not a fire conductive material but it melts at high temperatures and creates smoke. In case of fire it does not resist better than aluminum but its performance can be improved by the addition of fire retardants to the resin.

But above all, according to Henric Thorning, a researcher of the "Integrated Building Envelope", the main obstacle that GRP industry faces in promoting energy saving materials such as GRP is the outdated building regulations. These are written based on traditional construction materials such as glass, concrete or steel leaving no space for the development of new fields of construction.

Despite the above, the fire safety aspect in GRP facades is one of the most challenging technical aspects that still need to be solved.
There are however some optimistic researches leading to GRP facade systems that can probably be as fire safe as aluminum ones.

AESTHETICS

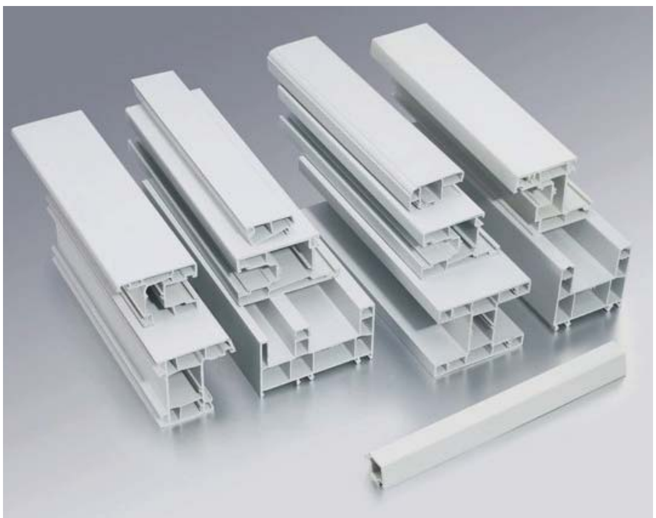
The aesthetics of a GRP window frame when compared with an aluminum one is difficult to be described. Aesthetics is a relatively subjective issue that can raise a lot of discussions.

However there are some facts that cannot be neglected:

- Slimmer profiles for windows allow a greater glass area and less obstructed view for the users

- Integrated profiles are relatively more simple in design, and detailing so the aesthetical result is not so intense

- Integrated GRP profiles can be designed so as to accommodate other functions such as locks, handles, hinges and accessories in a simple way



AG Holzmann Profile systems (source: http://agholzmann.com/en/style-categories.php)

DURABILITY - LOW MAINTENANCE

The durability and low maintetance of a facade is important for building owners as they want to reduce the amount of money and time they spend on it after its construction. Low maintenance is also important for the construction market, as it reduces the cost of labour required during the warranty period of a building.

This need has given the opportunity to GRP to showcase its excellent properties and has turned it into an extremely popular material, as it requires little or no maintenance in constrast with aluminum. There are some aspects that lead to this result:

- Corrosion resitance:

GRP shows excellent corrossion resistance properties even in aggressive chemical environments. Surfacing veil and UV additives can improve its weather durability. It is resistant to water and is unaffected by sustained saturation or moisture (high fibre content). On the other hand aluminum can be destroyed by galvanic corrosion. This can be prevented through anodizing or using other coatings.

- Impact resistance:

GRP does not permanently deform under impact even in sub zero temperatures in contrast with the aluminum that deforms easily after impact

COST

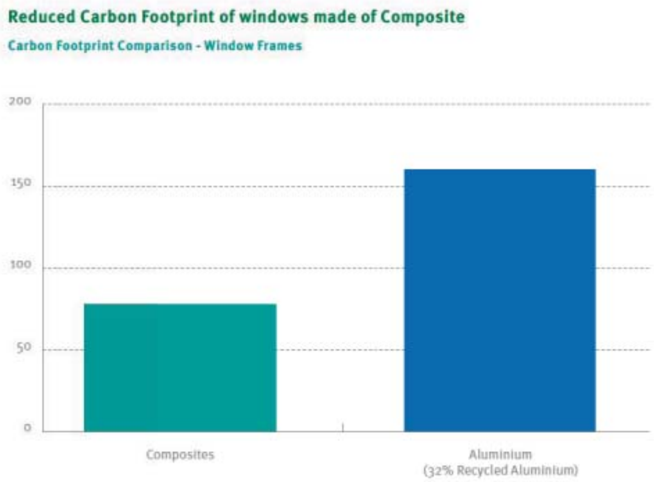
The cost of using integrated GRP window frames instead of aluminum is difficult to be defined. Having GRP frames with the same prices with aluminum ones would be one way of thinking when designing a competitive facade. But this mainly depends on the market and is does not always represent the truth.
Slimmer GRP profiles can leave more space for insulation or even usable floor space area. According to studies, a slimmer facade system that offers the interior of the building an extra 100 mm of space can increase the rental income so much that can even pay back for the entire facade.

SUSTAINABILITY

The sustainability[13] of GRP materials is maybe one of the most challenging aspects that need to be addressed. A resin manufacturer company (DSM) and a composite profile manufacturer company (Fiberline Composites) have recently collaborated in producing a Life Cycle Assessment (LCA)[14] on the use of composite profiles in windows.
This research covers the entire life cycle of the product, from the raw materials to the finilized windows and aims to compare the key environmental impacts of th material in comparison with aluminium, a commonly used material solution for making windows.

According to this research, products based on composite materials tend to have a significantly lower eco-footprint than traditional materials.
This can be explained and ahieved due to the several new raw materials for the production of the resins that have been recenlty introduced to the market. These new synthetic resins are no longer based on fossils, and therefore present reduced carbon and eco footprint.

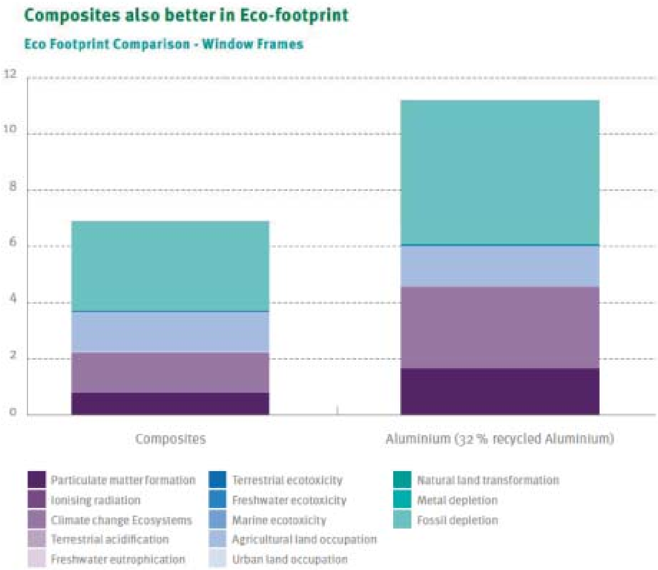
From the table below, it is clear that the new composite solutions presents lower carbon foorprint than their equivalent solution in aluminum.

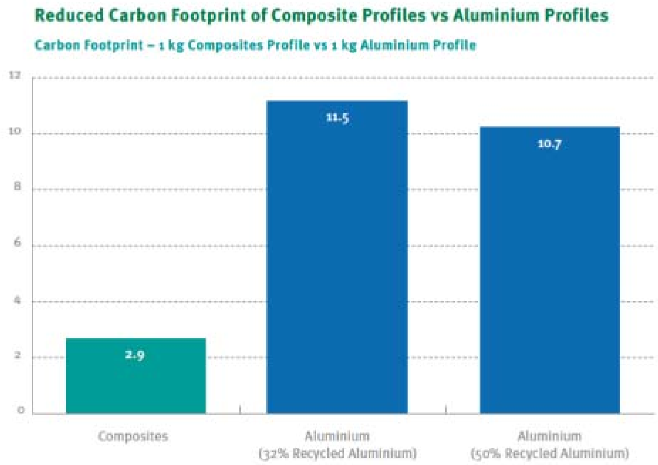


(source: DSC Composite Resin AG – www.dsmcompositeresins.com)

The same results can be also observed at the table below, representing the eco footprint comparison between composite materials and aluminium.

The above tables help to realize the positive contribution to the environment when composites are used for windows instead of aluminium.





(source: DSC Composite Resin AG – www.dsmcompositeresins.com)

[13] Sustainability is achieved when meeting the needs of the present generation does not compromise the ability of future generations to meet their own needs. (source: DSC Composite Resin AG – www.dsmcompositeresins.com)
[14] Life Cycle Assessment (LCA) identifies the material, energy and waste flows associated with a product over its life cycle to determine emvironmental impacts or potential improvements. The environmental impact, or Eco-footprint, is assessed in a number of key areasincluding resource depletion, global warming potentia, acidification and eutrophication, and human and eco toxicity. (source: DSC Composite Resin AG – www.dsmcompositeresins.com)

RECYCLING

The GRP sandwich panels are usually not recycled because of the difficulty of separating the different materials. However, comsposite profiles are recycled for cement manufacture. According to this procedure, 30% of the composite is used as energy source and 70% as raw material. "In this recycling application, granulated composite replaces fossil fuels and is used as a substitute for new raw materials.[15]"

A grinding mill at the plant reduces the composite to granulate, after which the calorific value of the granulate is adjusted by blending with other recycled materials in a patented process. The finished product is used as a substitute fuel and raw material. (source: http://www.fiberline.com)

The recycling of one thousand tonnes of profiles has been estimated to save up to 450 tonnes of coal, 200 tonnes of chalk, 200 tonnes of sand and 150 tonnes of aluminium oxide. And no dust, ash or other by-products are formed in the process. (Ref. Holcim, 2010).

However, the recycling of GRP materials still needs to be further developed as there are still non degradable substances included in the material. The glue for example used for the sticking of the parts of the module together should be replaced.

In case of integrated GRP profiles, the recyclability of the product may not be affected if the connection of the different elements can be made by a way of "clicking" them together. Disassembly will then be easier and recycling can occur after the end of the use of the product. In any case, the separation of the glass out of the GRP facade element is possible.

MANUFACTURING

GRP facade elements with high degree of integration can be easily manufactured in the factory and do not require much time for assebly in construction site. Thus, the cost of of the building is reduced, the amount of people and time at the construction site is also reduced and there is a better control of the quality of the product as it is manufactured in controlled conditions.

ARCHITECTS DEMAND

The architects demand for more integrated solutions for different functions in terms of design is also an important factor that explains the increase in the use of GRP in construction. GRP provides the architects with the ability to design an integrated products that is characterized by adaptability to the user, sustainability, functionality, ease of installation, etc. The integration of functions, including operable windows in a facade leads towards this direction.

INSTALLATION

Integrated GRP panels are mainly produced in the factories and are moved to the construction site when they are ready to be installed. The high degree of integration ensures low labour needed, low tooling cost and quick assembly, as the facade consists of less components which are already connected to each other before reaching the production site.

Furthermore, the installation of integrated panels becomes a lot easier due to the reduced weight of the elements. Integrated panels weight less if compared with conventional ones, since they consist of less componets. This makes the transportation of them on site less expensive, due to the reduced transport energy demand, and their installation easier, due to reduced weight.

(source: http://www.eurocell.co.uk/9/news/post/1213/how-recycling-upvc-can-benefit-the-environment)

[15] source: DSC Composite Resin AG – www.dsmcompositeresins.com

3.0_ TOPIC DEFINITION

3.1_ PROBLEM STATEMENT

As it has already mentioned above, the building's market has until now seen a great progress in the way it designs and manufactures facades. The Glass Fiber Reinforced Polymers is however still considered a new and experimental material in this sector. There are a few large scale buildings that have used it as a facade material but still there is not a developed system that can exploit all of its advantages.

For this reason there is nowadays an increasing demand for research on the integration of many features such as solar shading, ventilation, solar panels, windows and transparent sections in the GRP facade systems[16]. The most important feature among them that is the subject of this research is the integration of operable windows in a GRP facade unit.

DGMR is a consulting engineer company of the Netherlands and deals among others with building physics, fire safety and facade technology issues[17]. It is now involved with the construction and consulting of many buildings in the Netherlands of which the facades will been built out of GRP panels. These are the SoZaWe building in Groningen, the Stadskantoor in Utrecht and the Hilton Hotel in Schiphol. All three of these building are designed and detailed to be built out of GRP facade units with operable windows supported by aluminium frames that are bolted on the GRP panels.

As analyzed in the previous chapter, the use of a GRP facade system with integrated GRP operable window frames can lead to a better performance than of a corresponding system having a traditional aluminium frame. However until nowadays there is not a facade system developed or a large scale building made out of GRP facade panels and GRP operable window frames. Based on this lack of knowledge, DGMR was interested to investigating more the possibilities of designing an entire facade out of only two materials; the Glass Fiber Reinforced Polymer and the Glass. This quest will be the subject of research for my graduation thesis which will be conducted in association with DGMR.

Integrating a GRP window frame in a composite facade element is a challenging task. This challenge lies in the way in which the windows can be mounted on the composite walls. The outcome must present a high degree of integration and perform better than a traditional GRP facade sys tem with aluminium window frames. Of course the architectural aspects of such a solution should also be considered.

[16] A relative research on the integration of these features in a facade system is currently being carried out by Arup, Permasteelisa, Fiberline, 3XN Architects, Make Architects, Art Andersen and Cabot. The research's title is "The Integrated Building Envelope" and presents the development of a pre-fabricated modular facade system based on composites. The project also includes developing a business model that brings together producers, consultants and contractors in an innovative joint venture. It's purpose is to enable project-specific facade solutions facilitated by a systemic and modular approach.
[17] The DGMR Company is a consulting engineering company engaged in the fields of Building Physics, Energy and Sustainable Building, Fire Safety, Vibration technology, Façade technology, Industry and Environment, Traffic and Environment, Environmental Policy and Software and IT. (http://www.dgmr.nl/en/)

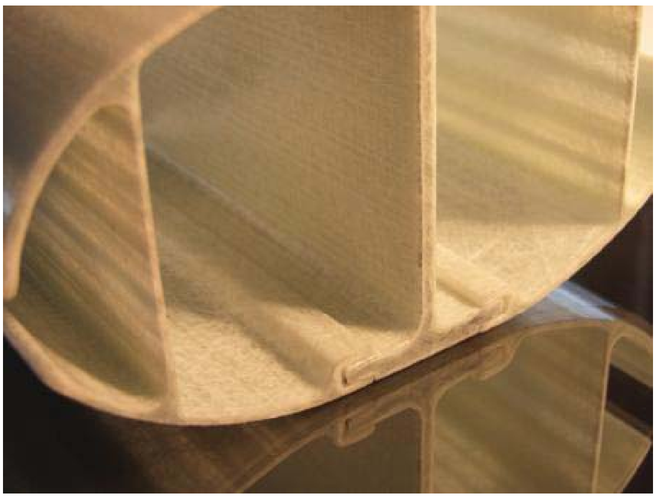
3.2_ AIM OF RESEARCH

The goal is to achieve the development of an integrated GRP façade system with operable windows where only two main materials (GRP and Glass) will be used. The design of the windows should obtain a high degree of integration and the entire façade should exhibit better performance values in several aspects over traditional façade systems.

Aim of this thesis is to provide an answer to whether a feasible GRP façade unit with integrated GRP operable window frames can be built, leading to a new way of thinking about GRP facades. The move away from aluminum manufacturers is now a demand of the market, as there is now a need for the production process to become clearer.

This graduation thesis aims to research on

- The development of a façade system that utilizes "new" materials
- The development of a GRP façade system with operable GRP window frames that shows a high degree of integration
- The performance advantages of this system over other conventional solutions
- The manufacturing procedures that can be followed for the production of it



GRP profile produced by Fiberline in collaboration with Arup, Permasteelisa, 3XN Architects, Make Architects, Art Andersen and Cabot (source: http://www.archello.com/en/company/fiberline-composites)

3.3_ RESEARCH QUESTION / SUBQUESTIONS

"What principles should a design of a Glass Fiber Reinforced Polyester (GRP) façade with integrated operable GRP window frames meet, in order to achieve high degree of integration and a great number of performance benefits over a conventional GRP façade?"

This question can be divided in several sub-questions:
•How can an operable window be attached to a GRP façade element without the use of aluminum or steel?

- Will the GRP window frame be a separate element or will it be integrated to the façade element?
- How will the detailing of such an element be?
- How can a GRP façade element with an integrated GRP operable window frame be manufactured?
- Which are the performance benefits of such a façade system?

3.4_ RESEARCH CONTRIBUTION

The research will contribute in several ways to the general knowledge about GRP facades:

-It will provide a design concept about how a GRP facade can be made. The designing of course of a GRP facade cannot lead to one exclusive result but it can provide the development of a general facade principle.

-It will provide the knowledge regarding whether a GRP facade is possible to be manufactured with the help of current technologies. The research will study the possibilities and the inabilities of current production techniques. The GRP facade design will be based on them, so that the final product will be as much able to be manufactured as possible.

-It will provide a guideline towards the direction that should be followed by other researchers. Since faults and mistakes and malfunctions will be pointed out during the design procedure and the performance testing/ calculation, a guideline on the right direction to which further researches should head will be determined.

3.5_ METHODOLOGY OF RESEARCH

The research will be carried out in three steps:

1) First step will be the **literature study**. Aim of this is to establish the knowledge regarding GRP's , the material's properties, the production techniques and the way it is used for facade applications. The literature study will include: research on the material, on case studies and on the current ways of producing GRP facades. Discussions and interviews with GRP production companies will also help to define which are the possible ways of creating GRP facade panels. Restrictions in production will be taken into consideration for the later step of design.

2) The second step of research will focus on the **analysis of solid wall facades.** Window framing materials will be further analysed, as well as connection principles between the window frames and the wall constructions. Seven different materials or combinations of them that are used for window framings will be researched, and two solid wall types (a conventional and a GRP wall will be explored in terms of connection with the frames.

3) Third step will be the **concept design of the new facade system**. After the literature research , all the restrictions and knowledge gained will be used as a feedback for the developmet of several facade concepts. These will include facades with both inwards and outwards opening window frames.

4) Fourth step will be the **evaluation of designs**. This will be achieved through observation, calculation and comparison. Aiming for high integration and better performance attributes, the new designs will be calculated and compared in terms of their performance and degree of integration with traditional facade systems.t the most important properties and comparisons made between these designs and traditional facade designs.

5) Fifth step will be the **conclusion on the final designs** that will result from the previous comparison. The final designs should manage to answer the research question of the thesis.

(source: http://nextdoorsystems.nl/)

4.1_ WHAT IS AFACADE MADE OF?

This thesis deals with the problem of designing a solid wall construction façade made by GRP panels and operable windows. Such a façade has been never made before, so there are no buildings that can be used as references during the design procedure.

In an attempt to understand the way solid wall constructions are built, an analysis of the current systems is crucial. The most commonly used materials for window frames and the connection details between the window frames and the solid walls will be studied. In the end, the advantages and disadvantages of every system will be compared to each other.

Aim is to produce a new façade design that will take advantage of the material's benefits and will integrate knowledge of previous construction systems.

The analysis of the current systems will be divided in two categories:

- Types of window frames' materials
- Types of wall-to-frame connections

Beehive texture at the facade of WAREHOUSE in Rotterdam designed by Marcel Breuer
http://reinierdejong.wordpress.com/2010/1/

4.2_ TYPES OF WINDOW FRAMES

TThere is a wide variety of materials that can be used as window frames. Below the most commonly used materials can be found. These are aluminum, steel, timber, PVC, fiberglass and their combinations (timber/aluminum and GRP/aluminum).

A short introduction of each material and the most important advantages and disadvantages of them are displayed.

GRP window frame prototypes (source: http://pinterest.com/pin/75364993735378958/)

The above materials differ in several aspects. Some of them are production cost, thermal resistance, maintenance requirements, strength and durability, fire, water and corrosion resistance, etc. Benefits and drawbacks can be undoubtedly found in the use of each material.

However, the comparison between them can lead to an overview of their performance.

4.2.1_ ALUMINUM FRAMES:

Aluminum window frames are made by extruded sections and can therefore consist of highly detailed and complex profiles. They are easy to work with, and are fabricated with accuracy which can be translated to close tolerances and tightly sealed joints. They also include small recesses for the insertion of weather-strip rubber seals, glazing and thermal break profiles.

They are light, stiff and strong but the addition of reinforcement bars can further increase their structural integrity. Aluminum frames are non corrosive, extremely durable and almost maintenance free due to their anodized and high-performance finishes. They are considered to be the least expensive material for a window frame solution and they are widely used, especially in large scale projects, where low cost, low maintenance and ease in assembly are of primary importance.

The biggest disadvantage of aluminum window frames is their high thermal conductivity which leads to an increased U-factor of the whole window unit. Aluminum is a poor insulative material which allows quick heat flow and increases heat losses during winter and heat gains during summer. In cases of cold climates, an aluminum frame can even loss so much heat that it can condensate moisture or frost on the interior part of the window. In order to reduce this heat flow thermally broken profiles are required. These consist of an inner and an outer shell connected to each other by a less conductive material. This is usually a heat-insulated plastic profile which acts as a thermal break between the inside and outside part of the window. Thermally broken aluminum profiles can reduce U-factor values from roughly 2.0 to about 1.0 or even 0.5 W/m2K and improve the energy efficiency of the window, but they also significantly increase the overall cost of the construction.

Advantages of Alumium Window Frames:
- Light-weigth
- Durability
- High strength
- Low maintenance
- Water resistance
- Corrosion resistance
- Resistance to warping and sticking
- Ease in cleaning
- Low cost if compared with other frame materials
- The most secure of all window frames
- Recyclable and reusable (if carefully disassembled)

Disadvantages of Alumium Window Frames:
- Good thermal conductivity
- Thermal breaks are required
- Poor condensation resistance
- High embodied energy
- Non reusable resource

4.2.2_ STEEL FRAMES:

Steel window frames are made by cold-rolled hollow sections produced by folding metal sheets. Unlike aluminum extrusion, folding steel manufacturing process makes highly detailed steel profiles impossible to be produced. However, the accuracy of the final product is still high and the steel profiles do present -like the aluminum ones- close tolerances and recesses for weather-strip rubber seals, glazing and thermal break profiles.

Steel sections present a lot of similarities in mechanical properties with the aluminum frames. They are characterized by high bending and torsion strength and high stiffness but in contrary to the aluminum ones they require no reinforcement bars in order to achieve structural integrity. They also provide high fire resistance and despite their relatively high cost, they are widely used in constructions where high strength and high load bearing capacity is essential.

Their main drawback is the same with that of aluminum frames and refers to the high thermal conductivity values of the material which lead to an increased U-factor of the window. Although steel is a less heat conductive material than aluminum, it still requires a thermal brake to reduce heat losses and avoid condensation. Thus, the frame is also in this case cut in two parts, an inner and an outer shell which are connected together by a heat-insulating plastic profile. Expect of their high cost, steel window frames are also generally heavier than every other window frame material, while they also require special treatment against corrosion. If they are not coated they need regular painting in order to prevent corrosion, but when they are protected they require very low maintenance.

Advantages of Steel Window Frames:
- Durability
- High strength
- Low maintenance
- Water resistance
- Resistance to warping and sticking
- Ease in cleaning
- Recyclable and reusable (if carefully disassembled)
- Fire resistance

Disadvantages of Steel Window Frames:
- Good thermal conductivity
- Thermal breaks are required
- Poor condensation resistance
- High embodied energy
- Non reusable resource
- High production cost

4.2.3_ TIMBER FRAMES:

Timber frames are the oldest type of window frames and have been through many years of developments and improvements before reaching their current state. They can be produced by various types of wood, hardwood (oak, larch, sweet chestnut) or softwood and they form the most classic choice of a window frame, showing undeniable aesthetical values. They are widely used as the material is easy to be found and milled into the complex shapes of a window frame.

The main advantage of wood in relation with other materials is the psychological aspect. Wood is easy to work with, nice in appearance and smell. It is therefore always pleasant to use it in the construction. Furthermore wood is a great thermal insulator. Regarding a thermal point of view, timber frames perform better than aluminum and steel, having U-values ranging from 0.3 to 0.5 W/m2K. Moreover if they are well designed, detailed, and annually maintained, they can last for a great period of time.

The main drawback of timber frames is their relatively high maintenance requirements. In order for them to be well maintained, several aspects need to be carefully considered. The most important one is mold which can be formed due to trapped water. For this reason, water must not be allowed to enter the construction and if it manages to penetrate, it must be quickly moved away. Furthermore the various timber elements must be placed in a distance from other components so that they can be able to dry out. In addition timber frames have to be impregnated with wood preservative for insects and pests and periodically re-coated for the maintenance of the high quality of the material.

Apart from the problems caused by water penetration there are also some other factors that restrict the use of timber frames. Wood demonstrates low temperature resistance which leads to expansion and contraction during humidity fluctuations. Gaps become bigger and heat losses are increased. Better quality and temperature resistant wood can be used in these cases, but this of course increases significantly the cost of construction.

Advantages of Timber Window Frames:
- Durability
- High thermal performance
- High availability of material
- Ease in customisation
- Variaty in finishes
- Recyclable and reusable (if carefully disassembled)
- Down-cyclable as fuel
- Low embodied energy
- Renewable resource
- Timber sequesters carbon diocide
- Easy to repair
- Low production cost

Disadvantages of Timber Window Frames:
- Hign maintenance required
- Stain or paint required every 3 to 5 years
- Lower life expectancy due to wear from sun, wind and moisture
- If not maintained, can swell, rot, warp and stick
- Low fire resistance

4.2.4_ TIMBER/ALUMINUM FRAMES:

Timber/aluminum frames have recently started to replace the older timber ones, as the combination of these two materials produces a more complete window system providing a lot more benefits than a simple one-material solution. The timber/aluminum window system consists of a wooden part/frame and an aluminum weatherboard that is applied to the exterior part of the window. In some cases the aluminum part only covers the exterior lower part of the window but more often the whole outside view of the frame is fully covered by aluminum cladding sheets, providing this way as sufficient protection from weather. The types of wood used for this type of window frame are the same with those used for timber frames. Hardwood can always be a choice and softwood shows in this case less drawbacks as the frame is better protected by moisture, warping and swelling.

By adding an aluminum weatherboard to a timber frame, the maintenance requirements of the window are significantly decreased as the aluminum creates a permanent weather-resistant surface. The wood is protected from weather conditions, does not rot or warp, and the thermal performance of the overall window remains high. What is more, the aesthetical result of a timber frame is retained on the interior part of the window, while on the outside a great range of weather resistant colors can be applied. The attractive appearance in combination with the high thermal performance and low maintenance requirements have made timber/aluminum frames very popular if compared with timber ones.

On the other hand, timber/aluminum frames still present some drawbacks that are mainly related with the use of wood. As wood demonstrates low temperature resistance, the wooden parts of the frames contract and expand during temperature fluctuations while the aluminum parts stay relatively intact. The gaps between the two materials increase and the thermal performance of the window is reduced. Moreover, the overall cost of timber/aluminum frames is relatively higher than timber frames, as the addition of aluminum in the construction raises the cost of the window frame.

Advantages of Timber/Aluminum Window Frames:
- Durability
- High thermal performance
- High availability of material
- Ease in customisation
- Variaty in finishes
- Recyclable and reusable (if carefully disassembled)
- Down-cyclable as fuel
- Low embodied energy
- Renewable resource (timber part)
- Timber sequesters carbon diocide
- Easy to repair
- Low maintenance
- Water resistance
- Corrossion resistance
- Resistance to warping and sticking
- Can be easily cleaned
- Higher life expectancy than timber frames
- Impact and scratch resistance
- Low maintenance required

Disadvantages of Timber/Aluminum Window Frames:
- Stain or paint required every 3 to 5 years
- If not maintained, can swell, rot, warp and stick
- High production cost
- Low fire resistance

4.2.5_ VINYL FRAMES (PVC):

Various plastic materials are used for window frames. The most common one is the PVC (polyvinyl chloride) with "ultraviolet light (UV) stabilizers to keep sunlight from breaking down the material" . PVC frames are manufactured with the same way as aluminum (extrusion process), thus allowing the production of extremely detailed sections.

Vinyl frames are easy to handle, resilient during installation and impact and scratch resistant. They are low cost and do not require any special treatment against corrosion or mositure. They have excellent thermal performance due to the low thermal conductivity of the material and the small chamber technology that minimizes the heat transfer within the frame. What is more, the chambers can be also filled with insulating material, which makes the PVC frames "thermally superior to standard vinyl and wood frames" . PVC frames can be produced in various colors providing a variety in their appearance and since the color is added to the material during its production process, the final product does not need any extra finish coating or maintenance over time.

On the other hand, PVC frames present various disadnvantages if compared with other materials. When exposed to high temperatures deformations and small movements of frame parts can occur due to the material's high coefficient of expansion, while in case of fire they do not provide efficient fire resistance. What is more, PVC frames are not rigid enough. The required structural rigidity can be achieved either by larger sections (sizes close to the dimensions of wooden frames) or by metal reinforcements added into the frame. In both cases, the final result is not rigid enough to be used in large scale constructions. The permissible installations size of PVC frames is thus limited. Another drawback of the use of this material is its environmental impact. Despite the fact that PVC frames can be easily recycled, still the manufacturing process and -to some extent- the product's life can be harmful to the environment.

Advantages of PVC Window Frames:

- Superior thermal insulation
- Light-weigth
- Durability
- Low maintenance – never needs painting
- Water resistance
- Corrosion resistance
- Resistance to warping and sticking
- Ease in cleaning
- Low cost if compared with wood or aluminum
- Availability of complex shapes
- Recyclability (A small amount of recyclate is sometimes used in new frames, but most PVC, if at all recovered, is downcycled)

Disadvantages of PVC Window Frames:

- Non reusable resource
- High environmental impact
- Low stiffness
- Reinforcements are required
- High thermal expansion
- Low fire resistance
- Difficult to repair

4.2.6_ FIBERGLASS/ALUMINUM FRAMES:

Fiberglass/aluminum frames are made by a combination of a fiberglass profile with an aluminum cover added on the exterior part of the frame. The fiberglass profiles are made by pultruded GRP sections while the aluminum covers are manufactured with extrusion. The two parts are joined together to form a new “composite” profile. The development of this profile is based in the need for new innovative and better performing window frames that take advantage of the future materials and try to combine them with the knowledge of the past.

Fiberglass/aluminum frames are light-weight, stiff and strong due to fiberglass, while the external aluminum cover creates an extra weather protection layer that increases the life expectancy of the final product. The internal fiberglass frame is protected by air, water and sun, so the overall frame has less maintenance requirements and the aluminum part also provides the frame with an extra impact and scratch resistance. As aluminum is easier to be repaired than fiberglass, in case of an external damage, the aluminum part can be replaced without being necessary for the whole window frame to be changed. What is more, the addition of the aluminum part at the exterior part of the window frame gives a variety in finishes that fiberglass cannot achieve by itself. But the main advantage of this type of frame is the optimal thermal performance of it. The part out of fiberglass that includes air cavities, as well as the insulative material that connects the fiberglass with the aluminum, helps to increase the thermal insulation of the window frame.

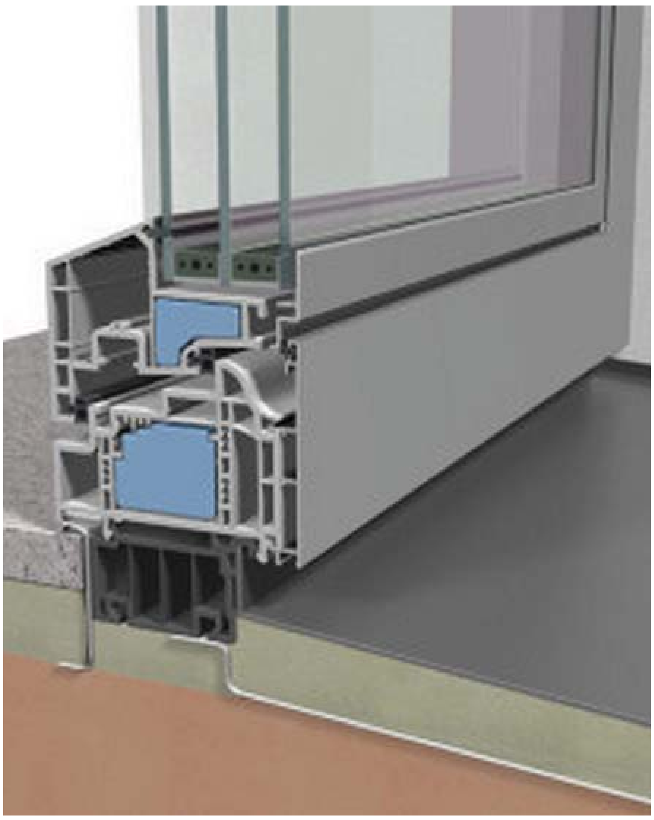
On the other hand, the combination of these materials into a frame creates some problems. The thermal expansion of aluminum and fiberglass is not the same, which results to uneven movements and not sealed enough joints between the frame parts. What is more, the cost of the frame is relatively high if compared with traditional aluminum frames and the thermal performance is lower than that of a fiberglass frame. The final product is relatively fragile (at least the fiberglass part of it) and for this reason, the transportation and installation of the frames on site need to be carefully considered.

Advantages of Fiberglass/Aluminum Window Frames:

- Superior thermal insulation
- Light-weigth
- Durability
- High stiffness
- Low maintenance – never needs painting
- Water resistance
- Corrosion resistance
- Resistance to warping and sticking
- Ease in cleaning
- Availability of complex shapes
- Smaller profiles if compared with other materials
- Low thermal expansion

Disadvantages of Fiberglass/Aluminum Window Frames:

- Non reusable resource
- High production cost
- Low fire resistance
- Difficult to repair
- Fragile final product
- Requires carefull installation
- Limited availability in shapes and colors
- Limited availability by producers



4.2.7_ FIBERGLASS FRAMES:

Fiberglass frames are made by pultruded GRP (Glass Fiber Reinforced Polymer) sections, and they can therefore consist of highly detailed and complex profiles. Fiberglass is a relatively new material and GRP frame products are quite new in the construction market. This is why not many different section options and color choices have been produced until today. However, the almost endless possibilities that this material can offer and its exceptional properties have established it as the future material in the façade sector.

Fiberglass window frames are extremely stiff and strong due to the glass reinforcement, and like other composite and plastic materials, they do not rot or decay and have low maintenance requirements. As the color is added to the material during the manufacturing process, the final product needs no painting or any other finish coatings. What is more, fiberglass frames are durable, corrosion resistant and dimensionally stable (low thermal expansion – sealed joints) in compared with other frame materials. While aluminum has the benefit of being strong and light weight, fiberglass shows one more added value. Fiberglass frames are highly energy efficient. In addition, the air cavities that are formed inside the frames (similar to PVC frames) can be filled with insulation which increases the thermal performance of the window (Fiberglass frames show U-values ever higher than timber frames).

One of the main disadvantages of fiberglass frames is their high cost. The manufacturing procedure of pultruded GRP window frames is extremely expensive and time consuming. For this reason, customization is also difficult, and the range of the final products is limited. What is more, the final product is fragile and difficult to be repaired, so the transportation and installation of fibergalss window frames on site must be carefully considered.

Advantages of Fiberglass Window Frames:

- Superior thermal insulation
- Light-weigth
- Durability
- High stiffness
- Low maintenance – never needs painting
- Water resistance
- Corrosion resistance
- Resistance to warping and sticking
- Ease in cleaning
- Availability of complex shapes
- Smaller profiles if compared with other materials
- Low thermal expansion

Disadvantages of Fiberglass Window Frames:

- Non reusable resource
- High production cost
- Low fire resistance
- Difficult to repair
- Fragile final product
- Requires carefull installation
- Limited availability in shapes and colors
- Limited availability by producers

4.3_ COMPARISON OF MATERIALS FOR WINDOW FRAMES:

In summary, the table below presents the basic properties of the frame materials that were discussed above. As can be seen, there is no perfect material for window frames. Each one has its advantages and drawbacks. The key factor for choosing the best is by deciding which characteristics – durability, low cost, energy efficiency, strength, light weigth- are important in each case, and choosing the material that presents a better performance on those characteristics.

FAÇADE SYSTEMS COMPARISON TABLE								
		ALUMINUM	STEEL	TIMBER	TIMBER/ALUMINUM	u-PVC	GRP/ALUMINUM	GRP
Façade characteristics	Light-weight	✓		✓	✓	✓	✓	✓
	Durability	✓	✓	✓	✓	✓	✓	✓
	High strength	✓	✓	✓	✓		✓	✓
	Low maintenance	✓	✓		✓	✓	✓	✓
	Water resistance	✓	✓		✓	✓	✓	✓
	Corrosion resistance	✓			✓	✓	✓	✓
	Resistance to warping, sticking	✓	✓		✓	✓	✓	✓
	Can be easily cleaned	✓	✓		✓	✓	✓	✓
	Low cost	✓		✓		✓		
	High security	✓	✓			✓		
	Low thermal conductivity			✓	✓	✓	✓	✓
	No thermal break required			✓	✓	✓		✓
	High availability	✓	✓	✓	✓	✓		
	Can feel comfortable (warm)			✓	✓	✓	✓	✓
	Availability of complex shapes	✓				✓	✓	✓
	Small tolerances	✓	✓			✓	✓	✓
	Variety in finishes	✓	✓	✓	✓	✓	✓	✓
	Fire resistance		✓					
	Insect resistance	✓	✓			✓	✓	✓
	Ease in production			✓	✓			
	Small thermal expansion	✓	✓	✓	✓		✓	✓
	Ease in customisation			✓	✓			
	High life expectancy (resistance to sun, wind, moisture)	✓	✓		✓	✓	✓	✓
	Resilience during installation			✓	✓	✓		
	Impact and scratch resistance	✓	✓		✓	✓	✓	✓
	Environmentally friendly			✓	✓			
	Wide variety of sizes and styles	✓		✓	✓	✓		
	No need for coatings					✓		✓
	Recyclability and reusability	✓	✓			✓		
	Renewable resource			✓	✓			
	Difficult to repair					✓	✓	✓

For a more complete understanding of window frames, ten of the most representative types of frames have been selected, in order to be further examined. These are:

- Aluminum double glazed frame (Schuco)
- Aluminum triple glazed frame (Schuco)

- Steel double glazed frame (Schuco)

- Timber frame_old construction (Scandinavian timber)
- Timber triple glazed frame (Josko)

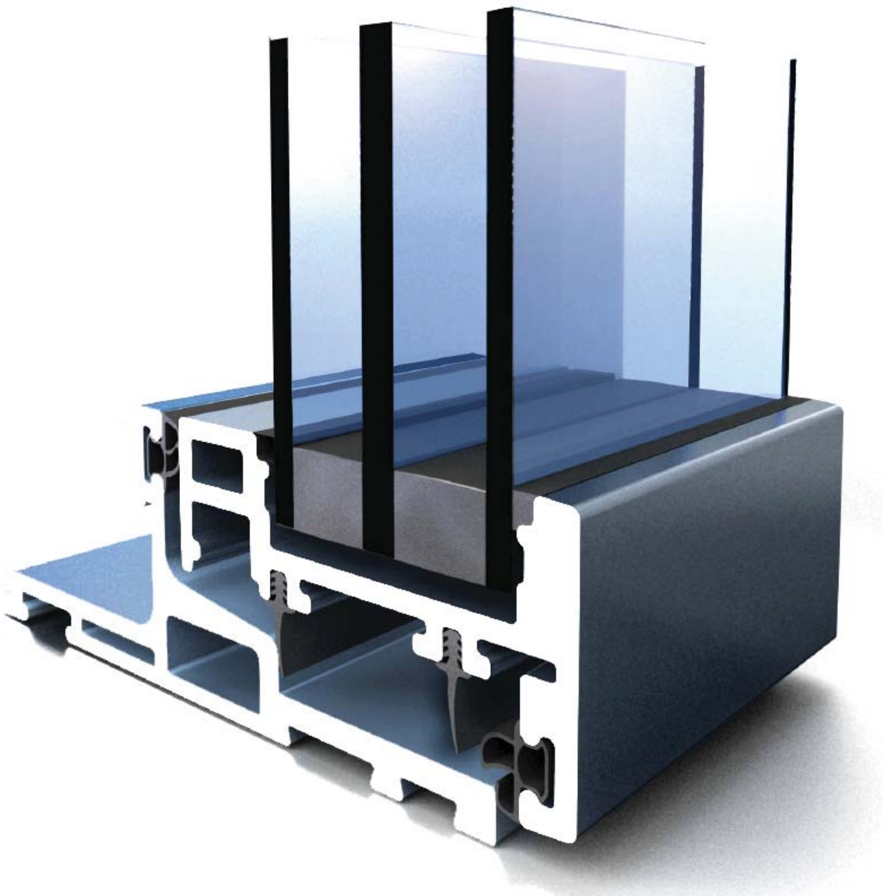
- Timber/Aluminum triple glazed frame (Josko)

- PVC double glazed frame (Inoutic)
- PVC triple glazed frame (Schuco)

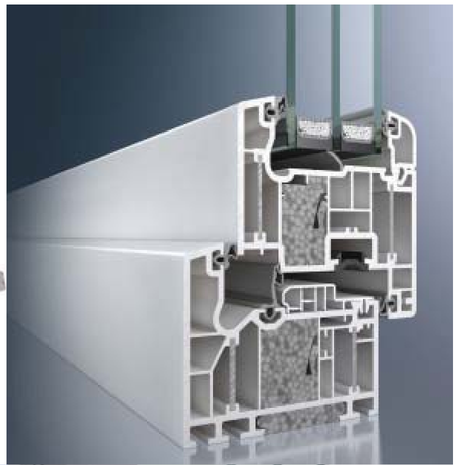
- GRP/Aluminum triple glazed frame (Josko)

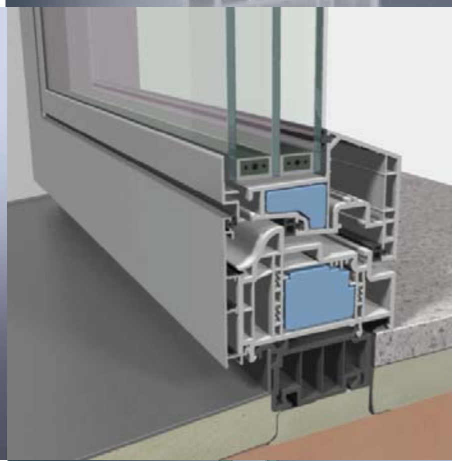
- GRP triple glazed frame (Ecliptica)

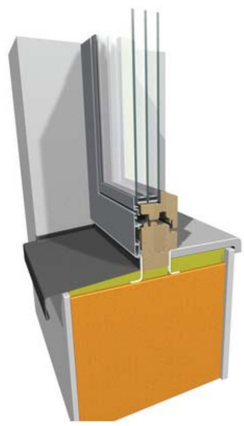
The objective is to identify the individual components of each window frame and determine the functions that each component serves.

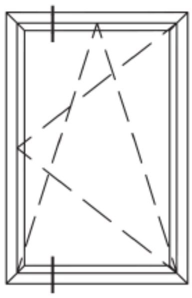




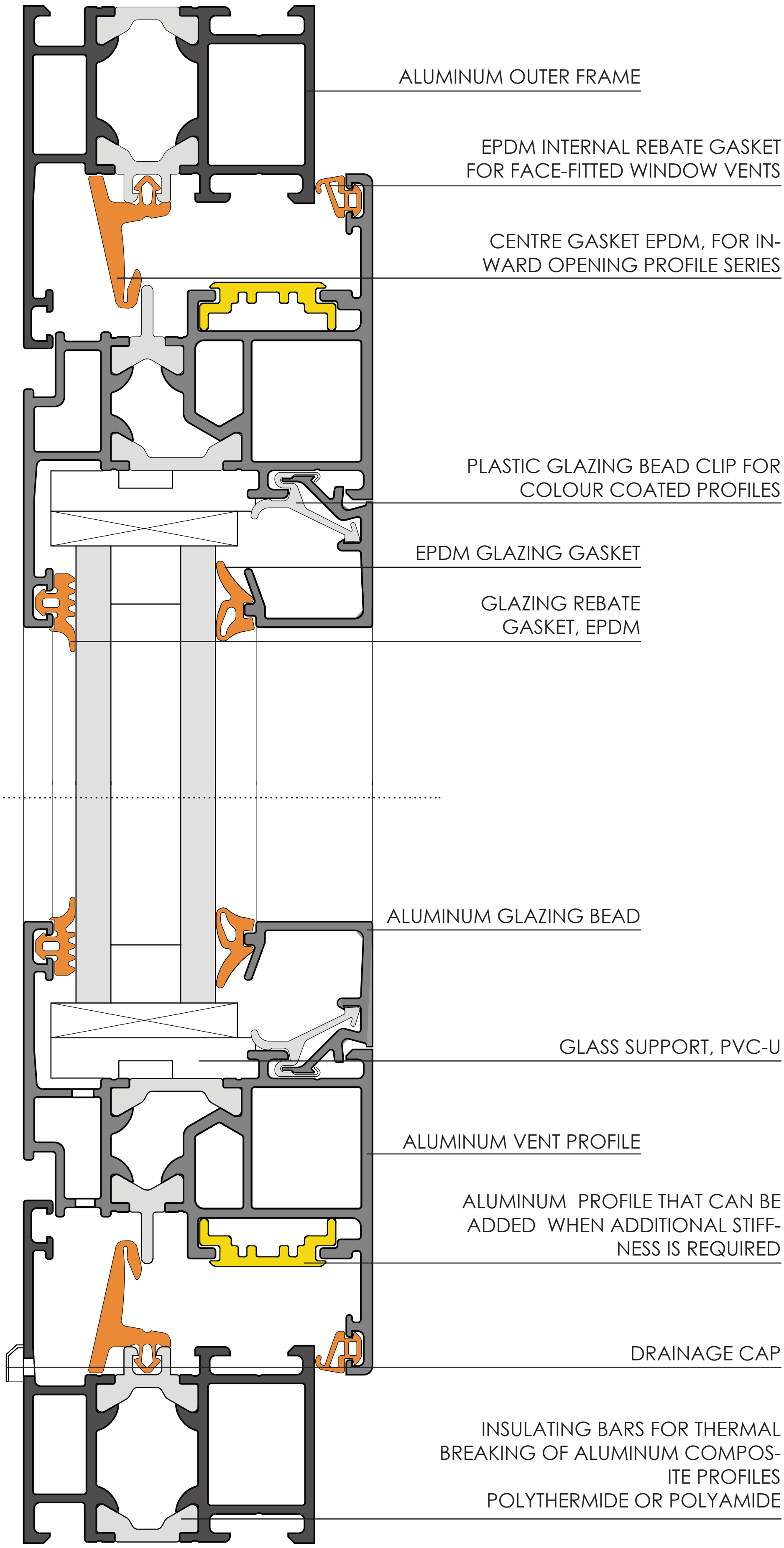


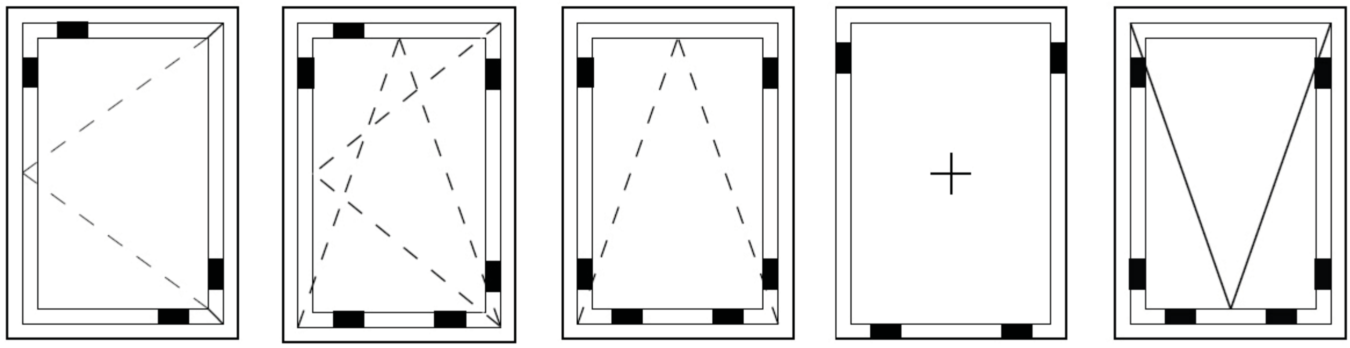





4.3.1_ ALUMINUM DOUBLE GLAZED WINDOW FRAME (SCHUCO):





Recommendations for galzing support
Possibel ways of opening the vent profile and different positions for the fixing of the glazing

SYSTEM DESCRIPTION:

Thermally insulated series with 50mm basic frame depth, suitable for all types of buildings where lower levels of insulation are required.

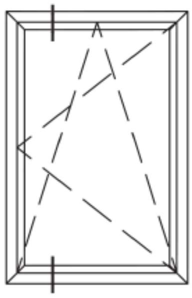
FEATURES:

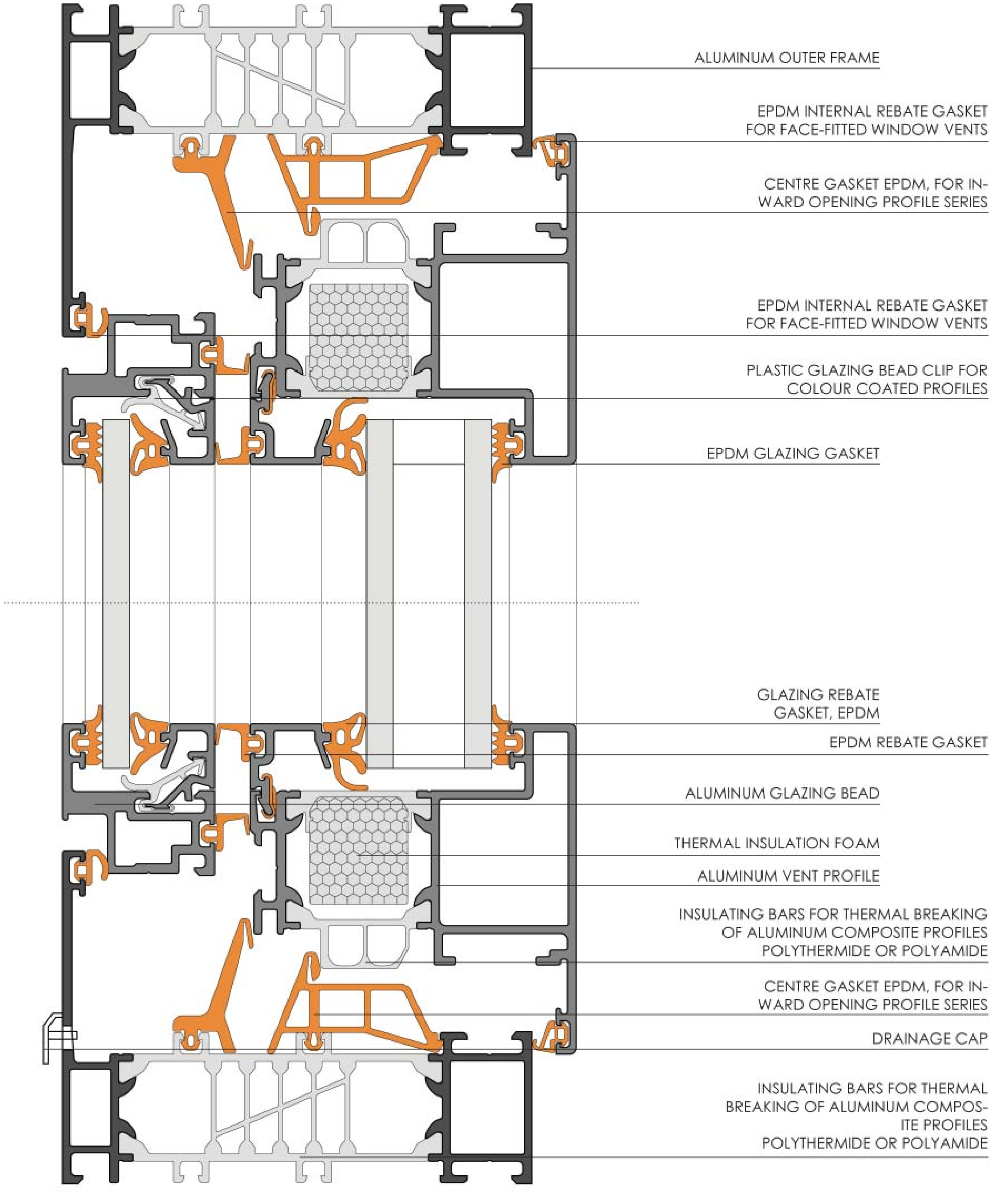
- Basic depth of 50 mm
- Inward and outward opening vents
- Vent weight up to 130 kg
- AvanTec concealed fittings up to 160kg for inward opening vents
- Burglar resistance to BS 7950 and EN V 1627 WK1
- Compatible door system
- Typical Uw 1.9W/m2K with double glazed unit
- Good thermal insulation due to wide insulation zone
- Window series with narrow face widths from 51mm
- Multicoloured profile design
- Concealed drainage
- Drainage at the lowest profile point
- Extensive range of profiles with face widths from 26 to 250mm
- Insert outer frame with adapter gasket to compen-sate for glazing thicknesses

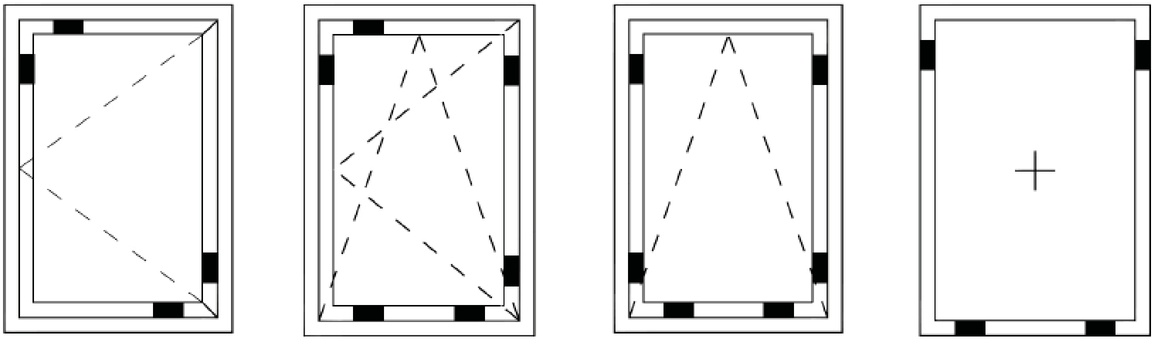
TECHNICAL INFORMATION:

Material: Aluminum
Type of construction: Thermally insulated
Security: Burglar resistance DIN V ENV 1627 to 1630
Air permeability DIN EN 12207: Class 4
Weathertigthness DIN EN 12208: 9A
Resistance to wind load DIN EN 12210: B5, C5
Thermal transmittance DIN EN 12412-2: Uf =2,5 - 3,7W/(m2K)

4.3.2_ ALUMINUM TRIPLE GLAZED WINDOW FRAME (SCHUCO):







Recommendations for galzing support
Possibel ways of opening the vent profile and different positions for the fixing of the glazing

SYSTEM DESCRIPTION:

The composite window system for intelligent project solutions provides thermal insulation using innovative insulating bars. Narrow face widths from 74.5 mm and solar shading, which is protected against the weather, set new standards.

FEATURES:

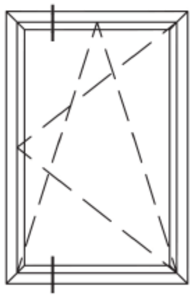
Outstanding thermal insulation due to innovative insulation bars: Uf values of 1.6 W/m2K (face width 103mm)

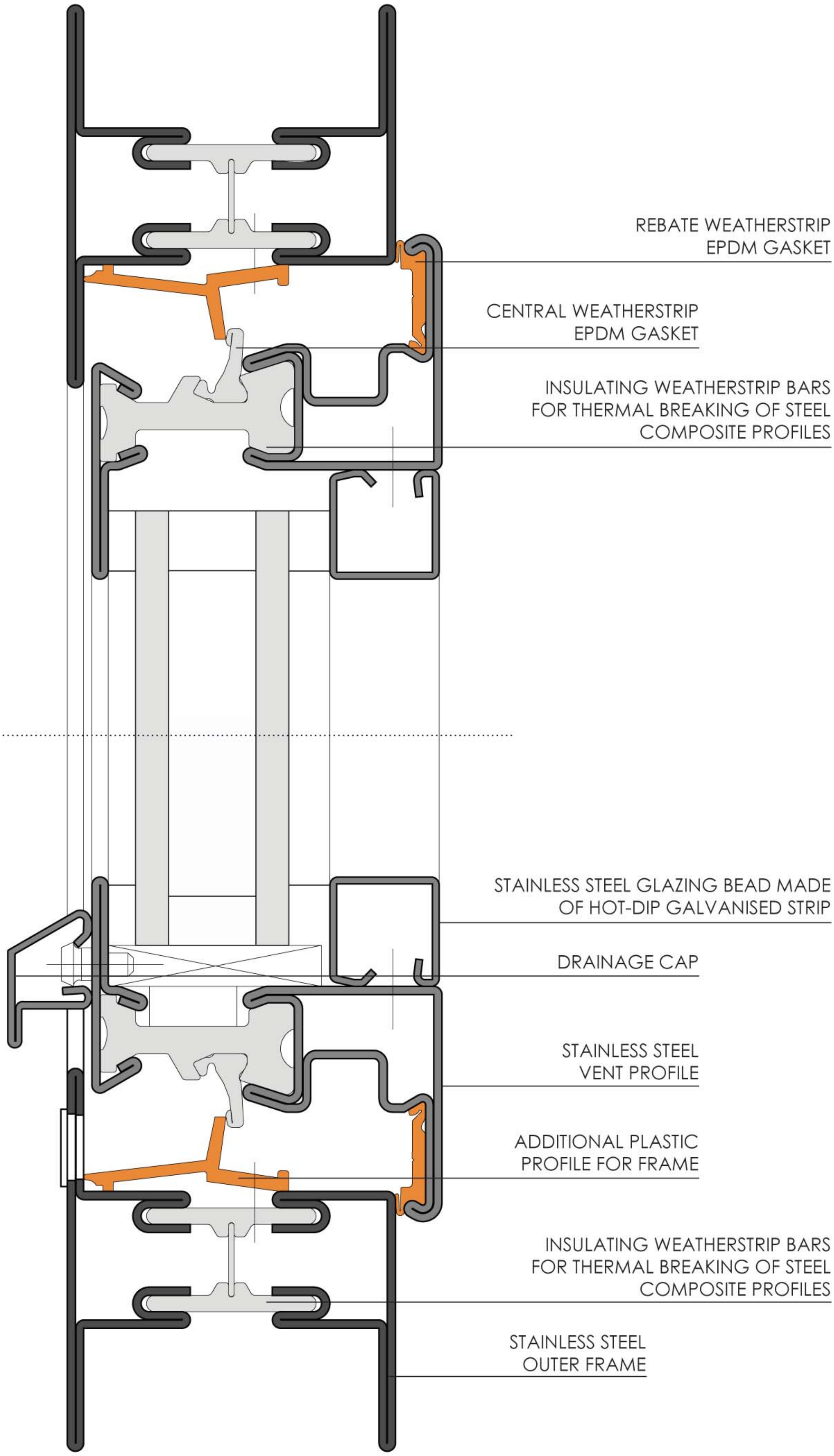
- Excellent noise reduction due to doble centre gasket and a 2-pane principle
- Controlled ventilation of gap between panes thanks to labyrinth gaskets
- Solar shading protected against weather
- Four drainage levels due to double centre gasket
- Inward and outward opening vents
- Drainage at the lowest profile point
- Hollow chamber insulating bar in outer frame with diagonal reinforcement for optimising dimensional accuracy and improving stability
- Glazing beads in blind-vent-look
- Solutions for glazing bars, face width 50 mm
- Opening types: turn/tilt, side-hung, bottom-hung, tilt-before-turn, double vent
- Max. vent weight 160 kg
- Burglar resistance up to WK3 (RC3) is possible
- Glass thickness up to 42mm for the vent and up to 75mm for the fixed light can be used
- An airborne sound insulation index of up to 48dB can be achieved using special glass
- Profiles available in a variety of colours
- Flush insulating bars prevent residual water collecting in the rebate

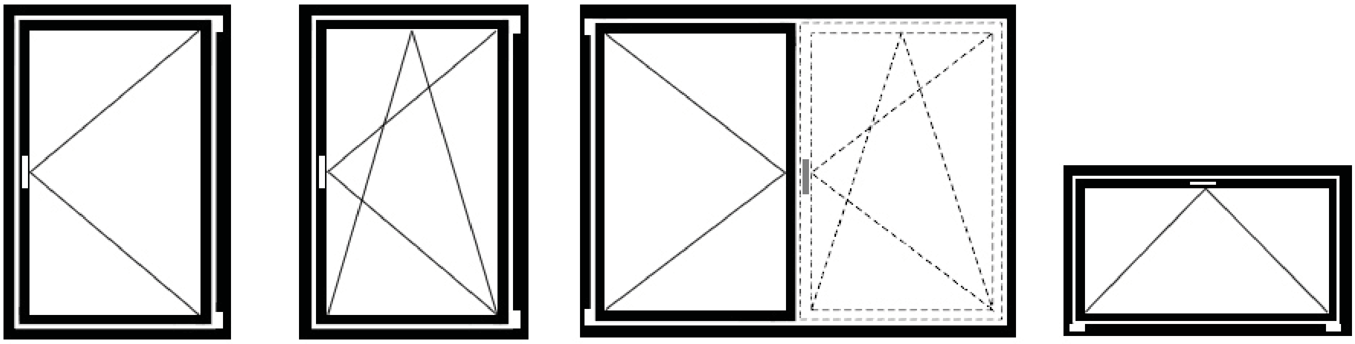
TECHNICAL INFORMATION:

Material: Aluminum
Type of construction: Highly thermally insulated
Security: Burglar resistance DIN V ENV 1627 to 1630 WK1, WK2, WK3
Air permeability DIN EN 12207: Class 4
Resistance to wind load DIN EN 12210: B5, C5
Thermal transmittance DIN EN 12412-2: Uf =1.6 W/(m2K)
Measurement of sound insulation DIN EN 20140: SSK 5
Watertigthness DIN EN 12208: Class E1050
Wind load resistance DIN EN 12210: Class C5/B5
Mechanical loading DIN EN 13115: Class 4
Long term functionality DIN EN 12400: Class 3

4.3.3_ STEEL DOUBLE GLAZED WINDOW FRAME (SCHUCO):







Recommendations for galzing support
Possibel ways of opening the vent profile and different positions for the fixing of the glazing

SYSTEM DESCRIPTION:
Robust welded stainless steel frames that support large and extremely slender windows.

FEATURES:

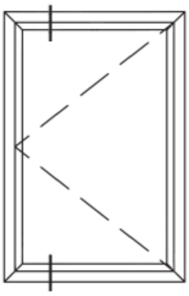
- Arched windows are possible
- Structural reinforcements can be added
- Easy-to-install range of concealed window fittings in stainless steel look (galvanised and chromated white)
- The profiles are suitable for:
  industrial areas
  coastal areas (salty air)
  areas with stringent hygiene requirements
  areas where resistance to de-icing salts is required

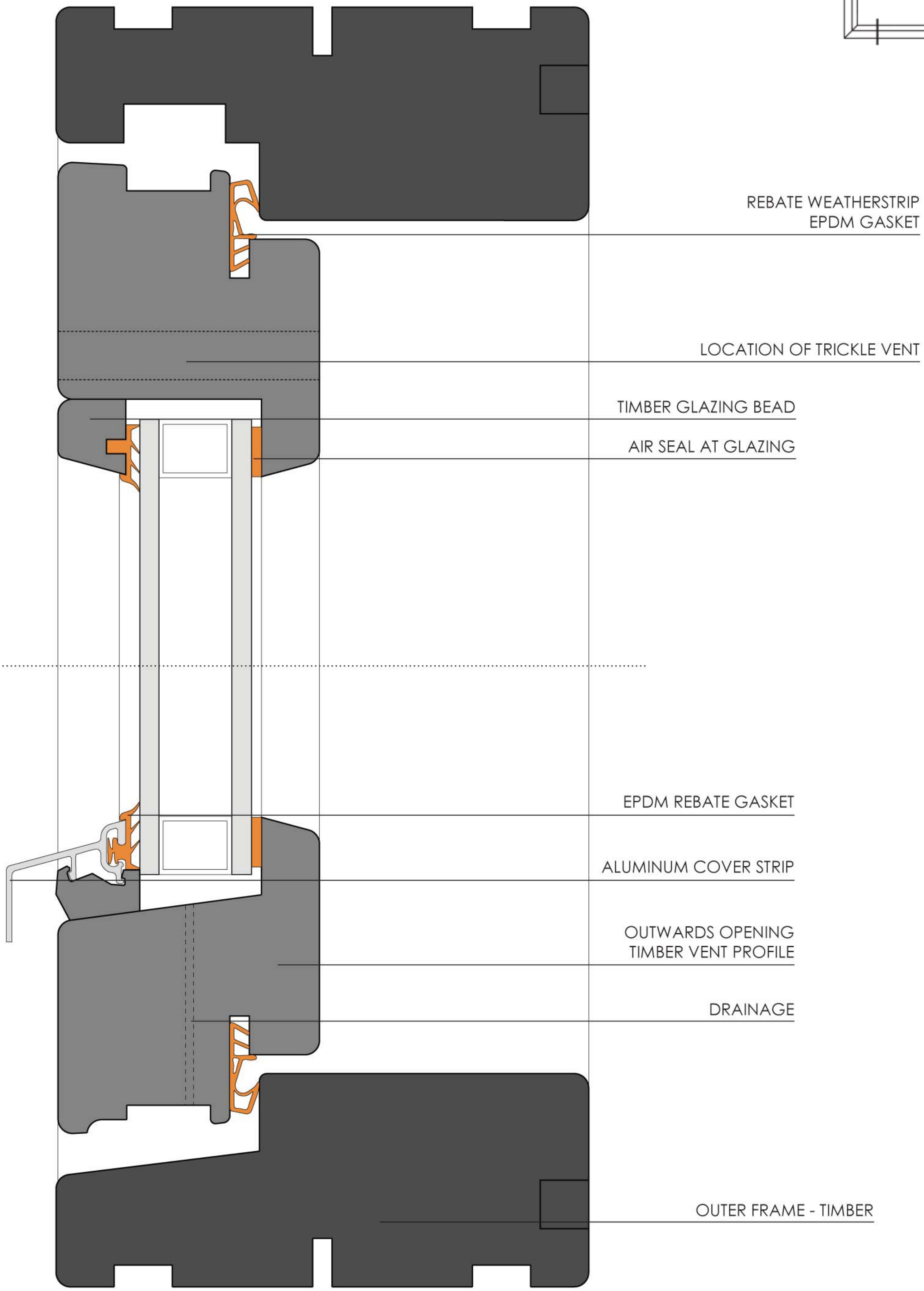
TECHNICAL INFORMATION:

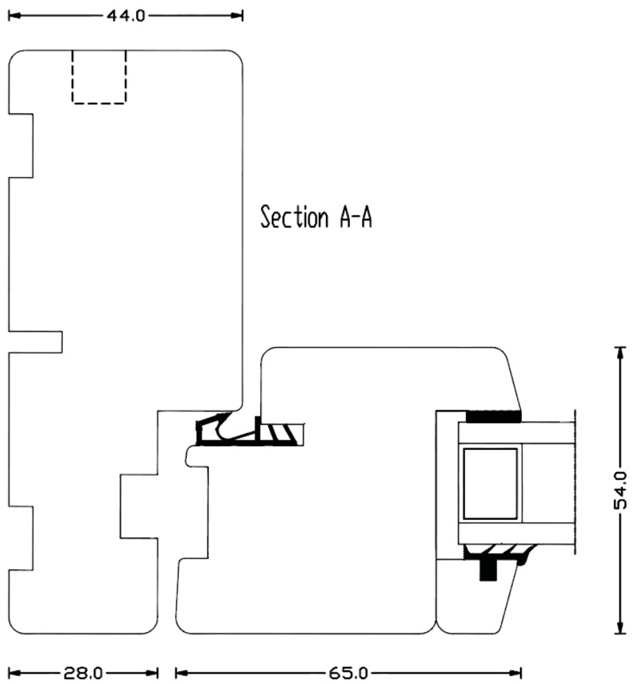
Material: Stainless steel AISI 316
Security: Burglar resistance DIN V ENV 1627: WK1-WK3
Air permeability DIN EN 12207: Class 3-4
Watertigthness DIN EN 12208: 8A - E1050
Sound insulation DIN EN ISO 140-3: to R_w 45dB
Resistance to wind load DIN EN 12210: C4, B4
Thermal transmittance DIN EN 10077-1: Uf =2,4 W/m2K
Load bearing capacity of safety devices: Requirement satisfied
Bullet proofing DIN EN 1522: FB 4 NS
Operating forces DIN EN 13115: Class 1
Metal profiles with thermal barrier: CW/TC2
TRAV test about technical regualtions for protecting glazing against falling out: Fall height 900 mm / Category A

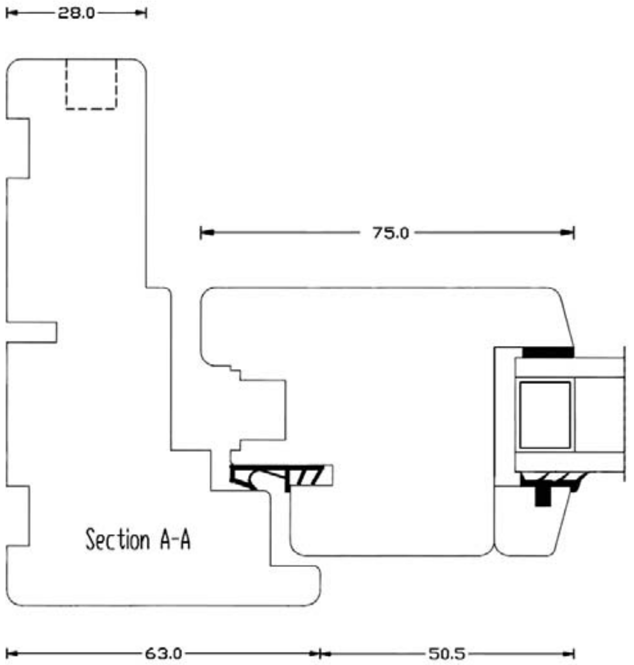
Netherlands Institute for Sound and Vision, Hilversum/NL (Architect: Neuterlings Riedjik Architecten, Rotterdam/NL) - Example of a completed project with Kanislo steel frames

4.3.4_ TIMBER DOUBLE GLAZED WINDOW FRAME - OLD CONSTRUCTION (SCANDINAVIAN TIMBER):









Outwards opening timber frame plane
Inwards opening timber frame plan (plus tilt and turn opening possible)

SYSTEM DESCRIPTION:

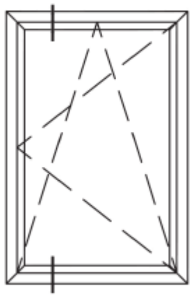
High performance, factory finished pure timber windows in softwood and hardwood.

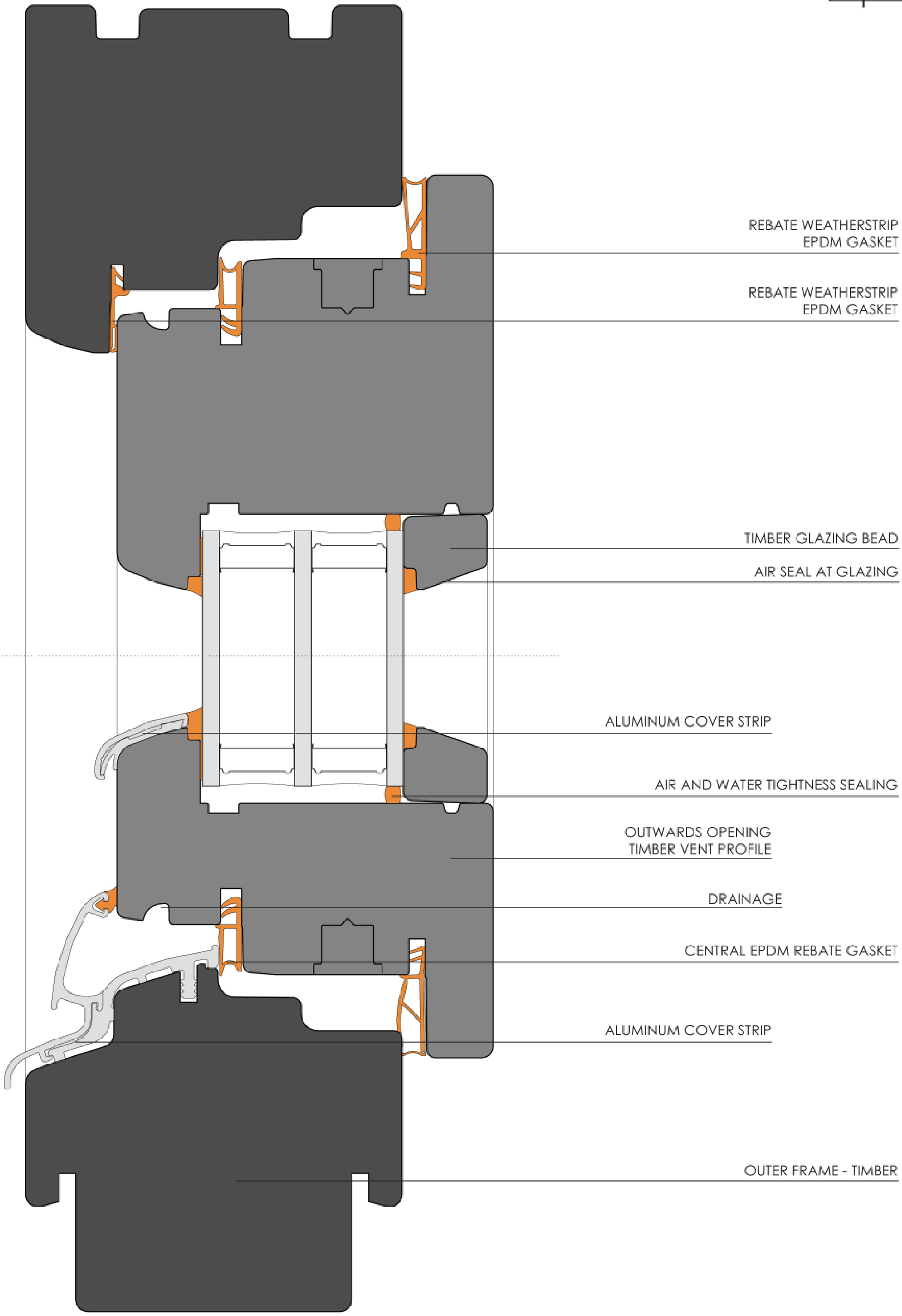
FEATURES:

Inward Opening: Side Hung, Tilt/Turn, Bottom Hung
- Outward Opening: Side Hung, Top Guided, Top Hung, Pivot Fixed Light
- Acoustic window: Inward opening Tilt/Turn or Side Hung

Example of a completed project with Scandinavian timber window frames - Architect unknown
http://www.scandinaviantimber.com/windows/timber.html

4.3.5_ TIMBER TRIPLE GLAZED WINDOW FRAME (JOSKO):





SYSTEM DESCRIPTION:

Rubin 90 is the evolution of the classic wooden windows and trumped - as the name suggests - on a 90-millimeter-thick wood.

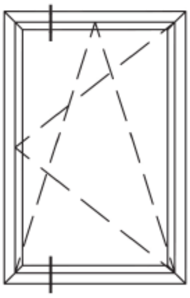
FEATURES:

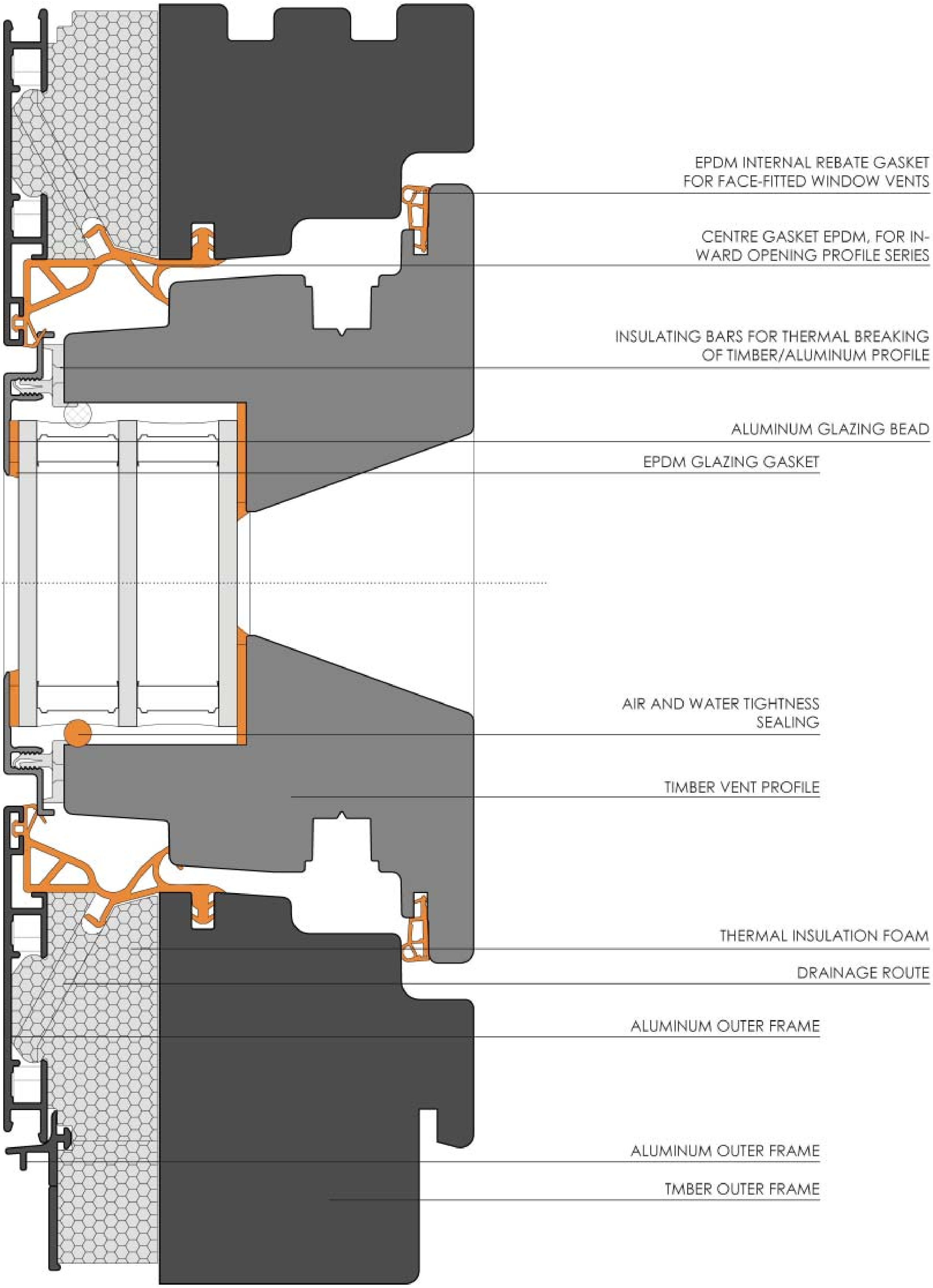
- System thickness 90mm
- Wood stained or oiled appearence
- Easy clean profile contours, maintenance free aluminum shell
- Proven timeless design
- Three seals technology for noise, air and water tightness
- No use of foam: PVC and CFC-free
- 15% higher stiffness and strength over traditional timber frames
- Basic burglary protection by standard mushroom pin lock
- Optional, also WK 2 tested and certified (for burglar resistance)
- Best thermal insulation due to the natural raw material wood
- Triple layers of glazing
- Suitable for passive houses
- Three standard seals for optimal sound, heat and airtightness values
- Aged, winter-felled wood used, in most cases from sustainable Central European forestry
- No foam used: PVC- and CFC-free

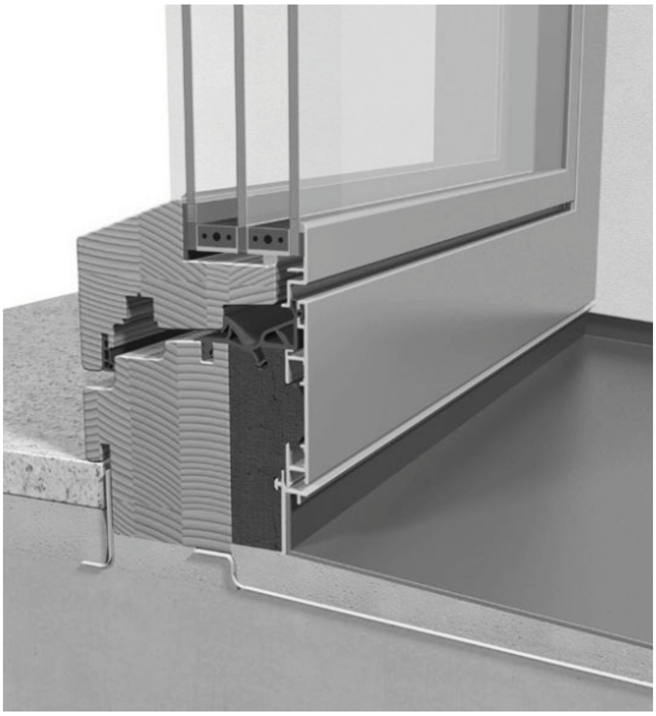
TECHNICAL INFORMATION:

Best value 3-fole glass U_w 0.73 W/m2K

4.3.6_ TIMBER/ALUMINUM TRIPLE GLAZED WINDOW FRAME (JOSKO):







SYSTEM DESCRIPTION:

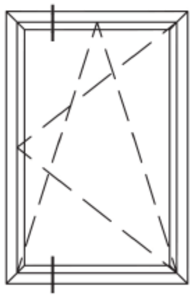
The Platin Passiv is a timber/aluminum frame from sustainable sources, that makes a contribution to climate protection and helps to heat energy savings.

FEATURES:

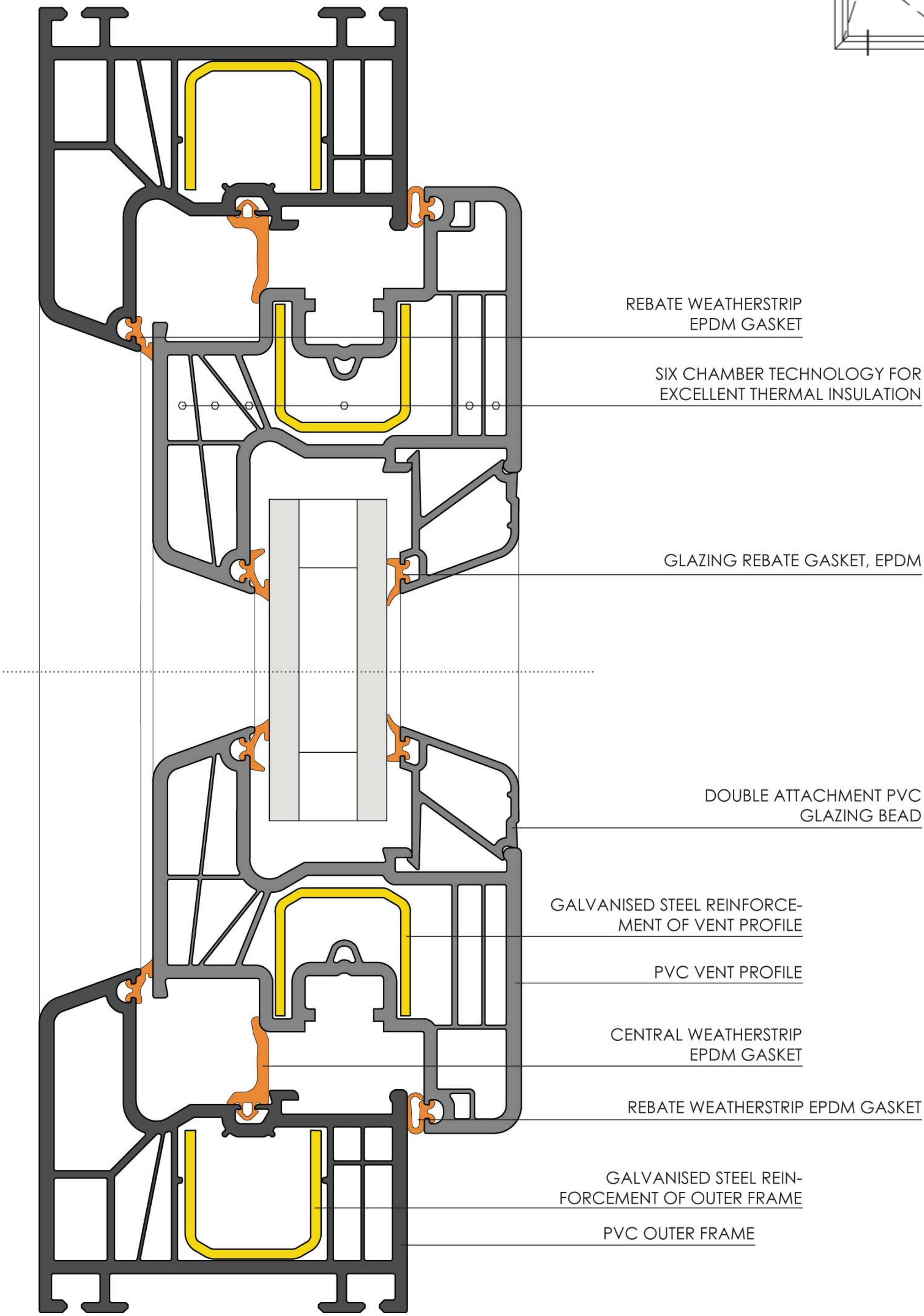
- Thermally optimal system thickness of 103 mm, of which 32 mm highly effective thermofoamInward and outward opening vents
- Externally flush to glass, internally and externally flush to frame
- Typical Uw 0.67 W/m2K with triple glazing
- Very slim frames ensure 20% more incident light, lowering heating costs
- Fully concealed fittings and turn limiter as standard
- Available in spruce, oregon and oak (from sustainable forests)
- Spruce and oak from domestic forests
- 90 mm thick wood (casement)
- Slim mullion covers for stable coupling
- 3 seals for optimal sound, heat and tightness values
- Fix glass bonding with the frame as standard – for more warmth, tightness and stability and less condensation
- Triple glazing Ug 0.5 as standard – for 30 % better energy value and greatly reduced cold radiation
- The slanting glazing rebate lip for improved flow of heat reduces the formation of condensation on the edge of the glass
- Component suitable for passive house

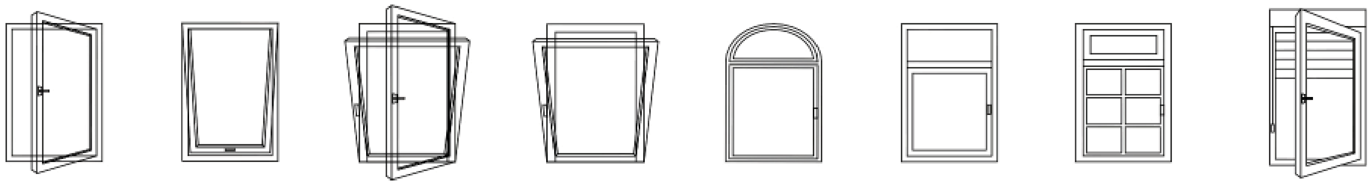
TECHNICAL INFORMATION:

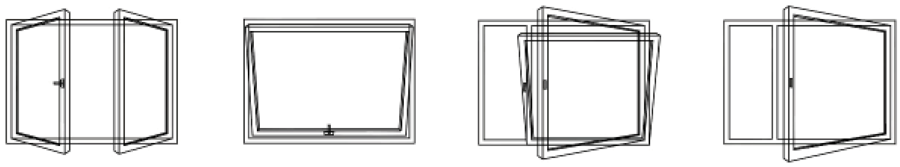
Material: Timber and aluminum
Type of construction: Thermally insulated
Security: Burglar resistance DIN V ENV 1627 to 1630 WK2



4.3.7_ PVC DOUBLE GLAZED WINDOW FRAME (INOUTIC):







Different window shapes and possible ways of opening the vent profile

SYSTEM DESCRIPTION:

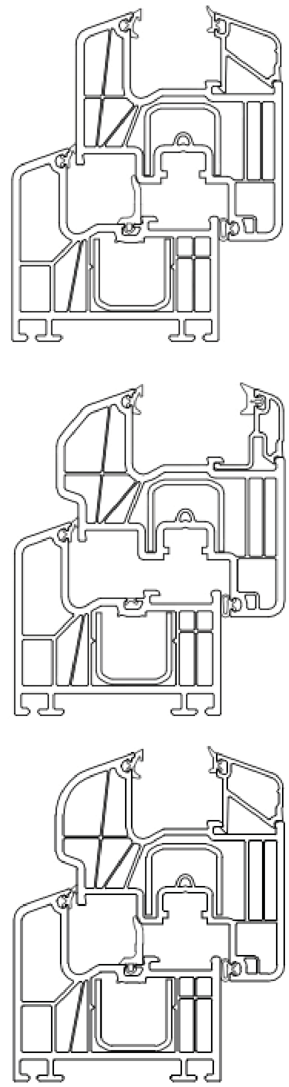
A unique PVC system having six-chamber design and structural depth of 76mm that achieves extraordinary thermal insulation parameters and enables the use of various types of double glazed and triple glazed units, which increase heat saving, improve soundproofing and security.
A special production technology ensures extraordinarily smooth surface of the profiles enabling very easy maintenance and cleaning.

FEATURES:

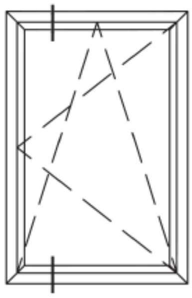
- 3 gasket profiles
- 6 chambers
- Various colour options
- Structural reinforcements for extra stiffness

TECHNICAL INFORMATION:

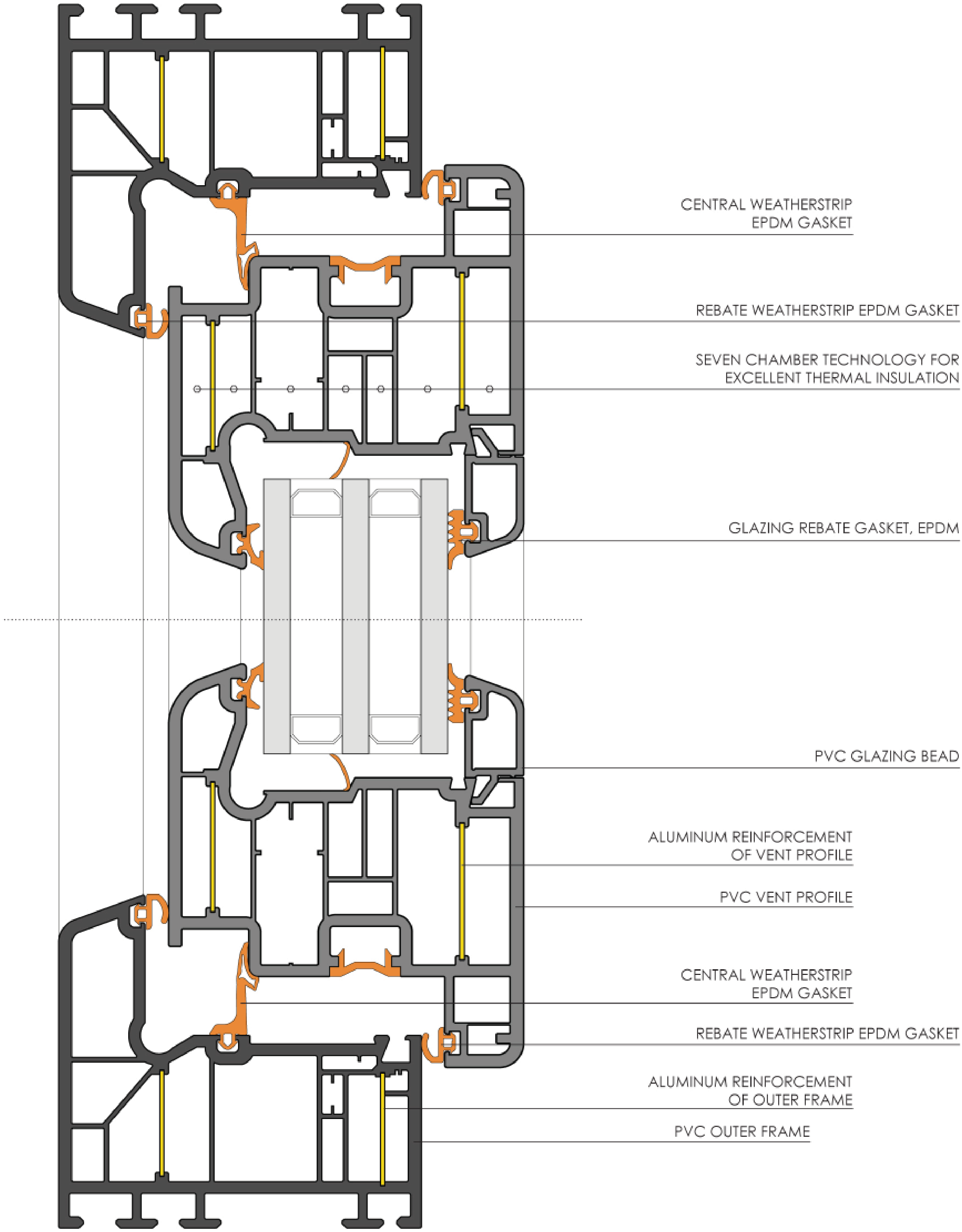
Material: PVC
U_w factor :
with triple glass and “warm” glass frame (PVC): 0.94 W/m2K
with double glass and standard glass frame (alumimnum): 1.30 W/m2K
U_f factor: 1.10 W/m2K
Number of chambers: 6
Number of gaskets: 3
Width of the profile: 76 mm
Maximum possible width of glass unit: up to 44 mm
Thickness of the profile walls: 2.8 mm
Noise reduction capacity: 32-49 dB according to glazing type
Double attachment of the glazing beads ensures higher security thanks to improved stability and resists the efforts to break in through the window or door.



Different window frames shapes (classic, semi-recessed polygonal, semi-recessed round)



4.3.8_ PVC TRIPLE GLAZED WINDOW FRAME (SCHUCO):



SYSTEM DESCRIPTION:

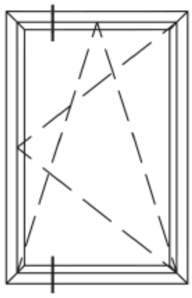
The new generation of PVC frames without steel reinforcements. The sysytem offers high thermal performance due to the three sealing layers and the 7-chamber technology, while offers high stiffness due to the aluminum reinforcement technique.

FEATURES:

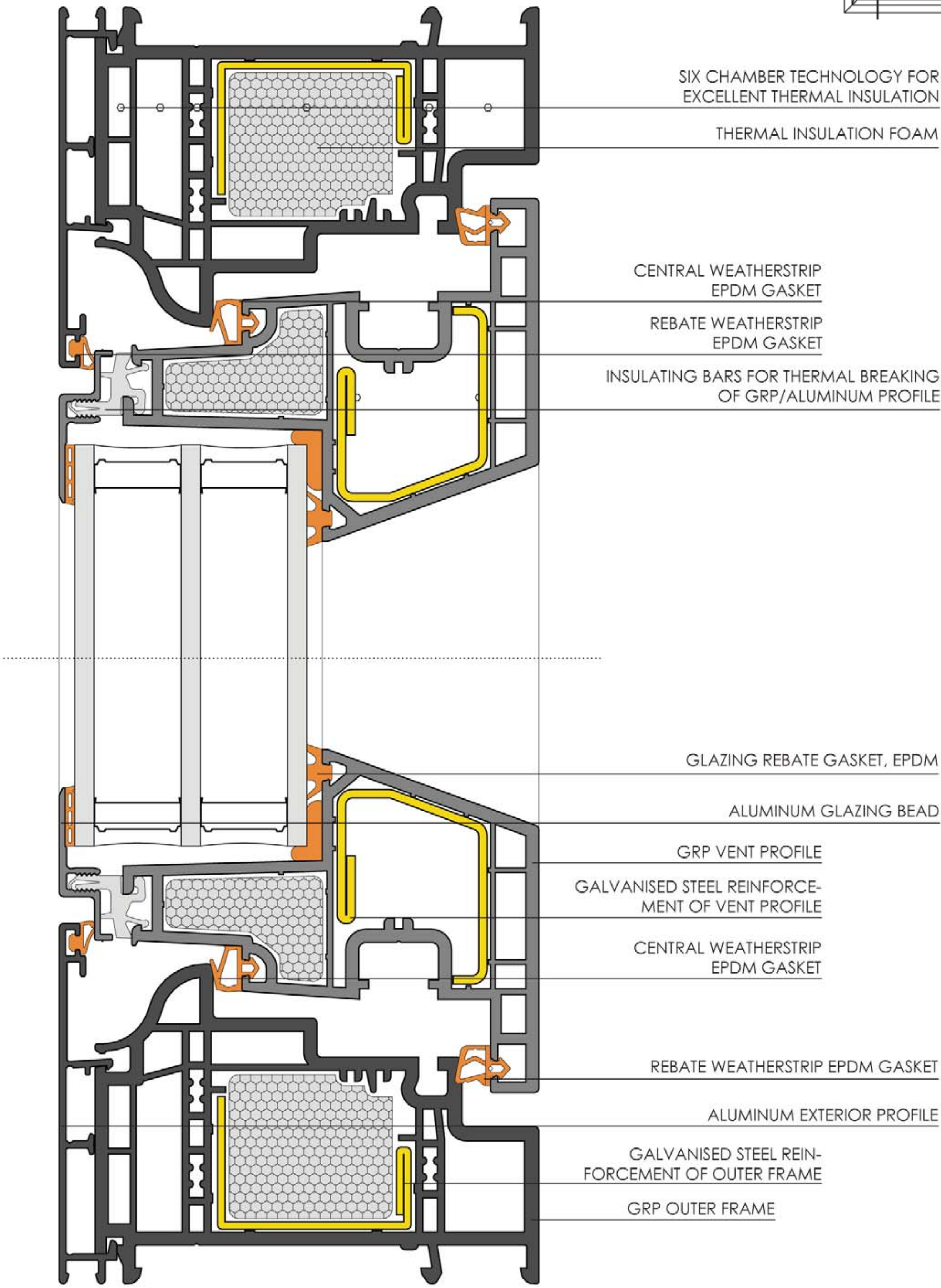
- No steel reinforcements in the profiles
- 7-chamber technology with optimized profile geometry with a mounting depth of 82mm for the highest thermal insulation
- Optimized spaces where additional foam can be added
- Wide profiles offer more security and higher resistance against burglary
- Excellent sound insulation
- Wing Geometry with internal fitting and 3 seals
- Various colour options
- 100% recyclable

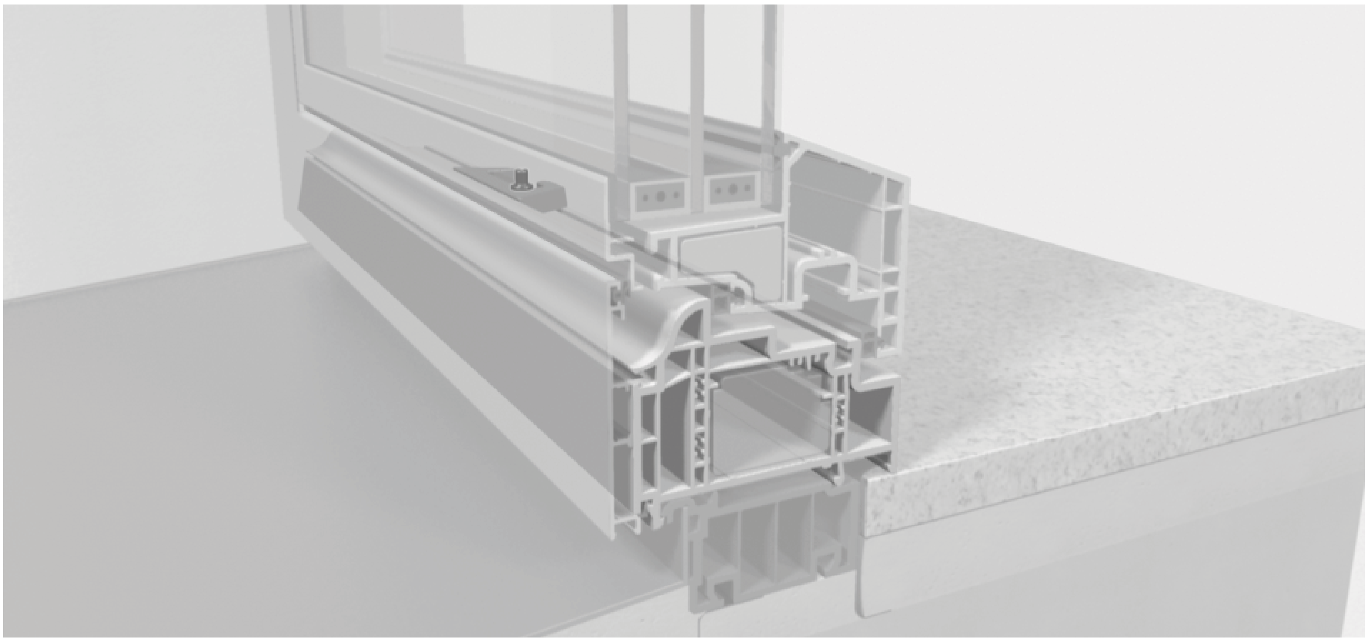
TECHNICAL INFORMATION:

Material: PVC
U_w value: 0.76 to 0.94 W/m2K
Number of chambers: 7
Number of gaskets: 3



4.3.9_ GRP/ALUMINUM TRIPLE GLAZED WINDOW FRAME (JOSKO):





SYSTEM DESCRIPTION:

The Safir GRP/Aluminum profile combines four qualities: a flush fit, sleekness, warmth and stability. Furthermore, the revolutionary composite/aluminium window offers more incident light thanks to its slim frame, a stable sash frame thanks to integrated fibreglass and much more.

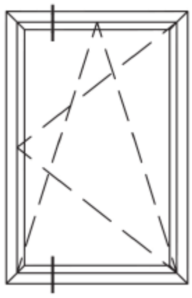
FEATURES:

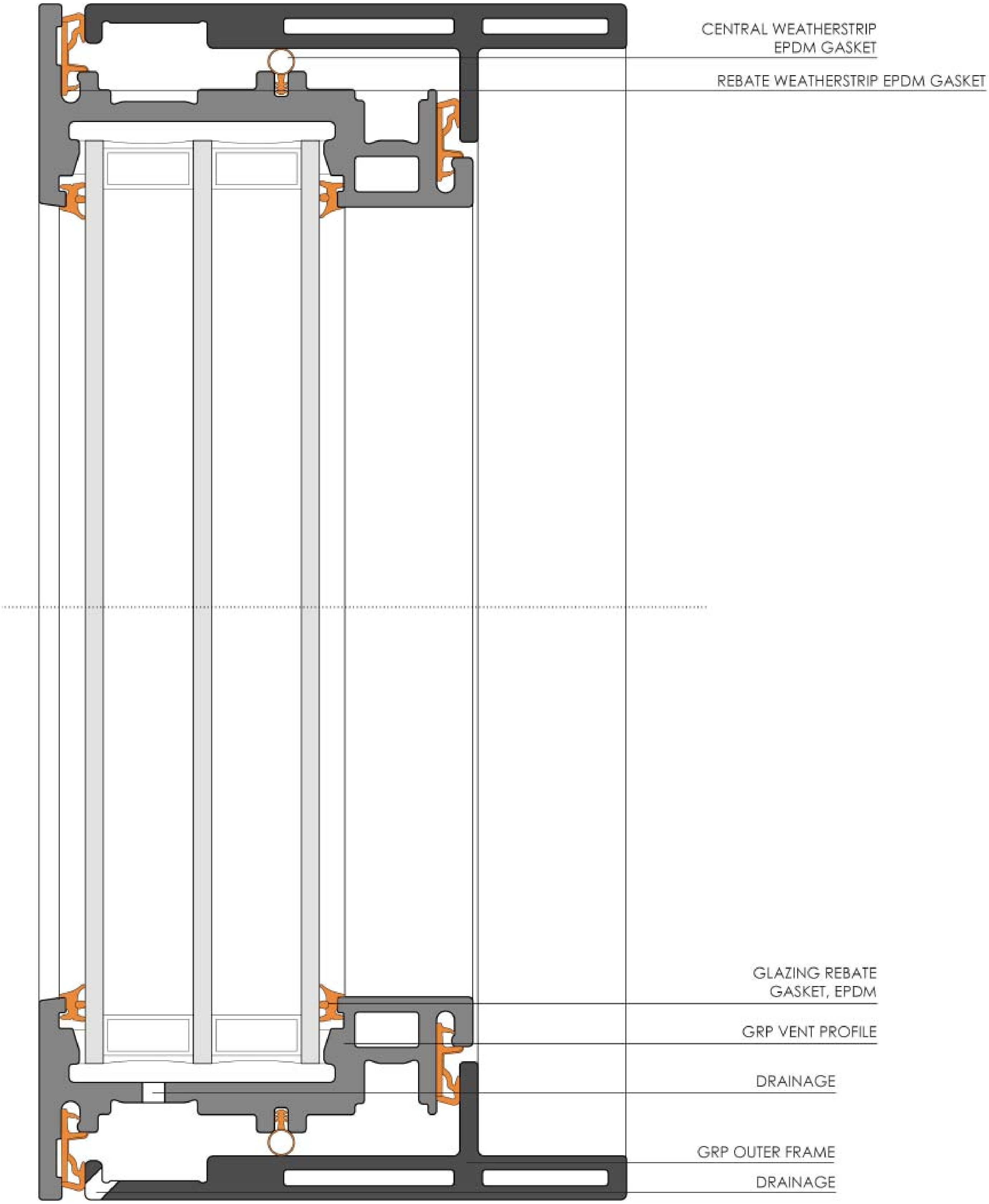
- Externally flush to glass, internally and externally flush to frame
- Extremely slim frame
- Internally sleek appearance without glass strips and joins
- Fibreglass-strengthened sash frame for greater stability, fewer drafts and up to 40% less weight than conventional PVC/steel profiles
- 3 seals for optimal sound, heat and tightness values
- 6 chamber technology
- Innovative, patented profile structure to distribute heavy glass weights evenly
- Innovatively positioned additional steel reinforcement for large dimensions
- Extremely slim mullion covers for stable coupling
- Fix glass bonding on both sides as standard – for more warmth, tightness and stability and less condensation
- Profile 100% recyclable
- Integrated environmentally-friendly thermofoam core for top heat values as standard
- Very slim frames ensure 20% more incident light, lowering heating costs

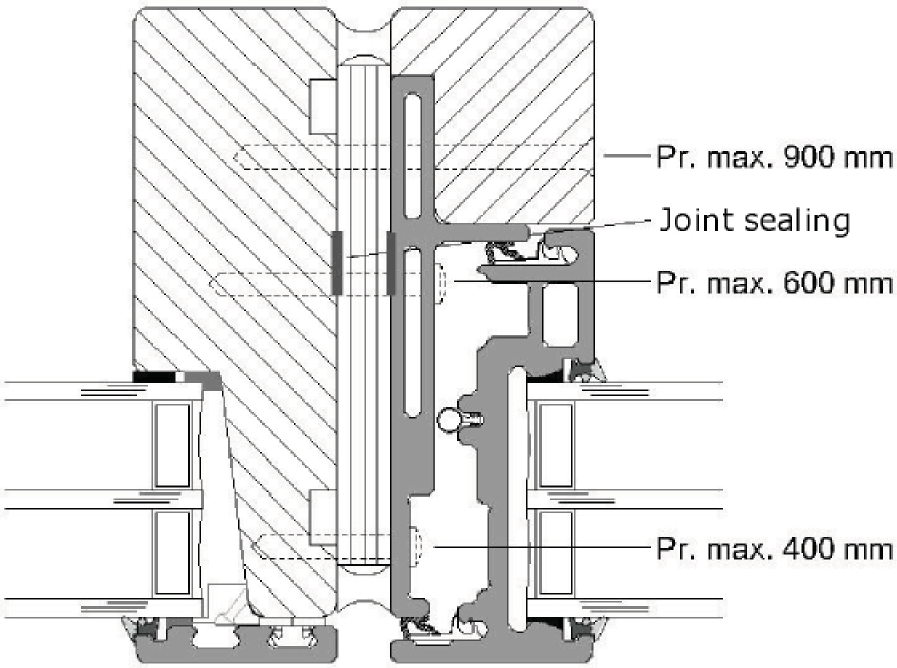
TECHNICAL INFORMATION:

Material: GRP/Aluminum
U_w factor of triple glazed window: 0.67 W/m2K
Number of chambers: 6
Number of gaskets: 3
Width of the profile: 100mm
Security: Burglar resistance DIN V ENV 1627 to 1630 WK2

4.3.10_ GRP TRIPLE GLAZED WINDOW FRAME (ECLIPTICA):







Horizontal section of a fixed (left) and an operable (right) GRP window frame by Ecliptica

SYSTEM DESCRIPTION:

GRP window frames are composed of glass and polyester. The combination gives enough strength and stiffness to the frame that can be designed with only 45mm visible framework. This makes the window elegant and leaves a bigger glass area fo the light to come in. What is more, the sun that enters the window helps the energy balance of the building.

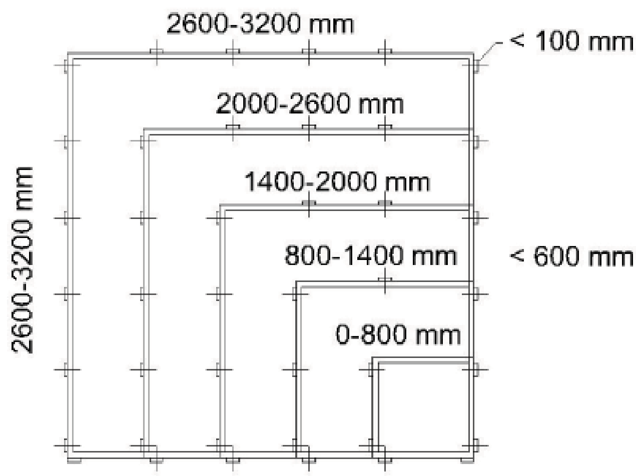
FEATURES:

700 times better thermal insulation than aluminum frames

- 4 times betther strength than wooden frames
- Sustainable solution
- 2-layer and 3- layer glass frames are possible
- Frame depth is 130mm
- The glass is bonded in order to achieve optimal protection from burglary
- Inwards and outwards opening windows (top and side hung / side hung)
- Maximum weigth must not excedd 350kg
- Variety of colours for the exterior view

TECHNICAL INFORMATION:

Material: GRP
U value U_w of the element: 0.71 W/m2K
Energy balance of the element Ew: +19.6 (+32)
Percentage of glass in the element: 87%



Possible sizes of the Ecliptica GRP window frame and support places

4.4_ WINDOW FRAME COMPONENTS – COMPARISON TABLE:

At the table below, the ten different examples of window frames are displayed. The frames are divided into five main components; the outer frame, the vent profile, the glazing layers, the glazing bead and the weatherstrip gaskets. Each of these five components is necessery to the frame and each one appers with a different shape, according to the material out of which the frame is made.
The outer frame is the non-movable profile that forms the connection between the operable window profile and the main wall construction.

The vent profile is the part of the window that can be let open and serves for ventilation reasons. There are many different types of vent profiles depending on the way the window opens (top hung, side hung, side/top swing, etc.)

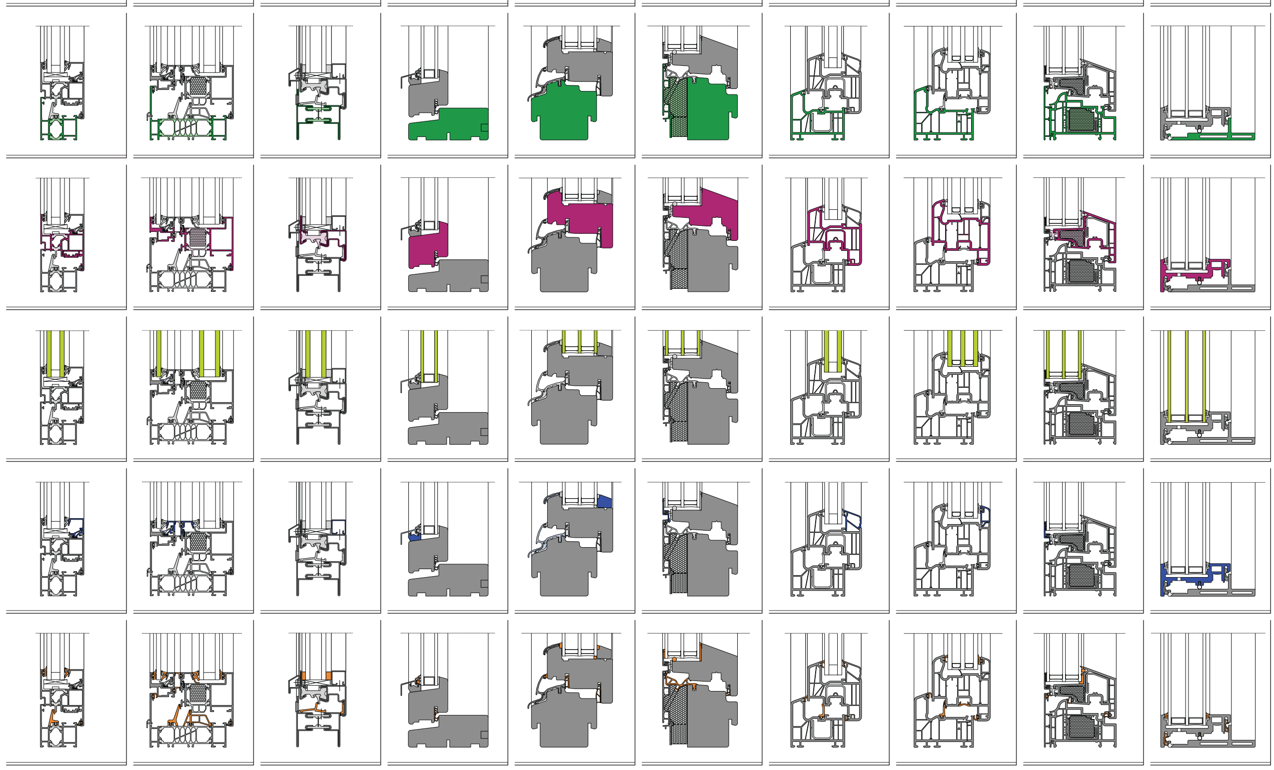
The glazing layers are the transparent part of a window frame. A typical window frame usually includes two layers of glass planes while the more advanced ones incude three in prder to achieve better thermal performance. The amount and width of glass planes also influence the quality of sound insulation of the window.

The glazing beads are profiles used for the fixing of the glazing planes to the window frame. Glazing beads according to their size, can adjust the width of the glazing space. In this way the same window frame can include two or three layers of glass by only changing the width of the glazing bead.

The weatherstrip gaskets are EPDM rebare gaskets that are used for the air and water – tightness of the window frame. The use of at least two EPDM gaskets is required by the building regulations.

COMMON TYPES OF WINDOW FRAMES _MATERIALS AND COMPONENTS

COMPONENTS OF A WINDOW FRAME



	ALUMINUM I	ALUMINUM II	STEEL	TIMBER I	TIMBER II	TIMBER/ALUMINUM	u-PVC I	u-PVC II	GRP/ALUMINUM	GRP
DESCRIPTION	ALUMINUM DOUBLE INSULATED WINDOW FRAME BY SCHUCO - AWS 50 SYSTEM PROFILES INWARD OPENING VENT	ALUMINUM TRIPLE INSULATED WINDOW FRAME BY SCHUCO - AWS 105 CC.HI SYSTEM PROFILES INWARD OPENING VENT	STEEL DOUBLE INSULATED WINDOW FRAME BY SCHUCO - JANISOL SYSYTEM PROFILES INWARD OPENING VENT	TIMBER DOUBLE INSULATED WINDOW PROFILE OLD CONSTRUCTION SCANDINAVIAN TIMBER SYSTEM PROFILES OUTWARD OPENING VENT	TIMBER TRIPLE INSULATED WINDOW PROFILE NEW CONSTRUCTION BY JOSKO - ROBIN 90 SYSTEM PROFILES INWARD OPENING VENT	TIMBER/ALUMINUM TRIPLE INSULATED WINDOW PROFILE NEW CONSTRUCTION BY JOSKO - PLATIV PASSIV SYSTEM PROFILES INWARD OPENING VENT	u-PVC DOUBLE INSULATED WINDOW PROFILE BY INOUTIC - PRESTIGE KLASSISCH SYSTEM PROFILES INWARD OPENING VENT	u-PVC TRIPLE INSULATED WINDOW PROFILE BY SCHUCO - THERMOPLUS SYSTEM PROFILES INWARD OPENING VENT	GRP/ALUMINUM TRIPLE INSULATED WINDOW PROFILE BY JOSKO - SAFIR SYSTEM PROFILES INWARD OPENING VENT	GRP TRIPLE INSULATED WINDOW PROFILE BY ECLIPTICA - 3LAYER GLASS SYSTEM PROFILES OUTWARD OPENING VENT

4.5_ WINDOW FRAME FUNCTIONS – COMPARISON TABLE:

At this table, the ten different examples of window frames are displayed again, but this time the compared aspect is their basic functions. The different parts of the frame perform different functions. At this table it is important to note the level of integration of the different frames. For some of them each function is performed by a different element, while at others, more integrated window frames (timber and GRP profiles), there is one element that brings together more than one functions.

The basic functions analysed below are thermal insulation, drainage, stiffness, sound insulation and andjustability of the glazing width.

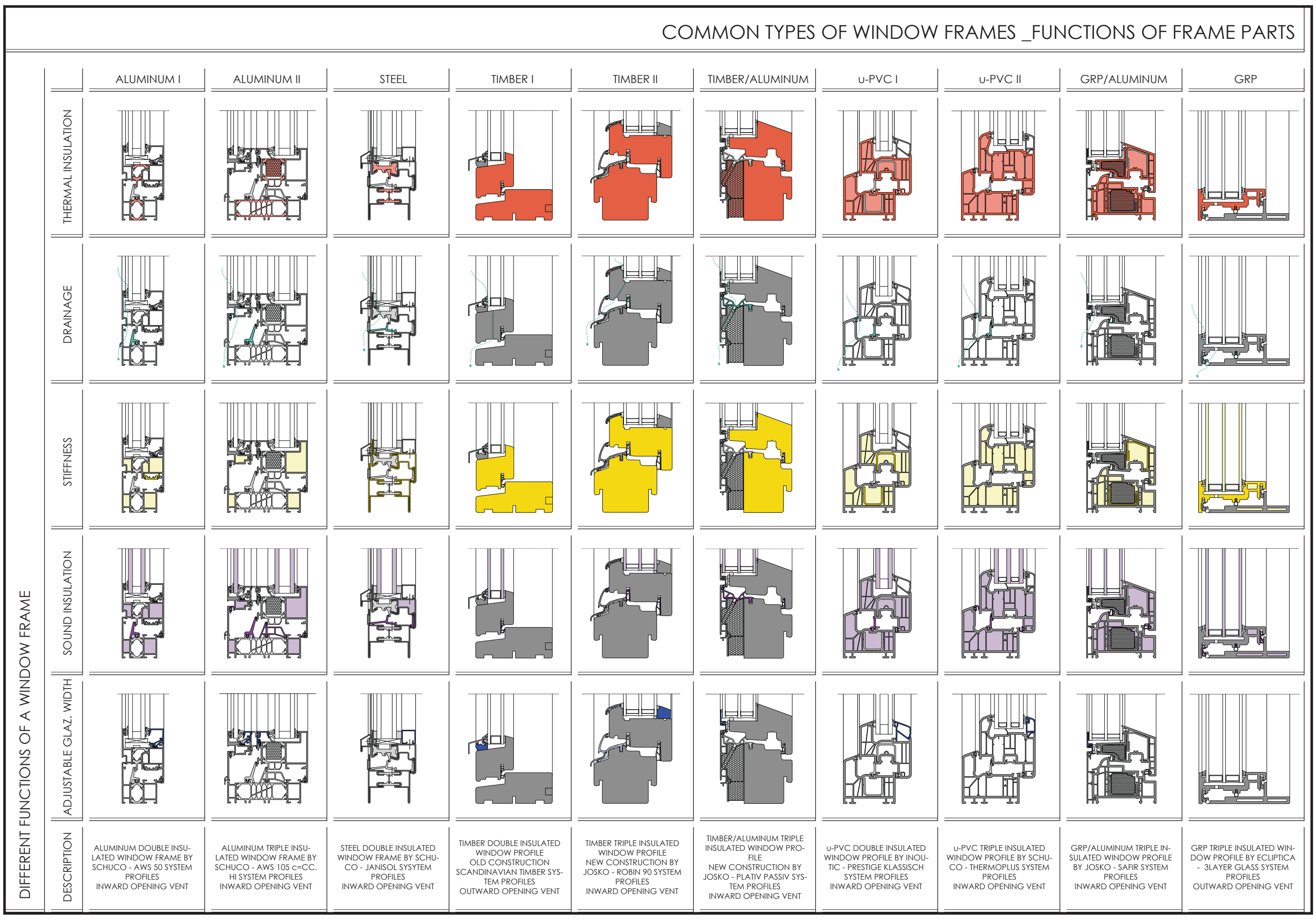
Thermal insulation between the exterior and interior part of the frame is achieved by the framing material itself or by thermally broken profiles. The framing materials with low thermal conductivity (mainly timber and GRP) do not need any extra insulation whereas window frames that consist of high conductive materials (aluminum, steel) require thermally broken profiles in order to achieve low U-values. The low insulative parts are connected to each other with a less conductive material (usually a plastic profile).

The drainage is the path though which the water that is inserted into the window frame can escape it. Drainage is crucial for the frames, as the trapped water must be quickly removed to the outside, otherwise it can accelerate the material's corrosion.

The stiffness of the window profile is achieved by the framing material or by other reinforcement materials that are inserted into the frame. The geometry of the frame (chambers) can also provide better stiffness.

The sound insulation is mainly achieved through the layers of glazing. However, the geometry of the frame can reduce sound transmittance to the interior. Multiple chambers technology (many chambers in different shapes) can help reduce the noise.

The adjustable glazing width depends of the glazing bead. The possibility of changing the glazing width is really important as the same frame can be used in different cases where a double-glazing or triple-glazing window is required. In this case, the glazing bead can be replaced with a smaller or bigger one that leaves to the glazing planes the exact width they require.



4.6_ ADVANTAGES AND DISADVANTAGES OF GRP WINDOW FRAMES IF COMPARED WITH OTHER MATERIALS

The above analysis of materials for window frames aims to highlight the advantages and disadvantages of GRP if compared with other materials. Conclusions should be drawn regarding how could a GRP window frame be improved and which functions need further development.

The advantages of GRP compared to other materials have been already mentioned. It is basically a light weight and high strength material that provides exceptional thermal insulation and corrosion resistance, while it can be produced in several complex shapes and satisfy almost any aesthetical requirements.

But what is also important, is to determine the defects of it, the problems and constrains of its use.

One main disadvantage of the use of GRP frames is their cost, as the production technique used is extremely expensive. What is more, the inability of the material to be repaired in case of damage can significantly raise even more the cost of maintenance, since the whole window frame has to be replaced with a new one.

What is more, customization is an issue than cannot be satisfied when using GRP window frames. Due to the high production cost that is mainly caused by the high production cost of the mold, not many different shapes of GRP profiles are available at the market. Despite the materials ability to form almost every possible shape, there are only a few different GRP sections. The variety of styles and shapes is extremely limited and the appearance of the frames cannot be easily differentiated.
However, the main restriction in making GRP profiles more competitive in terms of appearance and variety with the aluminum profiles is the reduced demand of composite profiles from the building market. But since composite have been recently become more popular and their use in building applications has been increased, a reduction of the production cost of GRP profiles can be expected in the near future.

Another disadvantage of the use of GRP frames is their inability to be flexible and satisfy different needs of construction companies in terms of profile sizes. The width of a double and a triple insulated profile made of aluminum, wood or steel can be easily adjusted by using the same vent profile and only changing the width of the glazing bead. In the case of GRP profiles, where the glazing bead and vent profile are integrated to only one element, the width of the frame cannot be flexible. This raises the costs of construction companies, as for every project having a different width of window frame a different mold for the GRP frames has to be produced.

Taking into consideration the above observations, some suggestions could be created.

The profile could be split into two pieces that can be easily connected to each other without the use of any screw. This could benefit the frame in several ways.

•The connection between the two parts could create an adjustable space where the exact number of glazing panes could be inserted according to the needs of each frame. The two parts of the profile (one acting as a vent profile and the other as the glazing bead) will be able to move and be adjusted during the installation of the frame on site.

•The idea of having two parts creating the movable frame of the window could help to the customization of the profile according to the user's aesthetical preferences. Several profile designs, acting as a glazing bead, could be created so that when combined with the other standard part of the frame, they could create various aesthetically different products.

•The split of the moving frame in two parts could also help reduce the maintenance cost of a GRP profile. When a single part profile is damages, it has to be completely replaced but when one part of a two-element window frame is damaged, it can be partially replaced, reducing this way the total maintenance cost of a building.

The above suggestions could be taken into consideration during the design procedure that will follow.

4.7_ TYPES OF WALL-TO-FRAME CONNECTIONS

At the following chapter the different ways of connecting a window frame with a solid wall construction will be analyzed. The walls are divided into two main categories, the traditional concrete/brick walls and the composite sandwich panel walls.

All the possible and so far existing combinations of window frame materials and solid wall construction methods are presented at the following table. As observed, the traditional wall structure can be combined with every framing material, while the composite wall structure has only been combined with aluminum frames.

Goal of this research it to provide a new method of constructing composite facades, by combining composite wall structures with GRP window frames.

EXISTING FAÇADE SYSTEMS								
		ALUMINUM	STEEL	TIMBER	TIMBER/ALUMINUM	u-PVC	GRP/ALUMINUM	GRP
Façade systems	Traditional Construction Method	✓	✓	✓	✓	✓	✓	✓
	Composite Structure (GRP sandwich panels)	✓	-	-	-	-	-	?

For a more complete understanding of the connection possibilities between the wall and the window frame, below the seven types of window frames and the two types of solid wall constructions are presented in their possible combinations.

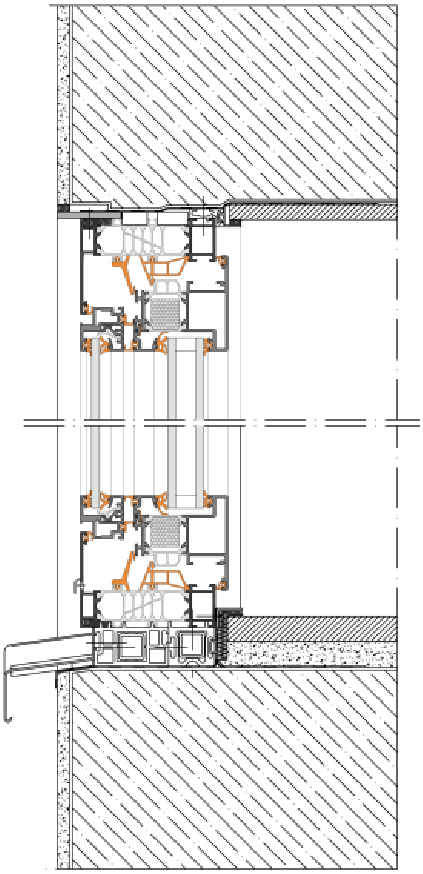
These are:

- Aluminum frame – Traditional Wall Construction
- Steel frame – Traditional Wall Construction
- Timber frame – Traditional Wall Construction
- Timber/Aluminum frame – Traditional Wall Construction
- PVC frame – Traditional Wall Construction
- GRP/Aluminum frame – Traditional Wall Construction
- GRP frame – Traditional Wall Construction
- Aluminum frame – Composite Wall Construction

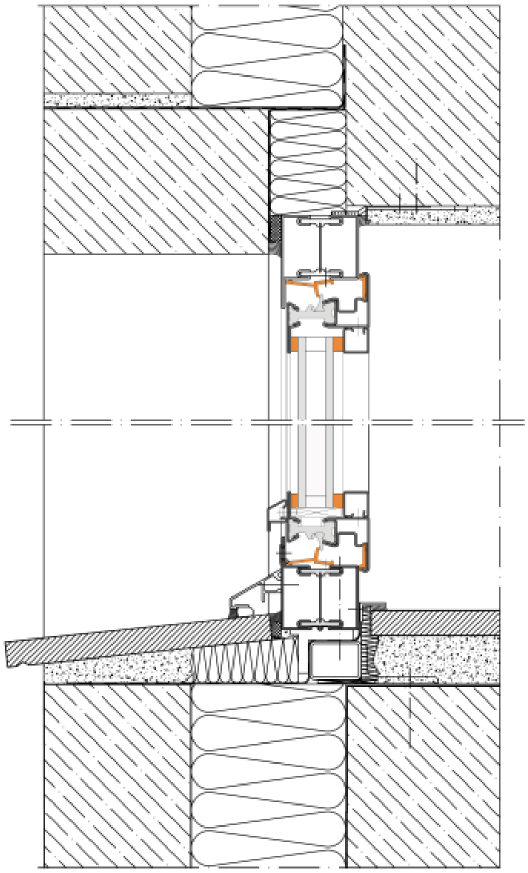
In cases where two different frames were presented for the same framing material (double and triple glazed options), the most advanced product has been selected for the analysis of the wall-to-frame connection.
Therefore, all window frames presented below, except steel frame , are triple glazed.

Of course the drawings below are only some representative examples of possible frame-wall connection principles.
A lot of different connection ways are still possible, but the cases below can give a general idea of how the problem of connecting a window frame to a traditional/composite wall can be solved.

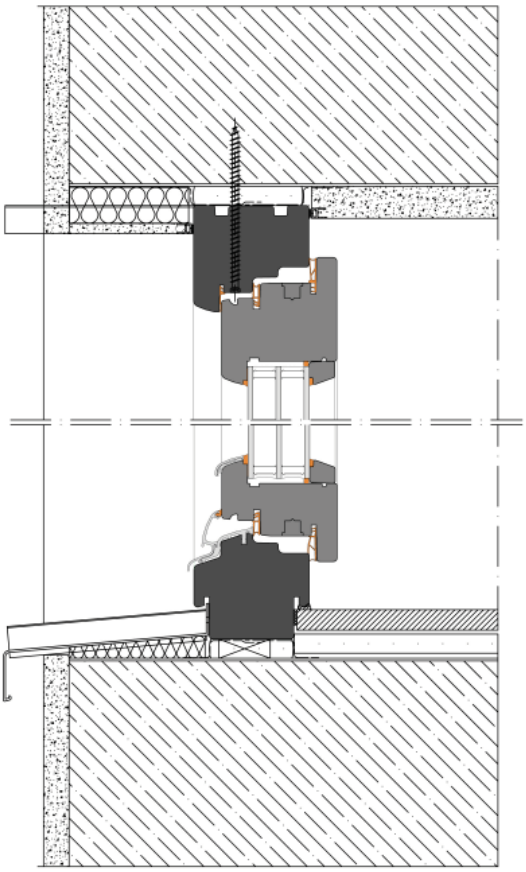
4.7.1_ FRAME MATERIALS AND CONNECTIONS:



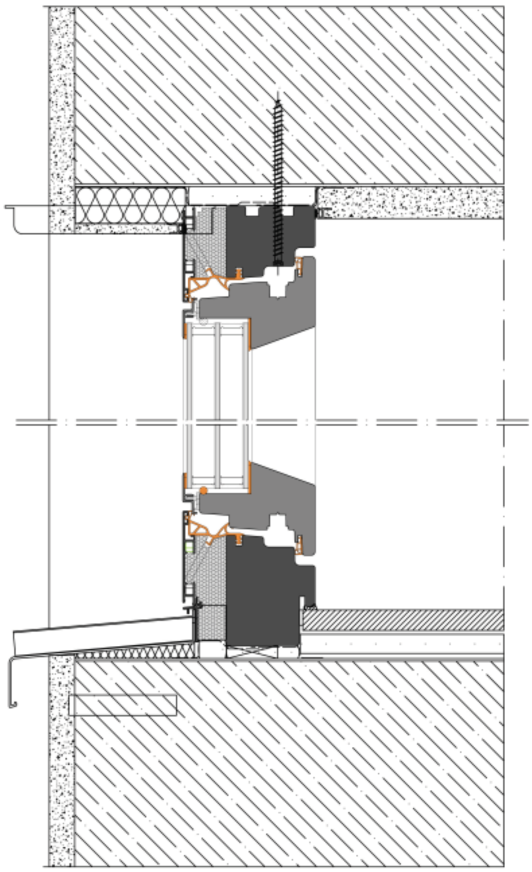
ALUMINUM FRAME_TRADITIONAL WALL



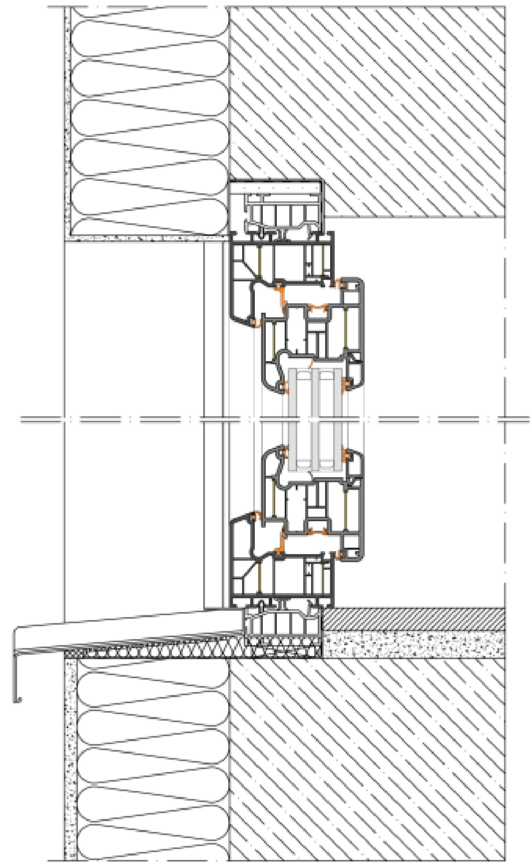
STEEL FRAME_TRADITIONAL WALL



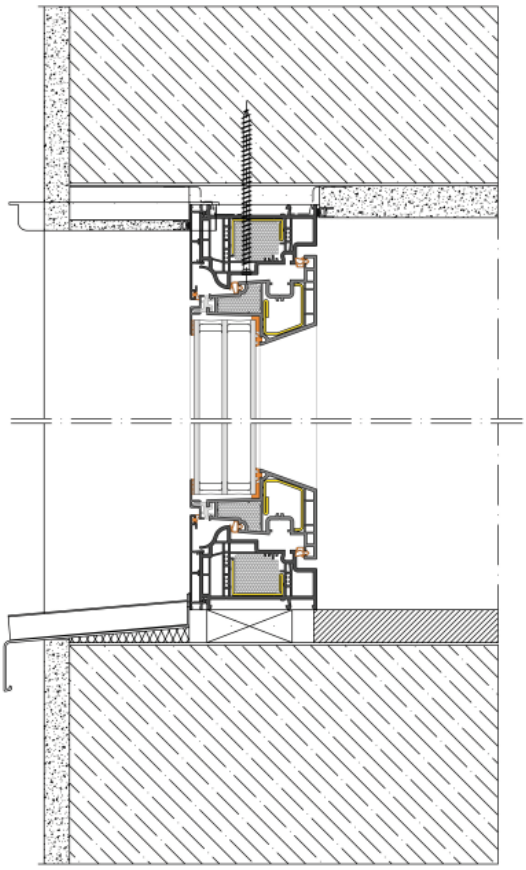
TIMBER FRAME_TRADITIONAL WALL



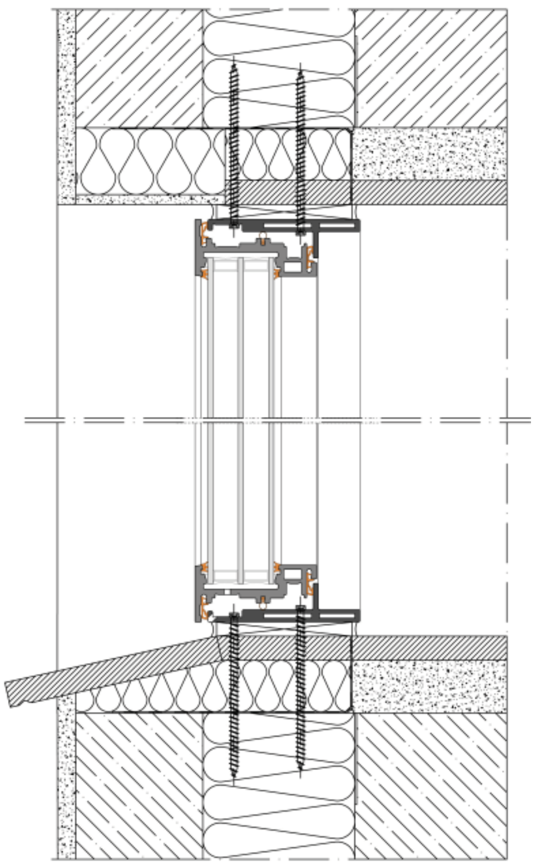
TIMBER/ALUMINUM FRAME_TRADITIONAL WALL



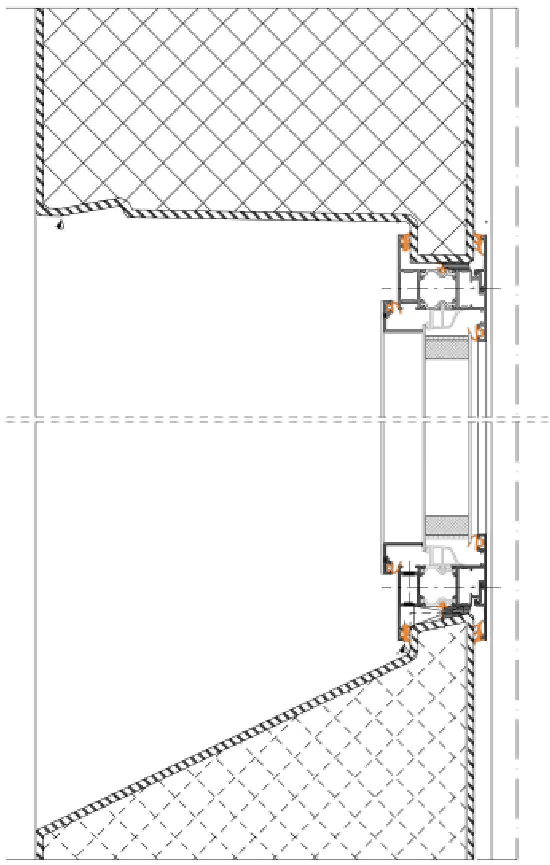
PVC FRAME_TRADITIONAL WALL



GRP/ALUMINUM FRAME_TRADITIONAL WALL



GRP FRAME_TRADITIONAL WALL



ALUMINUM FRAME_COMPOSITE WALL

4.8_ COMPARISON OF CONNECTION PRINCIPLES:

The conclusions drawn after the analysis of the above connection systems are crucial for the design of the new GRP façade. It is important to highlight the fact that every different framing material has different requirements on the way it is connected to the solid wall. These may vary according to the frame's thermal expansion coefficient, thermal insulation, water resistance, etc.

TRADITIONAL CONSTRUCTION METHOD:
Thus, when connecting to a traditional solid wall, aluminum and steel frames do need an extra profile that is surrounded by insulating foam. The wall is made with a recess where the connecting profile is inserted. Then the outer (not movable) frame is added.

Timber and timber/aluminum profiles in contrary do not need any additional thermal insulation. The connection medium between the frame and the wall is a piece of timber that is inserted on the wall's recess. The outer frame is attached on it.

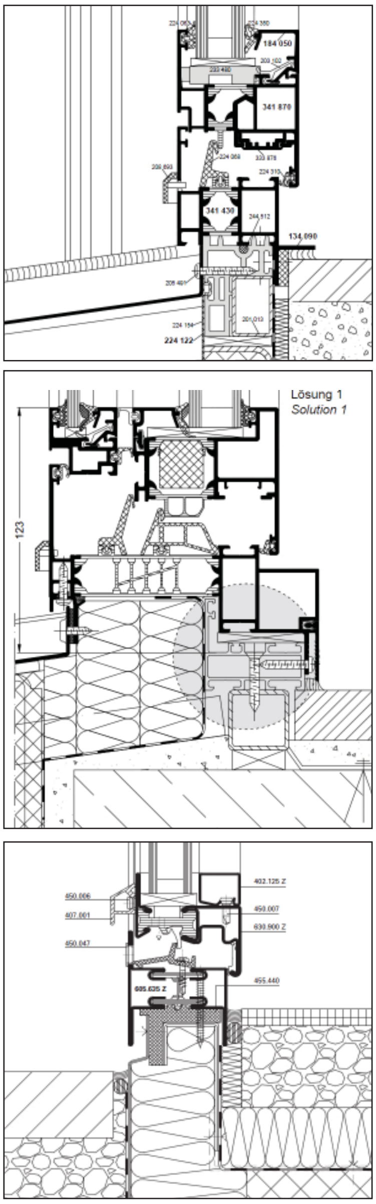
As with aluminum and steel profiles, PVC profiles also need an extra connecting element for their connection to the wall. The element is usually by the same material and is also surrounded by insulating foam which contributes to maintaining the excellent thermal performance values of the overall window frame.

GRP/aluminum frames have a similar way of connecting to the wall, with the timber and timber/aluminum frames. They only require an extra wooden element that is inserted to the wall's recess and connects the two parts of the façade. No extra thermal insulation is required.

The same principle of connection is also followed for GRP frames. In this case no recess in the solid wall is required. A wooden element is attached on the wall construction and the GRP frame is screwed on it.

In this way, the frame is kept in a distance from the wall. No extra thermal insulation is required. Each element (wall and frame) performs individually, while the connecting wooden piece helps maintain the optimal thermal performance of the window.

In any case the exterior parts of the connecting elements and wooden profiles are protected by water and humidity.

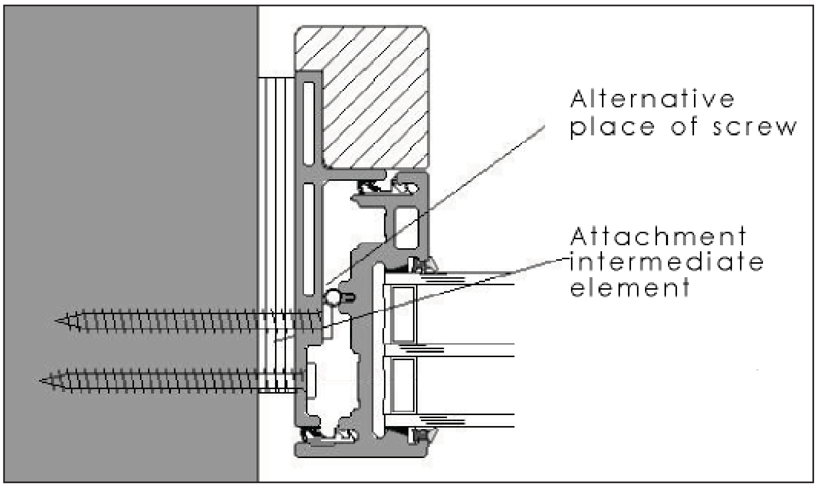


Connection details of aluminum double glazed, aluminum triple glazed and steel window frames (source: Schuco)

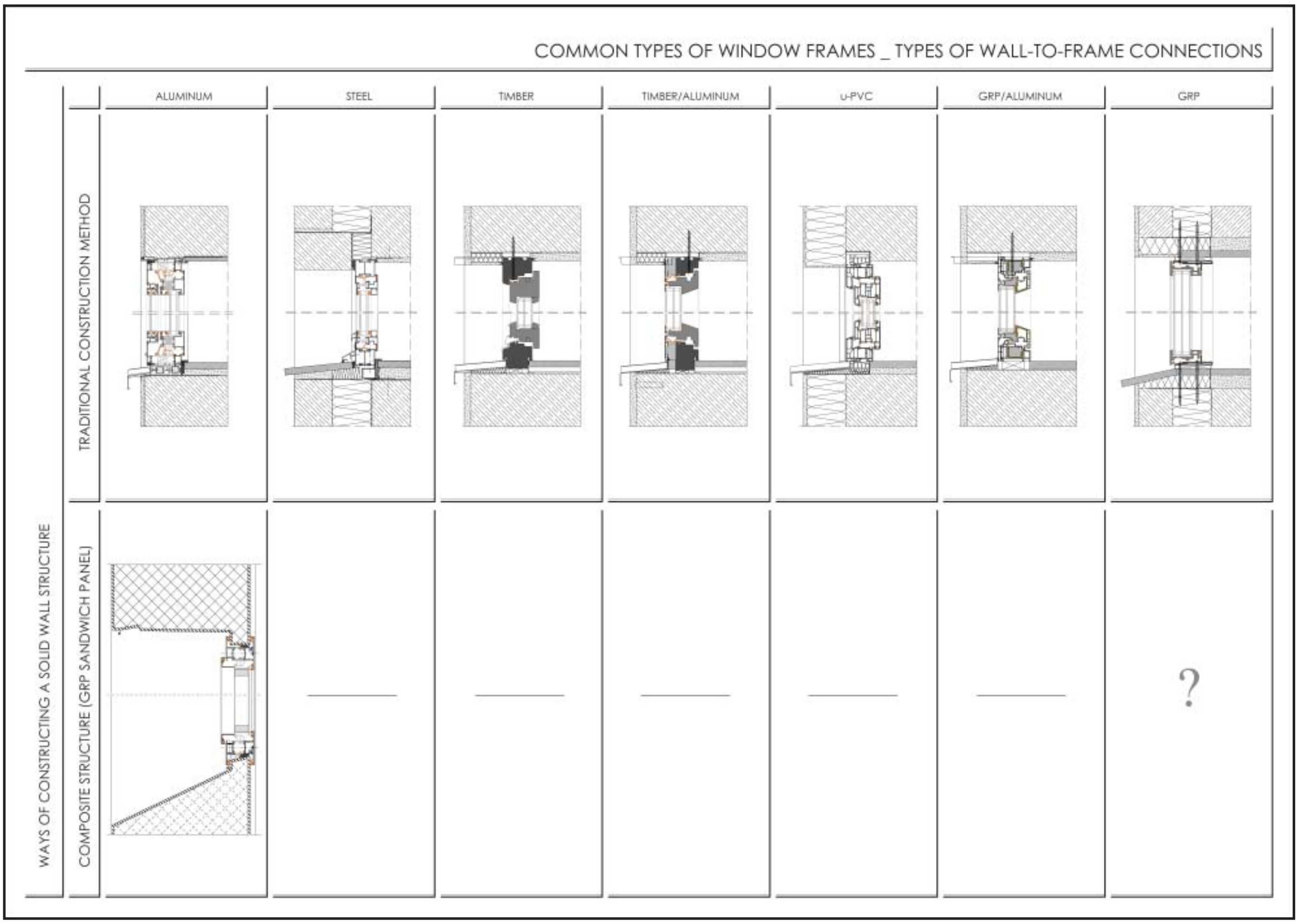
COMPOSITE STRUCTURE (GRP SANDWICH PANEL):
The connection method followed in case of a composite solid wall connected to a GRP frame is relatively similar with that of a traditional solid wall connected to a GRP frame.

The aluminum frame in this case is directly connected to the GRP façade element with the use of screws.

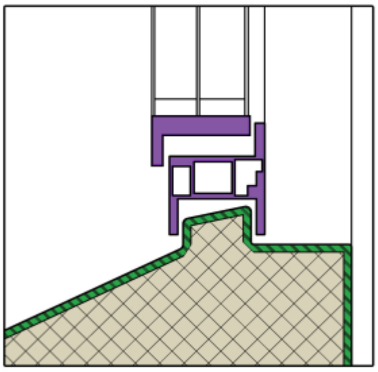
No extra thermal insulation in required and no other water-protection layer is added. The two elements are just attached to each other.



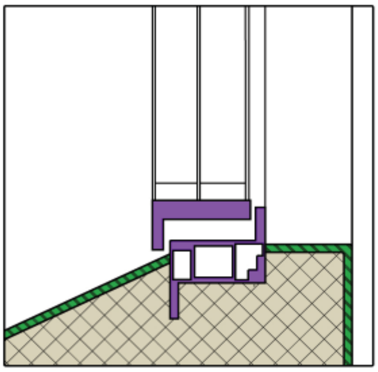
Connection detail of a traditional solid wall connected to a GRP window frame (source: Ecliptica)



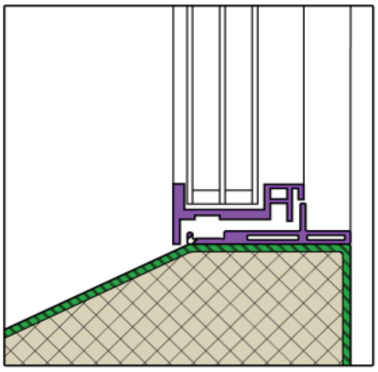
5.1_ STEPS OF DESIGNING AN INTEGRATED GRP FACADE:



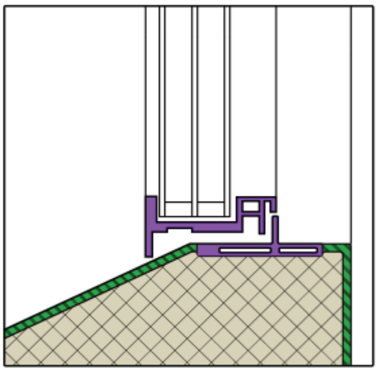
STEP1



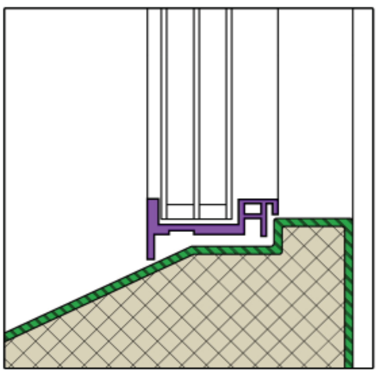
STEP2



STEP3



STEP4



STEP5

In order to design an integrated GRP facade, several steps will be explored. The starting point will be the current way of producing GRP facades, while several other possible developments of the current technique will be researched.

This procedure is divided in five main steps:

Step1: The current way of producing GRP facades. The aluminum frame is directly connected to the GRP panel. This method has been already realized in buildings. However, it is a relatively simple and low intelligence solution. Two elements (wall and frame) having a completely different behavior are attached to each other. The outcome is a non-integrated, conventional solution, using GRP and aluminum.

Step2: The second step is a more integrated version of step1. The solutions still consist of GRP and aluminum but in this case the aluminum frame is integrated into the GRP wall element. This creates a slimmer appearance of the window frame, while the outer frame is no longer visible from the outside or inside of the façade.

Unfortunately this step has already been tested and proved not working. The construction company Scheldebouw has already tried to manufacture a GRP façade with integrated aluminum frames. Tests and mock up models have proved that these two materials are impossible to be bonded to each other, as adhesion between them cannot be achieved. As a result, the frame is detached from the wall.

Step3: At the third step, the aluminum frame is replaced by a GRP frame. The connection is achieved with the same way as a GRP frame is connected to a conventional wall. The frame is attached to the wall by screws and no recess is required to be made at the shape of the wall. This solution is expected to show better thermal performance because of the replacement of aluminum with GRP, but still cannot be considered an integrated solution.

Step4: The fourth step consists of a GRP frame integrated into the GRP façade element. The frame is inserted into the element's mold during the manufacturing process and the final product is a wall, having the outer frame of the window integrated into it.

Step5: The fifth step is the fully integrated version of designing a GRP façade. The outer window frame has been removed in this case and the solid wall has been designed in a way so that it can function as both a wall and an outer frame. The recesses that are required for the outer frame are now integrated to the wall element. The vent profile of the window is in this case directly attached to the wall.

5.2_ RESEARCH DIRECTION:

By the analysis of the steps above, we can conclude that Step1 is the principle that has already been used in buildings until now, and step 2 is a solution that has been proved to be impossible. Furthermore, both Step 1 and Step2 are solutions that consist of a combnation of GRP(sandwich panels) and aluminum (window frames).

As this thesis aims to provide a facade solution that consists entirely of only GRP and glass and achieves a high degree of integration, only the steps 4 and 5 should be further researched. However, for the sake of complete understanding of how a fully GRP facade can be constructed, and which are the benefits of an integrated GRP window frame on it over a non-integrated one, step 3 will be also explored.

The main focus of the research will be given on the design of the GRP sandwich panel instead of the GRP window profile, as the panel will have to incorporate more than one function and integrate more than one element.

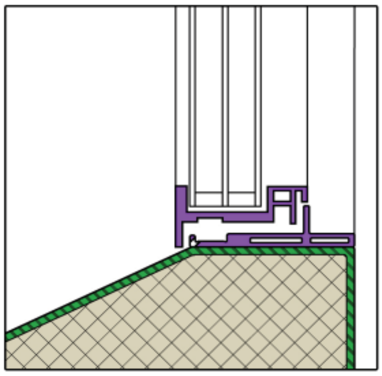
As there are already two manufacturing companies in Europe that produced pultruded GRP window profiles (Ecliptica and Xframe), the detailing of the window frame will be based on their existing products. Adjustments on the dimensions of the frames will be made so that they can serve the needs of the overall new design, but this thesis does not in any case aim to provide another window frame design.

Photos of GRP panels with aluminum window frames at Polux BV

5.3_ DEVELOPMENT OF POSSIBLE FACADE CONCEPTS:

The starting point for the design process of new GRP façade concepts is the development of various hand-made sketches. The sketches are based on the previous analysis of window frames, functions and wall connection principles and aim to provide a first idea of the GRP façade.

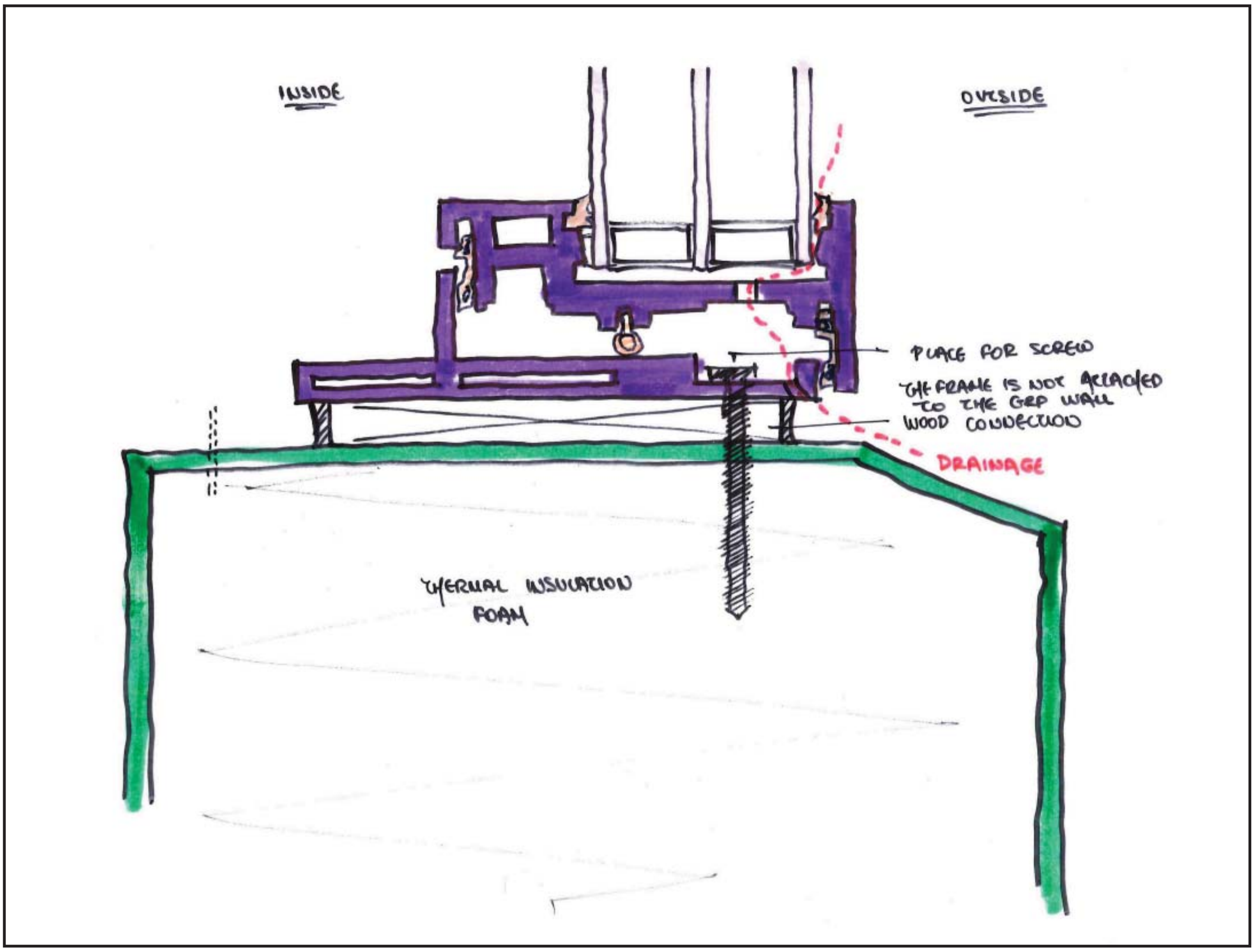
Several aspects, as water and air-tightness, stiffness and integration principles are explored. More specifically, based on Steps 3, 4 and 5, several sketches of possible façade concepts are presented below.



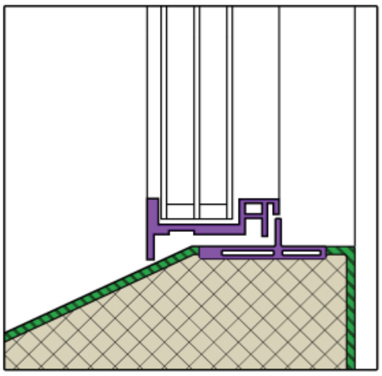
A GRP frame is attached to the GRP wall structure. An intermediate wooden element is added.

5.3.1_ STEP THREE (3)

At Step 3, a GRP frame is attached to the GRP sandwich panel. According to the instructions of Ecliptica[18] , a wooden intermediate element must be added between the panel and the frame. The joint between those two elements must be air and water tight during the whole life cycle of the façade.



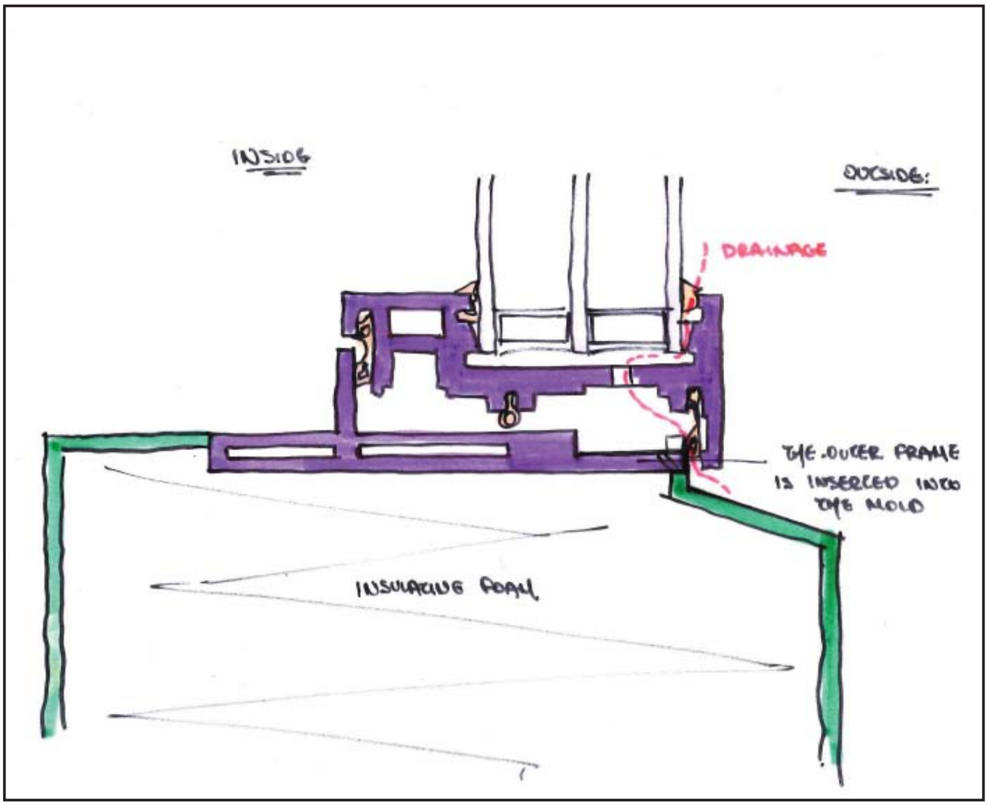
[18] Ecliptica is a GRP window frame manufacturing company in Europe

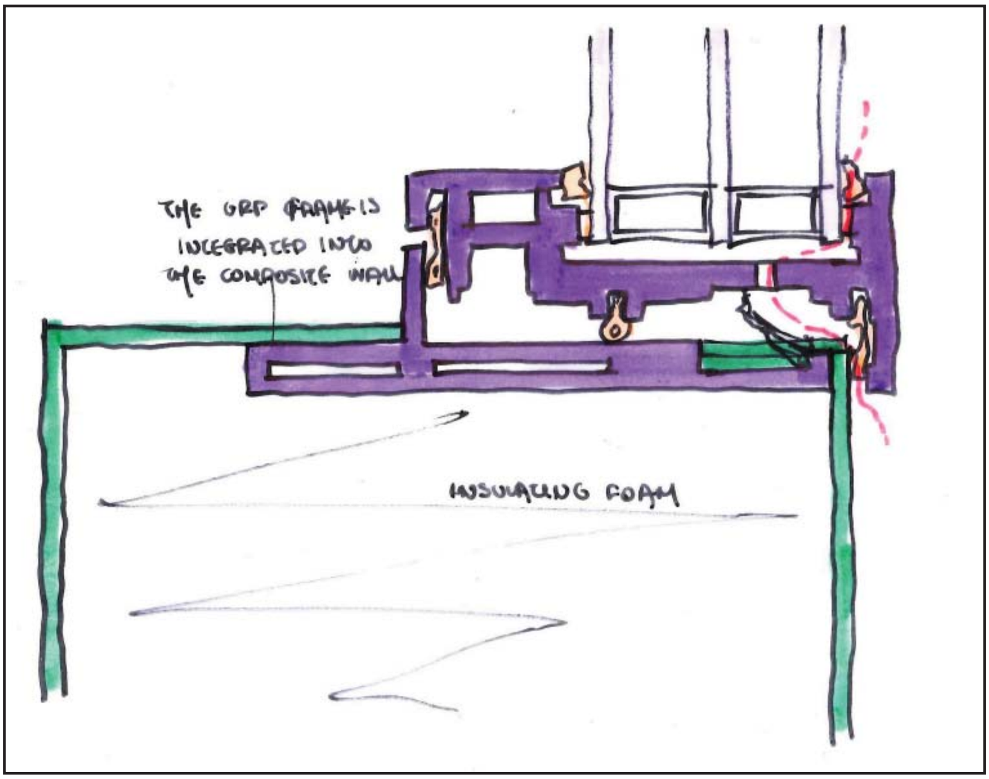


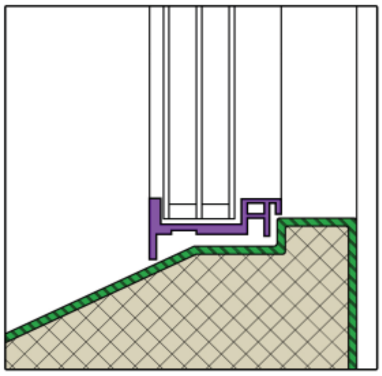
5.3.2_ STEP FOUR (4)

At Step 4, a GRP outer frame is inserted into the GRP sandwich panel. By this way high level of accuracy and small tolerances that are important for the water and air tightness of the window can be assured. The pultruded GRP outer frame is detailed enough to ensure great performance.

However the joints between the GRP panel and the outer frame need careful consideration. Water must not penetrate in the sandwich construction, so sealants must be applied.

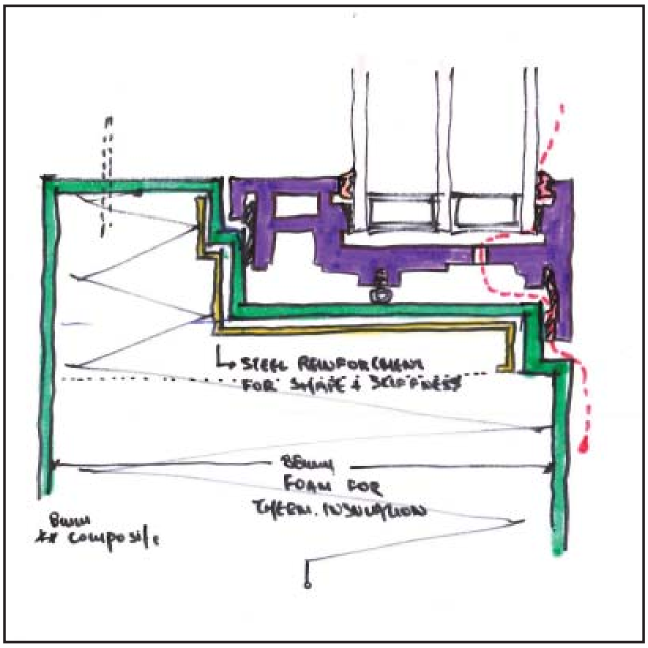


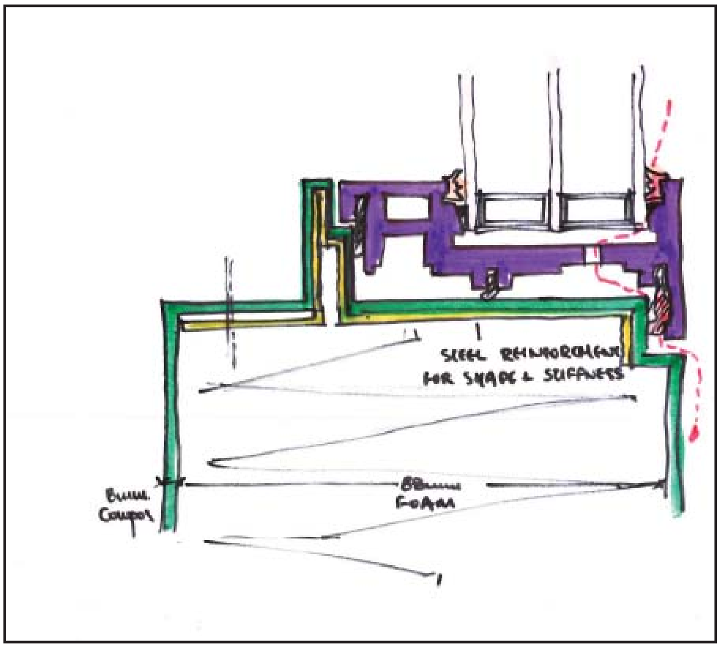


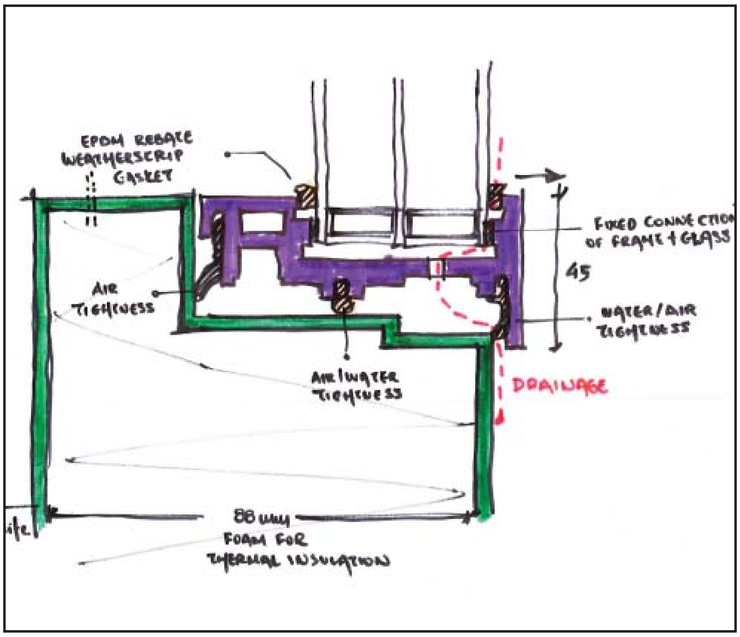


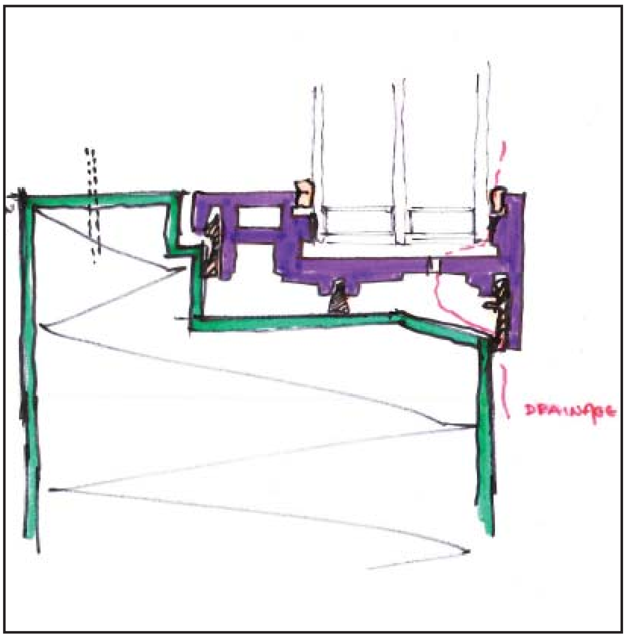
5.3.3_ STEP FIVE (5)
At Step 5, the vent profile is directly attached to the GRP sandwich panel, as this solution does not include a GRP outer frame.
The panel is detailed in that way so that it can serve the water, air tightness and drainage needs of the window.

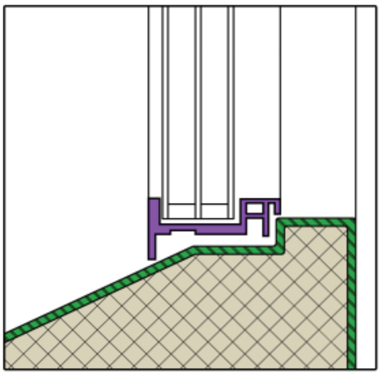
The tolerances of detailing requirements of such a panel need to be further researched. As the panel has in this case more than one function it has to be carefully detailed and perfectly manufactured for a perfect performance.

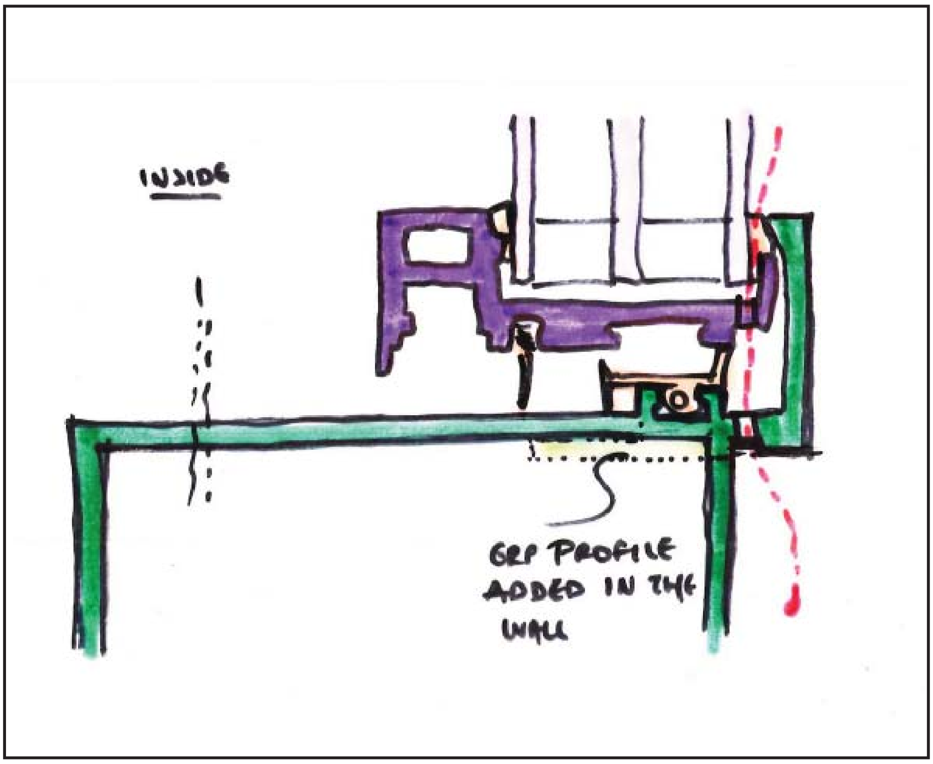


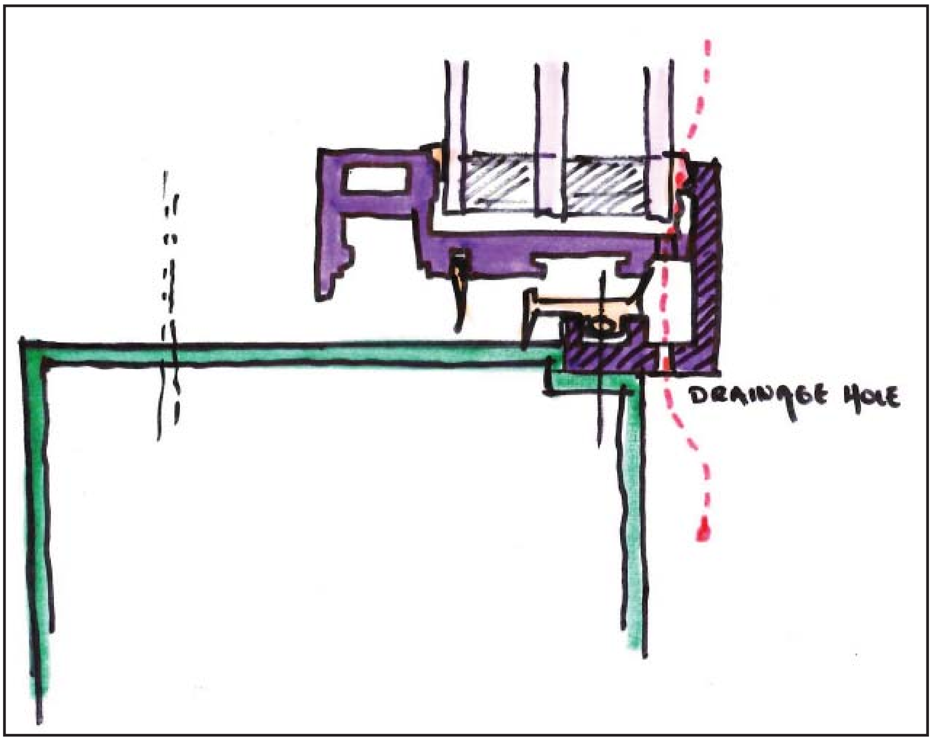









INSIDE
GRP PROFILE
ADDED IN THE
WALL


DRAINAGE HOLE

5.4_ FEEDBACK ON THE CONCEPTS:

After the development of the first concept sketches, the research continued with some technical feedback from a GRP façade manufacturer. Discussions with Jack Smit (director of Polux BV) and observations of existing GRP sandwich panels at the Polux production site, lead to many interesting remarks and suggestions.

-The minimum radius of a GRP panel can be 4mm. Every detail having minimum radius of 4mm can be easily manufactured.

-The tolerances of the designed details can be neglected. The tolerance of a GRP sandwich panel of 5 meters length is about 2mm in total. That means that tolerances at the details and recesses where the vent profile of the window will be attached do not exist. The design of such a detail can be manufactured with accuracy.

-Attention should be paid on the detailing in terms of the manufacturing techniques that are used. This will be further analyzed at the next chapter.

-In cases where a GRP outer frame has to be attached on a GRP sandwich panel (Step4), the panel has to be manufactured with a recess of exactly the same size as the outer frame, and then the outer frame can be glued on it. In this way we can assure that no water can penetrate in the sandwich structure.

-In order for the sandwich panel to be stiff enough, insulating foam has to be inserted between the two outer layers of fiberglass. Thin parts consisting of only two layers of fiberglass without any foam between them may fail and thus they can be never suggested for a façade element.

-No other reinforcement bar must be added in the sandwich panel construction.

-Other insert elements for water removal can be added. Plastic pipes of small diameter can be inserted in the sandwich panels if there is a need for water removal (This will be further explained afterwards).

In this case, the panel is manufactured without the inserts. Subsequently small holes are drilled and pipes are inserted in the structure. Careful needs to be paid during the sealing of the space between the pipes and the panel.

5.5_ FINAL DESIGN CONCEPTS

After the discussions with Polux, several final designs have been made. All of these designs are feasible according to the manufacturers and it is reasonable to say that there is not a perfect solution, but each one of the following designs shows some advantages and disadvantages.

As there are many different requirements and choices during the design of a new façade, it is impossible to conclude to only one optimal solution. Several concepts are produced in order to fulfill as many needs as possible.

The main differentiations of the following concepts are based on the position of the window at the façade (on the outside, on the inside, in the middle of the sandwich panel), and of course on the way/direction to which the windows can open (to the inside, to the outside).

For added convenience in the understanding of the following drawings, these have been divided into two categories; outwards (1) and inwards (2) opening windows. They are respectively displayed below.

5.5.1_ OUTWARDS OPENING WINDOWS

At the next five drawing the windows open to the outside but the position of the frame (outside-middle-inside) can vary, resulting to a different way of detailing.
Furthermore, at the first four drawings, the window frame is totally hidden from the interior of the building, while at the fifth drawing it only slightly revealed.
The water drainage at the upper part of the window opening also differs according to the different drawings. At the last two drawings, where the window frame is moved away from the outer side of the façade, the sandwich element is formed in a specific way so that it can remove the water that falls on the façade before it reaches the window frame. In this way the panel itself creates an extra protection against water penetration to the frame.
Of course in cases where the window frame is attached to the outer side of the building, this is not possible to happen. The water that falls on the window frame is in this case removed through the lower part of the frame to the outside.

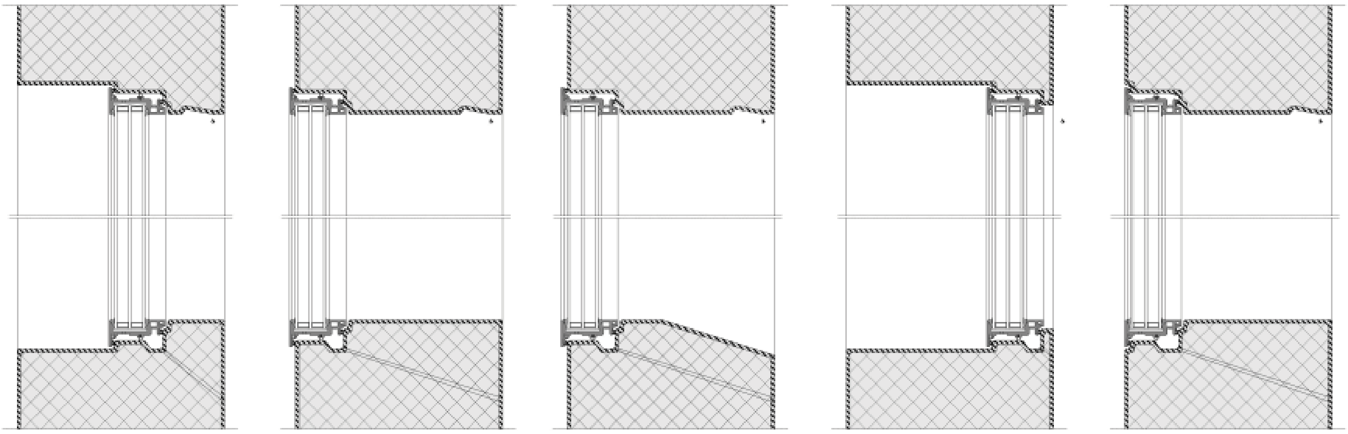
5.5.2_ INWARDS OPENING WINDOWS

The following five drawings present various pronciples of a GRP sandwich element having inwards opening windows. This is the most commonly used type of windows, especially in cases of high rises buildinds. The inwards openign windows are easier to be controlled by the user inside a building and can more easily withstand high wind forces at upper floors.

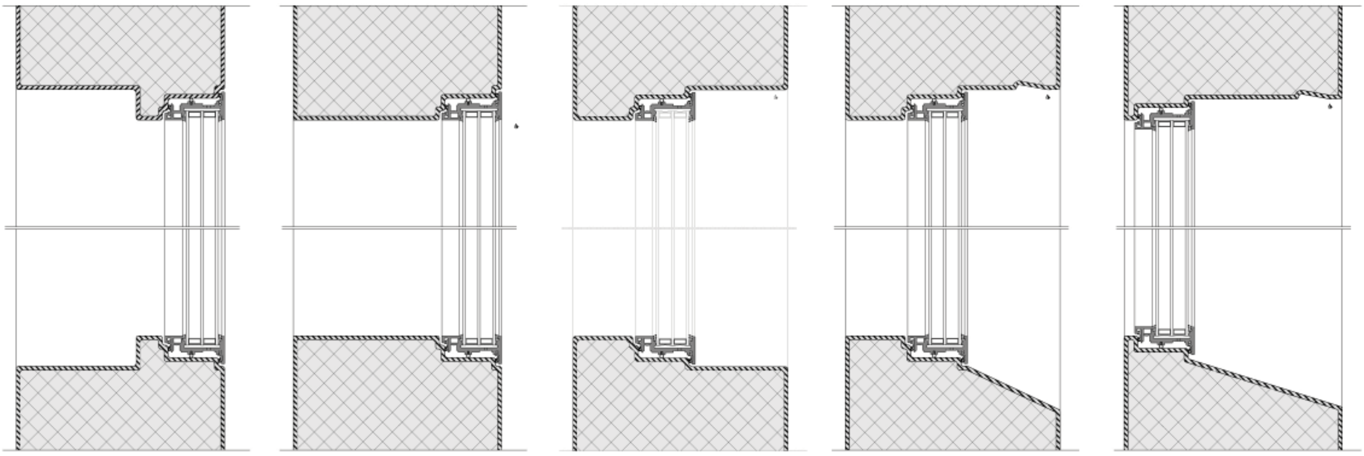
At these principles the position of the frame can again change according to the needs of each facade and the choices of the architect. The window frame is at the three first and fifth cases totally hidden from the outside of the building, while at the fourth drawing the frame is slightly revealed to the outside.

The water falling at the upper side of the window opening is in most cases removed by a small recess of the GRP element, before reaching the window frame, which creates an extra level of protection against water penetration.

At the lower part of the window opening, the design seems more complicated if compared with the first category of outwards opening windows, because of the need for water removal. The water that falls in the frame is gathered in a small recess, integrated in the GRP sandwich panel and is then removed to the outside by small plastic pipes that are inserted in the panel.



GRP sandwich panels with outwards opening window frames



GRP sandwich panels with inwards opening window frames

We can easily assume that there can be a lot more solutions that can be produced when designing a façade and these can strongly depend on the architect's will and the type of the building.

For example high rise buildings usually have inwards opening windows for higher safety of the users and convenience in use.

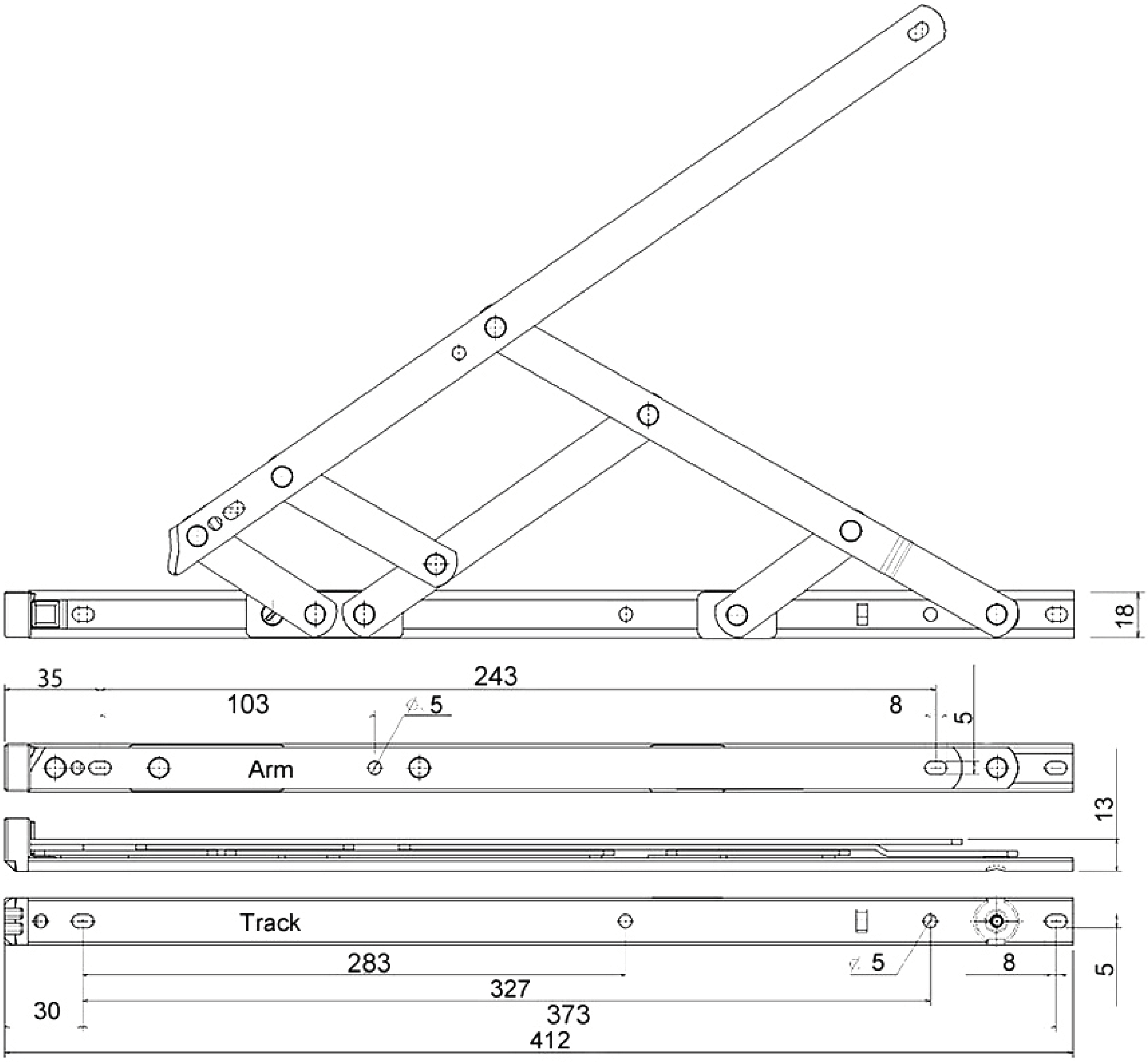
Aim of this research is not to provide a catalog of all the possible results, but to determine the basic principles and try to find solutions that can be easily applied to any possible design. For that reason the above drawings are considered sufficient, as they present a great variety of possibilities.
A selection of these principles will be examined and evaluated in the next chapter.

5.6_ HINGES FOR OPENING WINDOWS

For a more integrated facade result, the hinges used for the turning of the window should also be studied. The design is based on side hung opening windows and the hinges that are used for this research are a product of Sobinco[19] .

Aiming to a complete integration of window's functions into the composite facade, the integration of the hinges is also necessary. For this reason, concealed hinges are selected to be used. These are placed between the vent profile and the GRP sandwich panel.

The drawings below present the mechanism of concealed hinges for side hung opening windows[20] .



Side hung window hinge (source: http://www.handlestore.com/products/H01-16-inch-SH-Window-Hinge/NA/)

[19] http://www.sobinco.com/
[20] http://www.handlestore.com/products/H01-16-inch-SH-Window-Hinge/NA/

The panel is designed in a certain way, having a small recess in order to accomodate the window's hinges. The concealed hinges are inserted in the recess and mounted with screws in the panel. This way of mounting is chosen in order to make the replacement of the element easier in case of damage or break.

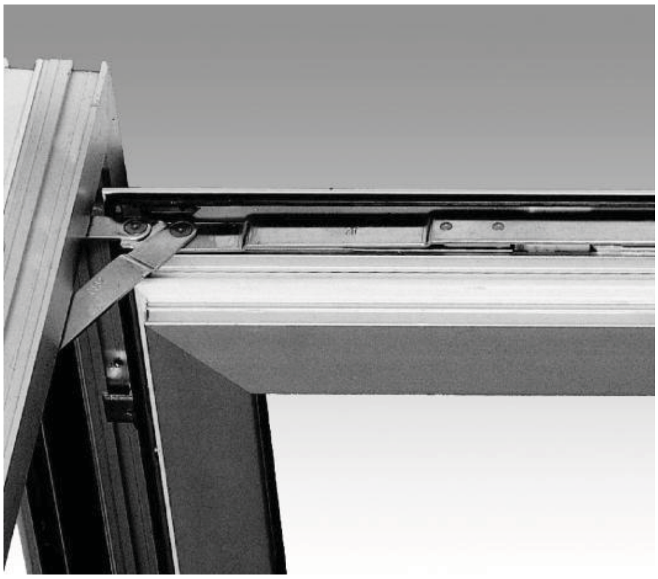
For a stiffer connection between the hinges and the sandwich panel, small wooden elements are inserted in the mold during the manufacturing procedure, in the exact places where the screws of the hinges will be placed. So the hinges are attached to a more stiff material than foam.

5.6.1_ ADVANTAGES OF THE INTEGRATION OF HINGES

The integration of the hinges to the interior part of the window and panel connection makes the visual difference between the opening and fixed windows minimum and contributes to a better aesthetical appearence of the whole facade.

Moreover concealed hinges are alwasys better performing than visible hinges in terms of acoustics, air and water tightness. Furthermore the risk of damaging the hinges during transportation, installation or other work to the building is decreased. The cleaning of the window frames i also easier[21].

A final facade concept design including the integrated hinges will be presented in a later chapter.



Photos of concealed hinges products by Sobinco (source: http://www.sobinco.be/en/products)

[21] http://www.sobinco.com/en/windows/side-hung-open-windows/concealed-screwed-invisi-hinges

6.1_ ANSWERING THE RESEARCH QUESTION

The step after the development of the design concepts is the evaluation of them in order to answer to thesis' research question:

"What principles should a design of a Glass Fiber Reinforced Polyester (GRP) façade with integrated operable GRP window frames meet, in order to achieve high degree of integration and a great number of performance benefits over a conventional GRP façade?"

Goal of this chapter is to define the benefits of an integrated GRP façade to a conventional GRP-aluminum façade. This will be achieved through observation, simulation, calculation and comparison.

The attributes that are considered to be the most important for a development of a fully GRP façade will be explored. These are:

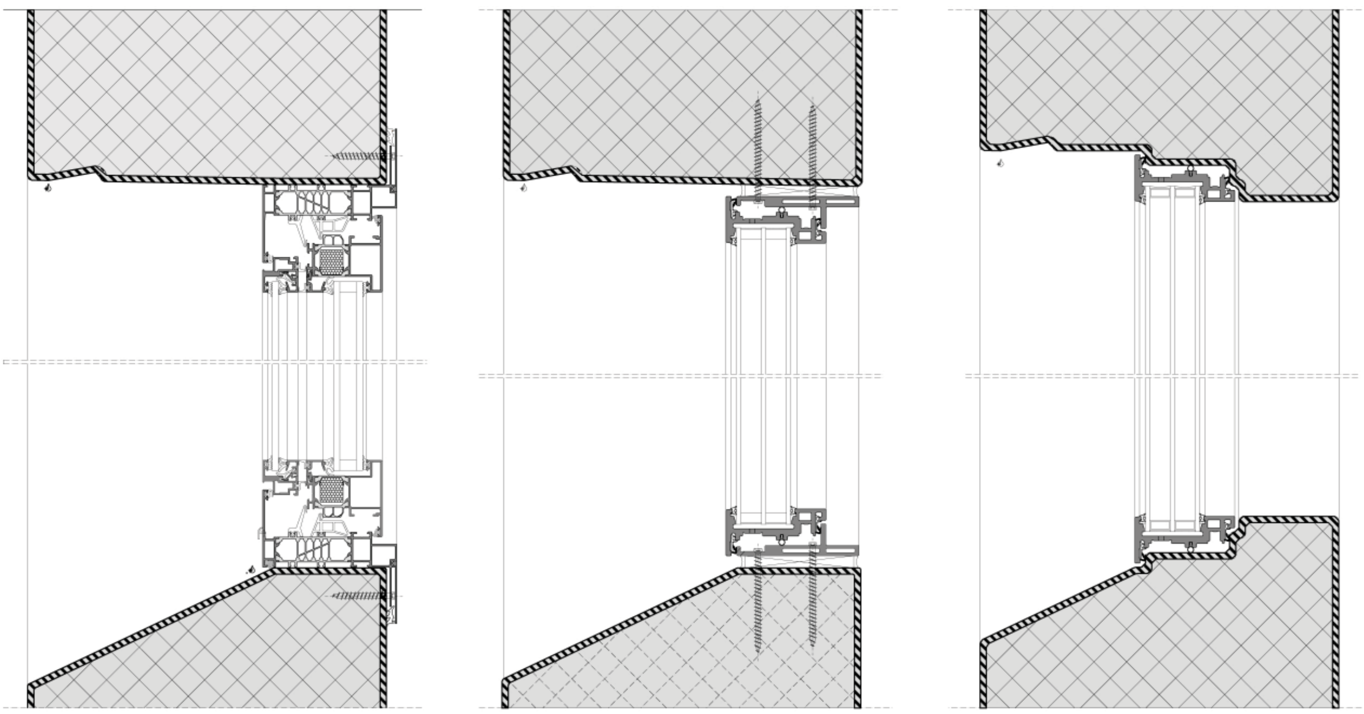
-Thermal insulation
-Acoustical performance
-Stiffness
-Weight
-Manufacturing method
-Manufacturing and installation time
-Production cost

Of course not all of these attributes are expected to present better values, but it is important to determine the main advantages in the use of GRP in facades.

In order to fully understand the differences between the different facades and materials used, most of the above attributes (when is needed) will be compared in three façade cases:

-A composite façade having aluminum frames (Aluminum_Schuco_AWS150CC.HI)
-A composite façade having GRP frames (Ecliptica frame)
-A composite façade having integrated GRP frames (Based on Ecliptica frame)

The representative drawings of each category are presented below.



A detailed calculation/comparison/observation for each attribute is following.

6.2_ THERMAL INSULATION CALCULATION

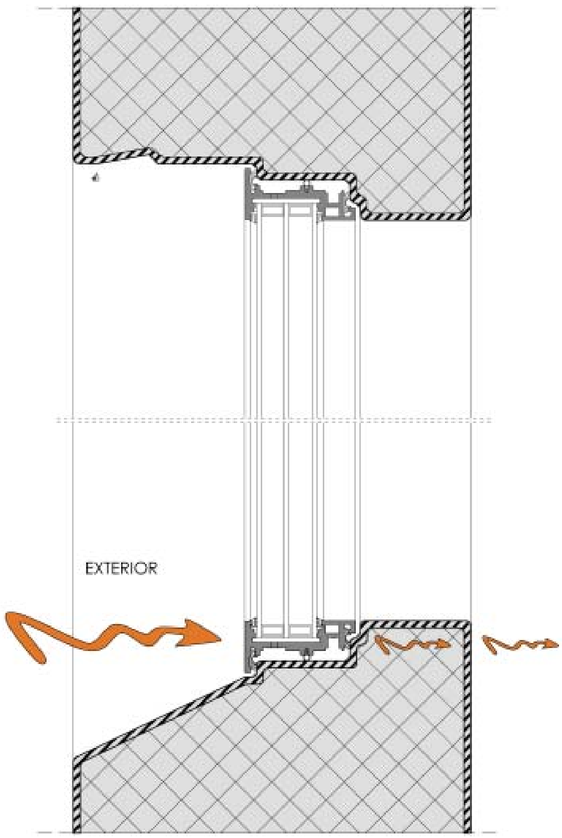
6.2.1_ COMPARISON OF TWO FACADES
This chapter will focus on the comparison of the thermal insulation of:

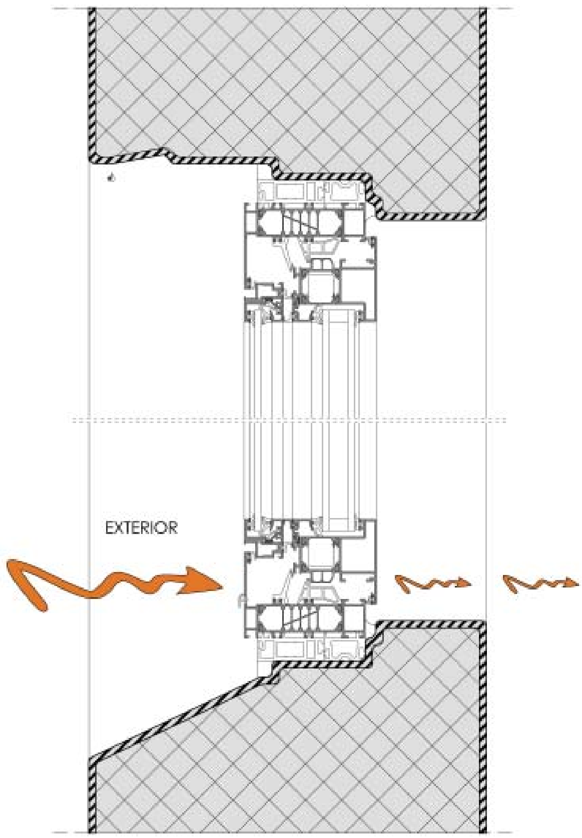
-A composite façade having aluminum frames
-A composite façade having integrated GRP frames

Assuming two exactly the same GRP sandwich panels, we design the two different window frames. The only difference in the way the heat is transferred from the outside to the inside is the window frame, as all the other factors for the calculations are the same.

We can therefore assume that for the comparison of two identical GRP facades, with different window frames, it is important to compare the thermal insulation values of the individual frames.

Of course the values of the thermal insulations can vary to every different window frame, but a comparison between two representative examples can provide us with an estimation of which material is better performing in terms of thermal transmittance.





6.2.2_ COMPARISON OF TWO WINDOW FRAMES

The frames that will be further calculated will be:

-The Aluminum window frame by Schuco AWS150CC.HI
-The GRP window frame designed during this thesis

Both window frames are tripled glazed. The value that will be compared will be the Uw value[22] of both frames. Uw value of the Schuco AWX 150CC.HI is provided by the manufacturer (Uw=1.40 W/m2K), so the only value needed to be calculated is the Uw of the GRP window frame.

6.2.3_ CALCULATION OF THE Uw OF THE GRP WINDOW PROFILE

During this calculation only the vent profile will be calculated. The software used for the two-dimensional calculation of heat transfer through the frame is Bisco v10.02. Before performing the calculation, the boundary conditions have to be also determined. These according to EN ISO 10077-2:2003 are:

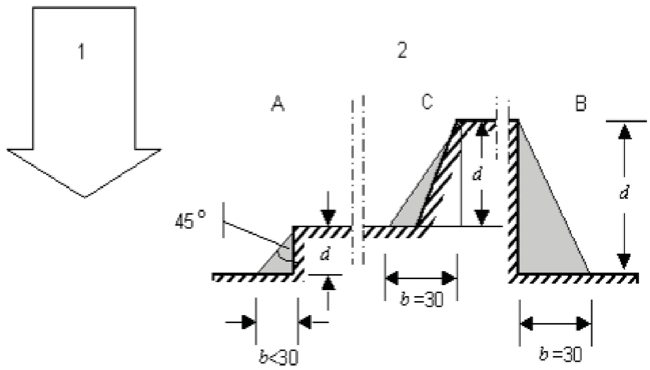
-External temperature: 0 ° C
-Internal temperature: 20 ° C

-External surface resistance for horizontal heat flow Rse=0.04 m2K/W

-Internal surface resistance for horizontal heat flow Rsi (normal)=0.13 m2K/W (normal/plane surface parallel to the glazing)

-Internal surface resistance for horizontal heat flow Rsi (reduced)=0.20 m2K/W (reduced radiation/convection– in edges or junctions between two surfaces)

The areas where increased surface resistance is noticed due to reduced radiation/convection are defined by EN ISO 10077-2 Annex B. These areas are graphically represented below.



Key
1.Direction of heat flow
2.Internal surface

Schematic representation of surfaces with an increased surface resistance due to reduced radiation/convection heat transfer. In the figure the increased resistances apply over the distances b and d, where b is equal to the depth d, but not greater than 30mm.

Example A: b = d when d ≤30mm
Example B: b = 30 mm when d > 30 mm
Example C: Application to a sloped surface; b = 30 mm when d > 30 mm

[22] The U-value shows how great the heat-flow density is through a construction where the difference in temperature is 1° C. In other words, how much heat passes through a particular construction where there is a difference in temperature of 1° C. The U-value is a benchmark for the comparative efficiency of thermal insulation for the building elements. It is expressed in units of Watts per square meter per degree of temperature difference (W/m2K). (source: A.C. van der Linden; A. Zeegers, Bouwfysika, Chapter 1 and Hong-Bo Wang, Thermal Transmittance (U-value) Assessment of glazing frame)

6.2.4_ CALCULATION RESULTS
The detailed input and output results of the calculations can be found in the index A.

After the calculation of the GRP frame, the following results have been produced.

The first image displays the thermal breaks of the GRP window frame. As it can be noticed, the area between the triple glass and the GRP vent profile (air) is the weakest area in terms of thermal insulation. We can therefore assume that the smaller this area is, the better the thermal insulation of the frame.

The second image displays the differences in temperatures inside the window frame. Having the lowest temperature at the outside surface of the frame (0 ° C), the diagram shows the gradual increase of the temperature inside the frame, until it reaches the highest point of 20 ° C at the inside part of the glazing.

The third diagram displays the heat flows in different areas of the window frame.

But, the most important value calculated by Bisco is the Uw of the frame which is Uw=1.107 W/m2K. This will be used for the comparison of the thermal performance of the GRP frame over an aluminum one.

Diagram1: Heat fluxes

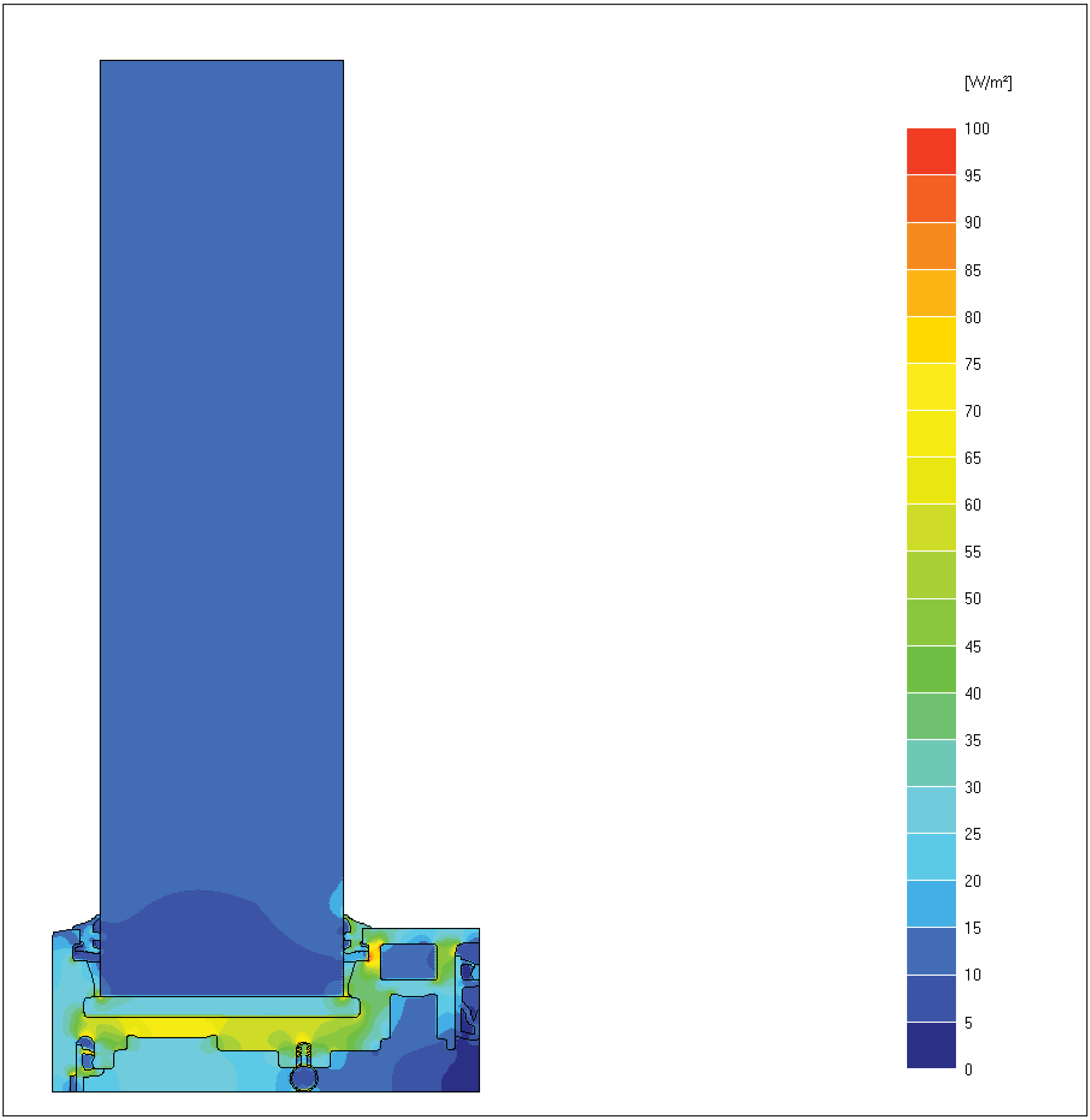


Diagram2: Temperatures

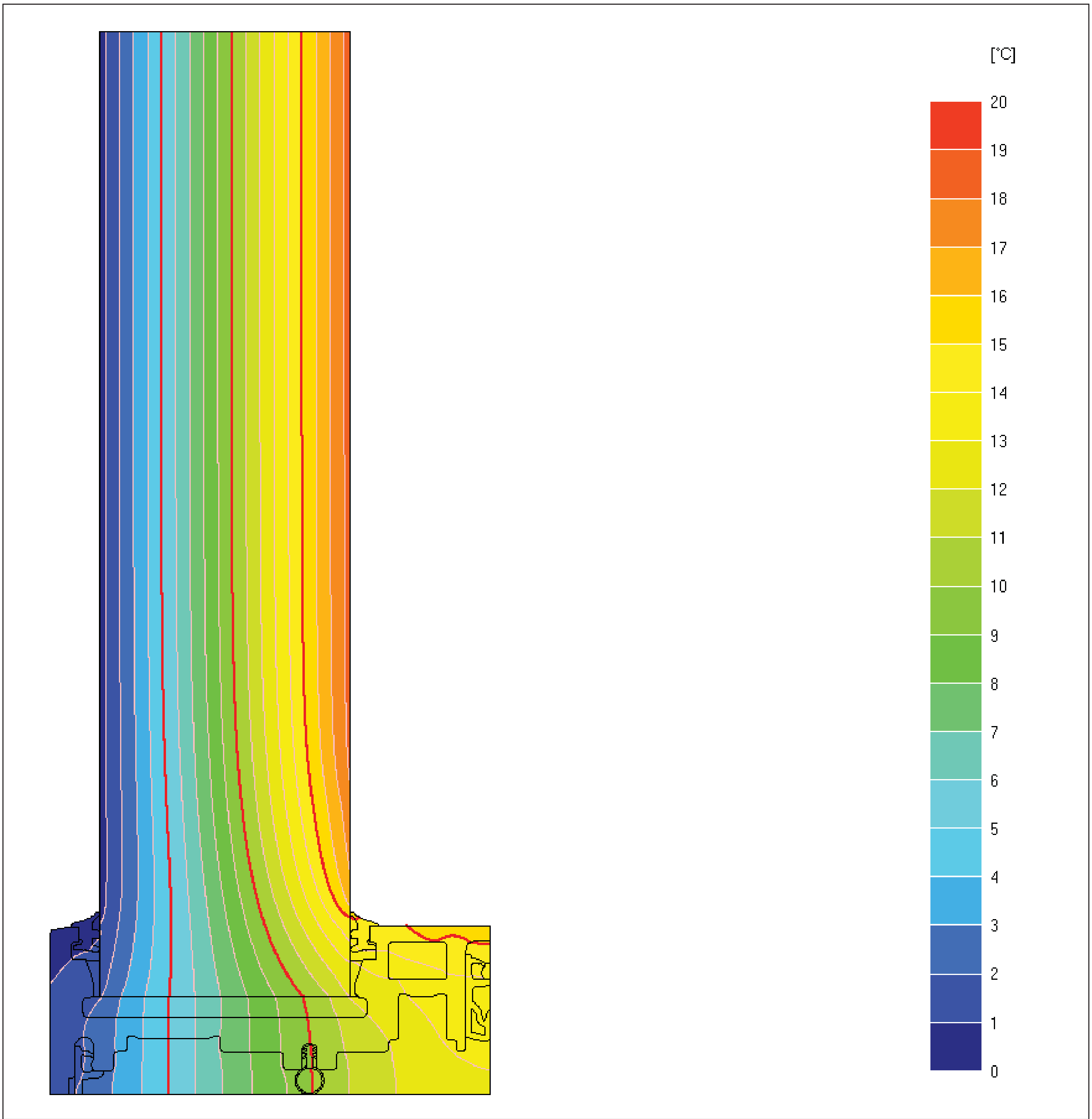
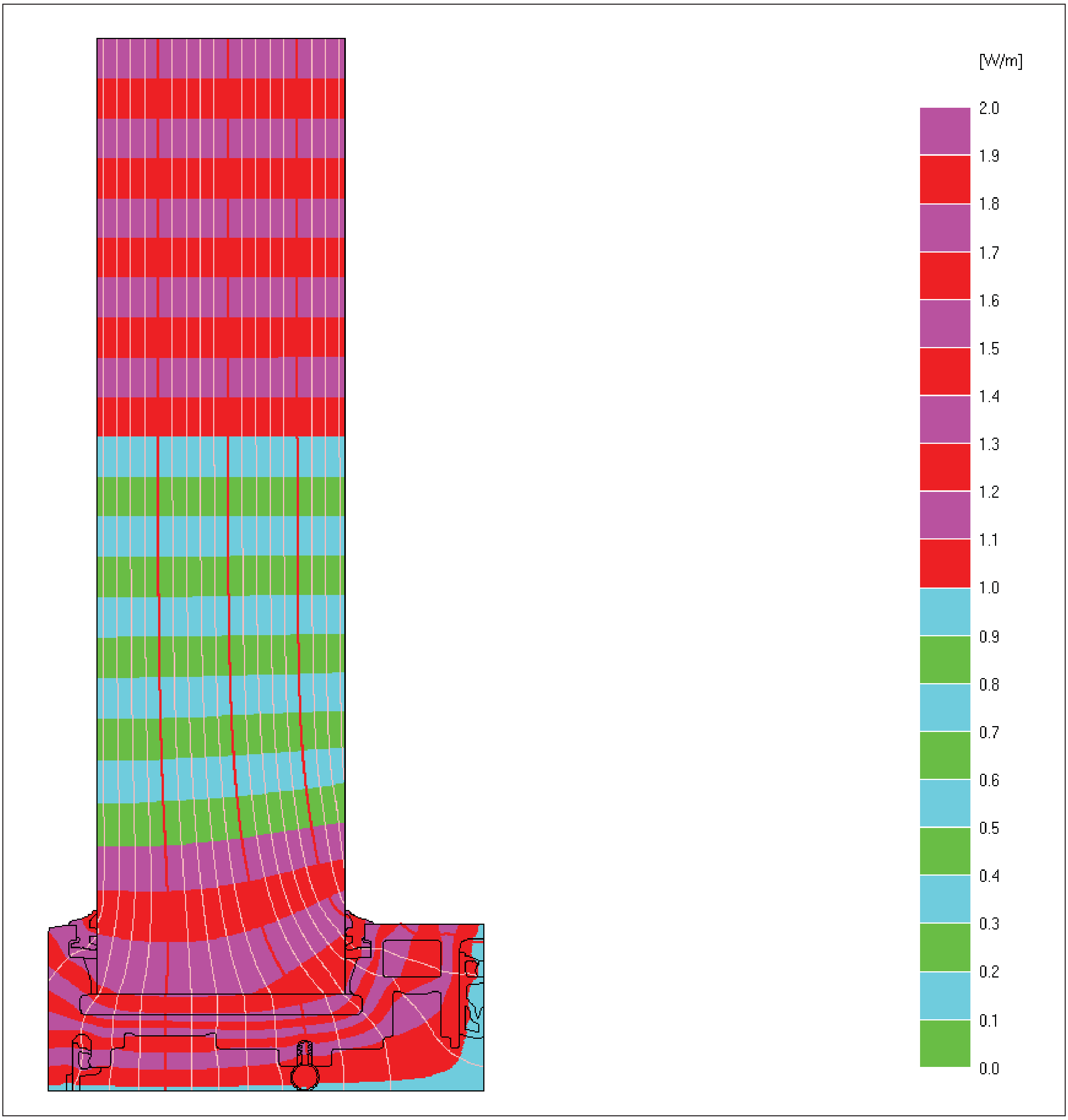


Diagram3: Heat flows



6.2.5_ COMPARISON

At the table below, the U values of all the window frames that have been analyzed at a previous chapter are displayed. Of course the comparison is between triple glazed window frames, so two of the frames (Aluminum AWS50 Schuco and Timber Scandinavian) are not included in the comparison.

From this table we can point out that GRP is NOT the frame material with the lowest U value. GRP seems to present a high Uw value (1.107 W/m2K) than many other materials such as timber (0.73 W/m2K), timber/aluminum (0.67 W/m2K), PVC (0.94 W/m2K), GRP/aluminum (0.67 W/m2K).

On the other hand, window frames having a combination of timber/aluminum and GRP/aluminum seem to present the lowest U value (0.67 W/m2K) among all materials. The values can of course range depending on each different window frame but from the comparison above we could assume that PVC or timber or even some combinations of those materials may are better insulative materials than GRP.

However, the thermal conductivity of a window frame is not only dependent on the U-value of the material but also on the height of the window frame. That means that a relatively high window frame having low Uw value, may present a higher value of thermal conductivity , if compared with a relatively short window frame with a higher Uw value.

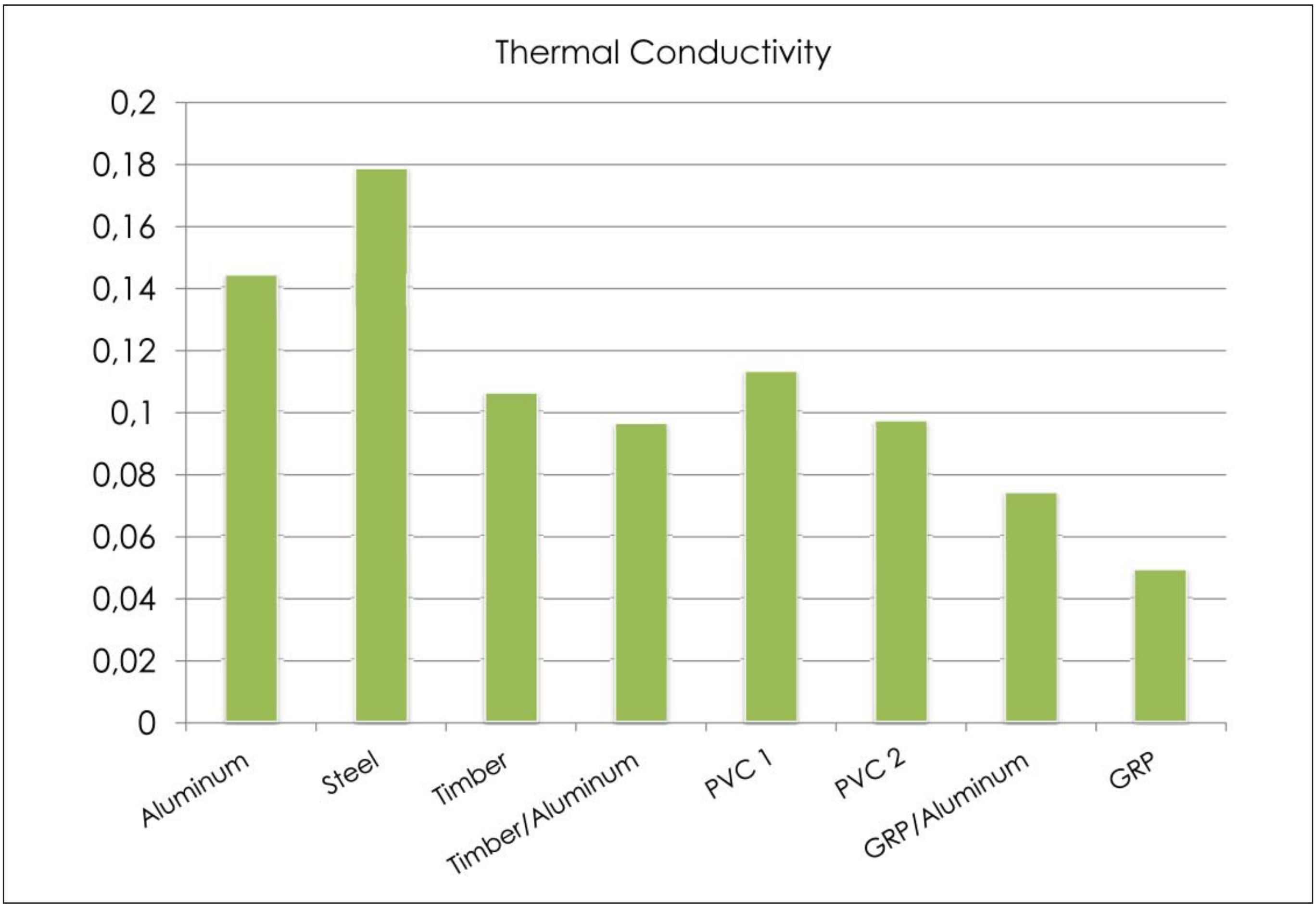
Thus, is it more important to determine the value of Thermal conductivity[23] of each window frame, in order to calculate the overall heat transferred from the outside to the inside through the window frame. For that reason the following table also presents the heights of each frame and the final value of Thermal Conductivity.

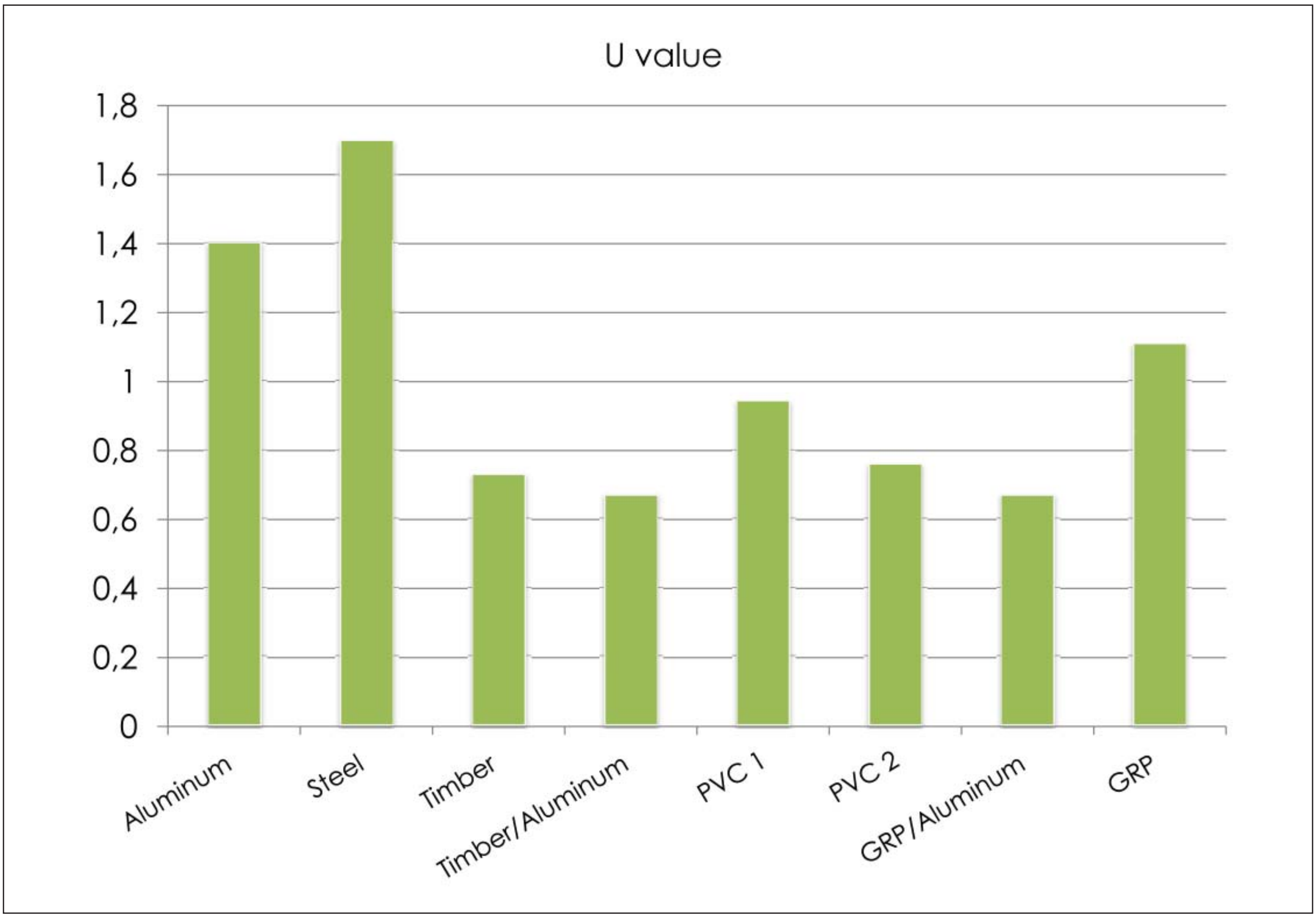
We can now point out that the window frame material that lets the minimum amount of heat to pass through its structure is the GRP. Despite having higher Uw value than other materials, the GRP frame's height is less than one half of the height of all the other window frames. The material of the frame is less and the area (height of the frame) from which the heat is transferred is also less, resulting to better values of thermal conductivity (0.049 W/mK).

THERMAL INSULATION				
		Typical Uw of triple glazed window frames (W/m2K)	Window frames' height (m)	Thermal Conductivity(W/mK)
FRAMING MATERIALS	ALUMINUM AWS 50 SCHUCO			
	ALUMINUM AWS CC.HI SCHUCO	1.40	0,103	0,144
	STEEL JANISOL SCHUCO	1,7	0,105	0,179
	TIMBER SCANDIANAVIAN TIMBER			
	TIMBER JOSKO	0,73	0,145	0,106
	TIMBER/ALUMINUM JOSKO	0,67	0,143	0,096
	PVC INOUTIC	0,94	0,12	0,113
	PVC SCHUCO	0,76	0,128	0,097
	GRP/ALUMINUM JOSKO	0,67	0,111	0,074
	GRP ECLIPTICA	1,107	0,045	0,049

[23] The thermal conductivity shows how much heat 'flows' through a layer of material 1 metre thick and with a surface area of 1 m², where the difference in temperature is 1 K (1 °C) (source: A.C. van der Linden; A. Zeegers, Bouwfysika, Chapter 1) It is expressed in units of Watts per meter per degree of temperature difference (W/mK)

The tables below present the relation between the U values and Thermal conductivity values of the window frames.





6.3_ ACOUSTICAL PERFORMANCE COMPARISON

6.3.1_ INTRODUCTION TO SOUND INSULATION

The acoustical performance of a façade depends on its level of screening against a noise source[23] and is determined by the sound insulation value.

The sound insulation can be distinguished in two main categories: Air-borne sound insulation and structure-borne sound insulation[24] , as presented to the diagrams below.

In the case of a façade, only air-borne sound insulation will be further discussed. As a façade is only liable to air-borne sound, it needs to act as a sound proofing layer that blocks sounds generated at the exterior environment.
The ability of a façade for sound insulation can be determined by the difference between the sound level of the exterior and interior environment which mainly depends on the frequency of the sound source.

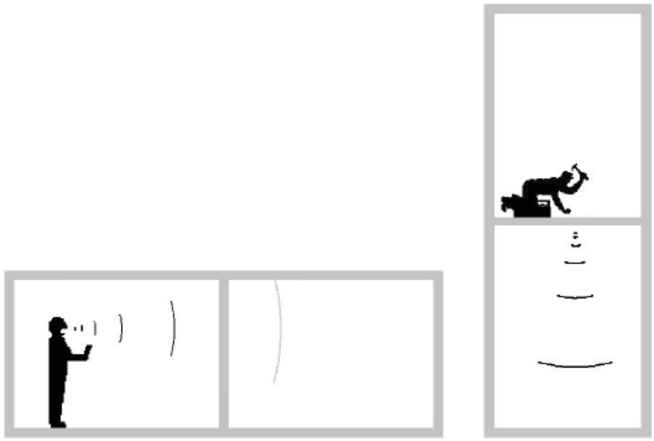
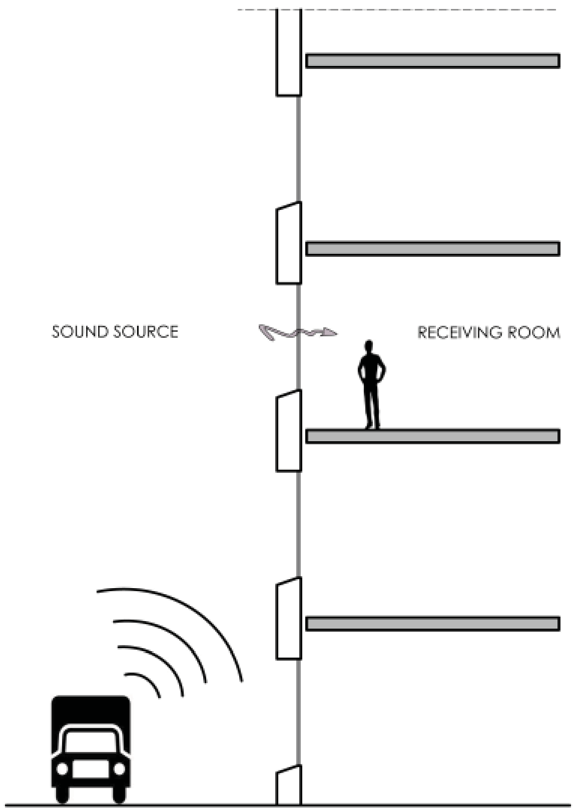


Figure: 1) Air-borne sound insulation and 2) Structure-borne sound insulation between tow spaces.
(source: Stijn Taelman, Sound insulation: Theoritical Background, System Zendow by Deceunlnck)



24 Stijn Taelman, Sound insulation: Theoritical Background, System Zendow by Deceunlnck
25 Air-borne sound insulation is the insulation against sound waves that are generated in the air (speech for example) while the structure or impact-borne sound insulation relates to the degree to which vibrations propagate in structures and are retransmitted into the air when they are directly connected (Chapter 11, Sound insulation and sound proofing, A.C. van der Linden; A. Zeegers, Bouwfysica, ThiemeMeulenhoff 2006)

At the table below the differences of sound sources in terms of sound level and frequency range are displayed.

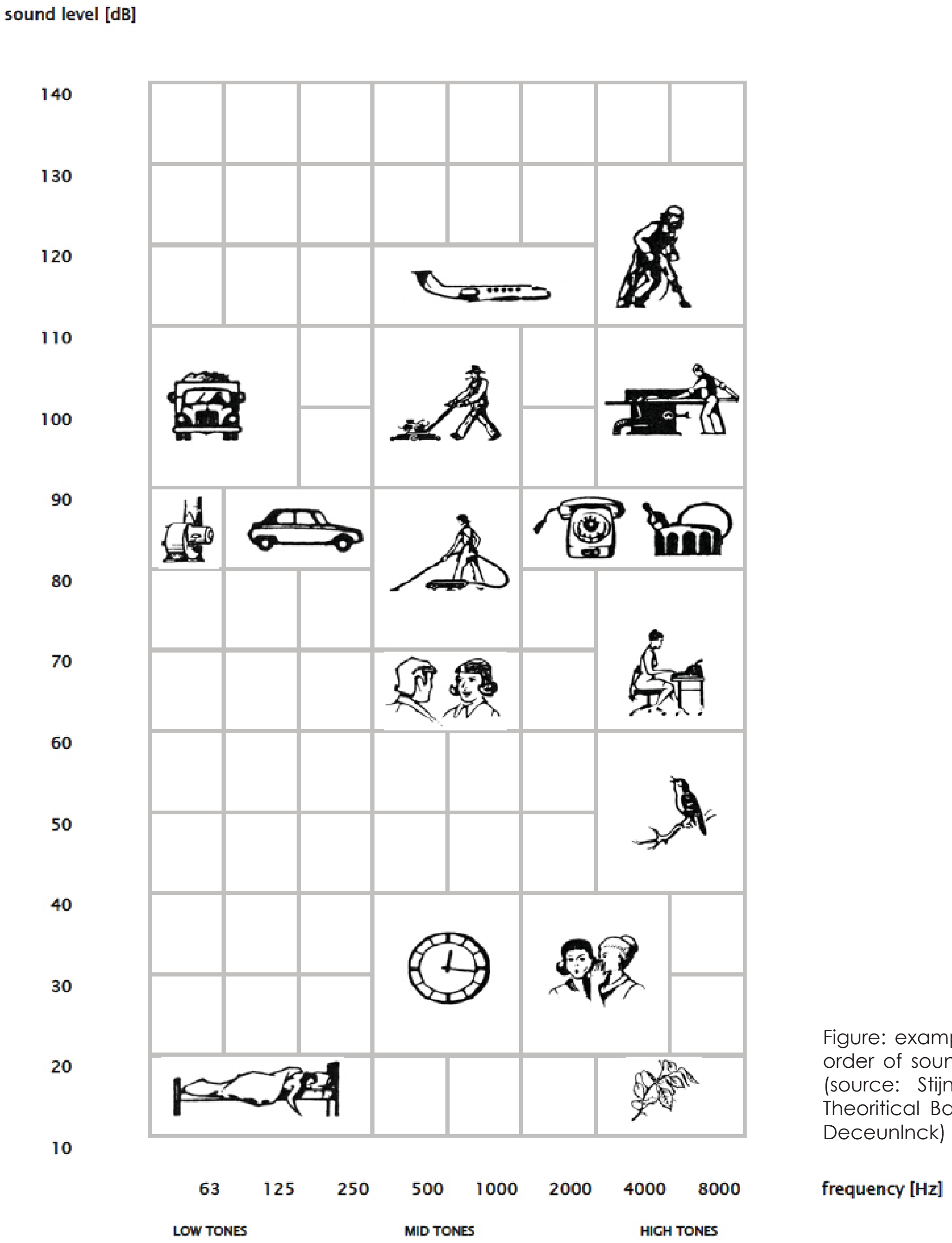


Figure: example sound sources arranged in order of sound level and frequency range. (source: Stijn Taelman, Sound insulation: Theoritical Background, System Zendow by Deceunlnck)

The sound level is expressed in dB and determines the "strength" of the sound source.

Sound can be one single frequency, but is usually made up of a number of frequencies. A frequency is expressed in Hz and determines the "pitch" of the sound source. Frequencies can be distinguished into three categories: low tones, mid tones, and high tones[26].

[26] Stijn Taelman, Sound insulation: Theoritical Background, System Zendow by Deceunlnck

6.3.2_ DETERMINING THE ACOUSTICAL PERFORMANCE OF A FACADE

Unit of measurement:
In order to examine the acoustical performance of a façade, the sound reduction between the outside and inside needs to be calculated. This is described by a single-number quantity Rw[27] (the weighted sound reduction index in dB) according to the European standard EN ISO 717-1.

Composite façades:
When the façade consists of more than one element, then the acoustical performance of it is determined by the air-borne sound insulation of all the consistent elements. In this way, the sound insulation of a composite sandwich façade – which is the subject of this research – is calculated as the average value of the sound insulation of a composite sandwich wall, the windows' glazing and the windows' frames.

Calculation conditions:
Before calculating the sound insulation of a façade, it is important to determine the conditions of its' exterior environment. We can assume that the building is located to an urban area, next to a road. The frequency range of urban road traffic and other urban noises is concentrated, according to the table shown above, to the low and mid tones. For this reason, these are the frequencies that need to be examined. More specifically, the sound reduction values of the different elements will be quested.

6.3.3_ DETERMINING THE DIFFERENCE BETWEEN A COMPOSITE/ALUMINUM FAÇADE AND A FULLY COMPOSITE FACADE

The sound insulation of each façade can differ from another due to the different designs and details that each one can have. For this reason, this thesis does not focus on performing numerical calculations of a specific composite façade element, but on determining the differences (benefits or drawbacks) that an entirely composite façade can present when compared to a composite-aluminum one.

The following cases will be therefore compared:

A) A composite-aluminum façade consisting of a GRP sandwich panel, a triple glazed window and aluminum operable frames.
B) A composite façade consisting of a GRP sandwich panel, a triple glazed window and GRP operable frames.

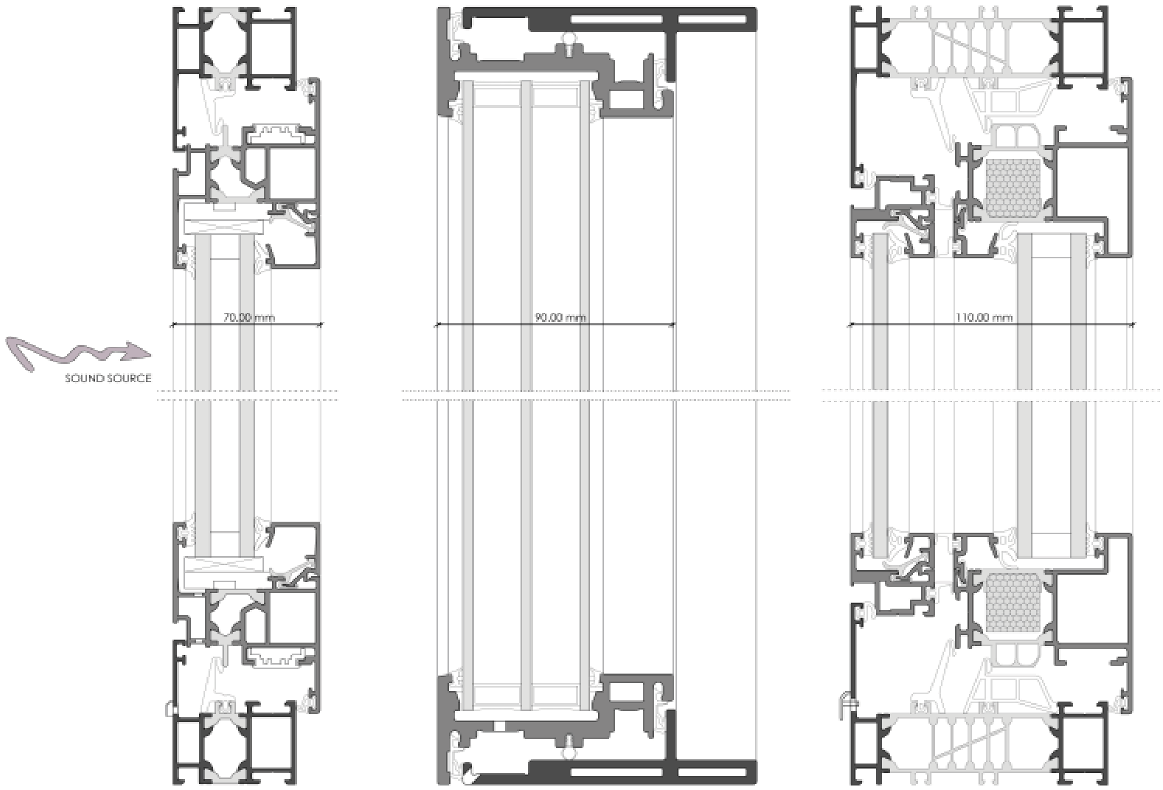
Goal of this comparison is to establish whether a completely composite façade can meet the acoustical requirements about the Sound Reduction Index Rw, as these are stated at EN ISO 10140-2 and EN ISO 717-1.
As there are already buildings realized according to case A that meet the acoustical requirements, aim of the comparison is to determine the differences between the two cases (A and B) that can cause a worst acoustical performance.

Having as a prerequisite the existence of two completely identical façade elements that consist of the same GRP panel and same glazing, the only factor that can change the acoustical performance of these facades is the different window frames.
Thus the difference in sound insulation of aluminum and GRP frames needs to be further explored.

[27] The Weighted Sound Reduction Index is a number used to rate the effectiveness of a soundproofing system or material. Increasing the Rw by one translates to a reduction of approximately 1db in noise level. Therefore, the higher the Rw number, the better a sound insulator it will be. (source: http://www.build.com.au/insulation/acoustic-insulation/performance-considerations/what-do-rw-ctr-and-nrc-mean-0

6.3.4_ ALUMINUM VERSUS GRP WINDOW FRAMES

A detailed calculation of the sound insulation value of a window frame is extremely difficult as no software until know can calculate the sound transmission of a material that has such a complex shape. For this reason, the Rw values of a frame are usually roughly determined during the design stage of a facade and can be only calculated after the construction of it.



In this case, the estimation of the Rw value will be based on an acoustics' software named BOA. According to this program, the Rw values of window frames mainly depend on the depth of the frame's vent profile, without being influenced by the frame's material.

The software's database provides information about the Rw value of window frames. According to that, a frame having a depth size between 50-70mm offers 33,4dbs of sound reduction, while a frame having a depth of 80-120mm offers 36.6dbs respectively. These values are calculated for the frequency range of urban road traffic (low and mid tones).

	WINDOW FRAMES // WIDTH 50-70mm				
Hertz	125	250	500	1000	2000
Ri	26	28	34	36	40
Rw	33,4 dB				

	WINDOW FRAMES // WIDTH 80-120mm				
Hertz	125	250	500	1000	2000
Ri	99	31	34	39	44
Rw	36,6 dB				

We can therefore conclude that:

-An aluminum frame of 70mm depth has a lower Rw value of about 3dbs than an aluminum frame of 110mm depth.

-The Rw value of a 110mm depth aluminum frame is slightly higher than that of a 100mm depth GRP one.

-The choice of the window frames' material does not influence the acoustical performance of them.

Of course the above given values can differ from the values measured in a laboratory. This is the reason why during the first rough acoustical calculations a safety value of 5dbs is added to the final result.

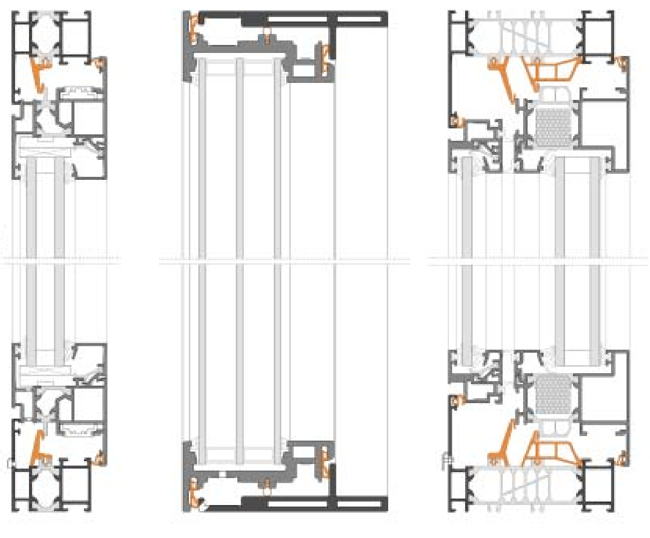
6.3.5_ OTHER FACTORS THAT MAY INFLUENCE THE SOUND INSULATION OF A FRAME

Except from the frames' depth there are also two important factors that can influence the acoustic performance of a window frame. These are the number and type of weather-strip gaskets and the quality and accuracy in the installation of the window frame.

NUMBER AND TYPE OF WEATHERSTIP GASKETS:
The weather-strip gaskets are usually made by EPDM rubber[28] and act as the frame's barrier against heat, air and sound. According to the European regulation for window frames the required amount of EPDM gaskets in a frame is two.

However, the most advanced window frames include nowadays three or even four gaskets. This of course improves the thermal and acoustical performance of the frame, as well as the air and water tightness.

We can therefore assume that the more gaskets are included in a frame the better its acoustical performance will be. Thus the frames showed below can be placed in a row based on their acoustical performance (if they are only compared according to the number of EPDM gaskets they include).



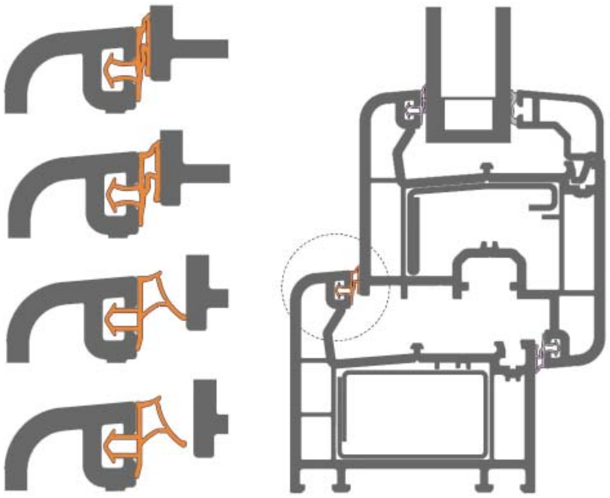
What is more, in order to achieve superior sound insulation, special Dual High Compression Seals are used between the sash and the frame as weather-strip gaskets. These can provide effective control of the environment including air-tightness, acoustic insulation and weather proofing.

High quality dual acoustical gasket (source: http://www.acefixings.com/deventer-m7049-weather-seal-brown-box-of-600-metres-p1484)

INSTALLATION OF WEATHERSTRIP GASKETS:
Apart from the properties, size and components of each frame, the acoustical performance can be also affected by the way in which the vent profiles are installed to the outer frames.

The accuracy during installation must be high and the tolerances of the elements have to be taken into account during the design stage, so that the installation of the frame to the façade can be successful. Otherwise if the vent profile is not well attached to the outer frame or the façade element, the effectiveness of the gaskets is reduced.

As can be seen to the image below, the two last cases where the EPDM gasket is not completely attached to the vent profile are expected to show lower acoustical performance than the two first cases.



Cases of wrong installation of weather-strip gaskets (source:http://www.modernepvc.com/public/pvc/catalogue/detail/id/feb42a050a07dc532d01b2b1882e8544)

6.3.6_ CONCLUSIONS

In summary several conclusion can be drawn regarding the comparison between an aluminum and GRP frame and their effect on the overall acoustical performance of a composite façade.

-The bigger the depth of the vent profile the higher the Rw of the window frame is.
-The Rw of the window frame does not depend on the material of it.
-The larger the number of EPDM gaskets included in a window frame, the better the acoustical performance of this frame is.
-The accuracy in installation and the small tolerances can improve the acoustical performance of the frame.

According to the above conclusion, we assume that is possible to design a completely composite façade that has the same acoustical values with a composite-aluminum façade if:

-The depth of the GRP frame is the same with the aluminum one.

-The number of EPDM gaskets included in the frame is the same.

-The composite construction can have the same or smaller tolerances in the connections with those of a composite-aluminum façade.

[28] EPDM rubber is an ethylene propylene diene monomer (M-class) rubber - a type of synthetic rubber that is used in a wide range of applications, but mainly for seals in window frames or where silicone must be avoided. (source: http://en.wikipedia.org/wiki/EPDM_rubber)

6.4_STIFFNESS COMPARISON

6.4.1_ DEFINING THE SCOPE OF THE COMPARISON

The structural integrity of a composite façade mainly depends on the stiffness of the composite sandwich panels, the calculation of which is not the subject of research of this thesis.

However, the goal is to compare a composite-aluminum façade and a completely composite façade with integrated GRP window frames, so as to define the benefits and/or drawbacks that the second system could have if compared to the first one.

In order to understand the difference between the two structures, we will compare three cases of a GRP sandwich panel having different window frames.

The cases analyzed are:

A) A composite façade having aluminum frames
B) A composite façade having GRP frames
C) A composite façade having integrated GRP frames

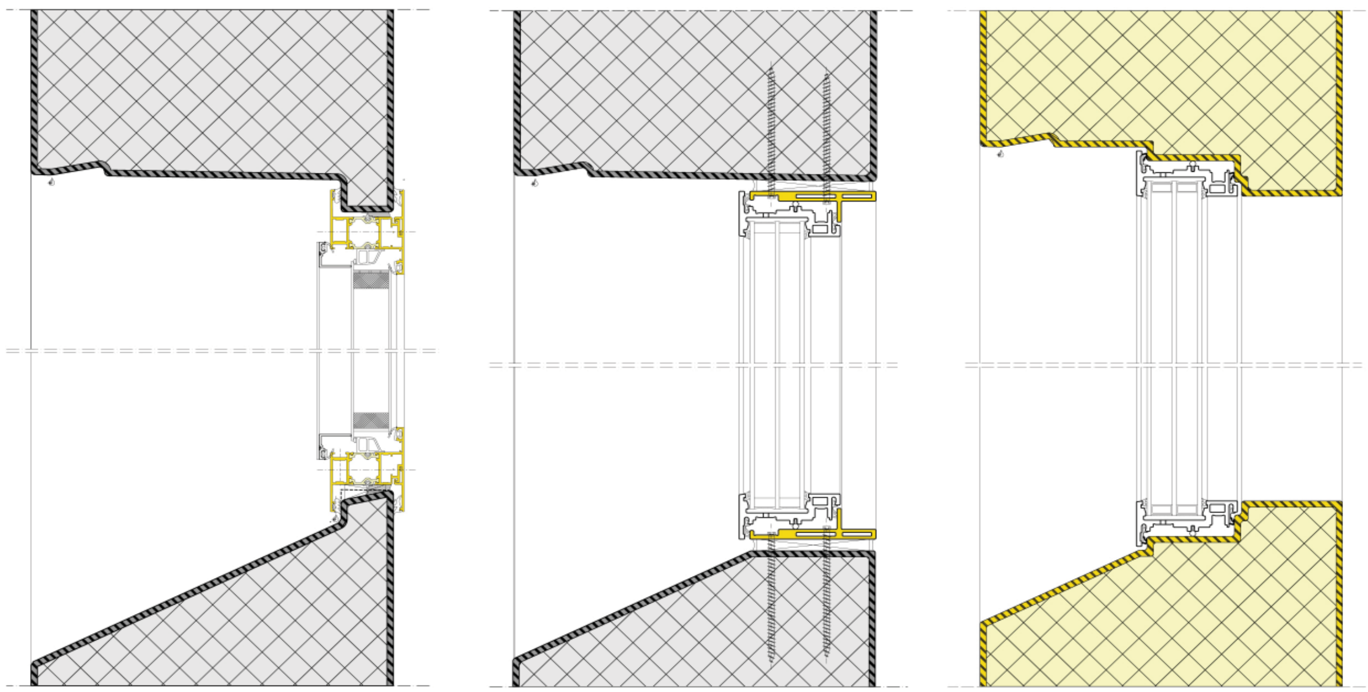
6.4.2_ THE COMPARISON

For the comparison, a reference project having a GRP façade is chosen. This is the Stadskantoor building in Utrecht.

Case A
The building is constructed according to the first case (A), so its façade consists of GRP sandwich panels and aluminum frames. The outer frame of the window is screwed on the composite wall and the vent profile is attached to it. No integration is achieved, as the window frame and the wall act as two completely different elements.
Both the frames and the panels have been tested in terms of stiffness, as the building has already been realized.

Case B
With reference to the above mentioned building, a detail of a similar GRP sandwich panel is designed. This design follows the principles of the second case (case B). The outer frame of the window is screwed to the composite panel and the vent profile is attached to it. The design shows no integration as both the window frame and the GRP panel serve two different functions.
The stiffness of the vent profile that has been used at the detail is a product of Ecliptica[29] , and has already been tested by the company.

Case C
With reference to the above mentioned building, a detail of a similar GRP sandwich panel is designed. This design follows the principles of the third case (case C). The outer frame of the window is integrated to the composite wall, forming thus one element and the vent profile is attached to it. The design is highly integrated, as more than one functions are embedded in only one element (wall).



[29] Ecliptica Windows and Doors is a Danish company that works in the direction of producing the best energy efficient products available on the market. It produces doors and windows in wood / aluminum and GRP.

The stiffness of the vent profile that has been used for the comparison is a product of Ecliptica and has been already tested by the company.
The three different cases (A/B and C) are presented at the drawing below. The yellow areas illustrate the elements used for the support of the operable window frames.

6.4.3_ DEFINING THE BENEFITS AND/OR DRAWBACKS OF HAVING A COMPLETELY COMPOSITE FAÇADE WITH INTEGRATED GRP WINDOW FRAMES (CASE 3) COMPARED WITH THE OTHER SOLUTIONS

As the first has been already realized in a building and the two next cases have been designed according to existing products, we can assume that all three solutions are stiff enough and present structural integrity.

Goal of this thesis is to determine which are the possible benefits of replacing an aluminum window frame with an integrated GRP one.

In terms of forces distribution, all three window frames are supported by other elements. In the first two cases these are the outer frames while in the last case this is the composite wall panel. The two first structures do not take advantage of the extremely high strength and stiffness of the composite wall, while they introduce an intermediate element between the wall and vent profile, in order to support the moving window.

On the other hand, the third case takes advantage of the structural integrity of the GRP panel, which is in this case used as the supporting element of the vent profile. The wall acts both as self supporting part of the façade and a supporting element for the window.

In this case, the **main advantage** achieved is the reduced use of the GRP material which leads to a **lower cost of the overall façade**. A GRP window frame consisting of a vent profile and an outer frame (two elements) is twice more expensive than an integrated frame (one element).
The manufacturing procedure (pultrusion) out of which the GRP profiles are produced is very expensive and the reduction of profiles needed in a façade to almost half, can significantly reduce the production cost of it.
More detailed calculations about the material use are presented at the weight calculation chapter.

6.5_WEIGHT COMPARISON

6.5.1_ DEFINING THE SCOPE OF THE COMPARISON

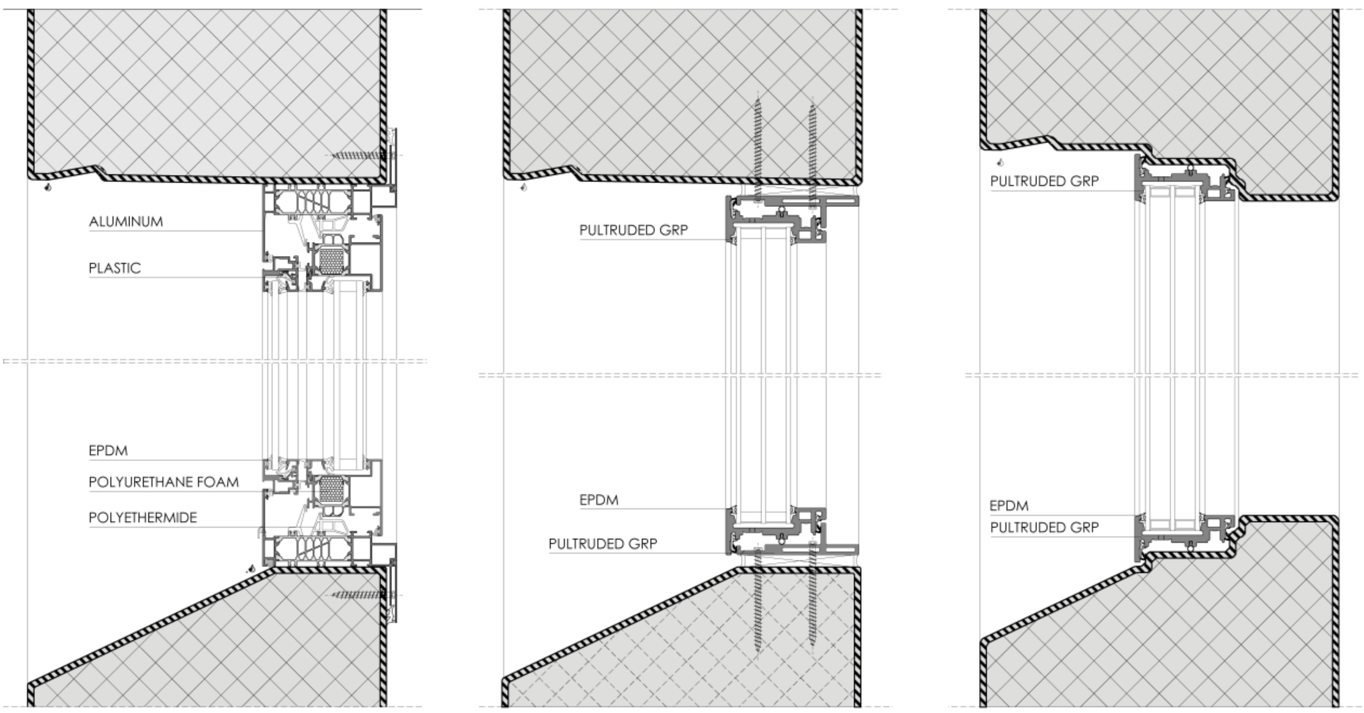
The current state of facade developments is closely related to the research on light-weight facade elements. As light-weight is considered a great advantage of a facade, especially for high rise buildings where the loads are exremely high, it is important to invent new materials and ways of using them, in order to achieve lightness of the construction.

This chapter aims to investigate whether the replacement of aluminum frames with GRP ones can help in the direction or weight reduction of a facade. For this reason, there are three kinds of window frames compared:

A) A composite façade having aluminum frames
B) A composite façade having GRP frames
C) A composite façade having integrated GRP frames

For all the windows we assume triple glazing but the glazing's weight is not calculated as it stays the same for the trhee cases.

Representative drawings of each one of the above solutions are presented below. The different materials used in each frame are also dispalyed.



6.5.2_ WEIGHT COMPARISON

The comparison of weight between the three above cases will be based on the different densitties of their materials and the amount of material use in each frame. The result will be calucated in kg/m.

Of course each different design of a frame can result to a different weight (Kg/m) value, but the calculations aim to provide a general idea about what is the weight relation between aluminum and GRP.

The materilas used in the frame are: aluminum and GRP for the profiles, EPDM fro the weatherstrip gaskets, plastic for the glazing bead supports, polyurethane foam as insulation and polyethermide as thermal breaking.

The elements' surfaces (m2) are calucalted in each case and then multipled by the density values (Kg/m3) of their specific material. The calculations of the three cases (A, B and C) are presented below.

ALUMINUM WINDOW FRAME					
		Materials	Materials density (Kg/m3)	Materials surface (m2)	Weight per m length (Kg/m)
Window frame elements	Vent profile	Aluminunm profile	2700	0,001	2700*0,001=2,7
		EPDM gaskets	110	0,0003	110*0,0003=0,033
		Plastic glazing bead clip	1200	0,00004	1200*0,00004=0,048
		Polyurethane foam (PUR/PIR)	30	0,0005	30*0,0005=0,015
		Polyethermide thermal break	1270	0,0002	1270*0,0002=0,254
	Outer frame	Aluminunm profile	2700	0,0008	2700*0,0008=2,16
		Polyethermide thermal break	1270	0,0006	1270*0,0006=0,762
		EPDM gaskets	110	0,0004	110*0,0004=0,044
Total				0,00384	6,016 Kg/m

GRP WINDOW FRAME / non integrated					
		Materials	Materials density (Kg/m3)	Materials surface (m2)	Weight per m length (Kg/m)
Window frame elements	Vent profile	Pultruted GRP profile	1650	0,0011	1650*0,0011=1,815
		EPDM gaskets	110	0,0001	110*0,0001=0,011
	Outer frame	Pultruted GRP profile	1650	0,0009	2700*0,0008=1,485
		EPDM gaskets	110	0	110*0,0004=0,044
Total				0,0021	3,311 Kg/m

GRP WINDOW FRAME / integrated					
		Materials	Materials density (Kg/m3)	Materials surface (m2)	Weight per m length (Kg/m)
Window frame elements	Vent profile	Pultruted GRP profile	1650	0,0011	1650*0,0011=1,815
		EPDM gaskets	110	0,0001	110*0,0001=0,011
	Outer frame	Pultruted GRP profile	1650	0	1650*0=0
		EPDM gaskets	110	0	110*0=0
Total				0,0012	1,826 Kg/m

6.5.3_ COMPARISON

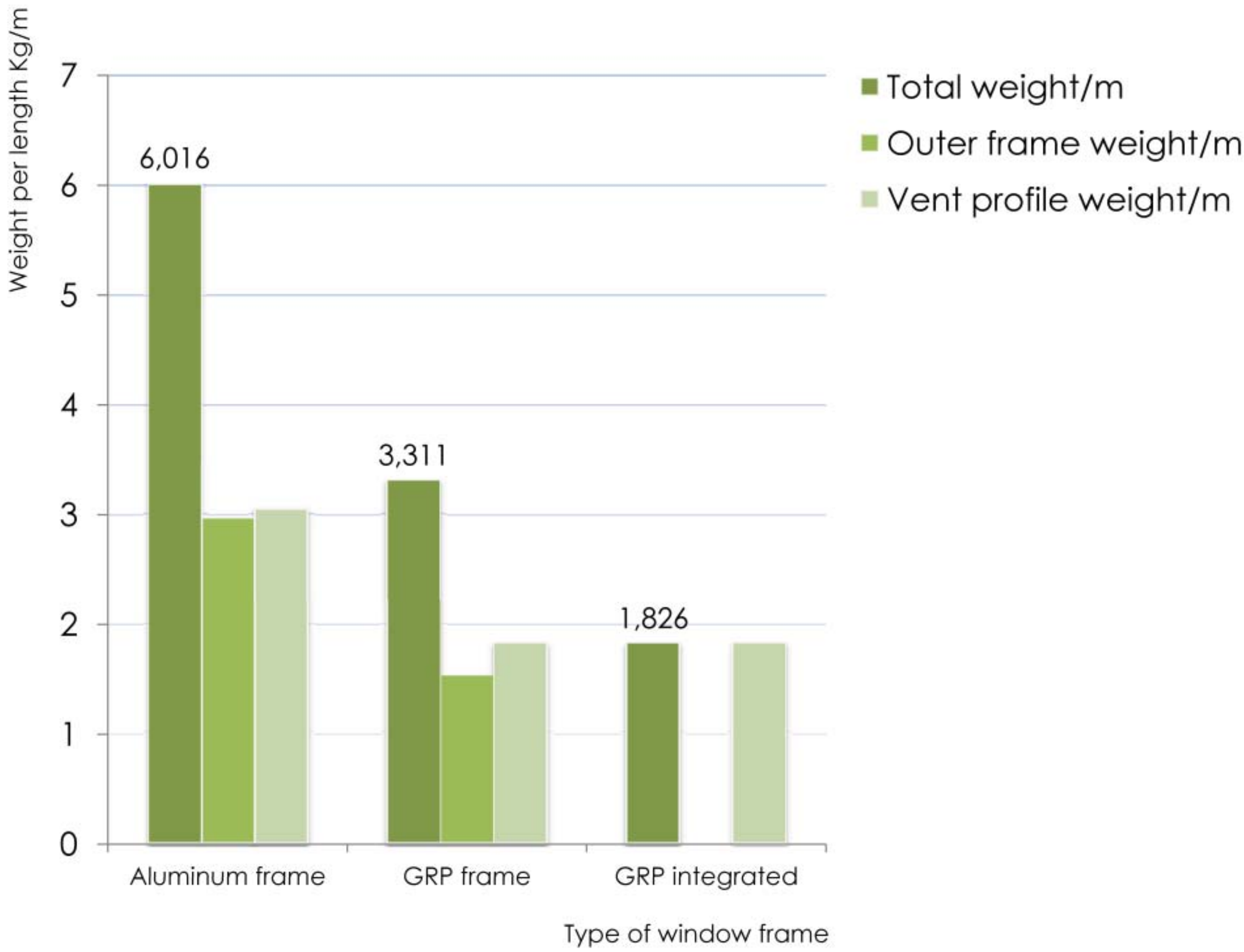
As can be concluded by the calculations:

-The material usage in the case of aluminum (0,0018 m2) is slightly lower than that of not integrated GRP frame (0.002 m2), but since aluminum's density is a lot higher than of GRP, the overall weight of an aluminum window frame is about twice than that of a GRP one.

-Since the integrated GRP frame uses a lot less material as it does not require an outer frame, the overall weight of the whole window frame is a lot less than of a conventional GRP frame.

-The integrated GRP frame weights less than one third of the weight of an aluminum frame.

The relation between the weight per meter length of the three window frames is also presented at the diagram below.



It can be therefore said that a GRP window frame is preferable, in terms of weight, from an aluminum frame.

The integration of the frame to the wall panels can even further reduce the weight of the facade.

6.6_MANUFACTURING METHOD

6.6.1_ DEFINING THE SCOPE OF ANALYSIS

Since one of the goals of this research is to provide the knowledge needed for the realization of a GRP facade, it is crucial to examine which are the possible ways of manufacturing a GRP facade element with integrated GRP window frames.

A GRP facade element consists of:

A) A GRP sandwich panel, and
B) GRP pultruded window profiles

This report will focus on the ways a GRP sandwich panel can be constructed.

6.6.2_ MANUFACTURING METHOD ANALYSIS

As referred at a previous chapter, there are two manufacturing ways that are more commonly used for production of GRP sandwich panels. These are Vacuum Assisted Resin Transfer Molding (VARTM) and Vaccum Injection Molding (VIM). Among these two the VARTM procedure is the most accurate one and the one used by the companies, so the design concepts' manufacturing process will be analysed accordign to that.

The following description over how can the previous design concepts be manufactured has been based on many discussion with Jack Smith, the director of Polux (a GRP manufacturing company of the Netherlands).

VACUUM ASSISTED RESIN TRANSFER MOLDING
This process has been analysed before but some really important aspects need to be pointed out again.

This procedure is achieved with the help of an extremely accurate GRP mold that consists of two parts. After the mold has been produced, the reinforcement material and the core of the sandwich panels are placed into the one part of the mold (the deeper one). After that the second part of the mold is placed over the top and the mold is tight sealed. The resin is the then released inside the mold and a vacuum helps so that the resin gets distributed everywhere to the interior of the mold.

According to the procedure described above, the element has to have a specific shape so that is can allow the division ot the mold in two parts. That means that extremely complex shapes with recesses cannot be easily produced, since after the manufacturing of the panel, the mold cannot be removed from it because of the recesses.

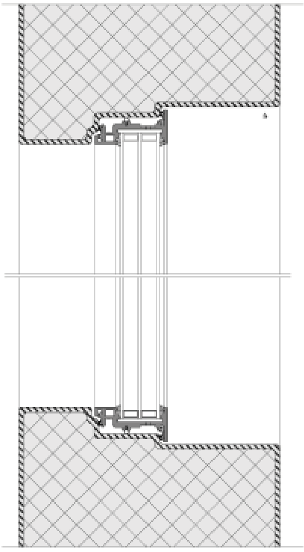
Of course solutions to these problems can be found, but they require more labout time and are also more expensive in compared with simple constructions. The concept designs that have been presented above can be divided in three categories acording to the simplicity or difficulty of production, due to the mold division problems.

In this way, there are three categories:

A) Simple designs
B) Complicated designs with recesses
C) Complicated designs with recesses and drainage pipes

Each one of these categories will be further analysed in terms of production techniques required when manufactured with VARTM.

SIMPLE DESIGNS



This category includes all the simple designs that do not have complicated recesses. The mold of this elements can be easily manufactured and split in two parts.

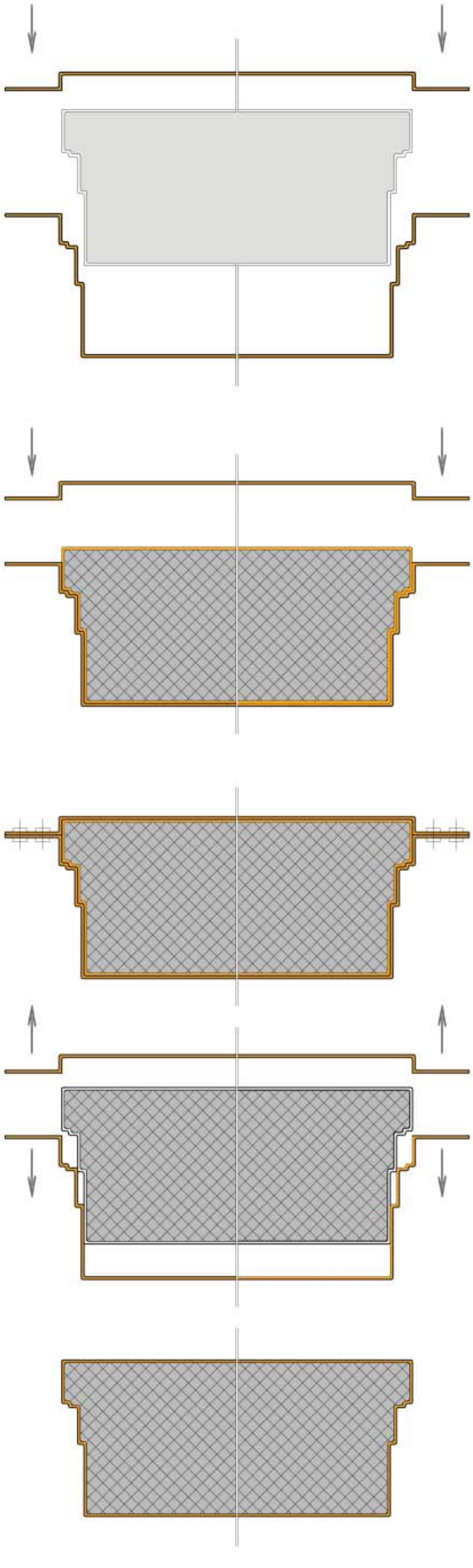
The procedure that follows for the manufacturing of the GRP panel is described at the diagram on the right.

As can be seen from te first image, the shape that needs to be manufactured allows the removal of the mold. No obstacles or recesses are there.

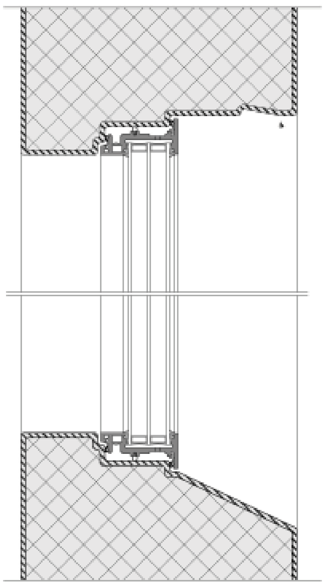
In this case, the deeper part of the mold is filled with glass fibers and then the core material is applied. The second part of the mold is placed on top and the mold is sealed.

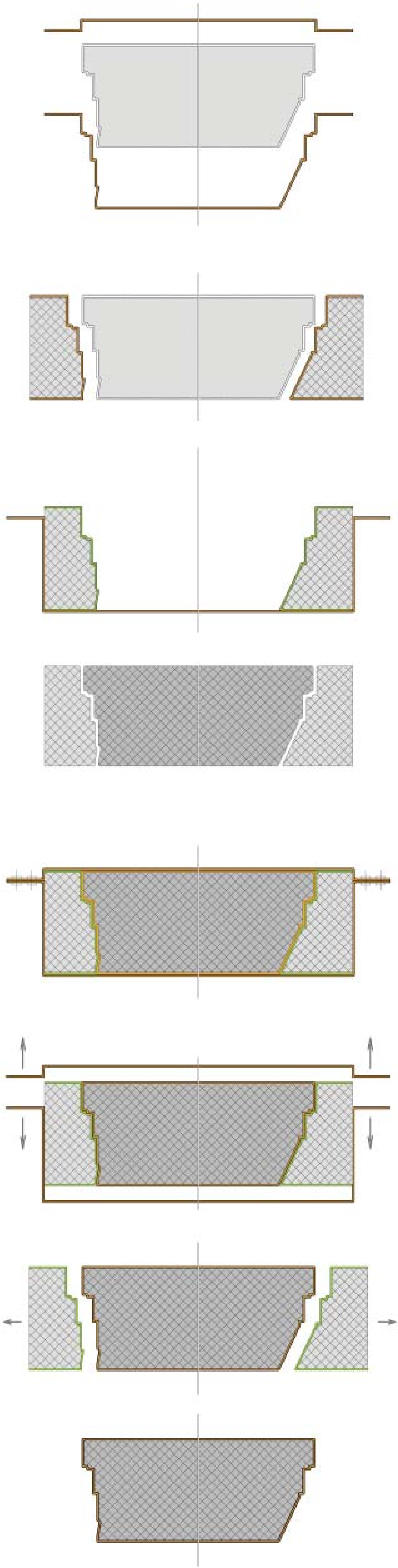
The resin is pured inside the mold and with the help of a vacuum is distributed everywhere.

After the drying period when the element is strong enough, both parts of the mold are carefully removed. The final product is shaped.



COMPLICATED DESIGNS





This category includes all the complicated designs that do have recesses. The mold of this elements cannot be easily removed after the completion of the panel.

Of course there is a solution when referring to those kinds of designs, as an auxiliary element is used during the manufacturing procedure. This is describes at the diagram below.

As can be seen from te first image, the shape that needs to be manufactured does not allow the removal of the mold after the panel is ready because of the shape of its recesses.

For that reason two auxilary molds can be used in order to make to outer mold less complicated.

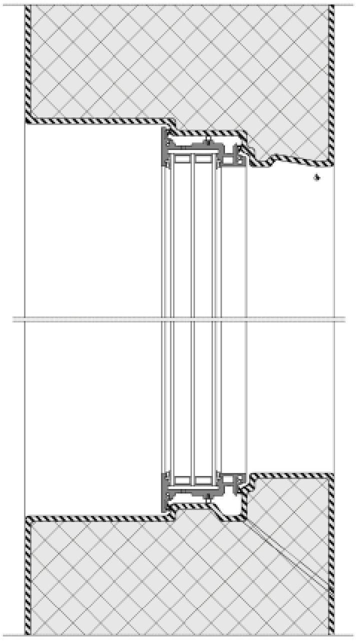
The two auxiliary molds having the reverse shape of what is needed are placed in the deeper part of the outer mold. After their placement, the outr mold and smaller molds are covered by glass fbers and then the insulative foam is applied.

The thiner part of the outer mold is closed and the construction is air sealed. The resin is consequently pured into the mold and with the help of a vacuum is distributed everywhere inside it.

After the drying of the resin, the two parts of the outer mold are removed. Then the inner molds are also remove and the panel is shaped at its final shape.

This pocedure is relatively more time consuming and labour intensity if compared to the first one. Furthermore attention should be paid to the connections of the inner mold to the outer mold. What is more, the surface quality of the areas of the panel that were attached to the inner mold is some times lower than of other parts and it depends on the ability and technique of the manufacturer.
On the other hand, this manufacturing procedure despite the disadvantages is widely used for facade manufacturing, as most of the facade elements are quite complex in design.

COMPLICATED DESIGNS WITH DRAINAGE PIPES (INWARD OPENING FRAMES)



This category includes all complicated designs of inward opening window frames.

The water that enters the window frames at inwards opening windows is gathered in a recess of the GRP panel and has to be quickly and carefully removed away from the facade.

For this reason small plastic pipes are inserted in the panel in order to help remove the stagnant water away.

The manufacturing procedure of this panel follows the same steps with the second case (complicated design).

After the manufacturing of the panel without pipes, small holes are drilled in the panel and plastic pipes are inserted into it. The pipes are inclined in order to ensure a fast removal of the water.

Special attention must be given to the way in which the holes between the plastic pipes and the pane have to be sealed in terms of air and water tightness.

Sealant (usually silicone) is applied.

6.6.3_ CONCLUSIONS

As described above, all the design concepts presented before can be manufactured with current techniques. Simpler designs are always les time and money consuming and can guarantee netter results in terms of quality, but more complex shapes can be also manufactured.

Inwards opening windows present a disadvantage over other solutions as they require extra pipes fpr water removal. These increase the cost and time for manufacturing and can cause serious problems when the holes are not well sealed and water can penetrate in the construction. On the other hand, a facade with inwards opening windows can be more attractive to architects and constructors, especially in cases of high rise buildings, since it is easier in use and safer for the user.

To sum up, there are advantages and disadvantages in the design of each concept. The choice of the final product depends mainly on the designer and the building's requirements.

6.7_MANUFACTURING AND INSTALLATION TIME

6.7.1_ DEFINING THE SCOPE OF THE COMPARISON

The time needed for a facade element to be produced at the production plant and installed on site is always related to cost.

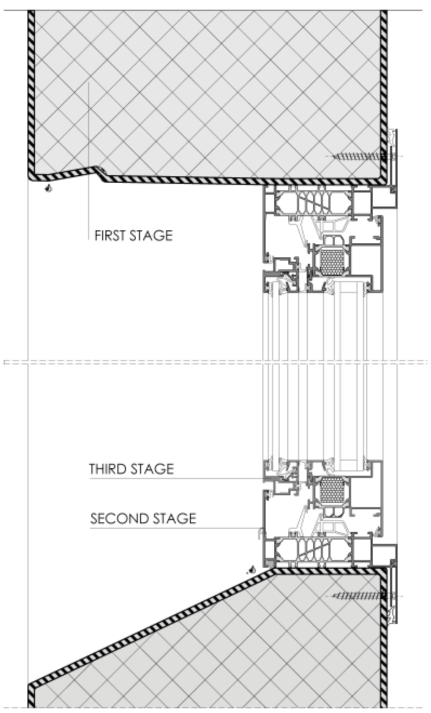
A delayed delivery of the facade elements can become unprofitable for the manufacturers and of course time demanding elements require more workers or more work payments.

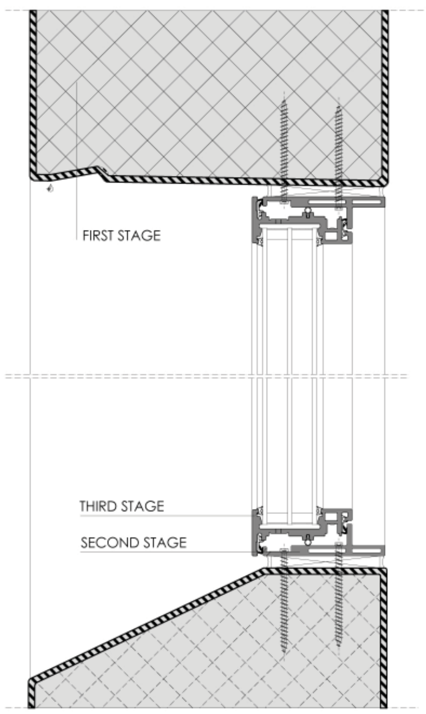
It is therefore important to determine which are the differences in time requirements of a composite facade having aluminum or GRP windowf frames. This chapter aims to investigate whether the replacement of aluminum frames with GRP frames can reduce the manufacturing and installation time of a facade.

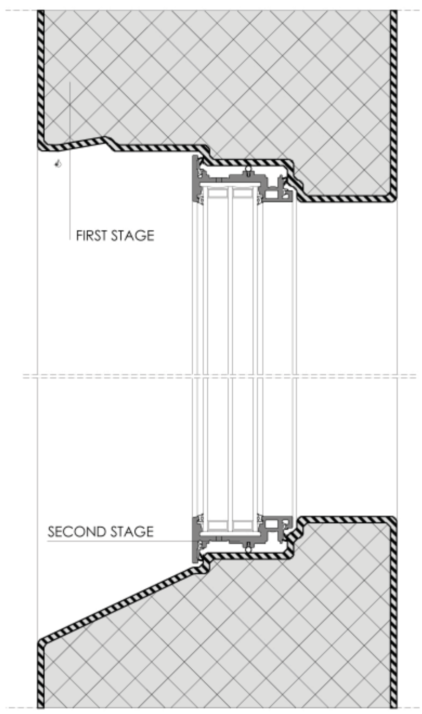
For this reason, there are three kinds of window frames compared:

A) A composite façade having aluminum frames
B) A composite façade having GRP frames
C) A composite façade having integrated GRP frames

Representative drawings of each one of the above solutions are presented below.







6.7.2_ COMPARISON

The comparison of the three cases is based on the four steps that are necessery for the production of a composite sandwich panel with window frames. The production can be divided as follows:

-Production of the GRP sandwich panel
-Attachment of the window's outer frame to the sandwich panel
-Placement of the vent profile to the outer frame/wall
-Transfer to construction site

STAGE 1: production of the sandwich panel:

The manufacturing time of one panel usually requires two days. During the first day the mold is filled with the materials of the panel (glass fibers and insulating foam) and then is closed so that the resin can be injected into it. After the resin has been spread, the panel is left to dry in the mold for the whole night.

During the second day, the mold is removed and the refinement work is done. Unnecessary pieces are removed and the element is polished. The rough edges are corrected and wherever is needed (in case of holes or other irregularities, some extra resin is applied to the final product.

The first step of the manufacturing is always the same for all the three window frame cases that are mentined above. The required time does not differ.

STAGE 2: attachment of the outer frame:
After the refinement of the panel, the outer window frame is attached (mainly with screws).
This stage is omitted in the case of the integrated GRP frame (case C). Since there is no need of a outer frame, the manufacturing procedure continues with the placement of the vent profile.



STAGE 3: placement of the vent profile:
After the installation of the outer frame in the two first cases (A and B) the vent profile is placed. This stage is completed at the factory. For the third case (integrated GRP profile), the placement is done immediately after the manufacturing of the GRP panel.

STAGE 4: transport to construction site:
The procedure followed after the manufacturing of the element at the factory is always the same in any case. The panels (including the outer and operable frames) are transfered on site where they are only placed in place.

The time needed for the assemply of the facade depends on the connection points and the detailing of the panels but not on the framing material that has been used.

6.7.3_ CONCLUSIONS

In summary, we can conclude to the following:
-The required time for a GRP panel with window frames to be ready for transportation on site is approximately two days.

-The integrated GRP profile presents a benefit over the other two cases. Since it has no outer frame, it requires less labor time to be attached to the GRP panel.

-The installation time is the same in every case.

-No other difference in time resulting from the choice of the framing material can be observed.

6.8_PRODUCTION COST

6.8.1_ DEFINING THE SCOPE OF CALCULATION

The cost of a building and therefore a facade is one of the most important aspects to be researched, when referring to the development of a new facade concept.

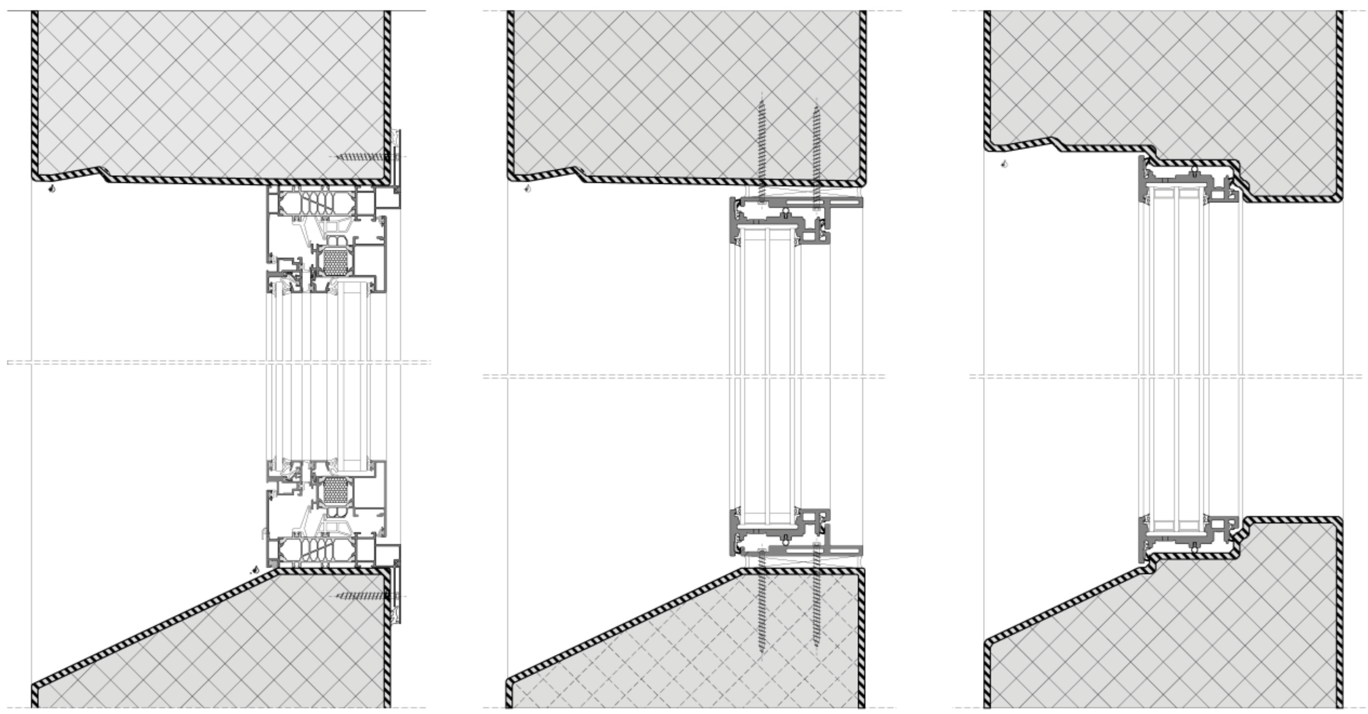
Goal of this comparison is to determine the difference that the replacement of aluminum frames and the integration of GRP ones in a sandwich GRP facade can cause. It is also very important to determine whether there are cost benefits when comparing a non integrated GRP facade with an integrated one.

For this reason the three cases of facades will be agiain compared:

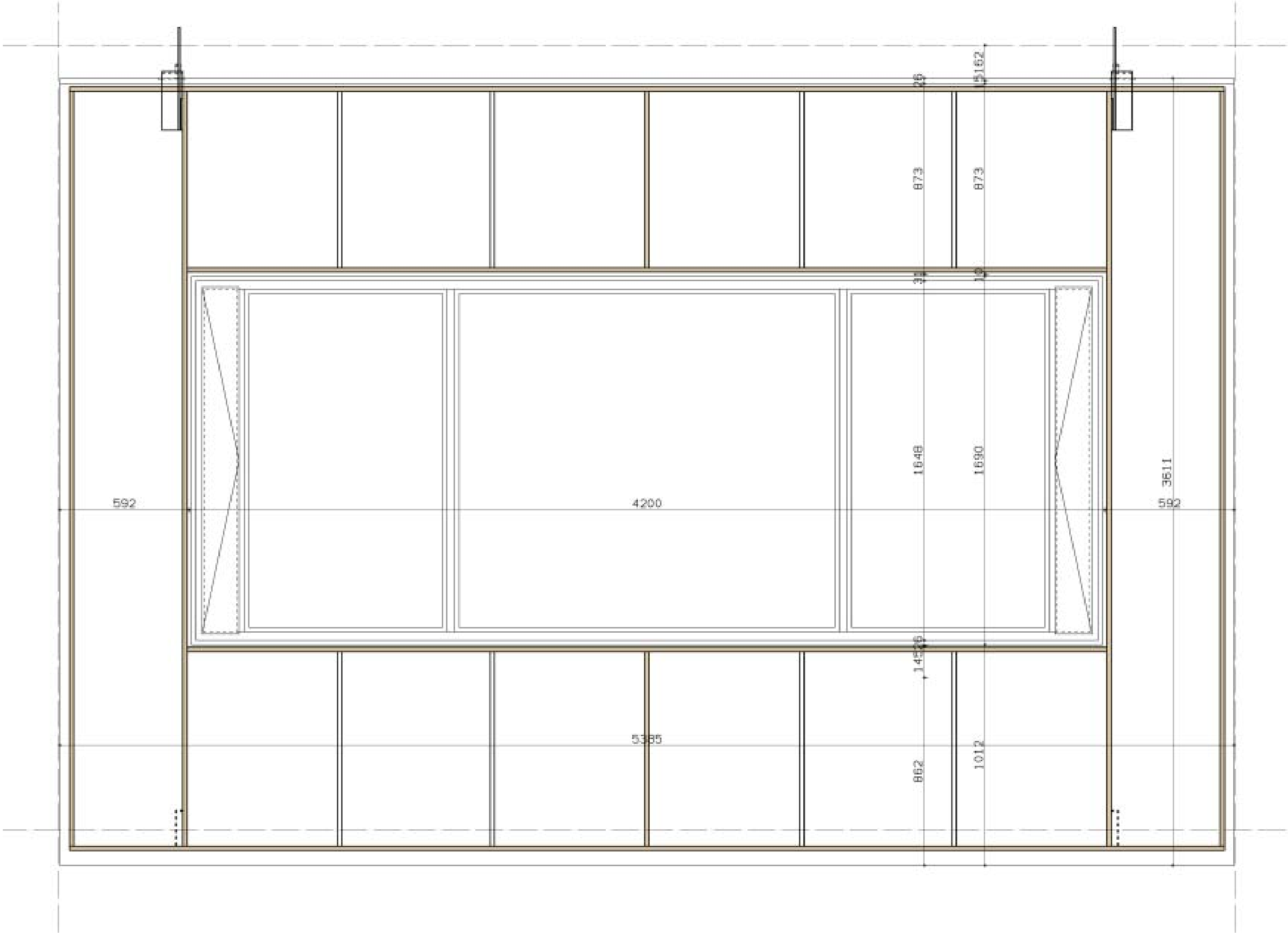
A) A composite façade having aluminum frames
B) A composite façade having GRP frames
C) A composite façade having integrated GRP frames

For all the windows we assume triple glazing.

Representative drawings of each one of the above solutions are presented below. The different materials used in each frame are also dispalyed.



In order to calculate the cost required for a total fcade element, the Stadskantoor building in Utrecht is used.
A part of its facade – one element will be analyzed.
This building is already realized having GRP sandwich panels and aluminum frames (case A).



According to the same drawing and dimensions of it, we assume that we replace the aluminum frames with GRP frames (case B) and that we also integrate the GRP outer frames into the panel (case C).

Thus, the comparison will include the same data and will only focus on the differences in window frames.

6.8.2_ THE CALCULATION

The calculation is based on each material's surface at the element and the price per square meter / meter or each material.

The prices used for the calculations have been discussed with Jack Smith (director of Polux) and are estimations of the current time.

Of course these values can change within a year or less and they are mainly determined by the demand of the individual materials, but the calculations below can provide a general idea about what is the price difference between a GRP/aluminum and a fully GRP façade.

Calculations of prices of the three different cases are displayed below.

ALUMINUM WINDOW FRAME						
	Materials		Material's area(m2)	Material's length (m)	Material's cost (€/m2)	Cost*area (€)
Facade elements	Aluminum window frame	Vent profile	7,1	10,14	350	7,1*350=2.485
		Outer frame		10,14		
		Triple glazing				
	GRP sandwich panel		12,35		650	12,35*650=8.027,5
Total			19,45			10.512,50

GRP WINDOW FRAME / non integrated								
	Materials		Material's area(m2)	Material's length (m)	Material's cost		Cost*area / Cost*length (€)	
Facade elements	GRP window frame	Vent profile	7,1	10,14	50 €/m	650 €/m2	10,14*50=507	7,1*650=4615
		Outer frame		10,14	50 €/m		10,14*50=507	
		Triple glazing						
	GRP sandwich panel		12,35m2		650 €/m2		12,35*650=8.027,5	
Total			19,45				12.642,50	

GRP WINDOW FRAME / integrated								
	Materials		Material's area(m2)	Material's length (m)	Material's cost		Cost*area / Cost*length (€)	
Facade elements	GRP window frame	Vent profile	7,1	10,14	50 €/m	650 €/m2	10,14*50=507	7,1*650-10,14*50=4.108
		Outer frame		0	50 €/m		0*50=0	
		Triple glazing						
	GRP sandwich panel		12,35m2		650 €/m2		12,35*650=8.027,5	
Total			19,45				12.135,50	

Furthermore, the price for one mold that can build the GRP elements is in all three cases the same and it is estimated at around 60.000 euro.

6.8.3_ THE CONCLUSION

As it can be pointed out from the tables above, the price of a GRP/aluminum facade element is about 10.510 euros, a price of a totally GRP element is 12.640 euros while an integrated version of a GRP facade element can cost a little lower to 12.135 euros.

The price of the GRP sandwich element stays in both cases the same at around 8.000 euro while the change of aluminum to GRP can cause a change in cost at about 2000 euro.

Of course the integrated solution, because of the reduced use of GRP material (it has no outer frame), is relatively less cost demanding, but still more expensive than the GRP/aluminum case. We can therefore calculate that the integrated GRP solution costs 1600 euros more than the aluminum solution, for each facade panel.

NOTE: The prices used for the calulations of the GRP sandwich panels (650euro/m2) and the aluminum window frames (350euro/m2) were based on the estimation of Jack Smit (director of Polux BV), while the price for the GRP window frames (650euro/m2) were estimated according to currently existing products in the market.

7.1_ CONCLUSIONS OVER THE COMPARISON

The outcome of the above research is that **the designing and manufacturing a Glass Fiber Reinforced Polyester (GRP) façade with integrated operable GRP window frames, having high degree of integration and a great number of performance benefits over a conventional GRP façade is possible.**

In order to sum up with the benefits and drawbacks of such a façade, the previously compared and discussed attributes, will be briefly mentioned and divided in pros and cons.
The advantages and disadvantages of each case are also displayed in the following table.

FAÇADE SYSTEMS COMPARISON TABLE				
			GRP/ALUMINUM CONSTRUCTION	INTEGRATED GRP CONSTRUCTION
Façade characteristics	Performance	Light-weight		✓
		High strength	✓	✓
		Low thermal conductivity		✓
		No thermal break required		✓
		Sound insulation		✓
		Small thermal expansion	✓	✓
		Durability	✓	✓
	Maintenance	Low maintenance		✓
		Water resistance	✓	✓
		Corrosion resistance	✓	✓
		High life expectancy (resistance to sun, wind, moisture)	✓	✓
		Impact and scratch resistance	✓	✓
		No need for coatings		✓
	Manufacturing and installation	Easy in manufacturing	✓	
		Quick assembly	✓	✓
		Quick installation		✓
		Availability of complex shapes	✓	✓
		Low cost	✓	
		Small tolerances	✓	✓
		Ease in customisation		
		Wide variety of sizes and styles	✓	✓
		Ease in disassembly	✓	✓

7.1.1_ ADVANTAGES

THERMAL INSULATION
The replacement of an aluminum frame with a GRP one can cause by more than one half the thermal conductivity value.

The U value of a triple glazed GRP frame (1.107 W/m2K) is lower than the U value of a triple glazed aluminum frame (1.40 W/m2K). Furthermore, the GRP profiles are a lot slimmer (smaller height) than the aluminum ones, which results to less energy (heat) been transferred through their structure (thermal conductivity). The thermal conductivity value of a GRP frame is 0.049 W/mK while of an aluminum frame is 0.144 W/mK (more than double).

ACOUSTICAL PERFORMANCE
The acoustical performance of a window frame does not depend on the material of the frame but on the width of the vent profile.

When comparing an aluminum frame with a GRP one, where the number of weather-strip gaskets is the same in both cases, and the glazing is of the same type, the only main aspect that influences the acoustics is the width of the window frame. According to BOA, the bigger the width of the window frame, the better the acoustical performance of it.

In this case, GRP window frames seem to have an advantage over aluminum ones, since they are relatively smaller in height but bigger in width. Since the outer frame does not influence the acoustic performance of the frame, an integrated solution of a GRP façade does not make any change in acoustics if compared with a non integrated product.

STIFFNESS
Integrated GRP facades manage to take advantage of the wall's thickness in order to reduce the material use. The integrated GRP window frame is supported completely by the wall and no need of an outer frame is required. This reduces by almost one half the materials used for the framing of the façade, resulting this way to the reduced cost of the facade.

Of course an integrated GRP solution is still more expensive than a GRP-aluminum solution, as it has been calculated above, but still the integration and reduction of the weight and material use, can significantly lower the price of a GRP facade panel.

WEIGHT
Weight is probably one of the most important advantages of an integrated GRP façade. A GRP window frame can weight 1,826 kg/m while an aluminum frame weights up to 6,016 kg/m.

The lower weight is based on the reduced use of the material (as the integrated GRP solution uses less material) as well as the lower density values of GRP over aluminum. By replacing thus the aluminum frames with GRP frames, we can reduce the weight of the framing by almost one third.

MANUFACTURING AND INSTALLATION TIME
The manufacturing and installation time of a GRP panel if compared to a GRP/aluminum one is almost the same. Regardless of the difficulties in manufacturing a fully GRP façade because of the detailing of the panels, the manufacturing time of every panel requires about two days. However, since an integrated GRP façade has no outer frame to be fixed on the panel, the labor time needed after the manufacturing of the sandwich panel is less than that needed when an aluminum outer frame needs to be fixed on the GRP wall (this step does no longer exist in a fully GRP façade).

7.1.2_ DISADVANTAGES

PRODUCTION COST
The production cost is probably the most important disadvantage of the use of GRP in facades. According to the price calculations displayed at the previous chapter, the cost of a 20m2 GRP façade with 7m2 of window can vary from 10.500 euro in case of aluminum windows, to 12.100 euro in case of integrated GRP window frames (1600 Euros difference per façade element).
If this is multiplied by the number of façade panels needed for a façade, we can assume that the cost of the whole façade can radically increase by the replacement of aluminum frames with GRP.

MANUFACTURING METHOD
The manufacturing of both GRP panels with aluminum frames and GRP panels with GRP frames is possible. However, the difficulty of producing an integrated, highly accurate and fine GRP façade is a lot higher when compared with a conventional GRP/aluminum façade.
In several times extra molds are required in order to achieve a more complex result which leads to a more time and money consuming procedure. Furthermore, in cases where the outer frame is integrated into the wall panel and the façade consists of inwards opening windows, the removal of the water becomes more difficult and risky.
Of course solutions are always possible and have been described at the above chapter, but still, the production of a fully GRP façade panel is undoubtedly a more difficult procedure.

7.2_ FINAL DESIGN

As it already mentioned before, there cannot be only one solution that has only advantages and no disadvantages at all. All the design concepts which have been presented display pros and cons, It is according to the building requirements that a concept may be concerned suitable or not.

However, two designs are selected to be more thoroughly presented. One design with an outward and one with an inward opening window will be further presented.

These are not the easier solutions in terms of manufacturing procedures needed, but are the most advanced ones, in terms of integration of functions.

The two following designs achieve:

-high thermal insulation due to the material's low heat transfer coefficient and the triple EPDM air tightness system

-acoustical performance values because of the vent profile's dimensions, the material properties and the triple air tightness system

-water and air tightness due to the triple EPDM gasket system and small tolerances

-high stiffness of the construction and at the same time low material usage due to integration of the windows frames into the composite panels

-low weight due to the material's density and the reduced use of it

-feasibility in manufacturing

-ease in assembly and installation

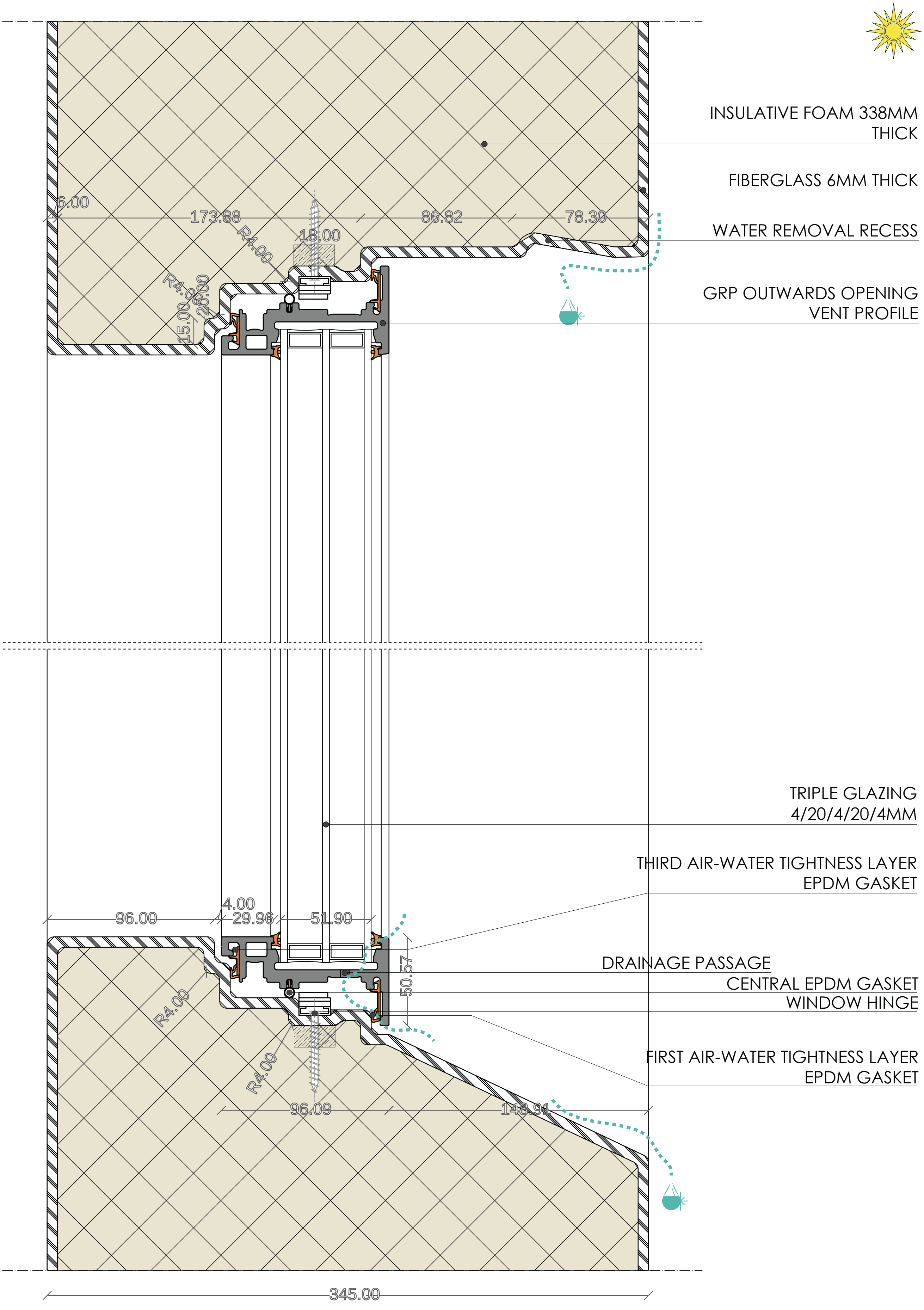
-less manufacturing, assembly and installation time needed

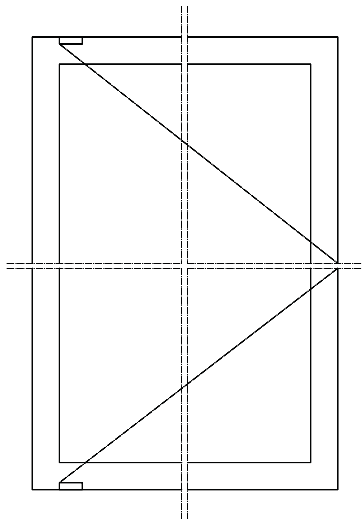
-high degree of integration of the façade's elements (integrated water removal recess, integrated hinges) into the sandwich panel

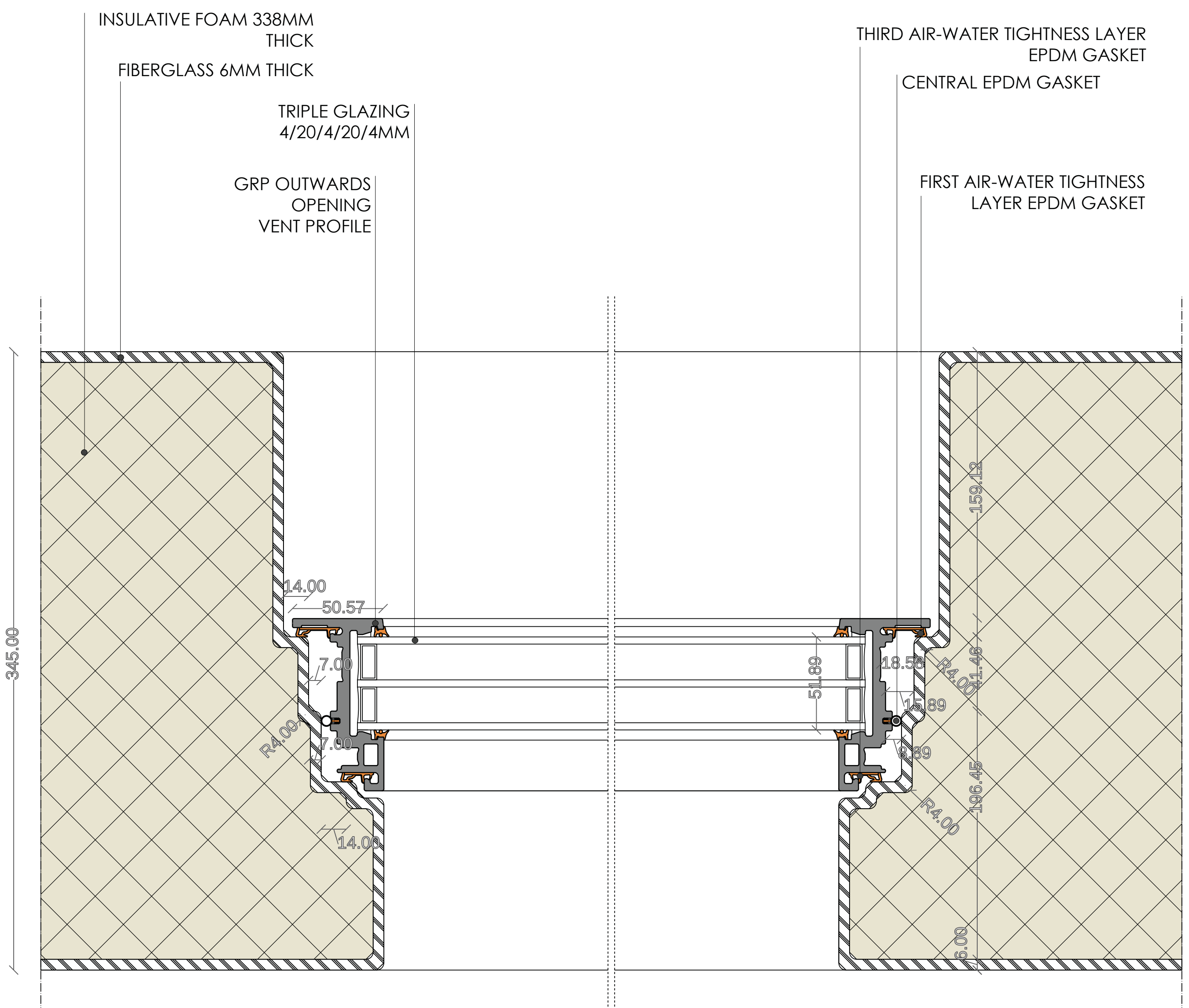
-ease in disassembly (since nothing is glued the disassembly of the façade becomes easier)
-high quality of the final product

Detailed drawings of the two suggested final designs are presented below.

7.2.1_ INTEGRATED GRP FAÇADE WITH OUTWARD OPENING WINDOW

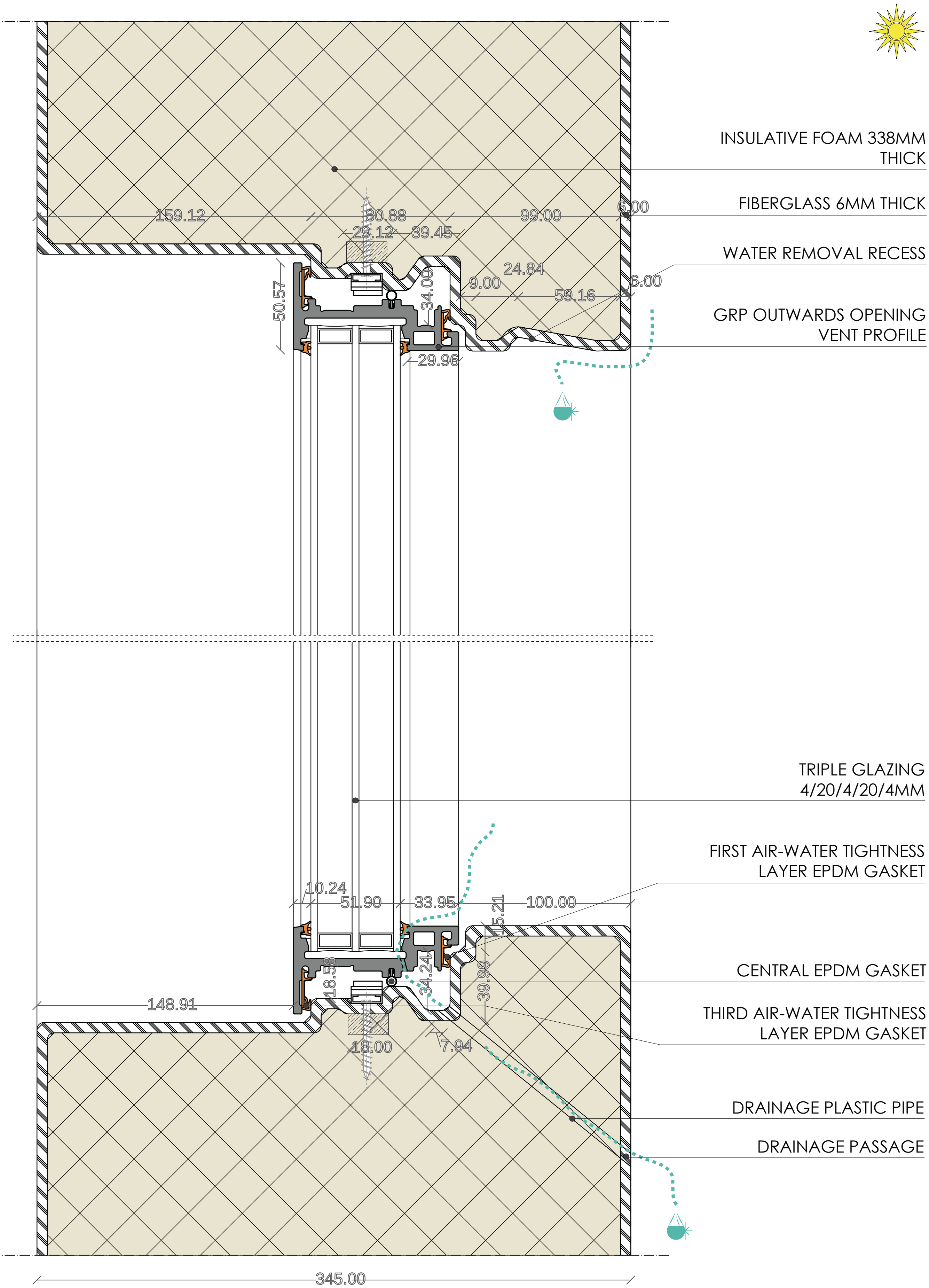


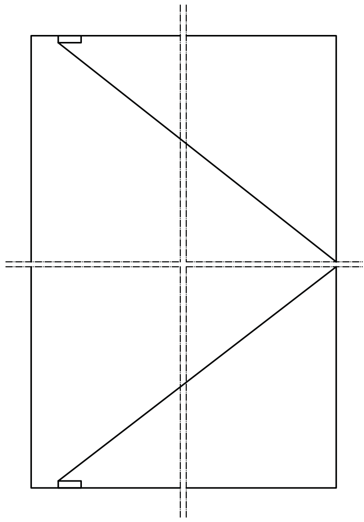


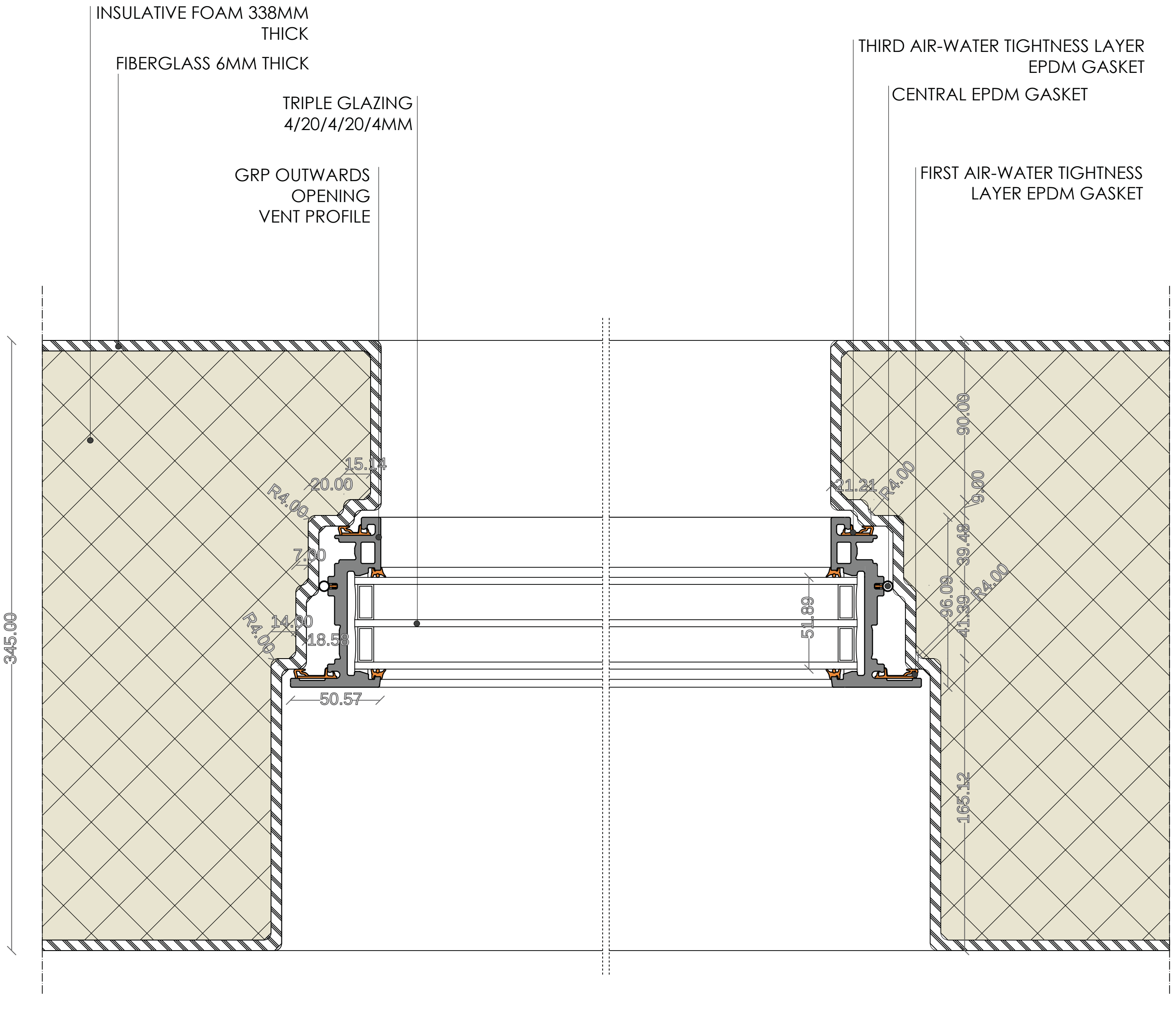


INSULATIVE FOAM 338MM THICK
FIBERGLASS 6MM THICK
TRIPLE GLAZING 4/20/4/20/4MM
GRP OUTWARDS OPENING VENT PROFILE
THIRD AIR-WATER TIGHTNESS LAYER EPDM GASKET
CENTRAL EPDM GASKET
FIRST AIR-WATER TIGHTNESS LAYER EPDM GASKET
345.00
14.00
50.57
7.00
R4.00
7.00
14.00
51.89
18.58
R4.00
41.46
15.89
6.89
159.12
196.45
R4.00
6.00

7.2.2_ INTEGRATED GRP FAÇADE WITH INWARD OPENING WINDOW






INSULATIVE FOAM 338MM THICK
FIBERGLASS 6MM THICK
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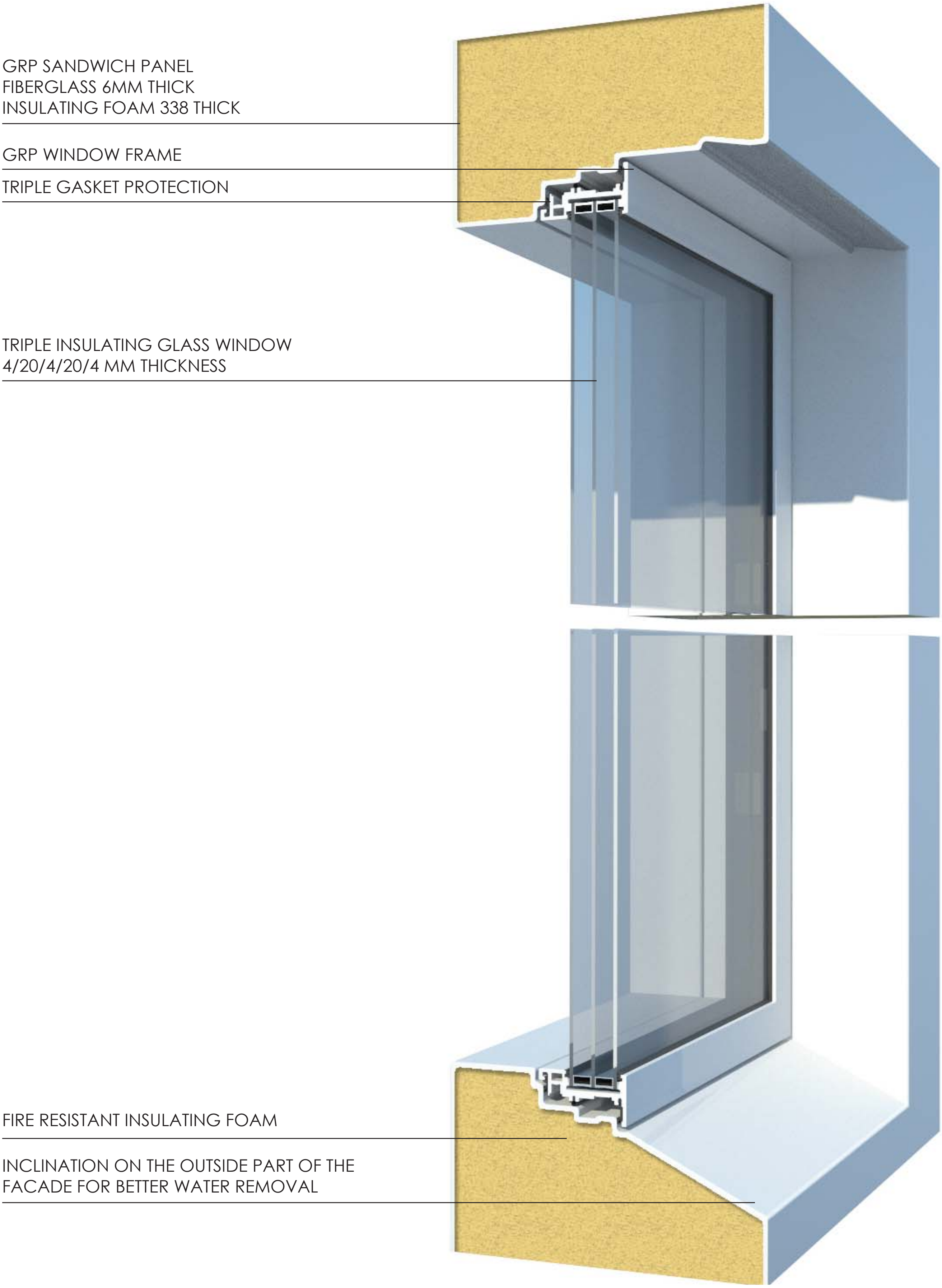
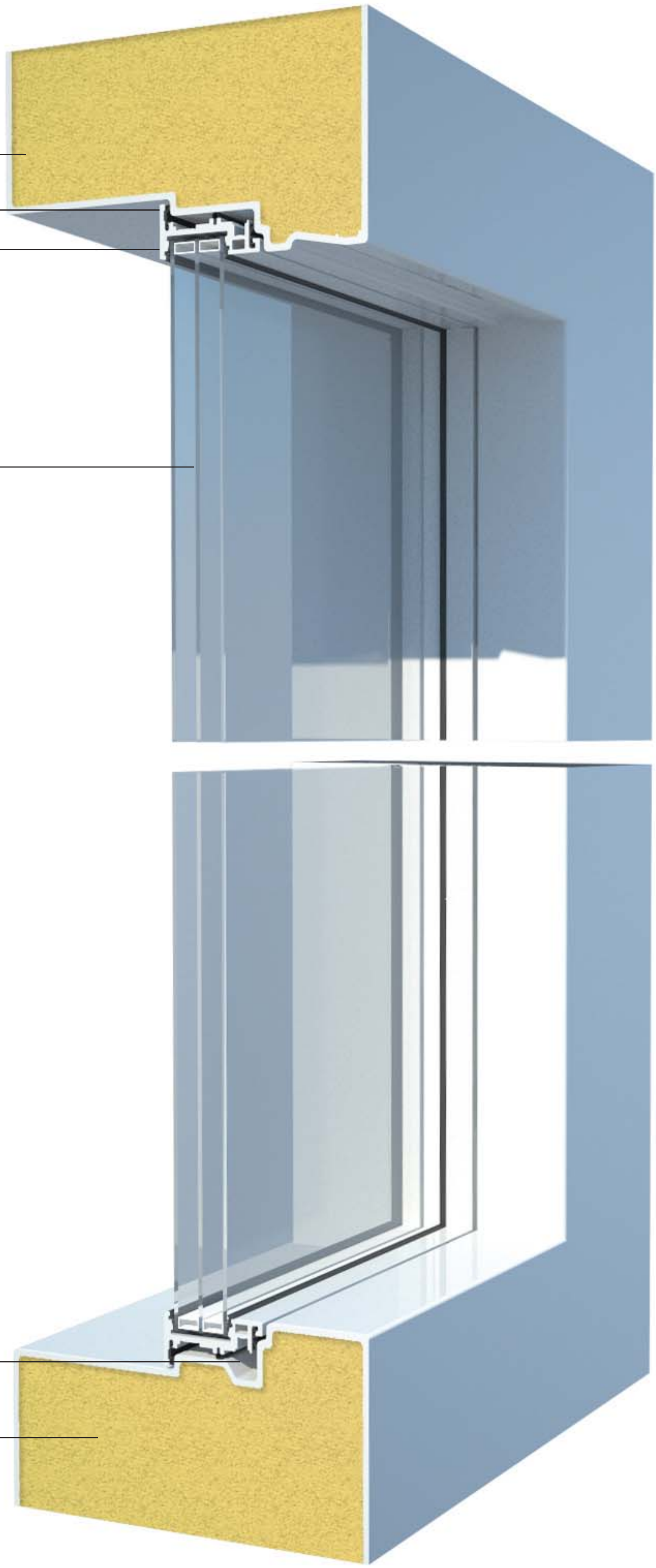
GRP OUTWARDS OPENING VENT PROFILE
THIRD AIR-WATER TIGHTNESS LAYER EPDM GASKET
CENTRAL EPDM GASKET
FIRST AIR-WATER TIGHTNESS LAYER EPDM GASKET
345.00
15.14
20.00
R4.00
7.00
14.00
18.58
50.57
51.89
21.21
90.00
9.00
39.48
96.09
41.39
165.12

7.2.3_ INTEGRATED GRP FAÇADE WITH OUTWARD OPENING WINDOW_ 3D RENDERING



7.2.4_ INTEGRATED GRP FAÇADE WITH INWARD OPENING WINDOW_ 3D RENDERING



8.0_ MOCK-UP MODEL

8.1_ NEED OF A MODEL

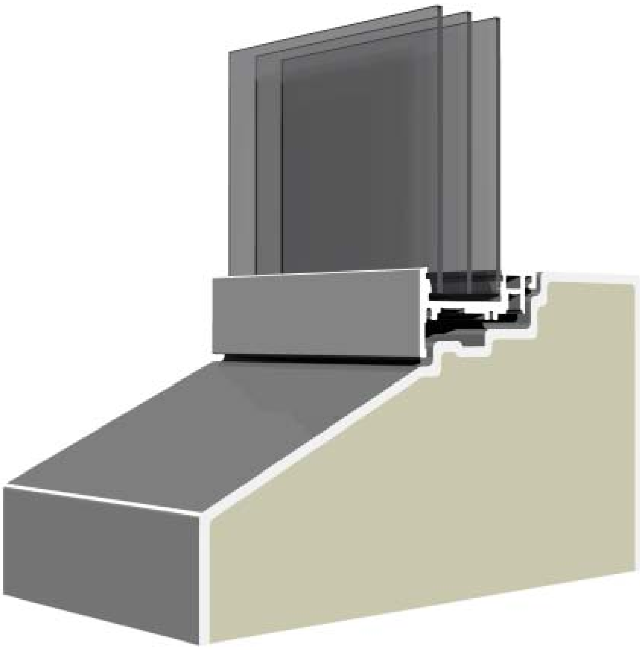
After the final design, the production of a small piece of the GRP product of this thesis has been realised, as the final step of this research. The mock up model consists of a GRP sandwich wall section of 120mm thickness and a GRP window frame element of the same thickness, that is attached on the wall. The outwards opening solution has been chosen to be built.

For the manufacturing of the model, the product has been divided into two main parts:

- the wall section part and
-the window frame part

The manufacturing company POLUX helped me during the whole manufacturing procedure of the sandwich wall section, by provididng me the knowledge, the materials and the equipment I needed. The production took place at the company's production plant in Medemblik (Netherlands).

For the production of the GRP window frame my tutor Dr. -Ing. M. Bilow offered me the use of his 3D printer. So, the GRP frame and the rubber gaskets of it were printed in 3D.



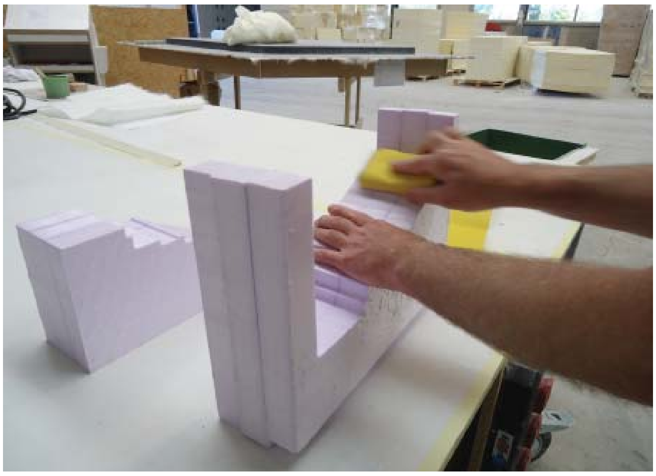
3D renderings showing the part of the composite wall and window frame that is going to be produced as a mock-up model

8.2_ BUILDING THE GRP SANDWICH WALL

Due to time limitations, the manufacturing of the wall element was made by hand lay-up, which is the most simple production technique used, when complex shapes have to be produced.

For this procedure, a detailed mold with the section's shape was necessary, and a filling piece of insulating foam had also to be produced.
These pieces are normally printed in foam by a CNC cutting machine, but due to time management issues, they were in this case cut by hand.

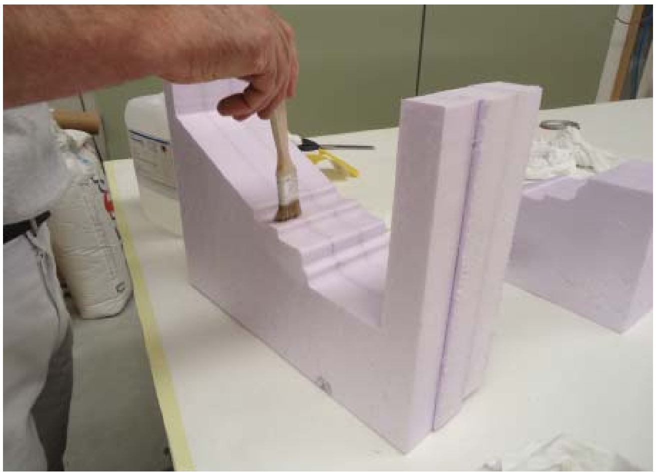
In the case of the outer mold, low density foam was used, because it was easier to be cut, while in the case of the inner foam, fire resistant foam was used, which was sanded by hand to the right shape.



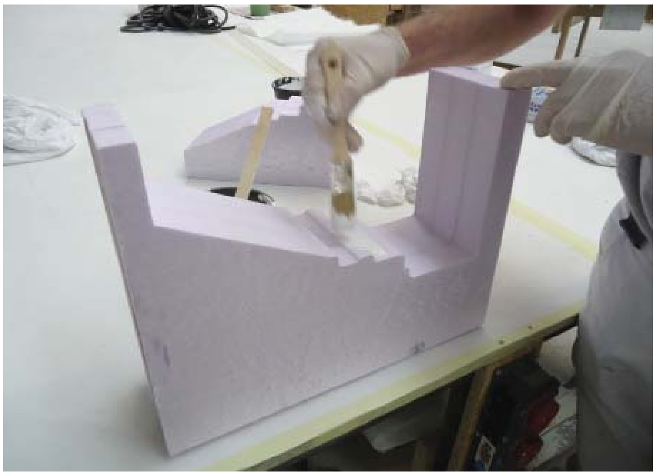
8.3_ STEPS OF THE WALL PRODUCTION

-1.
As a first step, the outer mold needs to be sanded, so that we can make sure that the surface is as smooth as possible.

-2.
As a second step, wax is applied to the mold in order to refine its surface.



-3.
A thin layer of Poly Vinyl Alcohol is then added, so that it can protect the mold from the resin that will be applied to it afterwards.



-4.
The first layer is then applied to the mold. The layer is let dry for an hour and a second layer of the same resin is added.

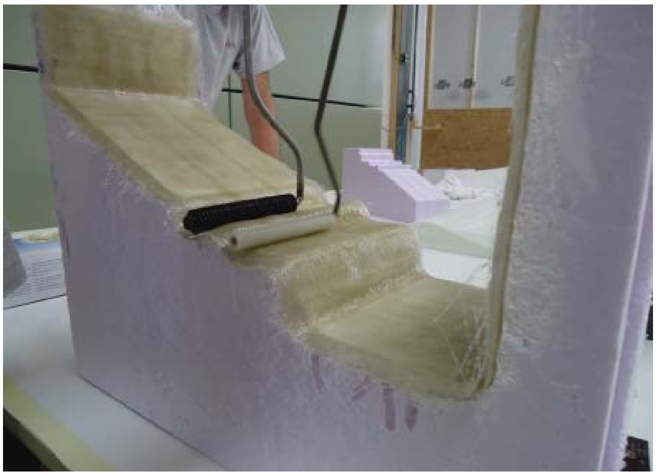
-5.
This is the apperance of the mold after two dry layers of resin.

-6.
After the resin is dry, the glass fibers need to be added. Two different kinds of glass fibers, with different thickness are added.

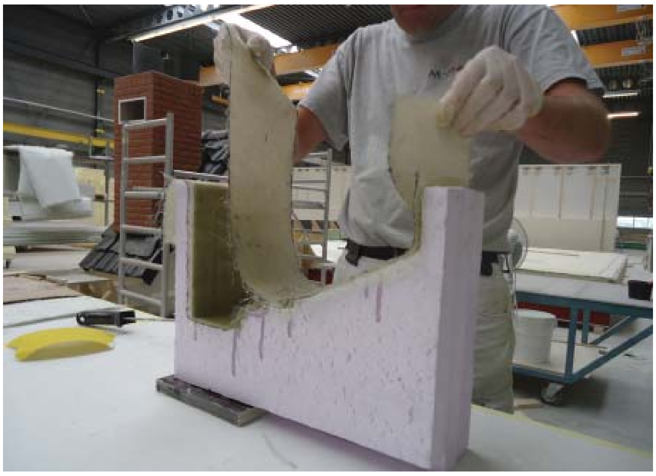
-7.
First two thin layers are applied and after they are dry the manufacturing is continued with more thicker layers. The number of them depends on the thickness of the glass fiber layer that we need to produce.

Each layer of glass fiber is covered by glue and then placed into the mold.

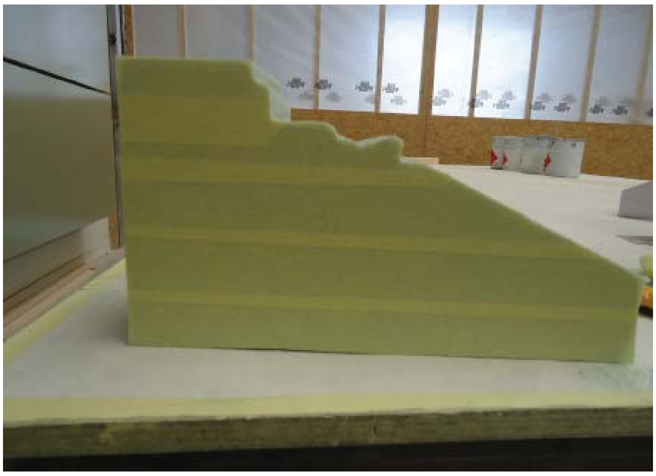
-8.
Special tools are used in order to place the fibers at their exact position and make sure that all the air bubbles are removed from the mold. This procedure is maybe the most difficult one, since no air must be trapped inside the fiberglass.



-9.
The thick layers of glass fiber are then added to the mold. The complexity of the shape must be reproduced with the glass fibers, so special attention needs to be paid.



-10.
Two thin layers and four thick layers of glass fibers where added to the mold in total. This resulted to a glass fiber thickness of 6mm.



-11.
The fibers are left to dry for at least one day and then the inner foam core needs to be added. The foam's lateral surfaces are covered with tape which will be later on removed, in order to stay clean.

-12.
A resin based glue is added to the mold.

-13.
The inner foam is added and is left to dry with the glue.

-14.
After about one hour the product is dry. The unwanted glassfibers are cut and the product is ready to be removed from the mold.

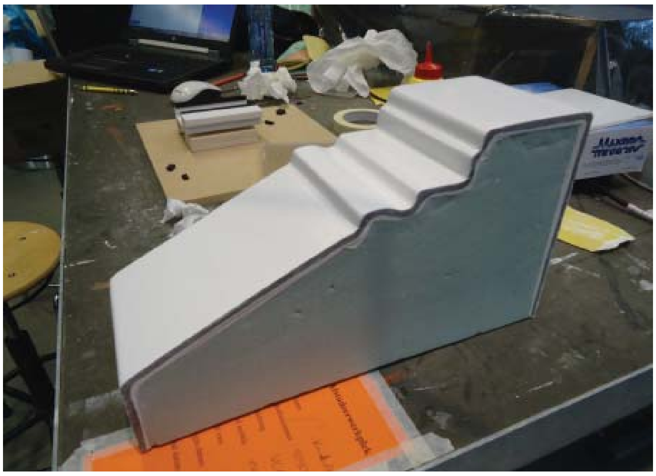
-15.
The edges are sanded and the final thickness of the product is revealed.

-16.
The outer mold is finally removed. The surface of the GRP is at first site rough and needs sanding and filling.

-17.
The sanding starts. The two layers of resin make sure that the product has enough resin thickness to be sanded.

-18.
After the first sanding, the surface of the product is remarkably smoother.

-19.
Filling the holes and recesses follows and then sanding is again necessery. This procedure can be repeated many times until the surface reaches a perfect stage.



-20.
The final product is this one. After the sanding, the product is painted in order to have a final look.

8.4_ STEPS OF THE FRAME CONSTRUCTION

As already mentioned above, the production of the window frame and the weather-strip gaskets has been made by a 3D printer.

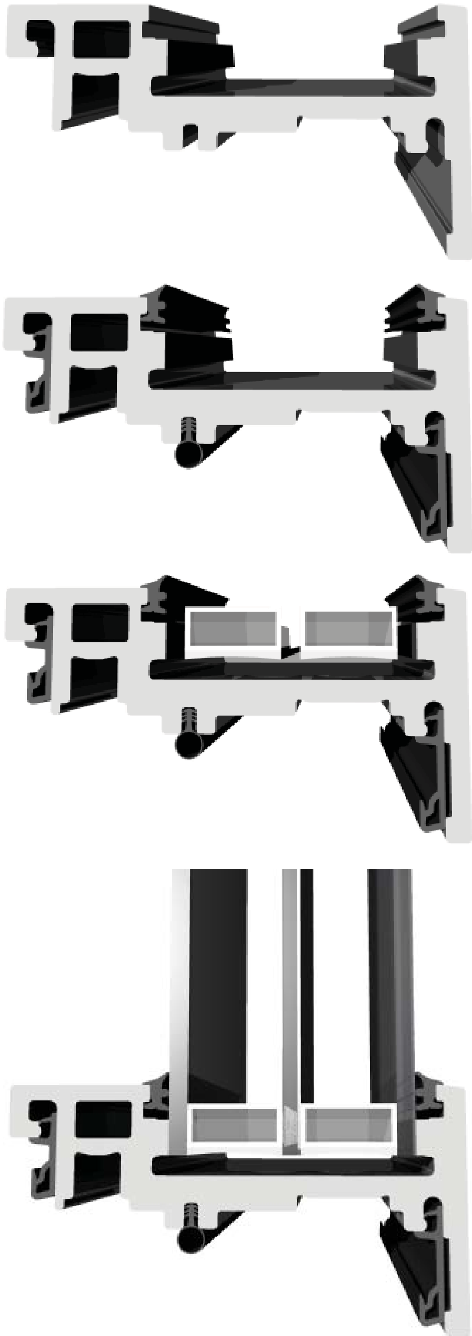
The complex shape of a GRP window frame can be only produced in reality by pultrusion. This manufacturing procedure is extremely expensive, as it requires expensive molds.

For the mock up model, the 3D printing method was selected as it can achieve a quite accurate and close to reality product.

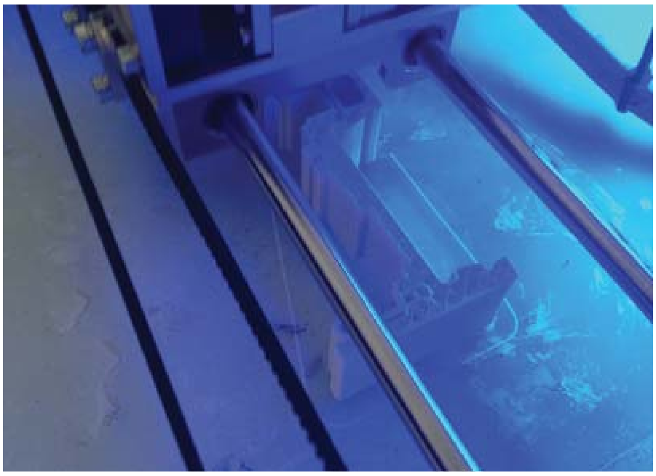
The total size - thickness of the whole model was based on the size limitations of the 3D printing (Maximum printed height is 200mm).

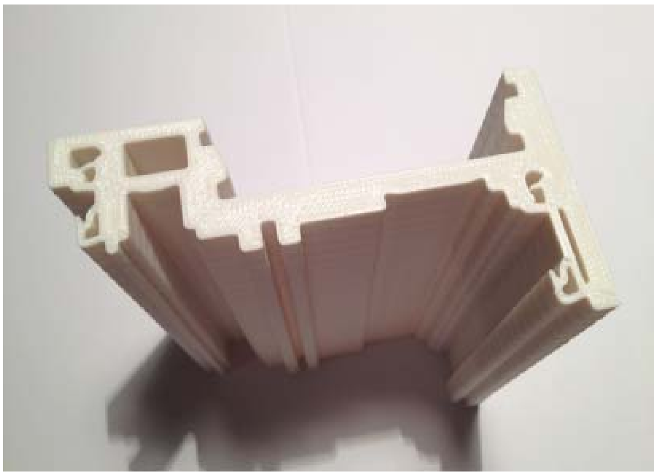
A short explanation of the production sequence is explained below.

> At first the main frame has been produced by 3D printing.
> The weather strip gaskets have been consequently added. These have been also produced by 3D printing, since their customized shape was not able to be found in the market.
> The spacers for the glazing and finally the triple glazing have been added.

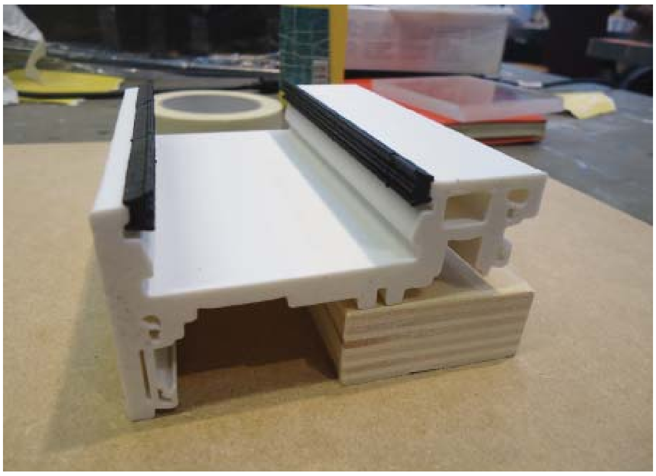


3D renderings showing the build-up of the composite window frame





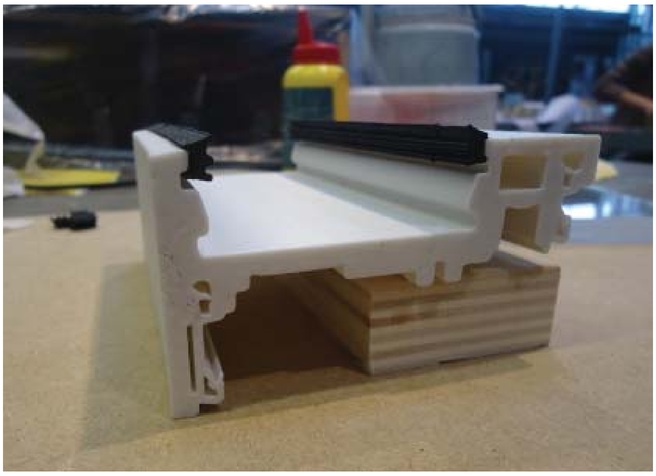
Photos taken during the 3d printing of the composite window frame. The first photo shows the frame being printed inside the 3d printer and the second one shows it right after the printing was finished. (photos: Marcel Bilow)



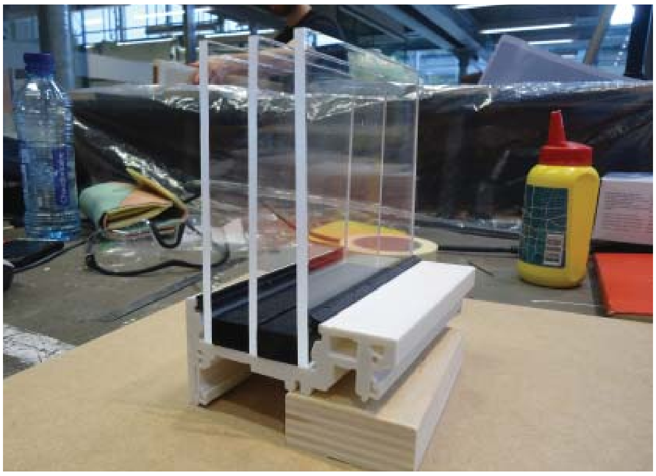
8.5_ ASSEMBLY AND THE FINAL MODEL

The assembly of the model and the window frame started with the attachment on the frame of the weatherstrip gaskets.

Some of them had already been printed together with the main window profile. The complexity and detailing of their shapes as well as their extremely small size made them impossible to printed on their own.



After the gaskets were attached to the frame, the rubbers hoding the glazing were added.



The spacers and glazing planes were after that added to the window frame.

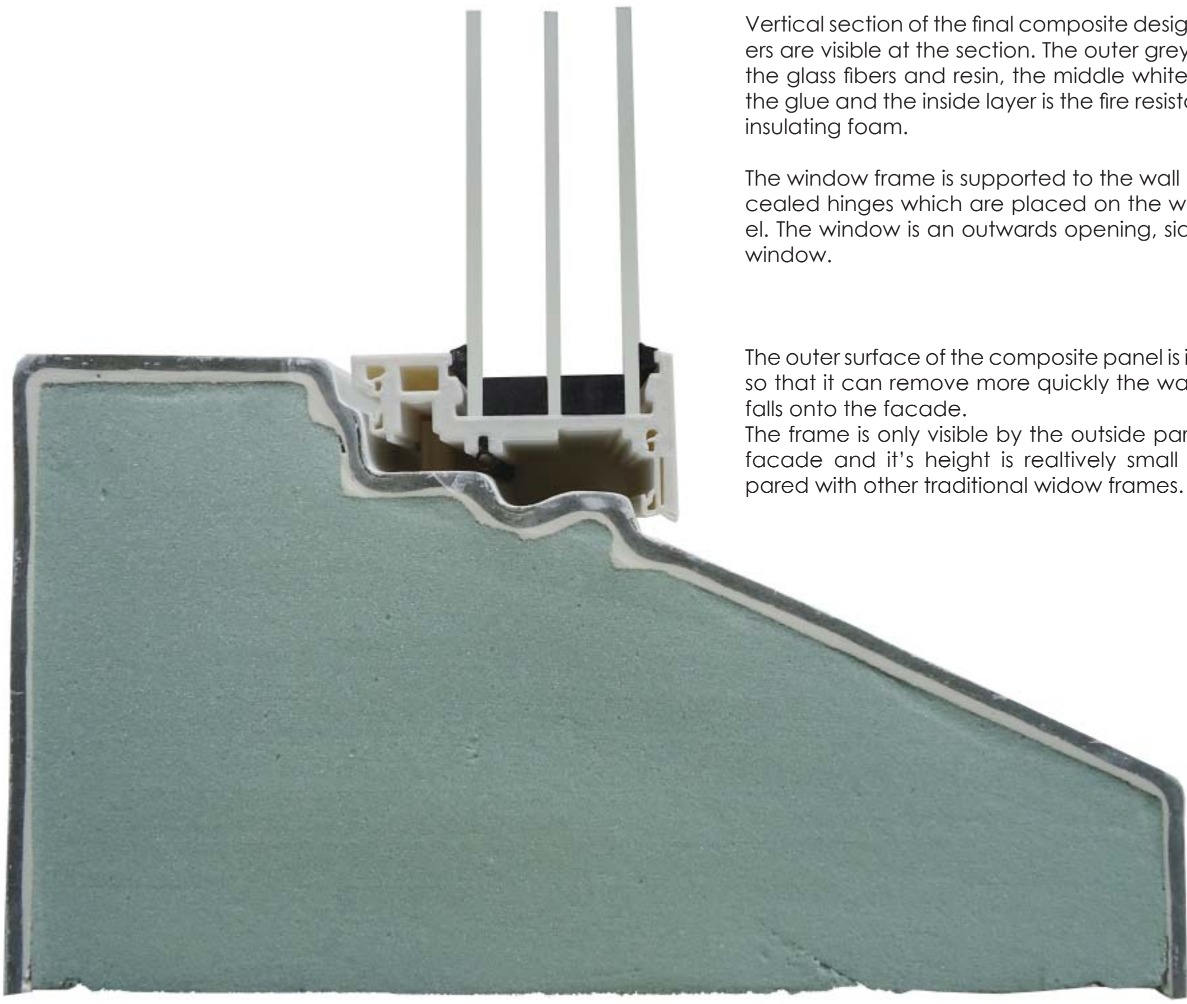
After the complete frame was ready, the frame was added to the wall part. The final model was then finished.

Horizontal section of the composite wall and frame
(Photo of the final model. The model of the wall is produced by glass fibers, resin and fire resistant foam, while the window frame is 3d printed. The production technique used for the wall part was hand lay-up)

Vertical section of the final composite design. 3 layers are visible at the section. The outer grey layer is the glass fibers and resin, the middle white layer is the glue and the inside layer is the fire resistant and insulating foam.

The window frame is supported to the wall by concealed hinges which are placed on the wall panel. The window is an outwards opening, side hung window.

The outer surface of the composite panel is inclined so that it can remove more quickly the water that falls onto the facade.
The frame is only visible by the outside part of the facade and it's height is realtively small if compared with other traditional widow frames.



9.0_ REFLECTIONS

9.1_ MOTIVATION

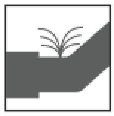
My fascination about this research topic goes along with the latest increase in the use of Glass fiber reinforced polymers in the construction industry and more specificaly in the field of facade construction. There are many different applications of how GRP materials are used in a facade structure. These applications can be categorized in structural or non structural and they all derive from the materials' specific advantages.

Lightweight, durability, low cost, high thermal performance, ease in production and aesthetics are only a few of the materials' characteristics. These have turned GRP into one of the most popular materials for the construction industry that is nowadays the second larger market for plastics.

Despite the great advantages that GRP materials display, there is until today unfortunately a difficulty of the acceptance of it, due to the lack of knowledge. While the applications of Glass Fiber Reinforced Polymers in buildings are only a few until know, there is yet no entrenched knowledge over the material's properties, production techniques, products and applications. Such reticence undoubtedly declines over the years, as more and more buildings of GRP are been built, but still there is a lot that need to be explored regarding this material and it's applicability.

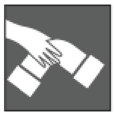
The increasing demand in the use of GRP in construction industry combined with the lack of knowledge and the inability of exploiting the full potential of it, gave me the urge and desire to deal with this material, since due to it's exceptional properties I consider it a material of the future.

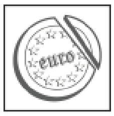
Meeting today's building and construction needs // Advantages of GRP material (source: Plastics, A material of choice in building and construction


Durable and corrosion resistant

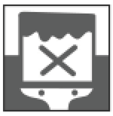

Hygienic and clean

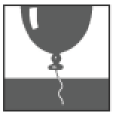

Insullation


Ease of processing


Cost effective


Environmentally sound


Maintenance free


Light weight

Building blocks for low cost housing made from Thermo Poly Rock -TPR (source: Assoociation of plastics manufacturers in Europe, Plastics, the facts 2012, An ana;ysis of European plastics production, demand and waste data for 2011)

9.2_ BACKGROUND STUDY_ THE REVOLT HOUSE

Alongside my studies at the TU Delft, I had the opportunity to gain some initial knowledge on GRPs as I chose to become a member of the Revolt House Project. This was the official participation of the TU Delft to the Solar Decathlon Competition of 2012.

My envolvement in this project lasted from 11/2011 to 03/2012, during which period I became a part of the envelope design team and consruction team of the House.

The design was about a sustainable floating "boat house" made entirely out of Glass Fiber Reinforced Polyester. The choice for the use of this material was based on a very wide range of factors: mechanical properties including the thermal conductivity and water resistance, lightness, commercial availability, transportability and versatility to build non-traditional shapes, etc were only some of them.

During my involvement in this project, I became responsible for the design and fabrication of the GRP floor construction of the house and I was prepared to work in a GRP manufacturing company of the Netherlands (Holland Composites) for the fabrication of the house's elements.

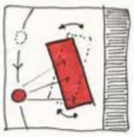
Unfortunately this project was forced to stop before it was built, but nevertheless, it provided me with a lot of knowledge about the possibilities of the GRP materials and made me more interested to study it further.

Basic design principles of Revolt House (source: Team Delft University of Technology, Project Manual #3, TUD_PM#3_2011-09-14)

It's Dutch

It's water proof

It's passively ventilated



It's mobile

It's more temperate

It's futuristic

3d rendering of the Revolt House , a lightweight floating house made by Glass Fiber Reinforced Polymers. (source: Team Delft University of Technology, Project Manual #3, TUD_PM#3_2011-09-14)

9.3_ CHALLENGES

During the course of this research several challenges were faced.

Since GRP started relatively recently to be used in architectural and more specifically in façade applications, there were not many bibliographic studies covering this topic. Most of the literature about GRP was written by and for aerospace engineers and was covering only the part of analysis of the material's properties and manufacturing procedures.

The research on the application of GRP in buildings and of current ways of producing a GRP façade was a relatively demanding task that was accomplished with the help of façade consultants from Dgmr and Composite specialists from Polux.

Furthermore the acquisition of several technical drawings and technical information about window framing systems was achieved after communication with almost all of the leading aluminum / steel / pvc manufacturing companies of the Netherlands. Dgmr was at that point helpful by providing me information about currently in building stage or already existing composite facades and their properties and testing results.

Although despite having in my hands several technical sheets about the material's properties, the main thing I was not able to get was a real GRP pultruded profile designed for window frame applications. The high cost and low availability of these profiles, in combination with the lack of existence of many GRP profile's manufacturing companies in Europe, made the communication and provision of a sample of their products almost impossible.

This challenge did not influence at all the outcome of my studies, but made the understanding and familiarity of this material and its applications more difficult to me. Having a sample of an existing GRP window frame would perhaps facilitate my perception about the detailing of it, and would make the procedure of designing my own window profile a lot easier.

9.4_ RELEVANCE AND SIGNIFICANCE OF RESEARCH

There are many reason why Glass fiber reinforeced polymers applications have experienced a rapid increase lately in the facade industry. As technology evolves, better performance and more economical and aesthetical requirements are needed. On this framework, GRP is seen as the material that can provide a new way of building.

There are undeniable advantages of the use of GRP in facades and these have been the shifting forces behind the increase of GRP facades applications.
Among others, the use of GRP can provide:

- Better thermal performance of a facade
- Reduced manufacturing assebly and installation costs
- Low maintenance costs
- Freedom of architectural design

Due to its benefits, it has recenly gained a position of respect among architects and constructors but there are still a lot to be done. This graduation thesis aims to provide the scientific research and knowledge needed, in order to restrain the reticence on this material and lead the facade construction towards a new way of thinking.

The development of a composite facade which allows operable windows without the use of aluminum or steel in the construction aims to provide a new, efficient, cost saving and aesthetically pleasing solution that will present great advantages over traditional ways of facade construction.

Furthermore, considering sustainability as a key factor for a successful architectural design, this research aims to contribute to a more energy saving architectural environment. The optimal thermal insulation of the GRP materials in combination with their low eco footprint when compared with other commonly used materials such as aluminum or steel leads can lead to this direction.

Technology progress (source: http://www.tnooz.com/2012/04/13/news/making-technology-progress-relevant-in-travel-dead-easy-dead-slow-or-just-dead-but-why/)

9.5_ FURTHER RESEARCH SUGGESTIONS

During the course of this research several challenges The completion of this thesis has resulted to the development of various possible design concepts of how an integrated GRP façade can be detailed and manufactured, and which are the performance benefits of it over a traditional GRP/aluminum façade.

However, as the time of 6 months (duration of the thesis) can become relatively small in terms of analyzing every aspect of this topic, it is sincere to say that there are a number or possible aspects that could be further explored.

AN ELEMENT PROTOTYPE

The topic of designing a completely composite façade is relatively new and only a few attempts have been already made, aiming to lead to the actual production of a façade element. Despite the few theoretical researches about a GRP façade that already exist, the missing element is still the application of the knowledge gained so far, to a real project.

As there is a relatively big difference between testing and calculating a façade's performance in paper and in reality, my belief is that the next step following this research should be the building of a one to one scale model. Several aspects regarding the façade's performance can thus be better calculated.

Sound insulation for example is the most difficult between all aspects, to be calculated without an actual model. A prototype can provide accurate acoustic calculations. Furthermore the air and water tightness can be better tested when having a model.

GRP PANEL IMPROVEMENTS

When referring to the GRP sandwich panel, there are some aspects that could be further researched and improved. Sound insulation is the most important among them. As the acoustic insulation of a GRP sandwich panel often reaches the lowest acceptable limit for a façade, further research should be dedicated for the improvement of its acoustics.

What is more, the integration of the window frames in the GRP panel can also be further explored. New building requirements create every day different needs for facades. More elements can be possibly be integrated in the GRP panel, leading to a decrease in the assembly time that is required on the building's site.

Furthermore the disadvantages of integrating many functions into one element should be also researched. As it was already mentioned, one of the drawbacks in having an integrated GRP façade with inwards opening windows is the difficulty and also risk in removing the water from the construction. The water that can be inserted between the vent profile and the GRP panel can, according to this thesis, be removed via plastic pipes that are inserted in the façade panel. In case of malfunction, there is a risk of water penetrating inside the construction.

source: DAC, Dansk Arkitektur Center, The integrated Building Envelope, Development of a pre-fabricated modular façade system, 2009

WINDOW FRAME IMPROVEMENTS

Improvements can also be made for the window frame. Having only one GRP element serving as a vent profile, the adjustability of the width of the glazing space is restricted. A possibility of being able to adjust the width of the window frame, and creating thus double or ripple glazed windows by the same GRP profile would reduce the cost of the profiles, as no many differentiations of the frame's dimensions would be necessary.

Furthermore, the integration of window frame's accessories such as handles into the vent profile would be another case of research. The appearance of the window frame and of the whole façade depends to a great extent on the detailing of small elements that are placed on the façade. The appearance of such a façade could be improved by the maximum degree of integration that the detailing of those elements can achieve.

AESTHETICS OF AN OVERALL GRP FAÇADE

Since aesthetics is very important for the design of a façade, and GRP is a material that has become very popular due to its ability to create different forms, a further research on different shapes and forms of a fully GRP façade and how can they be realized would be interesting. 3D shaped facades require different solutions in terms of operable windows and frame connections, and the possibility of being able to create a different architecture by the use of only GRP and glass could be further explored.

SUSTAINABILITY AND RECYCLABILITY

Last but not lease, being environmentally sensitive, I am aware that there are also improvements to be made in this aspect of the use of GRP. Although the carbon footprint of GRP has been proved to be lower than the equivalent solution in aluminum, and some GRP products can already be recycled, still the aspect of turning this material and the way we use it into an environmentally friendly one, is in my belief the most challenging task.

The integration of parts and the avoidance of glued connections is a step towards this direction, since all the parts can be easily separated and sent for recycling, but a more in depth research regarding sustainability should be carried out.

source: http://www.dow.com/coating/hiding/sustainability.htm

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- http://www.ecliptica.dk/
- http://www.inoutic.de/en/
- http://www.scandinaviantimber.com/
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SOFTWARE:

- BISCO version 10.0w: computer program to calculate two-domensional steady state heat transfer in free-form objects, Physibel software

- BOA

The majority of knowledge was acquired by recently published reports. There is not yet enough literature about building constructions and the use of GRP in facades.

INDEX A

BISCO - Input Data

BISCO data file: grp frame Model (1-2).bsc
Bitmap file: grp frame Model (1-2).bmp
1 pixel = 6.91648e-005 m

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6	418	0.0289	2676	0.1851	1031416	1	
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Col.	Type	CEN-rule	Name	lambda [W/mK]	eps [-]	t [°C]	h [W/m²K]	q [W/m²]
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4	MATERIAL		SILICONE	0.350				
5	MATERIAL		FIBERGLASS	0.350				
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31	EQUIMAT	- CEN_Xy_I NON VENTILATED	0.027
32	EQUIMAT	- CEN_Xy_I NON VENTILATED	0.027
33	EQUIMAT	- CEN_Xy_I NON VENTILATED	0.027
34	MATERIAL	EPDM GASKET	0.250
35	MATERIAL	EPDM GASKET	0.250
36	MATERIAL	EPDM GASKET	0.250
37	MATERIAL	EPDM GASKET	0.250
38	MATERIAL	SILICONE	0.350
39	MATERIAL	FIBERGLASS	0.350

Col.	ta	hc	Pc	tr	C1	C2	C3
	[°C]	[W/m²K]	[W/m]	[°C]	[-]	[-]	[-]
1							
6							
7							
8					0.025	0.73	0.333333
9					0.025	0.73	0.333333
10					0.025	0.73	0.333333
11					0.025	0.73	0.333333
12					0.025	0.73	0.333333
13					0.025	0.73	0.333333
14					0.025	0.73	0.333333
15					0.025	0.73	0.333333
16					0.025	0.73	0.333333
17					0.025	0.73	0.333333
18					0.025	0.73	0.333333
19					0.025	0.73	0.333333
20					0.025	0.73	0.333333
21					0.025	0.73	0.333333
22					0.025	0.73	0.333333
23					0.025	0.73	0.333333
24					0.025	0.73	0.333333
25					0.025	0.73	0.333333
26					0.025	0.73	0.333333
27					0.025	0.73	0.333333
28					0.025	0.73	0.333333
29					0.025	0.73	0.333333
30					0.025	0.73	0.333333
31					0.025	0.73	0.333333
32					0.025	0.73	0.333333
33					0.025	0.73	0.333333

Calculation parameters
Contour approximation margin (triangulation) = 0 pixels
Default temperature difference across airspace = 10°C
Bitmap border is no axis of symmetry
Maximum number of iterations = 10000
Maximum temperature difference = 0.0001°C
Heat flow divergence for total object = 0.001 %
Heat flow divergence for worst node = 1 %

BISCO Calculation Results

BISCO data file: grp frame Model (1-2).bsc

Number of nodes = 124247
Heat flow divergence for total object = 0.000726853
Heat flow divergence for worst node = 0.184835

Col.	Type	Name	tmin [°C]	tmax [°C]	ta [°C]	flow in [W/m]	flow out [W/m]
1	BC_SIMPL	INTERIOR REDUCE	14.72	17.95		1.11	0.00
2	MATERIAL	TRIPLE GLAZING	0.55	18.44			
3	MATERIAL	EPDM GASKET	13.19	14.52			
4	MATERIAL	SILICONE	1.26	1.88			
5	MATERIAL	FIBERGLASS	0.57	15.33			
6	BC_SIMPL	INTERIOR NORMAL	17.95	18.44		1.91	0.00
7	BC_SIMPL	EXTERIOR	0.55	1.29		0.00	3.02
8	EQUIMAT	NON VENTILATED	10.08	13.58			
9	EQUIMAT	NON VENTILATED	2.05	9.50			
10	EQUIMAT	NON VENTILATED	1.55	12.40			
11	EQUIMAT	NON VENTILATED	12.95	14.99			
12	EQUIMAT	NON VENTILATED	9.21	10.41			
13	EQUIMAT	NON VENTILATED	14.16	15.19			
14	EQUIMAT	SLIGHTLY VENTIL	13.38	13.94			
15	EQUIMAT	NON VENTILATED	0.75	1.40			
16	EQUIMAT	NON VENTILATED	13.00	14.09			
17	EQUIMAT	NON VENTILATED	1.66	2.60			
18	EQUIMAT	NON VENTILATED	13.22	13.50			
19	EQUIMAT	NON VENTILATED	1.77	2.59			
20	EQUIMAT	NON VENTILATED	13.92	14.30			
21	EQUIMAT	NON VENTILATED	1.44	1.99			
22	EQUIMAT	NON VENTILATED	0.65	1.01			
23	EQUIMAT	NON VENTILATED	14.37	15.23			
24	EQUIMAT	NON VENTILATED	0.88	1.18			
25	EQUIMAT	NON VENTILATED	13.85	14.36			
26	EQUIMAT	NON VENTILATED	9.40	9.86			
27	EQUIMAT	NON VENTILATED	9.95	10.35			
28	EQUIMAT	NON VENTILATED	9.58	10.29			
29	EQUIMAT	NON VENTILATED	14.13	14.42			
30	EQUIMAT	NON VENTILATED	9.53	9.85			
31	EQUIMAT	NON VENTILATED	9.49	9.84			
32	EQUIMAT	NON VENTILATED	10.02	10.30			
33	EQUIMAT	NON VENTILATED	10.01	10.31			
34	MATERIAL	EPDM GASKET	0.60	1.16			
35	MATERIAL	EPDM GASKET	13.80	15.28			
36	MATERIAL	EPDM GASKET	1.66	2.73			
37	MATERIAL	EPDM GASKET	9.20	10.43			
38	MATERIAL	SILICONE	12.14	13.09			
39	MATERIAL	FIBERGLASS	14.01	14.19			

Thermal transmittance of frame (EN ISO 10077-2)
Uf = (Q/(ti-te) - Up1*wp1 - Up2*wp2) / wf = 1.107 W/(m².K)
Q = 3.021 W/m
ti = 20.00°C
te = 0.00°C
Up1 = 0.601 W/(m².K) (top edge of bitmap)
wp1 = 0.1828 m (distance no. 1)
Up2 = 0.000 W/(m².K)
wp2 = 0.0000 m
wf = 0.0372 m (distance no. 2)