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Design and Simulation for Technological Integration of Bio-Based Components in Façade System Modules

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Abstract: Driven by environmental sustainability concerns, the integration of bio-based components in curtain wall systems is gaining traction in both research and the construction market. This paper explores the development and validation of a bio-based façade system within the Basajaun H2020 project (2019–2024). The project aimed to demonstrate the feasibility of introducing environmentally friendly bio-based components into the mature curtain wall façade industry. The paper focuses on identifying technological solutions for replacing key components such as frame profiles, insulation, and the tightness system with bio-based and less environmentally impactful alternatives, presenting the results achieved in the façade system design of the Basajaun project. These solutions aimed at creating a bio-composite-based curtain wall façade that adheres to the current building envelope standards and normative, implementing diverse façade typologies for vision panels, opaque sections, and integrated windows and, moreover, engineering the prefabrication process for industrialization and enabling wider market replication and simplified transport and installation. The results demonstrate that the Basajaun façade successfully integrates selected components and meets the performance requirements set by regulations: the façade is designed to withstand a maximum and typical wind load of 3.5 kN/m^2 and a typical load of 1.5 kN/m^2, the weighted sound reduction index obtained is R_w = 44 dB, and the thermal transmittance of the vision façade is 0.74 W/m^{2}K while that of the entire opaque façade is 0.27 W/m^{2}K (an additional internal wall is required to achieve the requested thermal transmittance)—the values are in accordance with reference standards and design requirements. However, questions remain regarding the workability of bio-based profiles as a commercially viable, ready-to-market solution that can replace traditional aluminum profiles in the curtain wall façade industry.

Keywords: bio-based building products; bio-based materials; building envelope; curtain wall façade; prefabrication; sustainable construction

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1. Introduction

The priority to reduce environmental impact and resource consumption is driving the construction sector towards the investigation of materials that are more environmentally friendly, motivated by their sustainability, renewability, and diminished carbon footprint [1,2]. In this scenario, bio-based incorporation represents a scientifically validated strategy to mitigate the ecological footprint of construction practices along the value chain and in building lifespans. It also reduces pollution and resource consumption [3–7]. Beyond the specific environmental impact achievable, introducing bio-based components offers the opportunity to rethink the building products in synergy between bio-economy and circular economy concepts while potentially benefiting the industrial-scale productive value chain [8,9]. However, in order to achieve optimal performance while minimizing maintenance issues, combining bio-based and synthetic polymers to create novel bio-composite materials is a viable option to improve, and it fulfils construction characteristics and delivers superior performance and value [10–13]. Owing to this opportunity, the sustainable construction applications of natural fiber bio-composites are demonstrating the impact in terms of renewability, cost-effectiveness, and potential as substitutes for conventional materials [14], even if further research is required to fully understand their life cycle assessment, cost, and long-term durability [15]. Primarily comprised of plant-based fibers and bio-resins, these composites showcase promising results in strength, ductility, and energy absorption, with applications ranging from concrete reinforcement to non-load-bearing elements like insulation and sound absorbers. Nonetheless, incorporating natural material systems in composite manufacturing processes introduces uncertainties in structural performance and fabrication parameters. Consequently, developing composite parts necessitates a bottom-up approach, treating the material system as an integral component of design and evaluation [16].

Therefore, the contemporary construction industry has shown a growing inclination towards the use of bio-based materials in façades. Their versatile nature and compatibility with modern design concepts have made them increasingly sought-after for façade applications [17]. Indeed, delineating the outdoor and indoor environments, the building envelopes must meet diverse requirements, including thermal, acoustic, and mechanical performance, while permitting the integration of various technologies and user safety. Implementing a bio-based strategy in these systems must adhere to all these demands [18–21]. Moreover, in order to design eco-conscious façade systems that achieve sustainable buildings, it is important to consider the potential for disassembly and reuse or recycling [22]. In response to these needs, the relevance of the lean prefabrication of façade modules is emerging as a strategy to address the industry's environmental impact, contributing to a more circular economy with advantages such as the reduction of CO_2 emissions, assembly time, and production waste while facilitating disassembly, maintenance, and product durability [23–26]. Within this framework, incorporating bio-based and bio-composed products as alternative construction materials with a minor environmental impact must comply with the façade requirements. This involves integrating wood-based materials, enhancing manufacturing processes, and increasing flexibility to cater to the specific needs of the construction market [27–29].

As part of the contribution to this research and innovation field, the Basajaun H2020 project under Grant Agreement 862942 (2019–2024) [30] aimed to introduce wood-based materials within building product systems to boost the adoption of biomaterials in the construction market. Within the project, a façade system was defined starting from the results of the FP7 European project OSIRYS (2013–2017) [31], in which building envelope products with innovative bio-composite materials are available, offering a diverse range of solutions for external façades [32,33]. The Basajaun façade was upgraded using bio-composite profiles to optimize manufacturing, a new frame profile shape, and a male/female transom upgrade for an easier on-site installation. The bio-composite profile's mechanical characteristics have also been improved, and the removable external cladding upgrade allows for off-site installation and on-site maintenance.

This paper presents the results of the iterative activities in the Basajaun H2020 project for designing and simulating the finalized integration of bio-based and less environmentally impactful components in façade system modules. The article outlines all the issues and decisions behind the design and adoption of eco-friendly products within complex structures such as façade system modules. The primary objective is to demonstrate how bio-based and alternative components, replacing the conventional ones in prefabricated façades, can be optimized and validated during iterative activities. The paper's objectives were to investigate and provide contributions in the scientific field as follows:

- Design bio-composed pultruded bar for profiles for the frame of façade system modules.
- Validate the bio-composed pultruded profile for the frame of façade system modules with mechanical simulations.
- Define alternative materials and components to support the introduction of eco-friendly solutions replacing conventional ones in prefabricated façade systems for insulation and tightness systems.
- Design a bio composite-based curtain wall façade system based on technical and normative requirements for real-case applicability in line with the current building envelope standard for curtain wall façade solutions. The design should support the development of multiple façade module typologies with different building envelope targets: (1) vision façade module, (2) opaque façade module, (3) window/opaque façade module.
- Validate with mechanical, thermal, and acoustic simulations the bio-based façade system modules to demonstrate compliance with the normative.
- Identify testing activities in manufacturing and lab environments to validate the feasibility of manufacturing and integrating components in façade system modules.

This paper is structured as follows: Section 2 outlines the methods and materials used to define bio-based and alternative components for façade systems, their typologies, and their validation in the decision and design stages. Section 3 presents the outcomes of the design and simulation activities of the components and the overall façade system modules. Section 4 highlights the successful aspects of bio-based and alternative components' integration in the façade while addressing further validation in the manufacturing and testing stages and gaps identified due to research and test limitations. Section 5 summarizes the main achievements related to the paper's goal of analyzing bio-based façade system modules' opportunities in supporting bio-based and alternative materials' integration and proposes further development in research and market analysis for commercialization purposes.

2. Materials and Methods

This section presents the methods and materials for the implementation of the bio-based components in façade system modules.

The methods defined below outline the stages of the process adopted for the development of the design and desk validation stages of the bio-based integration in façade system modules:

- Analysis for the selection of bio-based and alternative components for façade system module—Bio-based and less environmentally impactful alternative technologies were identified for their potential to meet façade design objectives and minimize carbon footprint. Components with the most significant environmental impact, such as frame profiles, insulation, and tightness system, were evaluated. The rise in eco-conscious practices has promoted the substantial research, development, and commercialization of bio-composites as sustainable alternatives [34]. To work for the Basajaun façade system, bio-composite materials must have advanced mechanical properties through the use of eco-friendly elements like bio-resin and wood. This progression encompasses meticulous raw material analysis, balanced composition, and comprehensive testing. The process involves the selection and evaluation of bio-based polyester and resin, preparation of fibers, pultrusion trials, initial flame retardancy tests, and mechanical characterization. Pultrusion emerges as a cost-effective and competitive method, transforming thermoset matrix and reinforcement into a consistent composite profile. The process involves die definition, impregnated fibers, curing, and cutting, ensuring a competitive edge in composite manufacturing [35,36]. The design supports the standardization and industrialization of multiple façade typologies. The following activities were conducted to achieve the result of designing a bio-based profile for the façade module system.

Upgrading a bio-composite material to improve mechanical characterization using sustainable material (bio-resin and wood material) is a crucial development for the Basajaun façade system. Specific analysis and investigation on raw materials, balance composition, and testing activities were conducted in the following phases:

- ◦ Selection and evaluation of bio-based polyester,
- ◦ Resin selection and preparation,
- ◦ Preparation of fibers,
- ◦ Pultrusion trials,
- ◦ First flame retardancy tests,
- ◦ Mechanical characterization profiles obtained,
- ◦ Bio-composite profile for façade system design.

The results expected for the mechanical cancerization were the reference for the profile design and the overall mechanical validation. Once defined as the façade system and the bio-composite profile, a preliminary study to address the pultrusion process was assessed to obtain an initial validation of the Basajaun bio-composite profile.

The most competitive approach to obtaining constant section composites is the pultrusion process. Employing the dies and the corresponding pulling equipment, the thermoset matrix and the reinforcement were transformed into a profile that was obtained in a competitive manner compared to the existing composite manufacturing approaches. Pultrusion technology mainly consists of forming a mold of impregnated fibers (in an open bath). The die is also responsible for curing the resin by means of a heating system (frequently using heat resistors). Once the composite is pulled out, it is cut into the desired length. An evaluation of the curing cycle of the selected bio-based polyether resin is then carried out.

Considering other alternative technologies, the Basajaun façade modules prioritize wood-based materials. The choice of fiber wood insulation over synthetic alternatives and conventional rock wool systems underscores a commitment to eco-friendly design. This decision reflects an effort to seamlessly integrate natural elements, showcasing a harmonious balance between ecological considerations and architectural functionality by guaranteeing thermal performances. A search was conducted on the EPD International portal [37], filtering EPDs of construction products related to mineral wool insulation and comparing its impact with wood-based insulation.

Similarly, for the tightness of the technological system, the Basajaun façade sealing has evolved to include tapes, membranes, and sheathing systems instead of traditional aluminum cladding. This design incorporates various technical and environmental factors, providing an enhanced building envelope solution. The tightness layer, which prevents air leakage and infiltration, uses materials such as membranes, sealants, or tapes. This airtight barrier improves energy efficiency and indoor air quality, and its components are selected based on market products.

- Identification of façade requirements—Requirements to design the façade for a real-market application were defined. The requirements were identified based on the normative standards in curtain wall façade and real case studies applications adopted as validation simulations for European applications. Due to the evolution and research conducted in the design phase, the final design of the façade optimized the number of system components, unit typologies, and dimensions. Based on the bio-composite material implementation activities, the bio-composite profile was designed to guide the framework of the Basajaun façade system. While curtain façade technology is a mature market for aluminum profiles, the utilization of pultrusion is far from being adopted for building envelopes, and specific requirements must be considered. Preliminary characteristics were considered to start designing the façade system, and Table 1 summarizes the main aspects to be considered for the utilization of the bio-composite profile. In particular, the primary considerations are as follows:

- Simple shape—The pultrusion process needs a more straightforward shape than other manufacturing processes (e.g., extrusion is a typical manufacturing process for aluminum profile), and this requires the profile to have a standard thickness and the absence of notches for fixing (specific corner connectors are needed).
- Mold cost—molds of a significant dimension for the pultrusion process for each profile (mullion, male transom, female transom) are expensive, and the three profiles should be designed as a single shape with a smaller profile for the male transom.

Table 1. Summary of the preliminary consideration of the bio-composite profile and the pultrusion phase.

Bio-Composite Manufacturing Components	Bio-Composite Profile Requirements	Basajaun Profile Design
Pultrusion activity	The maximum length of the profile is 4 m	Maximum façade height is 4 m
	Low tolerance during the pultrusion	Simple and reduced activities for cutting and machining
		Sharp or rounded corner for the bio-composite profile
		Thickness and dimensions
Molds	High time-consumption for the mold creations	Unique mold for multiple profiles and accessories for transoms and connection
	Expensive mold creation	
	A simple mold shape is required	Feasibility of the mold geometry needs to be checked
		Impossibility of manufacturing notches
Bio-composite material		Low UV resistance to be protected by façade components
		Test compatibility with silicones and sealants

The required achievement for each pilot is to have an innovative product that complies with all the requested outcomes for the façade and tries to fit with multiple climate scenarios in Europe. In Table 2, the building requirements are described, and the specific requirements of the Basajaun façade are collected, analyzed, and listed.

Table 2. Façade requirements definition based on local specifications in France and Finland.

Requirement	Vision Module Façade System (Finland)	Opaque and Window Module Façade (France)	Basajaun Façade System Simulation/Test
Airborne sound insulation	Sound insulation R′w ≥ 30 dB. SFS-EN ISO 717-1 [38].	Acoustic reduction index RA = 31	RA = 31 Simulation under EN 717-1:2020 [38]
Thermal transmittance	U Value of wall/façade: ≤0.17 W/m^{2}K U value of window: ≤1.0 W/m^{2}K	U Value of opaque: = 0.20 W/m^{2}K U Value window: ≤1.3 W/m^{2}K U Value door: ≤0.80 W/m^{2}K	Simulation under EN ISO 10077-2:2017 [21] EN 9869: 2014 [39] EN 15026:2007 [40]
Air permeability	A building envelope's air permeability rate (q50) may be a maximum of 4.0 m^3/(h m^2).	Air permeability < 0.4 m^3(h/.m^2)	Air permeability: <0.4 m^3(h m^2) Test under EN ISO 13830:2005 [20]

- Façade System Design—An iterative design process was implemented to refine the façade system configuration to guarantee component integration, off-site production principles, and reduced on-site activities. From the early stages, the design and requirements for the pilot buildings (test for façade applicability in real building cases) are strategic to satisfy different geo-clustering, architectural design, and project specifications. In particular, the following points are drivers: (1) the façade architectural design is crucial for product acceptability in the market, and requests made by architects, designers, and customers have a relevant role in the overall acceptance. (2) Performance definition: the performances are the key elements that need to be considered and balanced in façade engineering. They are related to local norms (acoustic, thermal) and also related to the overall façade performances to be achieved (air and water tightness, impact resistance). The above considerations address implementing a curtain wall system for both opaque and vision façade module systems by introducing bio-based components. Integrating male/female transoms enhances prefabrication, facilitating efficient on-site installation with improved air and water tightness. Mechanical improvements in the bio-composite profile accommodate higher loads, refining façade, and unit typologies. Moreover, an external off-site fin installation reduces on-site tasks for vision façades, while removable external cladding in opaque façades allows for off-site installation and on-site maintenance or finishing adjustments. Because of this analysis, the Basajaun façade system is defined based on requirements and on market standards for the curtain wall façade related to the specific norms of reference. Indeed, applying the Basajaun façade in demo buildings is the first validation on the market in real buildings with their stakeholders.
- Façade system design validation—An iterative process to simulate façade behavior to identify mechanical, thermal, and acoustic behaviors. This phase is a desk validation of the façade design and its components before the manufacturing. Based on the identified requirements, a set of validation tests during the integration of the components was defined at different stages of the development of the façade systems. Table 3 outlines the activities deployed for validation during design activities.

Table 3. Validation activities to validate the integration of alternative components into the curtain wall façade.

Validation	Test Conducted	
Thermal behavior (EN 13788) [41]	EN 9869: 2014 [39]	Simulation
Heat bridges and condensation risks	EN 15026:2007 [40]	Simulation
Acoustic insulation	EN 717-1:2020 [38]	Simulation

The mechanical simulations, conducted under maximum loads, attest to the module's resilience and viability under various conditions (maximum and typical wind loads are 3.5 kN/m^2 while the typical load is 1.5 kN/m^2). Additionally, the stress and deflection analyses for perimeter structures and cross-member connections provide crucial insights into the module's structural integrity. In the bio-based profiles, all the elements for the façade modules were calculated based on the maximum possible loads at 3.5 kN/m^2. The results demonstrate that the profile is verified for the vision façade module with a dimension of 1.56 m (b) $\times$ 3.85 m (h). The mechanical calculations reported are for the vision façade modules; the other façade typologies have lower loads and are verified consequently. For each specific building design, the calculations and development of the profile are based on project specifications. The loads adopted for the mechanical validation of the visions are as follows:

- Glass weight: 25 kN/m^3 × 0.029 m × 1.56 m × 3.85 m/2 supports = 2.18 kN at l/10 ends of the bottom transom.
- Façade wind load (suction): −3.5 kN/m^2. The wind load is uniformly distributed over the entire glass surface.
- The value of the linear live load is 1.0 kN/m at a 1.20 m height from the bottom edge.

The loads used in the calculation are the following combinations:

- ULS1 (Ultimate State Limit): 1.35 self-weight load + wind load (suction) × 1.5 + horizontal live load × 1.5 × 0.7.
- ULS2 (Ultimate State Limit): 1.35 self-weight load + wind load (suction) × 1.5 × 0.6 + horizontal live load × 1.5
- SLS1 (serviceability limit state): self-weight load + wind load (suction) + horizontal live load × 0.7.
- SLS2 (serviceability limit state): self-weight load + wind load (suction) × 0.6 + horizontal live load.

The thermal simulation of the vision façade module reflects the analysis that is aligned with the more stringent thermal requirements of the Finnish demo building. The assessment involves the determination of U-values for the various building junctions, which is important for evaluating the overall thermal performance. The finite element software demands specific thermal properties of materials, environmental temperatures, and surface resistances on both the cold and warm sides. The assessment, conforming to standards such as EN ISO 10211 [42] and EN ISO 10077-2 [21], calculates the total heat flow rate of the connection and thermal transmittance of the thermal joint—the reference for the conductivity values as reported in Table A1 in Appendix A.

The acoustic simulation presented for the Basajaun vision façade module provides valuable insights into its sound transmission loss characteristics. The simulation considers the design elements, including the proposed materials and structural configuration, to anticipate the sound insulation capabilities of the façade. This analysis is integral to the overarching design considerations, ensuring that the vision façade module not only meets mechanical requirements and thermal transmittance standards but also aligns with acoustic requirements.

The materials for the research activity were as follows:

- The outcomes of the experimental façades developed in the OSIRYS project [31] were used as a starting point for investigating the bio-composite profiles for façades and the development of an industrialized solution for market integration. On the other hand, the RenoZEB project [43,44] outcomes were used as a starting point for investigating the adoption of membranes and tape alternatives to metal sheets within the curtain wall façade market.
- Real-case demo buildings were adopted, one in Jyväskylä, Finland, and one in Bordeaux, France, to define some pilot cases for façade requirements identification in two climate conditions [45].
- Norms of reference for curtain wall façade designs such as EN 13830—Curtain walling—Product standard [20], EN 14019—Curtain Walling—Impact resistance—Performance requirements [46], and local norms for thermal behavior and acoustic performances to be achieved.
- Software adopted for simulations:
    - Mechanical simulations with AUTODESK INVENTOR PROFESSIONAL 2020.
    - Thermal simulation with THERM 7.7, following the conventions in EN ISO 10211 [42] and conductivity values as reported in Table A1, reference to Appendix A.
    - Acoustic simulation based on EN 717-1 [38].

3. Results

This section reports the results achieved by dividing the manuscript results into two subsections: Sections 3.1 and 3.2.

3.1. Bio-Based and Alternative Components for Façade System Module

The present paragraph reports on the technologies selected to replace conventional technological systems within the curtain wall façade. The Basajaun façade integrates strategic technologies to align with project objectives to minimize carbon footprint and disassembly complexities. Excluding glass, which is out of the scope of the Basajaun research investigation, the following façade components were identified for potential substitution with bio-based materials or alternative products with lower environmental impact. The reasons for substituting these technologies, their advantages, and their characteristics are explained later in Sections 3.1.1–3.1.3. Furthermore, an Embodied Carbon Assessment was conducted to evaluate the advantages of these alternative bio-based components, taking into account emissions from cradle to practical completion (A1–A5) [47,48]. A summary of the result of this assessment is given below, comparing the values of the embedded emissions with those of the alternative that would have been used by designing the modules as conventional:

- Frame profile—the conventional on-market curtain wall façade adopts an aluminum profile, with a European average of 36% of recycled content and an embodied carbon of about 44.03 $kgCO_2eq/mL$, while the bio-composite pultruded profile has 26.80 $kgCO_2eq/mL$ of embodied carbon.
- Insulation—the conventional on-market curtain wall façade adopts rock wool with an average A1–A5 GWP from EPDs of about 45.00 $kgCO_2eq/m^3$, while the wood fiber insulation used in Basajaun has an A1–A5 GWP of 1.63 $kgCO_2eq/m^3$ (biogenic carbon = 261.00 $kgCO_2eq/m^3$) certified by an EPD [49]. Insulation panels that guarantee the same thermal resistance were compared.
- Tightness layer and stiffness layer—the conventional on-market curtain wall façade adopts silicones, sealants, and aluminum sheets with an estimated embodied carbon of about 37.74 average $kgCO_2eq/m^2$ for an opaque façade module, while the membranes, tapes, and plywood implemented have an estimated embodied carbon of about 5.41 $kgCO_2eq/m^2$ of an opaque façade module (biogenic carbon = 15.10 average $kgCO_2eq/m^2$).

These technological components are implemented in the façade system module design. While insulation and membranes/tapes/plywood are commercial products to be implemented for façade, the bio-composite profile is an original product developed within the Basajaun project and a key development for a better understanding of the potential of this kind of product for market penetration in the building envelope sector. The following paragraphs focus on each technological system analyzed and implemented.

3.1.1. Bio-Composite Frame Profiles

The first trials were carried out with a commercially available bio-based polyester resin (technical data of this resin are shown in Tables 4 and 5). Based on the technical datasheet, curing was performed at 25 °C in 9–12 min, and this was performed using different temperatures to obtain an optimum time for the pultrusion process (3–5 min). A high-temperature catalyst with a 1% resin ratio was used in the three tests conducted. Figure 1 shows Dynamic Scanning Calorimetry (DSC) isotherms used to study polymerization at 100 °C to 120 °C, respectively, obtaining good results. The isotherms show the curing times at different temperatures to achieve process adjustment in pultrusion so that curing times can be aligned with pultrusion process speeds. The isotherms demonstrate that the bio-based formulation at different temperatures can work with the pultrusion process speed. The following steps were taken to conduct pultrusion tests with a sample profile to evaluate the feasibility of this resin.

Table 4. Properties of liquid resin.

Liquid Resin Properties	Units	Specifications
Viscosity (cone and plate @ 25 °C)	dPa.s	3.9–4.7
Specific Gravity (25 °C)		1.08
Volatile Content	%	35–40
Acid Value	mg KOH/g	16–20
Stability ¥ when stored in accordance with recommended limits	months	9
Gel time at 25 °C (1% Catalyst M and 1% Accelerator G)	minutes	9 to 12

¥: From date of manufacture.

Table 5. Properties of cast bio-based resin.

Cast Resin Properties	Units	Specification
Barcol Hardness (Model GYZJ 934-1)		36
Deflection Temperature under load † (1.80 MPa)	°C	72
Tensile Modulus	GPa	2.7
Tensile Stress	MPa	88
Tensile Elongation at break	%	4.8
Flexural Modulus	GPa	2.6
Flexural Stress	MPa	54

† Curing schedule 24 h at 20 °C and then 3 h at 80 °C.

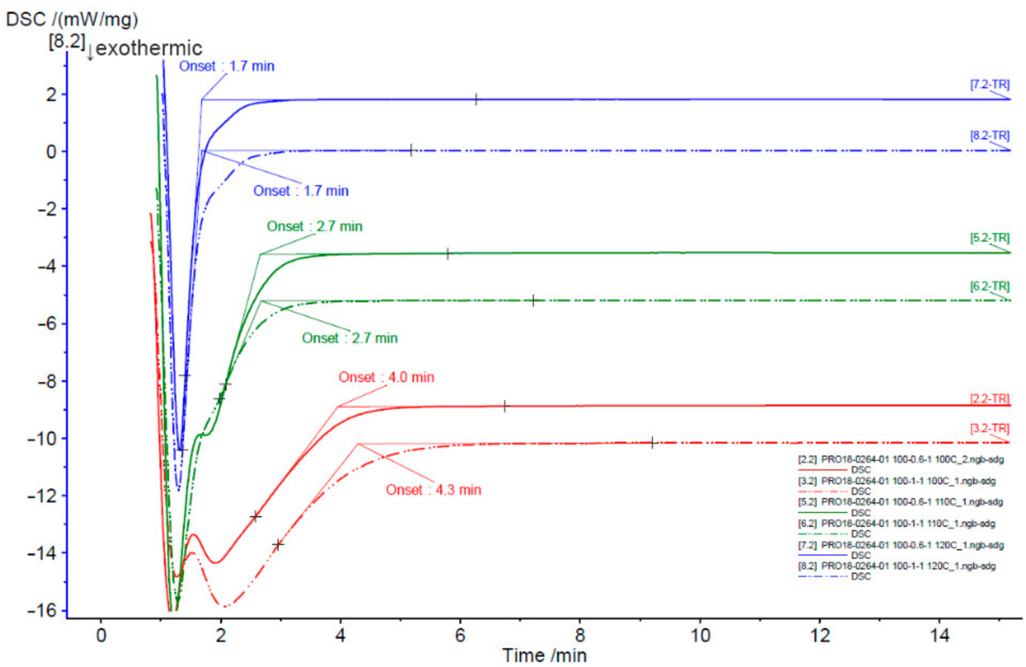


Figure 1. DSC isotherm studies were conducted to study polymerization. The graph with the same color continues, and the striped lines represent repetitions.

Rovings are continuous natural fibers adapted to be used in the pultrusion process. The fibers selected were made from basalt. This fiber is similar to glass fiber, and its properties are shown in Table 6. The basalt quarry stone is melted at about 1400 °C and formed into endless filaments through small nozzles. These are mechanically extracted after discharge at continuously high speeds, air-cooled, and wetted with a coating via a roller. The filaments are combined into multifilament yarn via a collecting roller and wound onto a spool. A low-twist, long-fiber basalt roving is needed to ensure good impregnation and good mechanical properties. A low-twist long-fiber flax with a 100% roving of 2000 Tex was evaluated.

Table 6. Basalt fiber properties.

Basalt Fibers Properties	**Units**	**Specification**
Single filament diameters:(±1) acc. ISO 137:1975 [50]	[µm]	13 to 17
Density:	[g/m^3]	2.6 to 2.8
Linear density acc. ISO 1889:1987 [51]	[tex]	4800 ± 5%
Specific tensile strength: acc. DIN ISO EN 10618 [52]	[cN/tex]	104.6 ± 5%
E-Modul acc. DIN ISO EN 10618 [52]	[GPa]	84.2 ± 5%
Linear expansion coeff.	[$\times 10^{-7}$/K]	6
Moisture content:		less than 0.1%
Size content	[%]	1.0 ± 0.1
Weight of the coil	[kg]	5 to 10
Stability at tension (20 °C)	[%]	100
Stability at tension (200 °C)	[%]	95
Stability at tension (400 °C)	[%]	82
Thermal limit application	[°C]	440
Vitrification temperature	[°C]	1050

In the first step, the needed amount of glass fiber was calculated, considering the characteristics of basalt fibers: linear density 4800 text; density = 2.65 g/cm^3; fiber volume fraction = 0.55%. The architecture of fibers used in the pultrusion tests at the pilot plant is shown in Table 7, which reports information for a profile section of 0.75 cm^2.

Table 7. Calculate fabric layers for testing using the bio-composite pultrusion section.

	Rovings		**Mat or Fabric**		**Fiber**				
Description	**Tex (gr/km)**	**No. of Threads or Layers**	**Gramagge (g/m^2)**	**Effective Width (m)**	**Weight (g/m)**	**Density (g/cm^3)**	**Volume (cm^3/m)**	**Fraction V. Local**	**Occupied Section (cm^2)**
Roving (basalt fiber)	4800	20			96	2.65	36.23	0.55	0.66
Total					96		36.23		0.66
Percentage of mold filling: occupied section/mold section × 100								Total	87.82

Pultrusion trials with bio-based polyester and basalt fiber were conducted to optimize the system's processability and assess the curing cycle. An optimum quantity of 4800 Tex glass fiber yarns (20 yarns) was used for these trials, and the obtained materials are shown in Figure 2; the section of the profile is 15 mm × 5 mm.

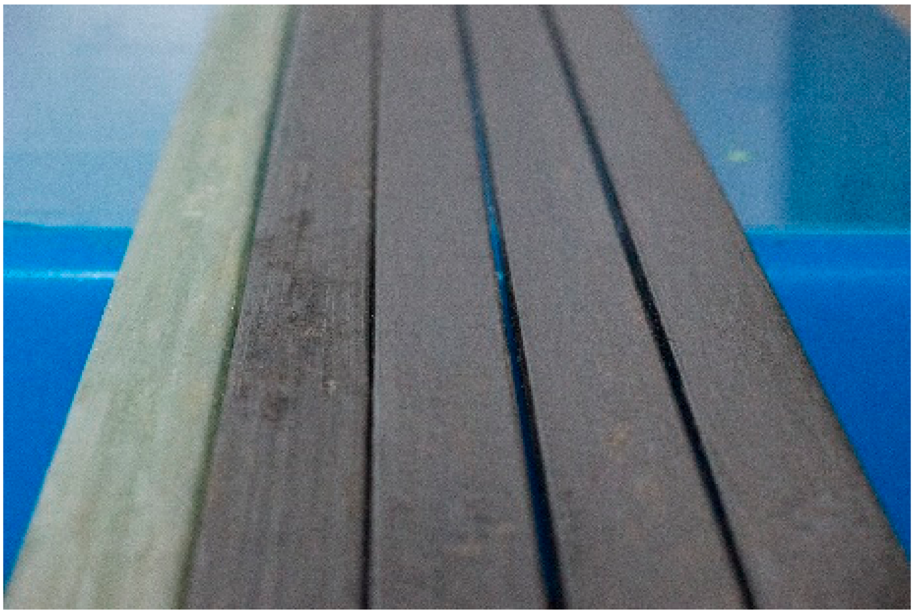


Figure 2. Optimized bio-based polyester and basalt fibers profile obtained by pultrusion (20 yarns of basalt fiber). Samples in AIMPLAS' facilities.

The next step was to put wood particles inside the profile to evaluate its feasibility. First, it was necessary to dry the particles because wood absorbs moisture on its own, and this water can inhibit the polymerization of the polyester resin. The result (Figure 3) reveals that the adhesion of wood particles was stable but that reducing the number of rovings (seven less) was necessary, a fact that can reduce the mechanical properties.

(**a**) (**b**) (**c**) (**d**)

Figure 3. Optimized bio-based polyester and basalt fibers profile obtained by pultrusion (13 yarns of basalt fiber). Samples manufactured in AIMPLAS´s facilities. Bio-based profiles (**a**); bio-based profiles pultrusion (**b**); basalt fiber in the resin (**c**); basalt rovings (**d**).

OMIKRON developed the first approach in its facilities with a cross-section of 100 mm × 8 mm, and the architecture of fibers used are shown in Table 8, using approximately 50% of the full section by basalt fibers in a profile section of 8 cm^2 (Figure 4).

Table 8. Calculation of fabric layers for testing with bio-composite pultrusion section by OMIKRON.

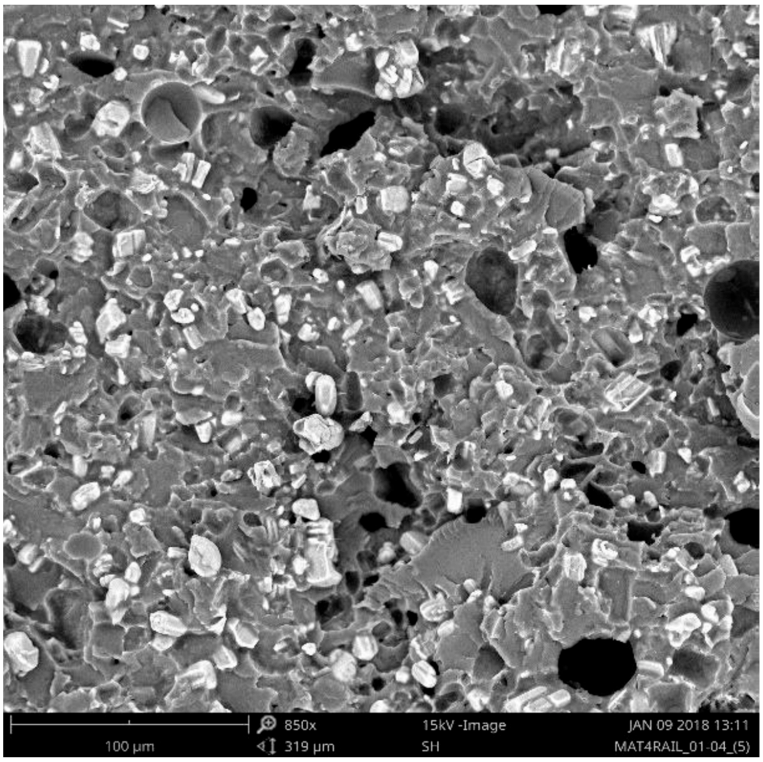
Description	Rovings		Mat or Fabric			Fiber			
	Tex (gr/km)	No. of Threads or Layers	Gramagge (g/m^2)	Effective Width (m)	Weight (g/m)	Density (g/cm^3)	Volume (cm^3/m)	Fraction V. Local	Occupied Section (cm^2)
Fabric (Glass Fiber)		2	500	0.1	100	2.55	39.22	0.28	500
Roving (Basalt Fiber)	4800	80			384	2.55	150.59	0.55	2.74
Total					384		150.59		4.14
Percentage of mold filling: occupied section/mold section × 100								Total	51.73

Figure 4. Bio-based polyester and glass fiber profile obtained by pultrusion obtained in OMIKRON's facilities.

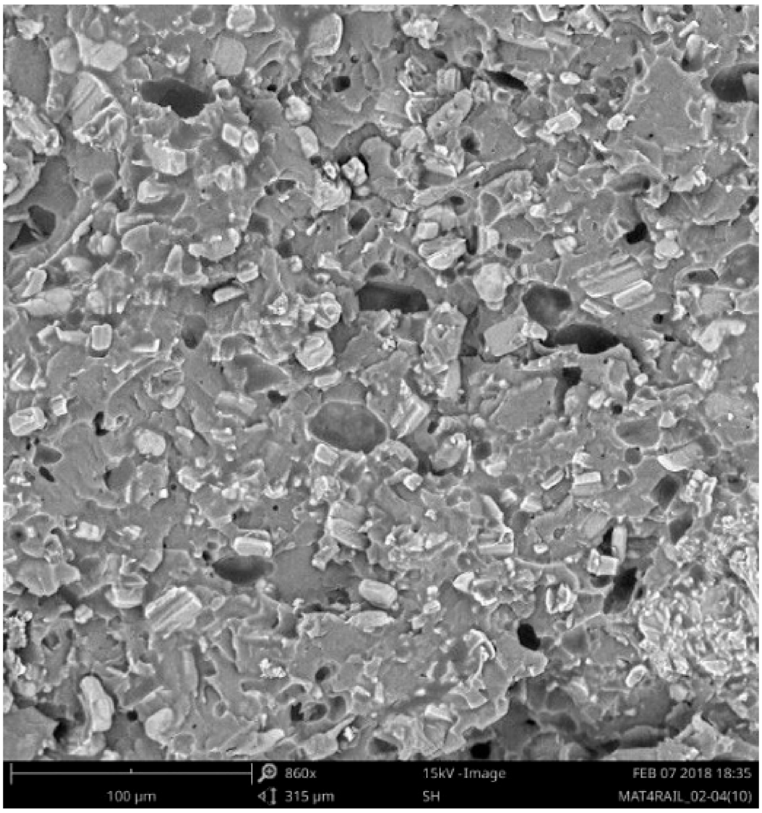
First, flame retardancy (FR) trials on this polyester system were conducted by dispersing two different halogen-free flame retardants. An optimal dispersion of the flame retardant into the polyester matrix is a key requirement to obtain a resin with good processability for any process. Two dispersion methods were tested to disperse the different solid FR additives: a three-roll calendar equipment and a dispersion and milling system equipment. Flame retardancy tests were carried out via the vertical flammability test according to the UL94 Standard, and samples for these tests were prepared as follows (considering the specifications described in the datasheet of the bio-based resin):

- The catalyst was mixed with resin.
- A hardener and liquid components were added to this mixture.
- Once the mixtures were prepared, they were stirred with the help of a high-speed mixer.

The initial tests for optimizing the dispersion of flame retardants and flammability tests were started on the reference materials. The high-speed mixer dispersion was effective, as seen in Figure 5, achieving a good dispersion, as shown in the images from a quality check based on the homogeneous dispersion of the whitest particles (flame retardant).



(**a**)



(**b**)

Figure 5. Evaluation of the dispersion quality of FR particles (the whitest particles) in the resin. The FR particles' dispersion appears to be homogeneous in the samples analysis. FR1 dispersion (**a**); FR2 dispersion (**b**).

Subsequently, the mixture was poured into a mold so that samples for the UL94 flammability test (12.5 cm × 1.2 cm × 0.4 cm) could be obtained. Table 9 shows the flammability rating that the UL94 follows, and the test results are shown in Table 10.

Table 9. Flammability rating UL 94 of bio-based profile.

	Flammability Rating UL 94		
	V-0	**V-1**	**V-2**
Burning time after flame application (s)	≤10	≤30	≤30
Total burning time (s) (10 flame applications)	≤50	≤250	≤250
Burning and afterglow times of specimen after second flame application (s)	≤30	≤60	≤60
Dripping of burning specimens (ignition of cotton batting)	No	No	Yes
Specimens completely burned	No	No	No

Table 10. Flammability tests.

Description	**Classification UL94**
Bio-based resin Only resin	Not classifiable
Bio-based resin + FR 1 20%	V2
Bio-based resin + FR 1 30%	V0
Bio-based resin + FR 1 40%	V0
Bio-based resin + FR 2 30%	Not classifiable
Bio-based resin + FR 2 40%	Not classifiable
Bio-based resin + FR 2 50%	Not classifiable
Bio-based resin + FR 1 20%+ FR 2 40%	V2

All these dispersions increased its viscosity, an important parameter than might be considered for the pultrusion process because the Basajaun profile can use a lot of basalt rovings and fabrics, and the resin must correctly impregnate the fibers, improving the viscosity.

Another analysis was carried out by covering the resin with two types of coatings to compare the cone calorimeter results and a future relationship with SBS tests. Two types of coatings were tested with coating layers applied at a 400 gsm dry film weight: the first coating was a hybrid inorganic–organic coating technology for indoor and outdoor decorative and protective applications with the capability to form a hard, decorative, and mar-resistant coating with easy-to-clean properties, an exceptional weathering speed, UV-light degradation resistance, water resistance, and a good color and gloss retention (T-1-2 bio-based with coating); the second was an unsaturated polyester-based fire-resistant coating system designed for composites comprising three functional layers, each having specific features to deliver comprehensive fire and thermal protection to standard composite structures (F-1-2 bio-based with coating). These products covered a resin specimen test for cone calorimeter tests, according to ISO 5660-1, and we combined both to obtain several results; the most promising was the formulations T-1-2 and F-1-2. Indeed, the results in Figure 6 show the following: peaks of the average rate of heat emission were 183 kW/m^2 at 380 s (T-1-2) and 163 kW/m^2 at 440 s (F-1-2) while the uncoated sample achieved a higher heat emission (403 kW/m^2) in a shorter time period (160 s); the peak rate of the heat release was 354 kW/m^2 at 360 s (T-1-2) and 305 kW/m^2 at 420 s (F-1-2) while the uncoated sample achieved a higher heat release (759 kW/m^2) in a shorter time period (140 s); the peak of the smoke production rate was 11 m^2/s at 310 s (T-1-2) and 10 m^2/s at 400 s (F-1-2) while the uncoated sample achieved a higher smoke production (20 m^2/s) in a shorter time period (120 s).

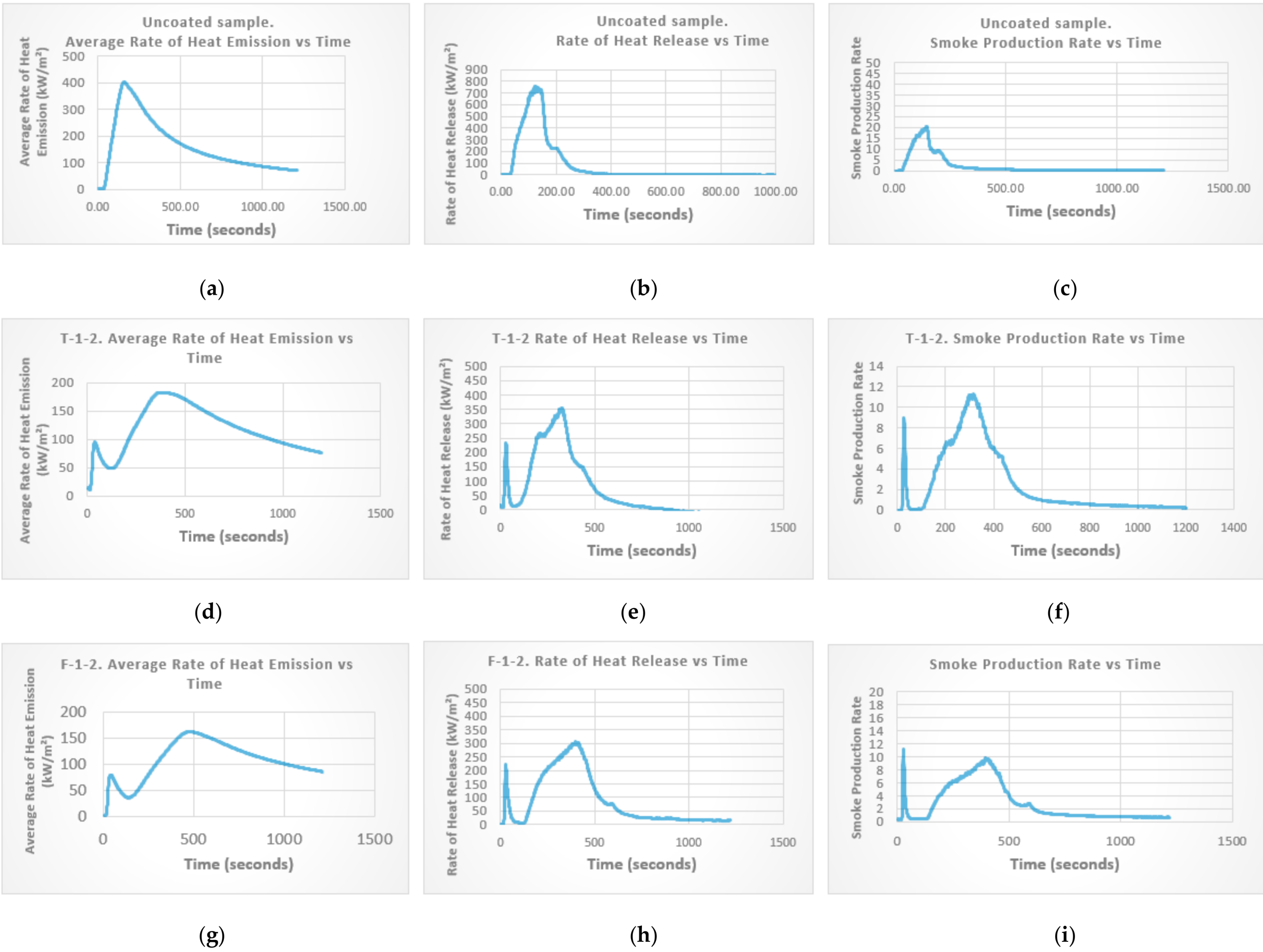


Figure 6. Cone calorimeter tests of the resin were performed using two types of coatings. Average rate of heat emissions for uncoated sample (**a**); rate of heat release for uncoated sample (**b**); smoke production rate for uncoated sample (**c**); average rate of heat emissions for T-1-2 sample (**d**); rate of heat release for T-1-2 sIle (**e**); smoke production rate for T-1-2 sample (**f**); average rate of heat emissions for F-1-2 sample (**g**); rate of heat release for F-1-2 sample (**h**); smoke production rate for F-1-2 sample (**i**).

The uncoated resin sample gave a rate of heat emission (MARHE) of 403 kW/m^2 and a Peak Heat Release Rate of 759 kW/m^2. When we applied our two different two-coat systems onto the resin (T-1-2 and F-1-2), MARHEs achieved values of 183 and 163, with Peak HRRs of 354 and 305, respectively. Remarkably significantly improved results were demonstrated.

Based on this value, the expectation is a D or E classification under EN 13501 testing for heat emission properties (SBI testing) for these coated samples (only resin). The results are in line with the expected bio-based reaction to fire to be achieved for façade integration.

Further activity was the main mechanical characterization to compare properties. On the one hand, pultrusion specimens obtained were analyzed to validate the structural stability of the Basajaun profiles used for all the façade systems; on the other hand, the interaction between the resin (bio-based resin) and the flame-retardant additives was evaluated (Table 11). Using flame retardant in the resin matrix was detrimental to the mechanical properties, reducing sixty percent of the mechanical resistance of the resin. The use of FR alone did not guarantee acceptable fire protection for construction. Therefore, the use of special coatings to increase fire resistance was studied.

Table 11. Mechanical characterization of pultruded profiles and resin with FR.

Sample	E	SD	R	SD	%R	SD	Poisson Ratio	SD	Apparent ILSS	SD	Break Mode
	MPa		MPa		%		μ		MPa		
Resin with glass fiber cured (2 h 70 °C)	38,400	1920	584	2.7	1.44	0.14	0.25	0.04			
Resin with basalt fibers with cured cycle (2 h 70 °C)	39,200	1500	431	73	1.11	0.16	0.07	0.06	10.7	0.8	simple shear
Resin with basalt fibers without cured cycle (20 rovings)	38,600	852	378	9	1.01	0.03	0.16	0.25	10.5	0.6	simple shear
Resin with basalt fibers and wood particles without cured cycle (13 rovings)	26,700	837	426	1.6	1.6	0.08	0.24	0.14			
OMIKRON sample (longitudinal direction)	30,500 [ANM3]	244	453	26.1	1.5	0.1	−0.04	0,05			
Bio-based resin (Only Resin)	1870	410	45.5	8.6	2.6	0.7	0.22	0.21			
Bio-based resin (Only Resin) + FR 1 20%	2160	270	25.9	2.7	1.5	0.2	0.26	0.32			
Bio-based resin (Only resin) + FR 1 30%	2060	319	22.1	1.3	1.6	0.4	0.35	0.14			
Bio-based resin (Only resin) + FR 1 40%	2380	730	18.1	1.1	0.96	0.2	0.23	0.33			
Bio-based resin (Only resin) + FR 2 30%	2750	1130	13.7	3.4	0.4	0.06	−0.12	0.28			
Bio-based resin (Only resin) + FR 2 40%	3000	1020	17.1	2.7	0.51	0.03	0.22	0.06			
Bio-based resin (Only resin) + FR 2 50%	4160	1100	20	1.6	0.43	0.01	0.74	0.17			
Bio-based resin + FR 1 20% + FR 2 40%	3550	128	19.3	1.5	0.55	0.07	0.72	0.25			

Another type of characterization was performed by comparing longitudinal and cross directions for flexural properties of the OMIKRON samples to clarify the mechanical range in both directions and accurately ensure the security of the mechanical properties for the bio-based profile. With a profile with 100 mm, a standardized test specimen for both directions was not obtained (only the longitudinal direction). To compare relative values, Table 12 shows 30–40% of the flexural properties between cross and longitudinal directions, which are good values in comparison with common pultruded composites.

Table 12. Flexural properties of OMIKRON samples.

Test	Flexural Modulus	SD	Flexural Strength	SD	Deflection at Flexural Strength	SD
	MPa		MPa		%	
Flexural properties according to EN ISO 14125 [53]	32,100	792	572	26	6.9	0.4
Flexural properties in longitudinal direction (non-standardized tests)	18,800	1580	409	35	2.0	0.4
Flexural properties in cross direction (non-standardized tests)	8790	985	125	4	1.6	0.2

Based on the results achieved, an iterative process in profile design was conducted, focusing on the pultrusion requirements and preliminary mechanical characterization. Some initial structural validations were made, considering the vertical mullion and horizontal transom. To guarantee the design used, and to optimize the thickness of the profiles, some calculations with different thicknesses were made. Based on the preliminary design reported in Figure 7, the mechanical characterization was performed.

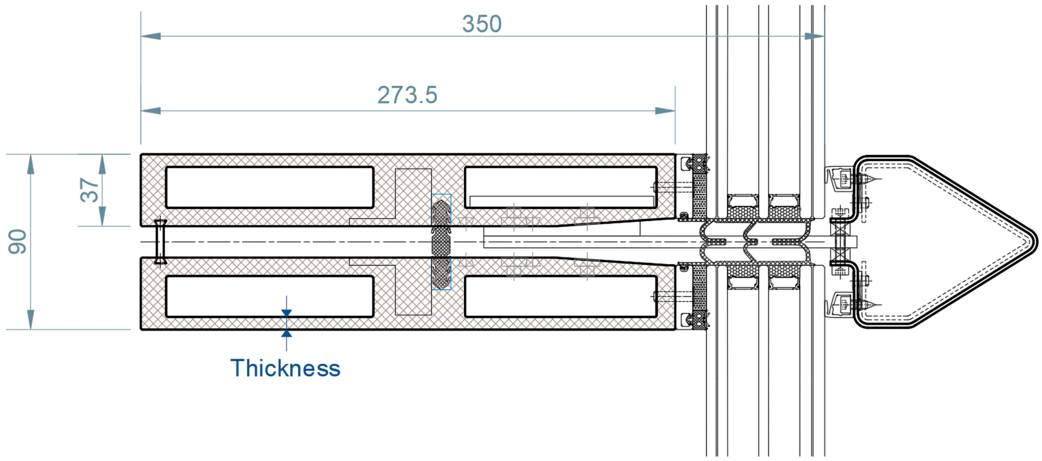


Figure 7. Preliminary bio-composite profile for mechanical characterization.

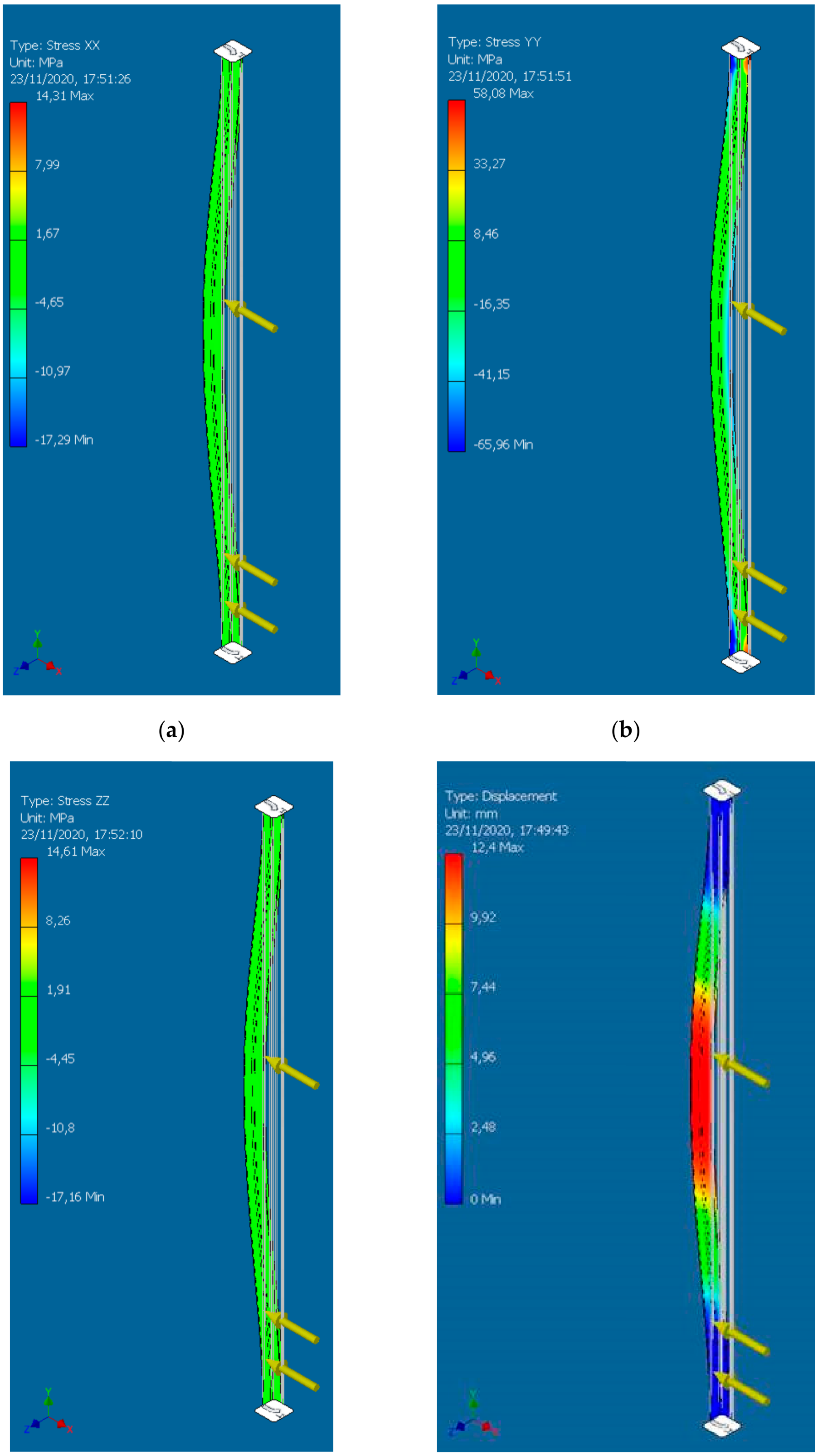
After the analysis conducted with the worst modulus of elasticity to obtain the maximum possible loads to check different thicknesses of the profiles (6.5 mm, 8 mm, and 10 mm), the calculation with the appropriate modulus of elasticity based on data reported in Table 11 was performed using a profile thickness of 8 mm, calculating mullions and transoms considering the weight of the glass, the façade module with the higher loads, and the load reported for mullion in Table 13 and for transom in Table 14. Figures 8 and 9 report the results achieved as useful for the profile design.

Table 13. Lists of loads for mullion (8 mm).

Maximum Wind Load = 2.00 kN/m^2	
Loads:	
WL = 2 kN/m^2 × 0.79 m × 7.65 m =	12.1 kN
WL_{ult} = 1.5 × 12.1 =	18.13 kN
E = 1 kN/m × 0.79 m =	0.79 kN
E_{ult} = 1.05 × 0.79 kN =	0.83 kN
E2 = 1 kN/m × 0.79 m × 0.7 =	0.553 kN

Table 14. Lists of loads for transom (8 mm).

Maximum Wind Load = 2.00 kN/m^2	
Loads:	
WL = 2 kN/m^2 × 0.79 m × 1.58 m =	2.5 kN
WL_{ult}= 1.5 × 2.5 =	3.75 kN
DL = 25 kN/m^3 × 0.027 m × 7.65 m × 1.58 m/2 Blocks =	4.1 kN
DL_{ult}= 1.35 × 4.1 =	5.51 kN

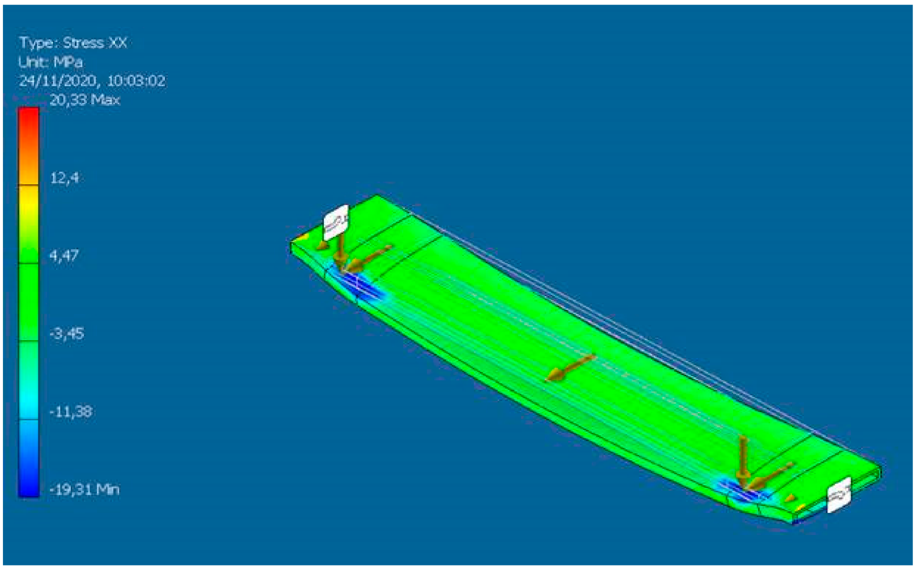


(**a**) (**b**)

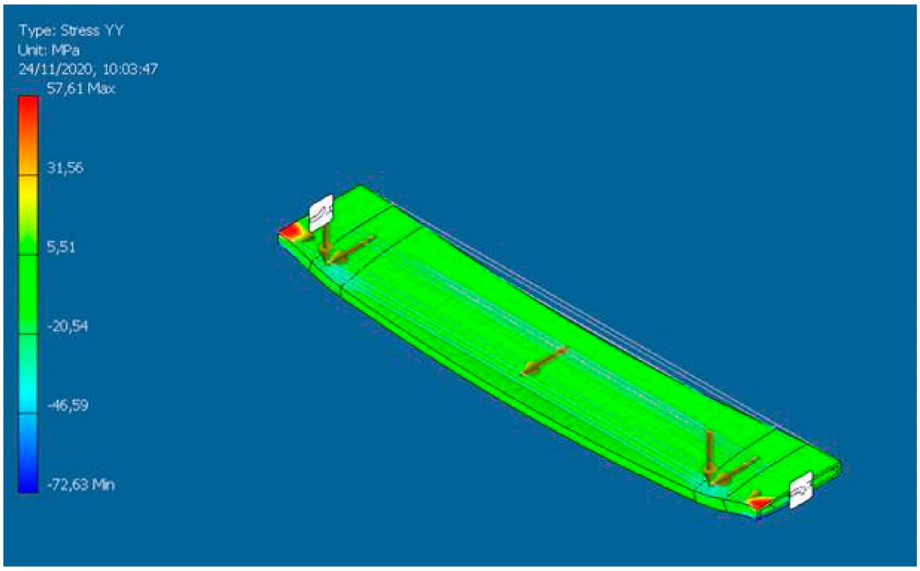
(**c**) (**d**)

Figure 8. Stress XX is a max of 14.31 MPa with permissible stress: 75 MPa (**a**); Stress YY is a max of 58.08 MPa with permissible stress: 185 MPa (**b**); Stress ZZ is 14.61 MPa with permissible stress: 75 MPa (**c**); displacement max is 12.4 mm with permissible deformation <7650/250 = 30.6 mm (**d**). The arrows depicted in the figures represent the resultant of the load, and are proportional to it.

Based on mechanical characterization and manufacturing process requirements, the following profile was designed (Figure 10) and used for the definition of the façade module system. The figure highlights in red the relevant tolerances required by the façade manufacturer (different from the usual practice in aluminum profiles) to ensure compliance with the curtain wall façade requirements. It is important to note that for pultrusion process reasons, the minimum radius of the grooves is 1 mm and the internal tolerance of the cavity is ±1 mm.

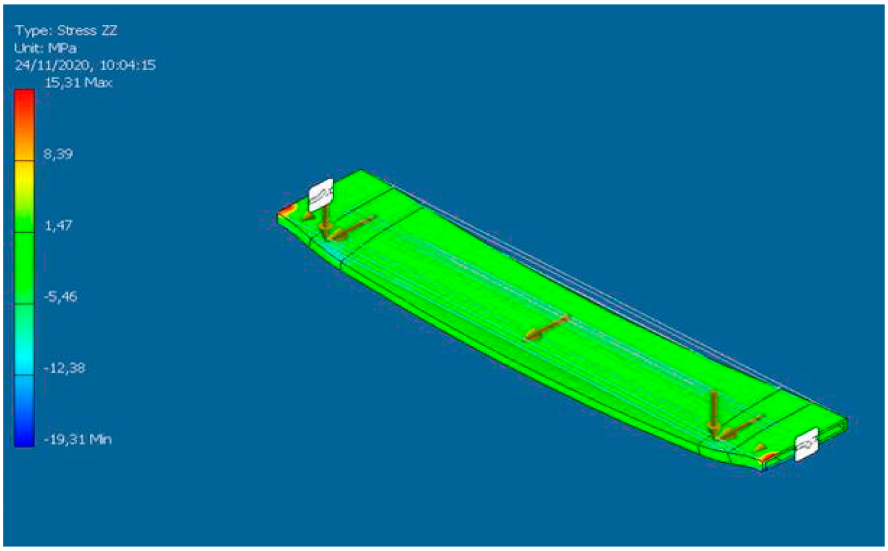


(**a**)

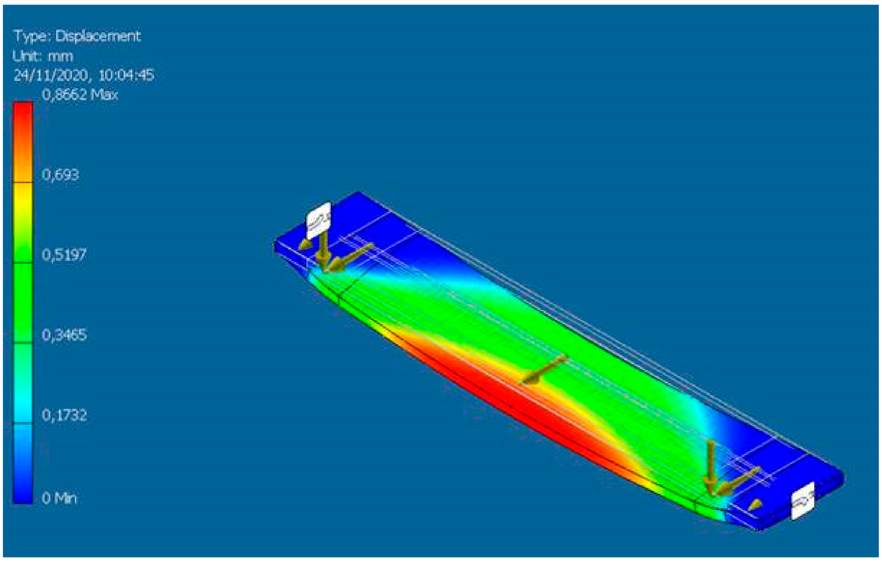


(**b**)

Figure 9. *Cont.*



(**c**)



(**d**)

Figure 9. Stress XX is a max of 20.33 MPa with permissible stress: 30 MPa (**a**); Stress YY is a max of 57.61 MPa with permissible stress: 75 MPa (**b**); Stress ZZ is a max of 15.31 MPa with permissible stress: 30 MPa (**c**); displacement of 0.87 with a max permissible deformation < 7650/250 = 3.16 mm (**d**). The arrows depicted in the figures represent the resultant of the load, and are proportional to it.

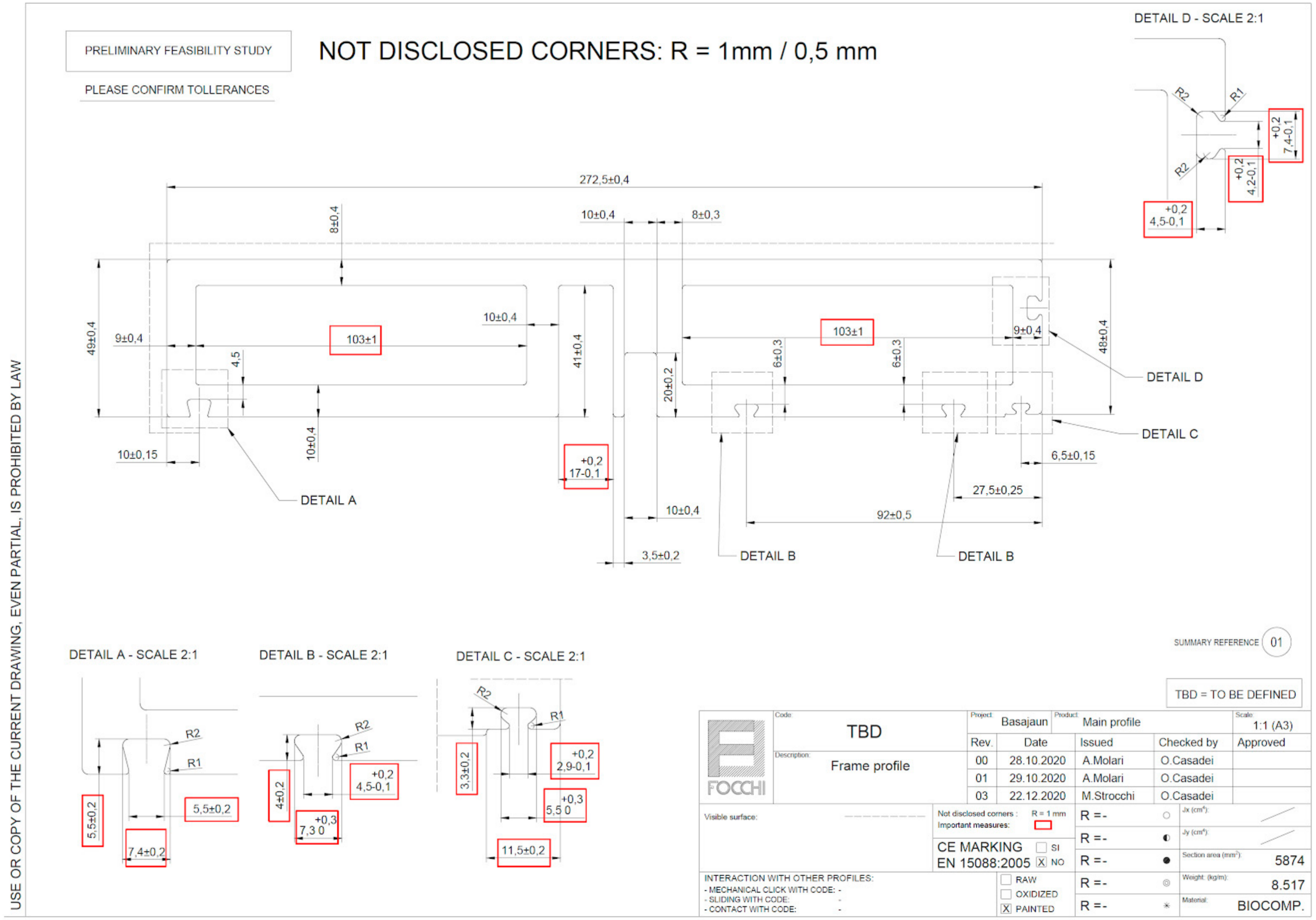


Figure 10. Basajaun biocomponent pultruded profile for transom and mullion; in red are the tolerances to comply with the façade manufacturer's requirements with bio-based profile pultrusion processes.

3.1.2. Wood-Based Insulation

For the Basajaun façade modules, a wood-based insulation material was analyzed. Table 15 summarizes the products on the market with similar physical characteristics to those of wood fiber used in Basajaun. Specifically, the table shows the average values of products from suppliers with at least three EPDs available on the EPD International portal [37].

Table 15. Comparison of the insulation alternatives.

	Wood Fiber Insulation Used in Basajuan	**Average Rock Wool Products from Supplier A**	**Average Rock Wool Products from Supplier B**
Gross density (EN 1602) [54]	55.00 kg/m^3	72.33 kg/m^3	80.00 kg/m^3
Thermal conductivity (EN 13171) [55]	0.038 W/(mK)	0.034 W/(mK)	0.035 W/(mK)
Fire classification (EN 13501-1) [56]	Class E	Euroclass A1	Euroclass A1
Water vapor resistance	5 (EN 12667) [57]	Not specified	1 (EN 12086) [58]

Two considerations emerged as relevant to address the façade design. Firstly, mineral wool products possess excellent fire resistance capability, whereas wood fiber is highly flammable and, therefore, requires special consideration during the design phase. Secondly, it was observed that mineral wool is typically denser for the same thermal conductivity. Consequently, a thickness of equal thermal resistance will result in a heavier material. Considering the wall's thermal lag requirements, this factor must be given due importance.

3.1.3. Alternatives Seals and Gaskets

In the Basajaun façade, a reflective fire reaction vapor barrier screen, comprising an upper layer of aluminum film and a lower layer of fiberglass fabric, was integrated. Table 16 compares the sheets analyzed in the project with other market products.

Table 16. Comparison of the sealing sheets alternatives.

	Reflective Fire Reaction Vapor Barrier Screen Used in Basajuan	**Example of an Average Sheet as Conventional per Façade Module Type A**	**Example of an Average Sheet as Conventional per Façade Module Type B**
Material	Aluminum—PE-Glass fiber	PET	PUR.PP
Fire classification (EN 13501-1) [56]	Class A2-s1, d0	B-s1, d0	Class E
UV resistance	✔	✔	✔
Water impermeability	Class W1	Class W1	Class W1
Water vapor transmission (Sd) [m]	0.08	0.02	0.14
Tensile strength [N/5 cm]	3000/3200	250/210	210/205
Thermal conductivity [W/(m∗k)]	0.0007	0.17	0.22
Vapor resistance factor [μ]	185	40	200

Notably, the selected membrane was characterized by its exceptional resistance to fire and impermeability to water, which aligns with the need to safeguard the insulation. This is particularly critical in the case of Basajaun, where the insulation material is vulnerable to damage from such risks.

Furthermore, the stiffness layer provides structural support and rigidity to the overall assembly, utilizing materials such as sheathing panels or metal framing members to distribute loads and resist deformation or movement. Usually, in the opaque sections of the building's façade, the role of providing structural support to internal wall and stiffness to the overall system is often assigned to aluminum sheets. For bio-based façade system module design, a wood-based alternative is adopted using plywood panels.

3.2. Bio-Based Façade System Design

This chapter presents the final design of the bio-based façade system resulting from the previous developments, requirements, and considerations. In addition, it also lists and describes the unit typologies developed for two pilot buildings (one in Finland and one in France) and the related final system designs. The paragraphs focus on each façade system designed and simulated within the project. The three main façade systems are depicted in Figure 11. The façade modules designed within the system are (1) a full glazed vision façade module with structural silicone, (2) an opaque façade module and (3) an opaque façade module with a roller shutter and a window integrated. In the next paragraphs, the façade module systems design are presented.

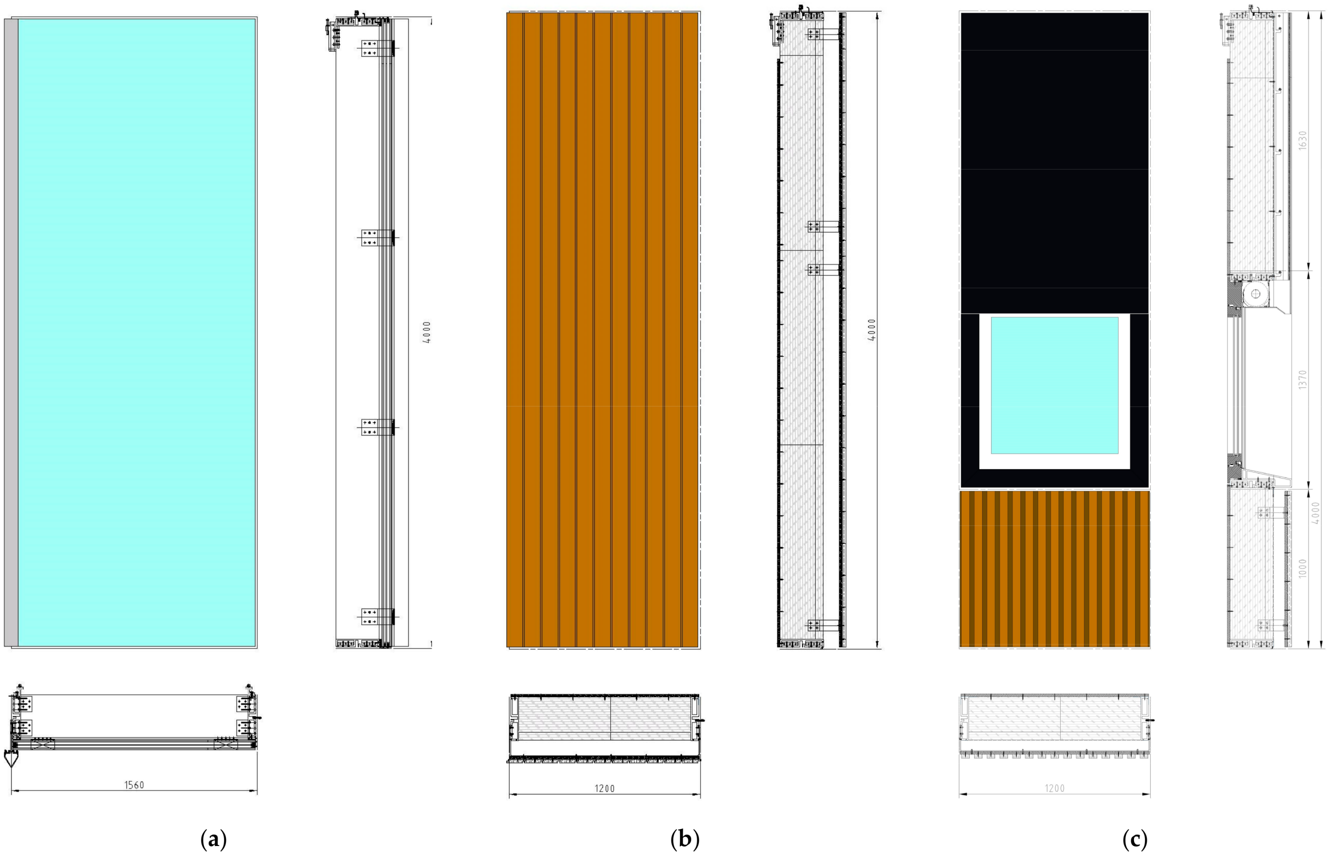


Figure 11. Drawings of façade modules (elevation, vertical section on the right, horizontal section at the bottom): vision façade module (**a**); opaque façade module (**b**); window façade module (**c**).

3.2.1. Vision Façade System

The Basajaun vision façade system (Figure 12 and Table 17) includes design considerations and structural simulations to ensure performance achievement based on norms and market requirements. The incorporation of structurally sealed glass in the bio-composite frame underscores the commitment to both the aesthetic and functional aspects. The thermal simulation, although maintaining consistency with the initial design, serves as a critical reference point for the module's thermal behavior.

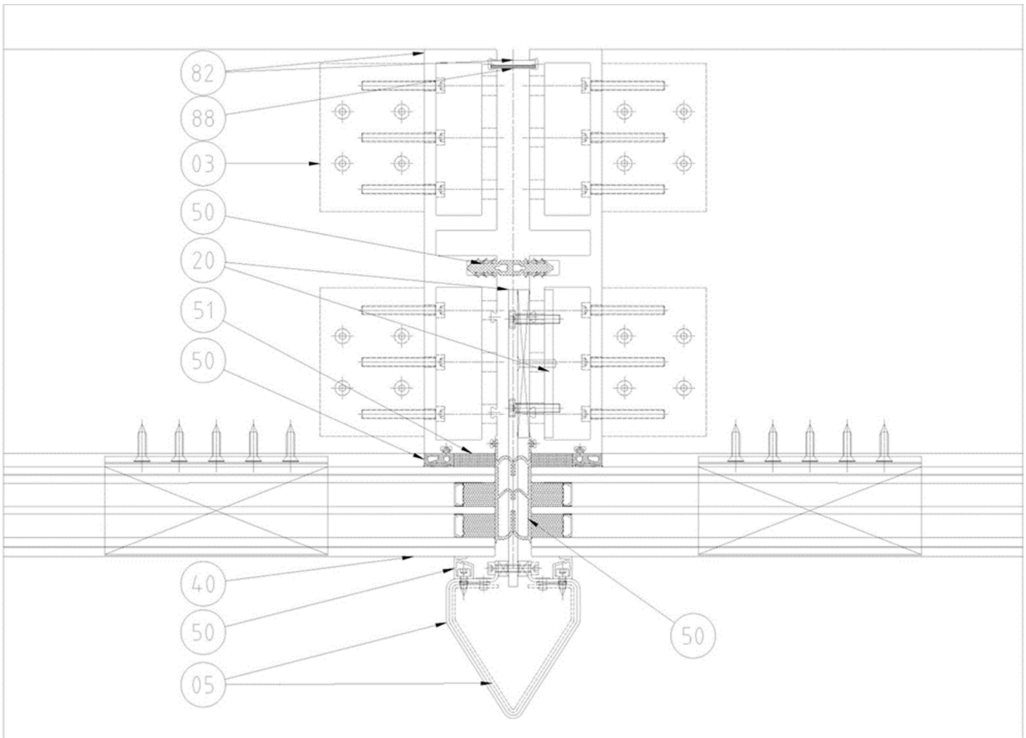


Figure 12. Final solution: horizontal section of Basajaun vision façade module. The numbers for the components' identification refer to Table 17.

Table 17. Basajaun vision façade module technologies.

Figure Code	Layer	Objectives	Characteristics
03	Aluminum bracket mill finish	To connect the transoms to the mullions	Structural part
05	Aluminum sheet	External finishing	-
20	Stainless steel sheet AISI316	To connect the external fin to the frame	Structural part
20	Stainless steel sheet AISI316	Internal support	Structural part
40	GL-1 TGU	-	Triple glass unit
50	EPDM gasket	Second water barrier	-
50	EPDM gasket	Glass support	-
50	EPDM gasket	First water barrier	-
50	EPDM gasket	Finishing gasket	-
51	Structural silicone black color	To join the glass to the frame	Structural part 9 mm × 27 mm
82	Bio-composite profile—internal key	To join two units	Thickness 3.5 mm
82	Bio-composite profile—mullions	To bead the unit load and connect it with the structural slab	Thickness 8/10 mm
88	Foam rubber	To not vibrate the internal key	-

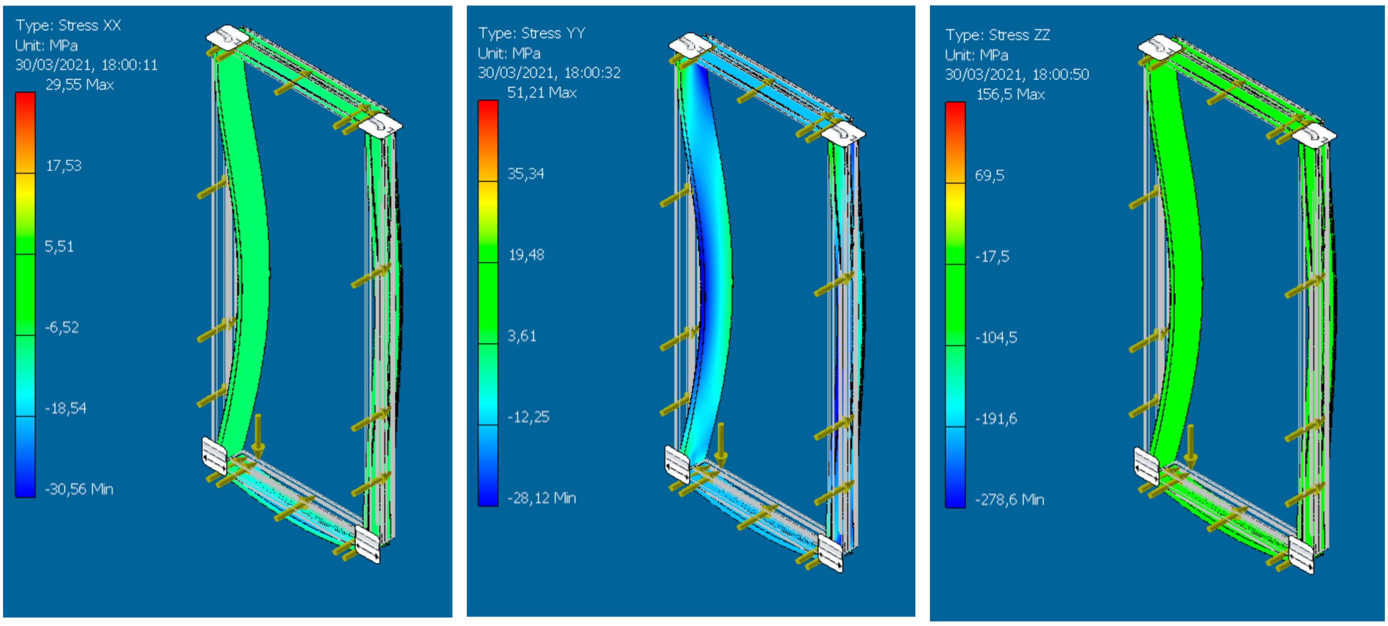
The modular façade systems were validated during the design stage for the mechanical simulation and thermal simulations.

Based on the defined loads presented in Section 2, the permissible thresholds are as follows:

- The perimeter structure stress analysis requested is as follows:
  - Stress XX—Permissible Stress: 38 MPa.
  - Stress YY—Permissible Stress: 125 MPa.
  - Stress ZZ—Permissible Stress: 38 MPa.
  - X Deflection—Max. Deformation < 3850/300 + 5 = 17.83 mm.
  - Y Deflection—Max. Deformation < 1560/500 = 3.12 mm.
  - Z Deflection—Max. Deformation < 3850/300 + 5 = 17.83 mm.
- The cross-member connection stress analysis requested is as follows:
  - Stress—Permissible Stress: 227 MPa (250/1.1) Aluminum 6082 T6.
  - X Deflection—Max. Deformation < 1 mm.

Figure 13 reports the results of the mechanical simulation of the vision façade module system. The simulation results show how the maximum stress achieved is lower than permissible stresses for XX and YY and higher (156.5 MPa) than the permissible stress (28 MPa) in ZZ. For ZZ, an in-depth analysis is conducted to evaluate the amount of area with the maximum stress. Figure 14 shows that the value is 156.5 MPa only in a small area, so the profile is considered adequate.

Figure 15 shows the compliance with the permissible stress (227 MPa) of the aluminum plates used for the connection of the bio-composite profiles (transom and mullions) with a maximum stress of 212.9 MPa.



(**a**) (**b**) (**c**)

Figure 13. Perimeter structure stress analysis: stress XX is 29.55 MPa with permissible stress 38 MPa (**a**); stress YY is 51.21 MPa with permissible stress 125 MPa (**b**); stress ZZ is 156.5 MPa with permissible stress 38 MPa (**c**). The arrows depicted in the figures represent the resultant of the load, and are proportional to it.

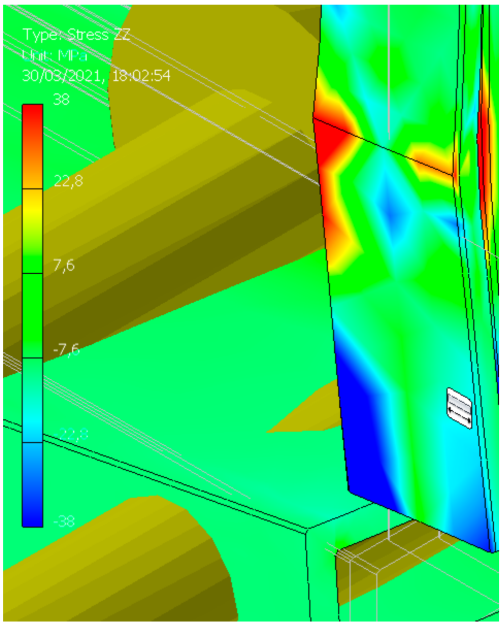


Figure 14. Mechanical simulation results: the cross-member connection stress analysis with the maximum stress ZZ is exceeded in a small area; the profile is considered adequate.

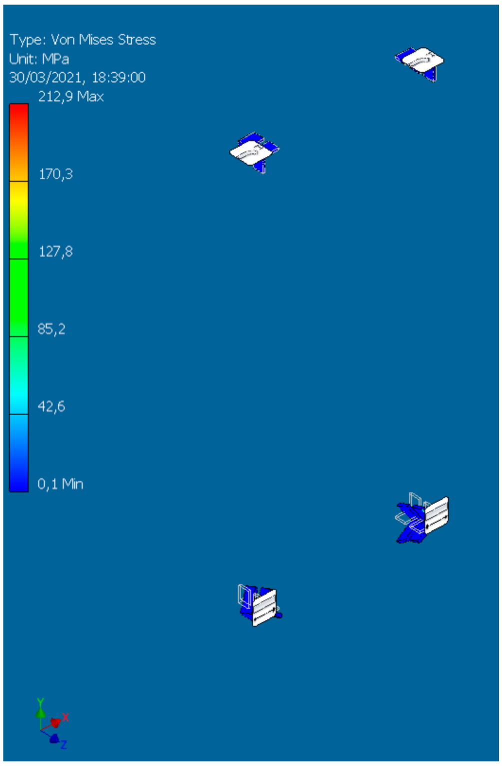
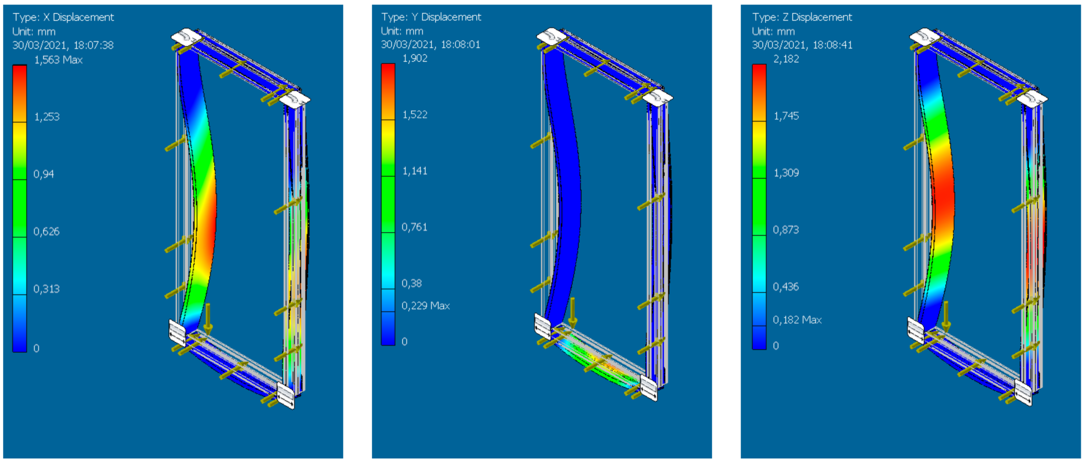


Figure 15. Mechanical simulation results for cross-member connection stress analysis: max stress is 212.9 MPa with a permissible stress of 227 MPa.

Figure 16 reports the result of the deflection of the bio-composite frame. The simulation demonstrates the compliance of the bio-composite profile frame along the whole perimeter with the load. Figure 17 reports the cross-member connection deflection compliance.



(**a**) (**b**) (**c**)

Figure 16. Perimeter structure deflection analysis: X deflection is a max of 1.56 mm with permissible deformation < 3850/300 + 5 = 17.83 mm (**a**); Y deflection is a max of 1.90 mm with permissible deformation < 1560/500 = 3.12 mm (**b**); Z deflection is a max of 2.18 mm with permissible deformation < 3850/300 + 5 = 17.83 mm (**c**).

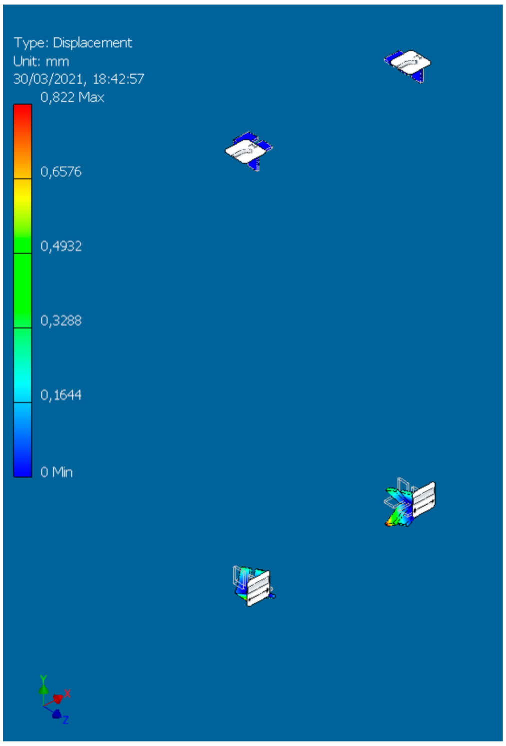
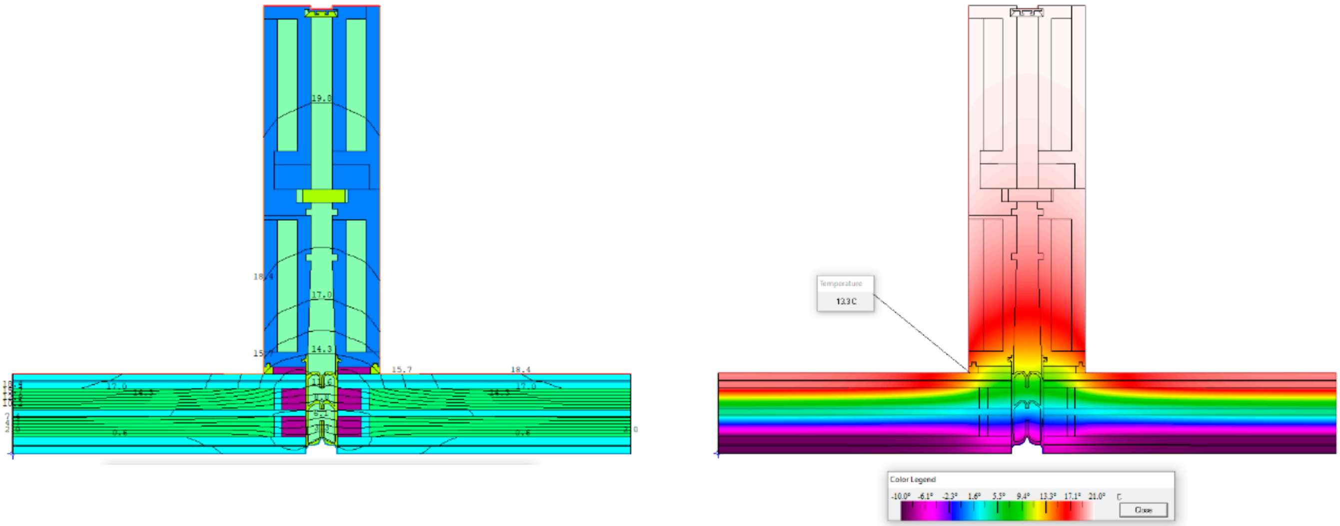


Figure 17. Cross-member connection deflection analysis has a max of 0.82 mm deformation with permissible deformation < 1 mm.

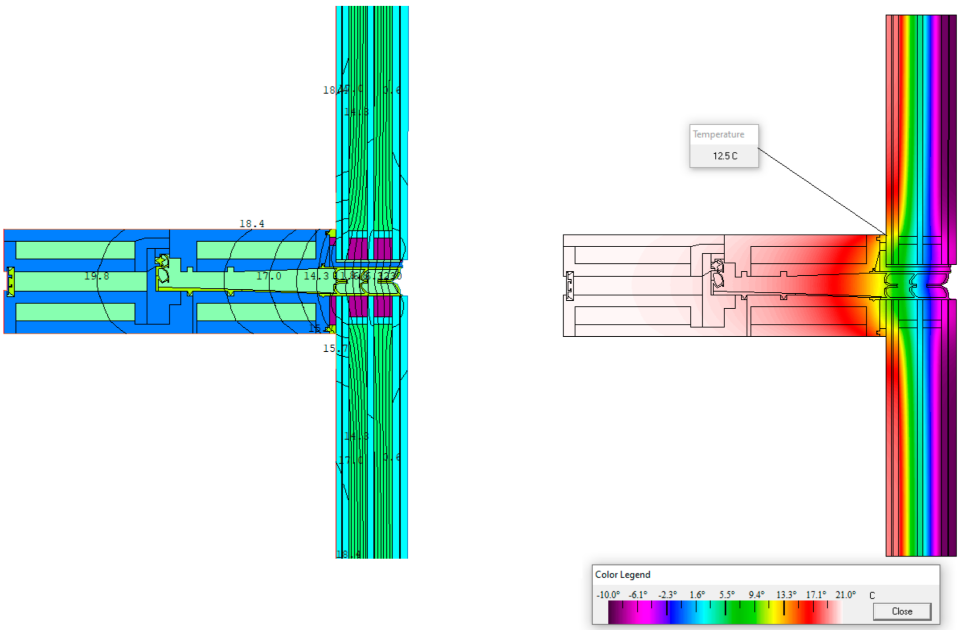
For the thermal behaviors, the values obtained for key nodes of the vision façade system, such as "Node 1 mullion-mullion" (Figure 18), "Node 2 transom female-transom male" (Figure 19), "Node 3 transom-roof interface" (Figure 20), "Node 4 transom-ground interface" (Figure 21), and "Node 5 male transom-female transom" (Figure 22) with joints with opaque parts, demonstrate U-values that meet or exceed the defined standards. In summary, the technical characteristics affirm that the overall curtain wall U-value is 0.74 W/m^{2}K, satisfying the verification criterion of being less than or equal to 1 W/m^{2}K. The U-value was calculated by Equation (1) utilizing the data reported in Table 18. This thermal analysis underscores the commitment to achieving energy efficiency and thermal comfort within the envisioned architectural design.

$$Ucw = \frac{\sum(Ug \times Ag) + \sum(Us \times As) + \sum(UTJ \times ATJ)}{\sum Ag + \sum As + \sum ATJ} \quad (1)$$



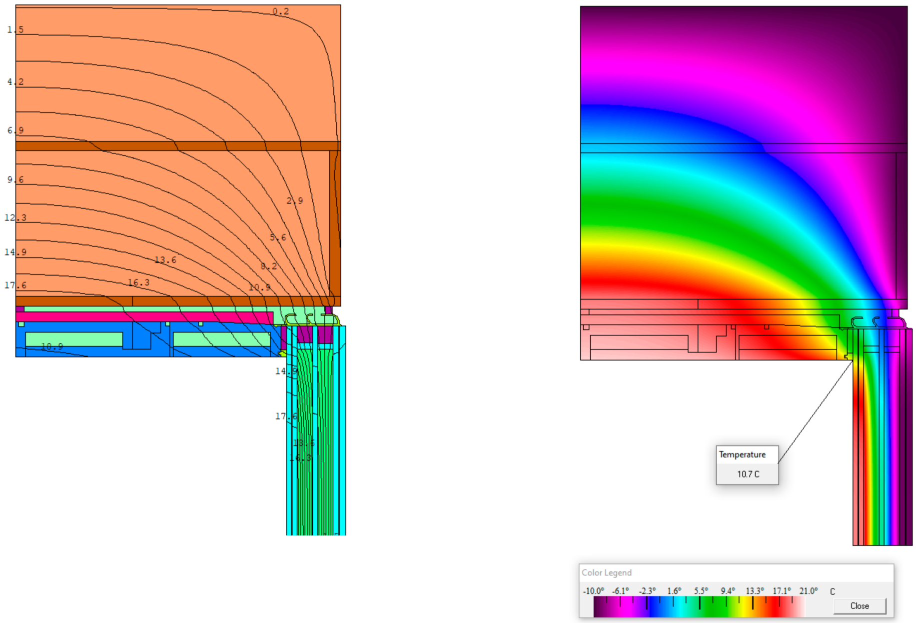
(**a**) (**b**)

Figure 18. Vision façade module nodes' thermal simulations for "Node 1 mullion-mullion": node transmittance analysis with U TJ = 2.253 W/m²K (**a**); condensation analysis with Tsimin = 13.3 °C ≥ 10.2 °C is verified (**b**).



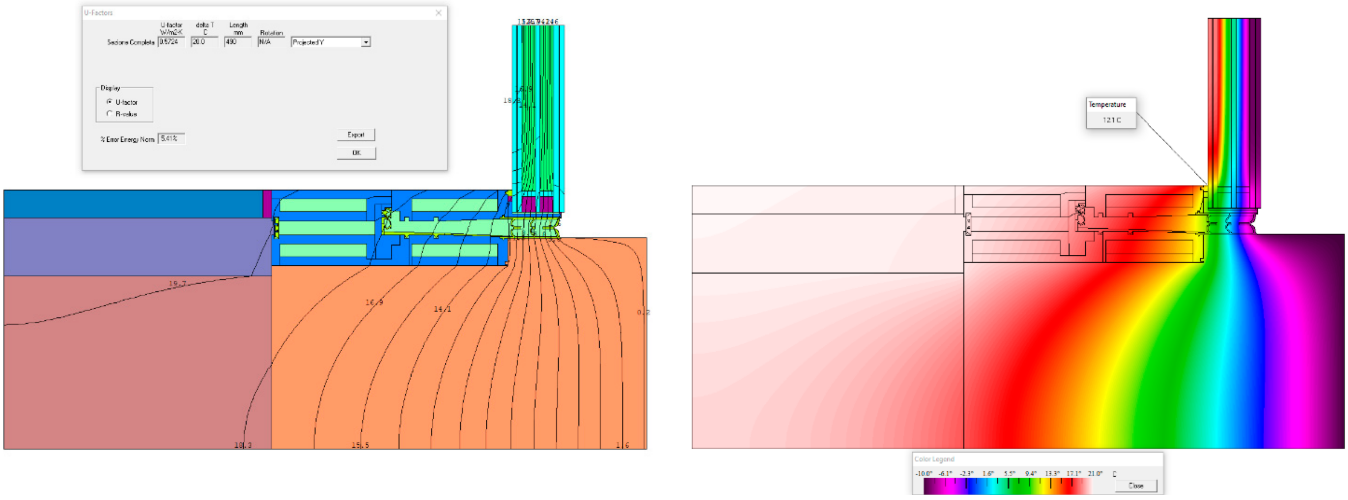
(**a**) (**b**)

Figure 19. Vision façade module nodes' thermal simulations for "Node 2 male transom-female transom": node transmittance analysis with U TJ = 2.331 W/m^{2}K (**a**); condensation analysis with Tsimin = 12.5 °C ≥ 10.2 °C is verified (**b**).



(**a**) (**b**)

Figure 20. Vision façade module nodes' thermal simulations for "Node 3 mullion-roof": node transmittance analysis with U TJ = 0.556 W/m^{2}K (**a**); condensation analysis with Tsimin = 10.7 °C ≥ 10.2 °C is verified (**b**).

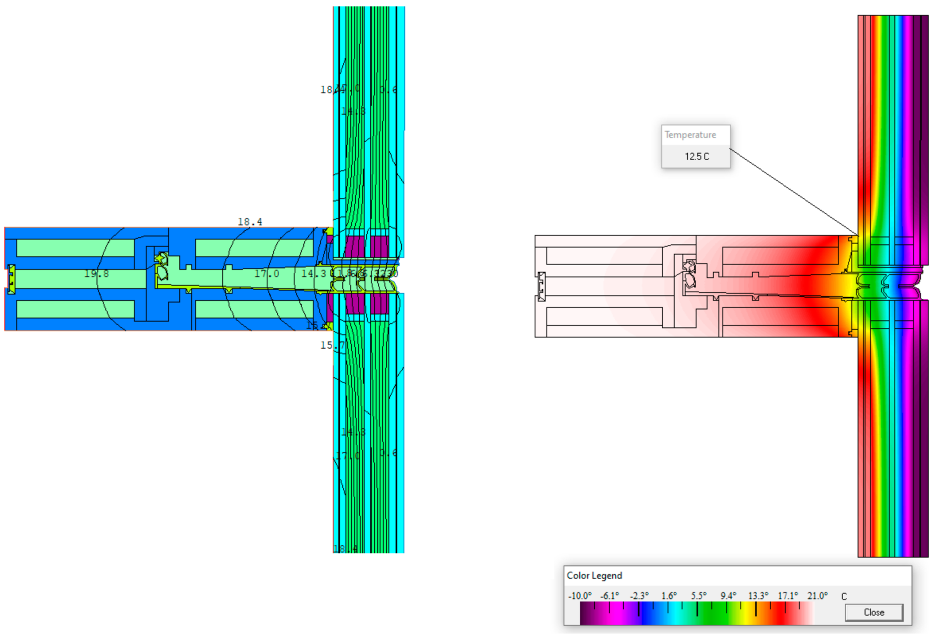


(**a**) (**b**)

Figure 21. Vision façade module nodes' thermal simulations for "Node 4 transom-ground interface": node transmittance analysis with U TJ = 2.331 W/m^{2}K (**a**); condensation analysis with Tsimin = 12.5 ≥ 10.2 [°C] is verified (**b**).

Table 18. Transmittance value of the vision façade module.

Node	Length m	Area m^2	UTJ W/m^{2}K	UTJ × A W/K
Node 1	0.9	2.498	2.253	5.630
Node 2	0.9	0.614	2.331	1.431
Node 3	0.36	2.525	0.556	1.404
Node 4	0.30	2.304	0.521	1.201
Node 5	0.24	2.732	0.852	2.328
Glass		44.894	0.650	29.181

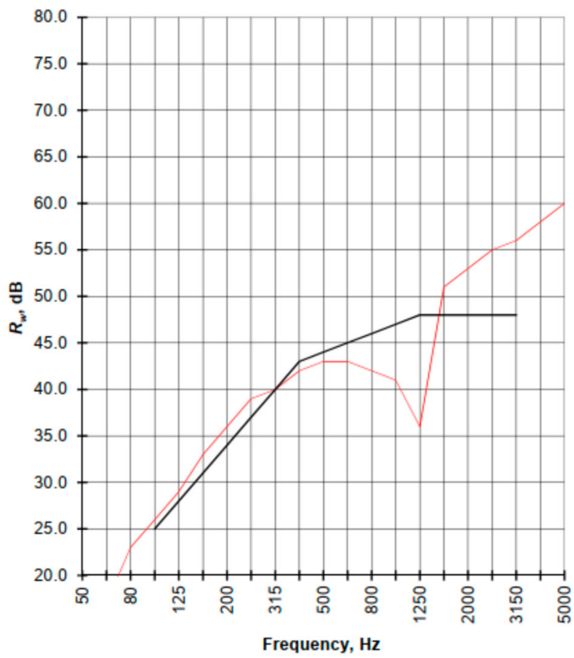


(**a**) (**b**)

Figure 22. Vision façade module nodes thermal simulations for "Node 5 male transom-female transom": node transmittance analysis with U TJ = 2.331 W/m^{2}K (**a**); condensation analysis with Tsimin = 12.5 ≥ 10.2 [°C] is verified (**b**).

For what concerns the acoustic simulation, the result for the vision module façade system is reported in Figure 23 with an insulation of R_W = 44 dB.

f (Hz)	R (dB)
50	13.0
63	17.0
80	23.0
100	26.0
125	29.0
160	33.0
200	36.0
250	39.0
315	40.0
400	42.0
500	43.0
630	43.0
800	42.0
1000	41.0
1250	36.0
1600	51.0
2000	53.0
2500	55.0
3150	56.0
4000	58.0
5000	60.0



SS-EN ISO 717-1

R_w	44 dB	C	=	-2	dB
max. dev.	12.0 dB	C_{tr}	=	-5	dB

Figure 23. Vision façade module acoustic performances with results of R_W = 44 dB. — Test plots; — Reference curve.

3.2.2. Opaque Module Façade System

The Basajaun opaque façade module (Figure 24 and Table 19) has an internal layer that comprises a plywood plate, providing structural support for an internal partition; two membranes; a vapor barrier on the inner surface, and a breathable counterpart on the outer, both exhibiting class A fire reaction properties, encapsulating the façade system. The insulation features a wood fiber material (fire reaction class E), ensuring both thermal efficiency and environmental sustainability protected for fire reaction owing to membranes. The fixation system for the external cladding, affixed to mullions, not only ensures stability but also allows for the convenient maintenance and replacement of cladding components. The comprehensive integration of materials, such as plywood and bio-composite profiles, underscores a commitment to quality and performance. The cladding system is maintained interchangeably. The connection system was revised, and steel plates were intended to be used for the connection between the frame and the external finish.

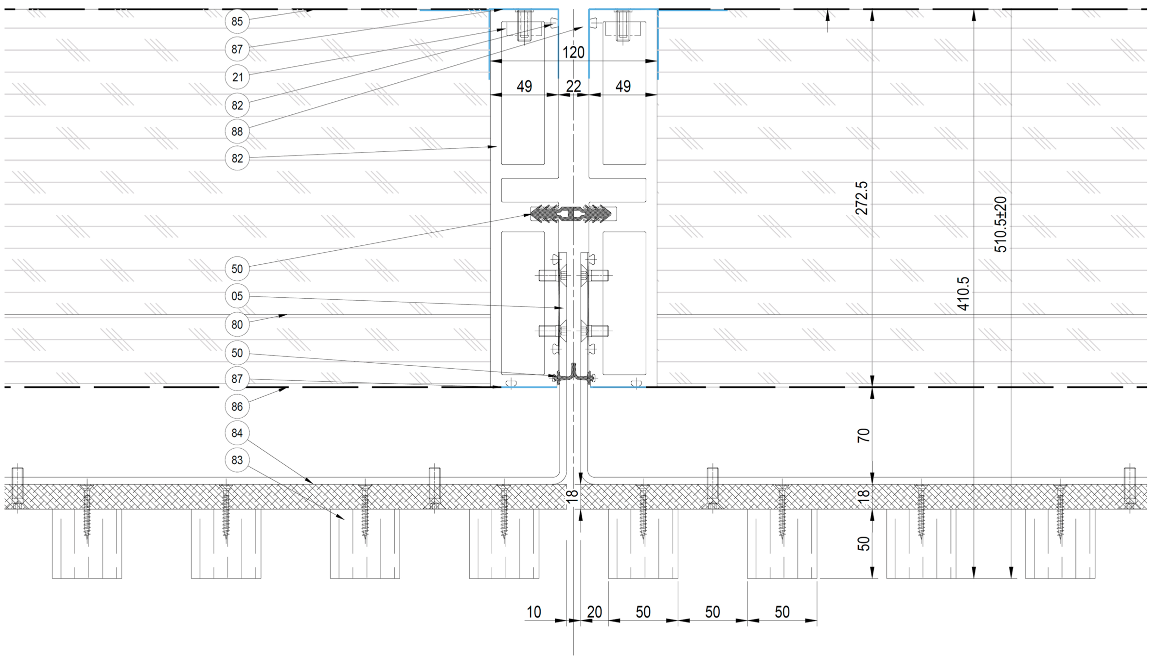


Figure 24. Final solution: horizontal section Basajaun opaque façade module. The numbers for the components' identification refer to Table 19.

For the mechanical simulation, the opaque façade module was verified because the loads on the façade were lower than those on the vision façade module already discussed in the related paragraph.

The thermal simulation of the opaque façade module was conducted to assess the overall thermal transmittance of the opaque façade module based on multiple node thermal simulations. The result achieved was a thermal transmittance of 0.27 W/m^{2}K, which was higher than the 0.20 W/m^{2}K requested by the French regulation and even more for the Finnish requirement of 0.17 W/m^{2}K. To address this issue, a new simulation was defined with an internal wall to be realized on-site with a layer of 70 mm on the wood fiber insulation and a 12.5 mm plater board. The thermal transmittance for the opaque façade plus the interior wall achieved 0.17 W/m^{2}K, suitable for both building requirements.

Table 19. Basajaun opaque façade module technologies.

Figure Code	Layer	Objectives	Characteristics
05	Stainless steel sheet AISI 316	To connect the external cladding to the frame	Structural part
21	Stainless steel accessory	To connect the anchor to the profile	Structural part
32	Galvanized steel bracket	-	-
50	EPDM gasket	Second water barrier	-
50	EPDM gasket	First water barrier	-
80	Insulated panel—fiber wood	Insulation	0.036 W/m^2K transmittance
82	Bio-composite profile- Mullions	To bead the unit load and connect it with the structural slab	To bead the unit load and connect it with the structural slab
83	Wooden Lamellas	External finishing	Reaction to fire class B1, s0-d0
84	Plywood	Internal plywood for false wall	Reaction to fire class B1, s0-d0
85	Internal membrane	Vapor barrier	Reaction to fire class A2, s1-d0
86	External membrane	Water barrier, wind load resistance	Reaction to fire class A2, s1-d0
87	Tape bioadhesive	To stick the membrane to the frame	-
88	Foam rubber	To not vibrate the internal key	-

Regarding the acoustic simulation, the result for the opaque module is shown in Figure 25, with an insulation of R_W = 44 dB.

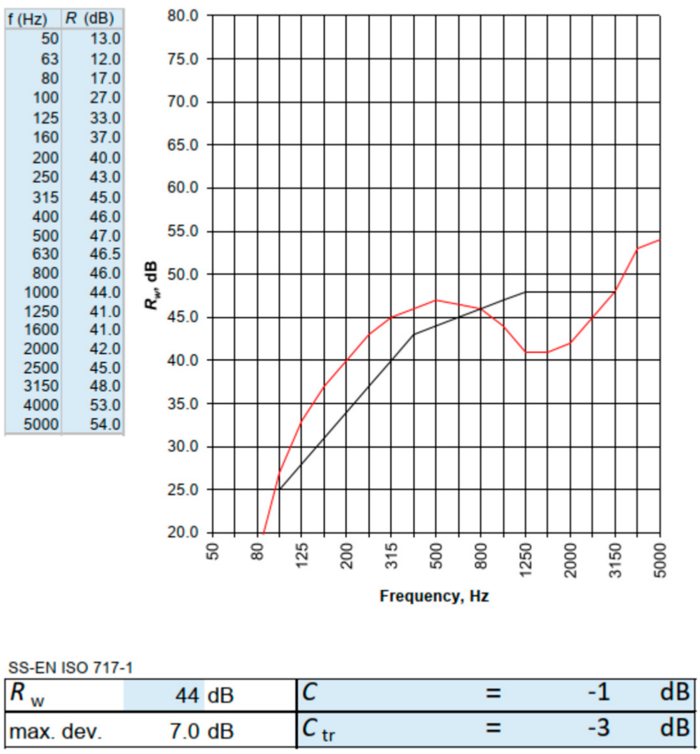


Figure 25. Opaque façade module acoustic performances with results of R_W = 44 dB. — Test plots; — Reference curve.

3.2.3. Window/Door Module Façade System

The opaque façade system was also equipped with a window or door product (Figure 26 and Table 20) to have a window/door façade module. This façade system requires the introduction of a window/door, a roller shutter, and a new bio-composite profile for the integration of a window/door into the façade system. An on-market wooden window product was integrated into the façade, with a bio-composite profile designed for this façade system. Additionally, a shading system in the window façade system was integrated with an external roller shutter.

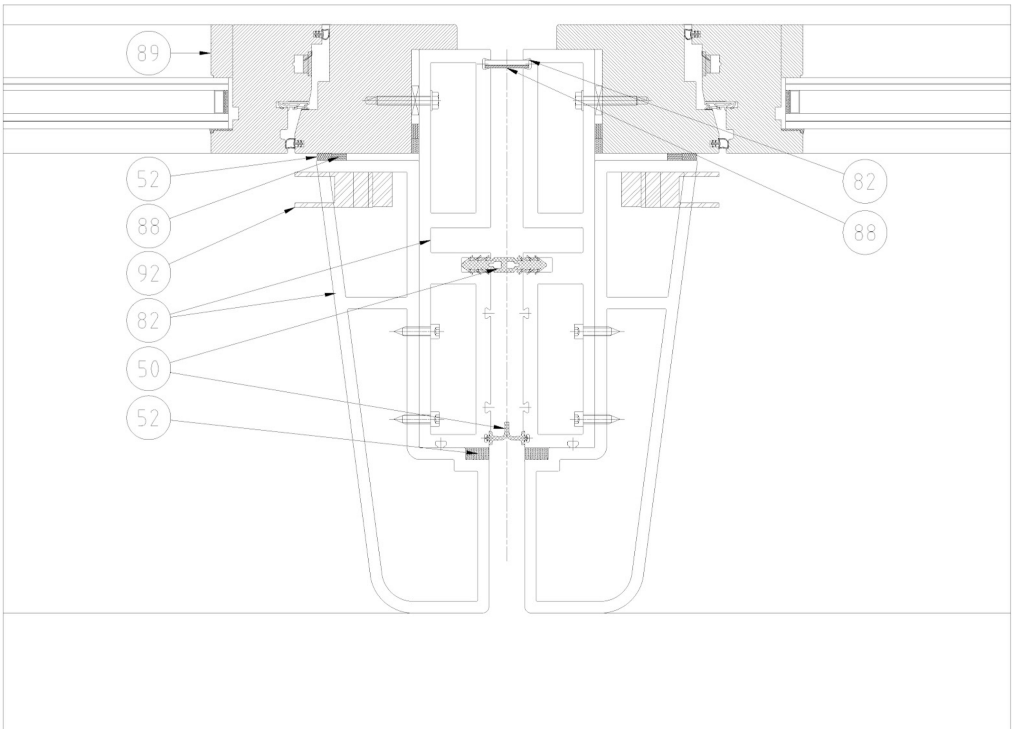


Figure 26. Final solution: horizontal section Basajaun window façade module. The numbers for the components' identification refer to Table 20.

Table 20. Basajaun window façade module technologies.

Code	Layer	Objectives	Characteristics
9	Openable	Natural ventilation	-
50	EPDM gasket	Second water barrier	-
50	EPDM gasket	First water barrier	-
52	Water seal silicone black color	To join the external frame to the internal frame	-
52	Water seal silicone black color	To join the openable to the frame	-
82	Bio-composite profile–internal key	To join two units	Thickness 3.5 mm
82	Bio-composite profile–mullions	To bead the unit load and connect it with the structural slab	Thickness 8/10 mm
82	Bio-composite profile–external frame	To cover the bio-composite profile—aesthetical aim	-
88	Foam rubber	To not vibrate the internal key	-
88	Foam rubber	To not drop the silicone	-
92	Roller shutter	to guarantee shading elements	-

4. Discussion

The development and design of bio-composite pultruded bars for façade system module frames for a bio-based façade system are feasible but require specific considerations from façade designers and a collaboration with the pultruded company. Based on this design and a simulation validation, also in comparison to the initial point of reference [31], the results can be discussed in two subjects of analysis:

- Bio-based pultruded profile for curtain wall façade.
    - Mechanical characterization: Mechanical characterization in line with curtain wall façade load requirements is achievable. This result is a balance between the formulation of resins and additives adopted, as well as the profile design (minimum thickness of 8 mm).
    - Profile shape: The specific design of a profile to comply with the pultrusion process differs from the extrusion adopted in aluminum bars, which can be a critical stage. The profile shapes are acceptable for production, and the grooves make the profile complex in terms of manufacturability, but also, owing to the expertise of the pultruded, it is feasible. Care must be taken when lacing up the rovings for grooves realization in the profile mold.
    - Tolerances: Usual tolerances for aluminum profiles are ±0.3/0.4 mm, which is acceptable for the external side but not feasible for internal parts. For bio-composite pultruded profiles, internal cavities require a tolerance of ±1 mm due to the inserts in the mold for their realization. These cavities are prepared with floating inserts, which are not fixed in the tool, and only the material (resin, roving, fabric) keeps them in the right position. Another aspect is the creation of small radii < 1 mm and the lacing up of the rovings to these areas in the profile mold. Notably, larger-curvature radii necessitate simpler gasket designs, which consequently affect the façade system design. The gasket grooves must be carefully designed and validated during initial bar pultrusion activities, and this will be part of the overall validation process for façade bar manufacturing.
    - Fire reaction: Beyond the adoption of fire retardants within the composite solutions, an alternative proposal for an extra coating of one layer of 250 µm or two layers of 650 µm was evaluated. The adoption of this coating would have guaranteed a profile fire reaction in Class A. However, due to the coating dimensions, its adoption needed to be evaluated before the profile design and mold manufacturing to allow for post-pultrusion application.
    - Shrinkage: Evaluated by the pultruded manufacturer to have a final profile designed by the façade designer, the adoption of bio-resin replacing conventional resin causes a different material shrinkage. If the shrinkage is significant, the shrinkage value is in the dimension of the production mold.
- Bio-based façade module system design.
    - The mechanical simulation for the façade's bar demonstrates the feasibility of a load stress façade module system. However, the required load capacity of the frame necessitates bars with larger dimensions than extruded aluminum profiles, with limitations on bar lengths. For façade manufacturing reasons, to keep the bar weight below 25 kg, the bar has a maximum length of 4 m. This bar length allows for addressing façade module dimensions. While the longer bar length facilitates façade module design, it also raises issues about its workability during cutting and machining processes for façade manufacturing due to the weight restriction of close to 25 kg. This aspect is a potential limitation for manufacturability and should be investigated during façade manufacturing.
    - The results achieved demonstrate that the curtain wall façade system's alternative components with lower environmental impacts [48] can also be technologically integrated into façade systems. Bio-based profiles, membranes, and tapes for tightness systems have emerged as technological alternatives to metal sheets and sealant systems in façade design. Membranes offer valuable alternatives due to their Class A fire reaction as well as for vapor barrier, water resistance, and wind load capability. However, bio-based profile and wood insulation are not in fire reaction in Class A, and this raises issues on specific market adoption where, as usual, practice or specific norms have request on Class A material. Further investigation is needed into market applications, particularly in markets like the UK,

where only Class A insulation is permitted. This limitation, especially following recent tragic fire events in multistorey buildings, warrants further discussion.

- Despite achieving the required thermal transmittance, using a 70 mm insulation layer in the internal wall raises concerns about adopting wood fiber insulation in curtain wall façades. To maintain the same thermal resistance, wider façades must be designed, impacting system size.
- Bio-composite-based curtain walls can be designed to comply with technical and normative requirements for real-world applicability. Additionally, multiple façade system typologies can be designed with the same profile. The overall system design appears to be in line with the requirements of the pilot references. Indeed, based on mechanical, thermal, and acoustic simulations, the bio-based façade system modules demonstrate compliance with the norms.
- The design results only partially validate the façade system, and specific tests are necessary to confirm the adoption of the bio-based profile. Tests must be conducted to verify the adhesion between tape/membrane systems and bio-based profiles. The tests should confirm the compatibility of structural silicone in direct contact with the bio-composite profile for the vision façade module system. This opportunity requires investigation into the adhesion behavior of the bio-composite profile with structural silicone and other sealants to be used in façade manufacturing (vision façade module) and during the installation stage (tightness sealing for curtain wall façade). For a comprehensive demonstration of the façade system in line with the European certification for façade testing, compliance with EN13830 will confirm the air- and water-tightness, wind load resistance, and impact resistance of the façade. Only through these tests can the validation of the designed technological system be confirmed.

5. Conclusions

The Basajaun façade system design demonstrates the technological integration of alternative eco-friendly components into curtain wall façade products. While environmental considerations have already shown the impact of these solutions in previous research activities, the iterative process for designing the façade module system in this paper also demonstrates that the desired results can be achieved technologically. However, replacing conventional components requires expertise to be acquired at different stages (design, pultrusion process, and façade manufacturing) to apply alternative products effectively. Thermal, mechanical, and acoustic performances can be achieved in line with curtain wall façade requirements on a European scale. The aforementioned activities demonstrated that the Basajaun façade system design is successfully aligned with the stipulated objectives and requirements of the Basajaun project, demonstrating accomplishments in several key areas. The achievements include the formulation of a novel bio-composite profile with enhanced mechanical properties, addressing the specified project requirements.

Beyond the achievements obtained by the Basajaun façade system, further steps must be planned with the aim of validating the façade system modules and, overall, demonstrating their marketability as follows:

- Enhancing the proportion of bio-based components in the profiles, with a specific emphasis on the resin content, to contribute to a more sustainable and environmentally friendly product.
- Conducting specific prototyping and test validation to demonstrate how the bio-based façade system achieves the normative standards based on established procedures. The results of the testing activities are published [59].
- Validate the Basajaun façade system design to demonstrate its applicability in pilot buildings with the development of the pilot detail design to investigate the consequences of a real-case design for manufacturing.
- Validate in the production line the façade manufacturing process to demonstrate the feasibility and cost-effectiveness of the tapes/membrane system replacing the

metal sheet and sealant as well as to understand the critical aspect for the cutting and machining of pultruded profiles with basalt fibers and their movement operations due to their higher weight than usual aluminum profile.

- Investigate the cost of bio-based façade modules, understand their competitiveness compared to conventional curtain wall façade systems, and determine any potential premium pricing for their adoption.

The bio-based façade module in curtain wall façade is an opportunity, but at this stage, it is not yet ready for market adoption. More investigation and further research on bio-based profile should be adopted to support its adoption and to demonstrate its competitiveness with conventional solutions.

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Conflicts of Interest: This information only reflects the authors' views and neither the Agency nor the Commission are responsible for any use that may be made of the information contained herein. The authors declare that they have no financial interests or personal relationships that could have influenced the work presented in this article.

Appendix A

Table A1. Conductivity values adopted for thermal simulation analysis.

Material	Thermal Conductivity	Source
Wood fiber insulation	0.038 W/mK	Manufacturer
Plywood, timber	0.13 W/mK	EN ISO 10456 [60]
Gypsum plasterboard	0.25 W/mK	EN ISO 10456 [60]
Bio-composite	0.35 W/mK	Assumed
EPDM gasket	0.25 W/mK	EN ISO 10456 [60]
Internal seal	0.35 W/mK	EN ISO 10456 [60]
Air cavity (unventilated)	Geometry-dependent	EN ISO 10211 [42]

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