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Article

A1–A5 Embodied Carbon Assessment to Evaluate Bio-Based Components in Façade System Modules

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Abstract: As the construction industry moves toward sustainable building practices, incorporating wood-based materials into building envelope systems has become a priority. This paper investigates the environmental impact of three custom bio-composite Façade System Modules (FSMs) through an Embodied Carbon Assessment (ECA), focused on the Global Warming Potential indicator of life cycle stages from cradle to practical completion (A1–A5). The evaluated FSMs were developed within the Basajaun H2020 project (G.A. 862942), by substituting and combining conventional materials with other bio-composite products to form hybrids from bio-based polymers and wood. A benchmark ECA was conducted, simulating alternative FSMs devised with common practice solutions for the curtain wall façade to facilitate a comprehensive comparison. The life cycle inventory encompassed detailed technical information, fostering the utilization of primary data for accuracy. The study particularly highlights considerations over three technological systems of the modules that incorporate increased use of wood-based components and a novel bio-composite material: the frame profiles, the insulation equipment, and the seal system. Despite the challenges due to the Basajaun FSMs' weight, the findings reveal that replacing the currently used materials with wood-based materials and bio-composites reduced the embodied emissions, particularly substituting aluminum frame profiles. The insights presented here offer indicators toward circular, environmentally conscious, bio-composed building envelopes, emphasizing the need for continued analysis and refinements as a consequence of increasing the accuracy of the available primary data from the supply chain and concerning end-of-life scenarios.

Keywords: bio-based building products; bio-based materials in construction; pultruded bio-composite profiles; green buildings; embodied carbon assessment; carbon footprint; modular façade systems; sustainable construction; building envelopes; innovative design



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1. Introduction

With the escalating concerns over resource consumption and the environmental impacts of the construction sector, the shift toward sustainable practices has become imperative [1,2]. The introduction in the construction industry of bio-based materials and wood products is one of the key topics to introduce and implement more sustainable practices in the whole value chain and during the building's life [3–6]. Moreover, the bio-economy and circular economy concepts exhibit synergies, particularly in the construction sector [7], and the adoption of circular and bio-based construction practices can also yield positive outcomes for the workforce and the surrounding community [8]. However, an indispensable concern for bio-based materials' competitiveness is the provision of dependable components that exhibit controlled durability with minimal maintenance requirements [9].

However, it may not always be feasible to produce completely bio-sourced materials that possess the required attributes to fulfill construction needs. Instead, bio-composite materials have the potential to offer exceptional construction characteristics and deliver superior performance and value [10]. They can also be realized through the pultrusion process, which is a well-established practice even in civil engineering [11,12]. A bio-composite material is a type of composite material comprised of a diverse array of organic as well as inorganic components, such as bio-based and synthetic polymers. Through the combination of these materials, a novel material is produced with the potential for improved performance over the individual constituent materials [13,14]. A comprehensive review of the sustainable construction applications of natural fiber bio-composites from Ahmad et al. states that they can be renewable, cost-effective, and potential substitutes for conventional materials. These bio-composites, primarily comprised of plant-based fibers and bio-resins, have applications ranging from reinforcement in concrete to non-load-bearing members like insulation and sound absorbers, showing promising results in terms of strength, ductility, and energy absorption [15]. However, more research is needed on their life cycle assessment, cost, and long-term durability to fully understand their potential and limitations [16].

Another relevant direction in contrasting the issues of the construction sector's environmental impact is the improvements in the lean prefabrication of façade modules, thanks to their advantages in circular and low-carbon development [17–19]. A large amount of eco-conscious façade systems are available to enable high-performance building design. For designers, a challenge lies in identifying novel technologies and sustainable systems that can ensure the building's structural integrity, acoustic and thermal requirements, and aesthetic appeal [20], in addition to adequate performances, minimized carbon footprint, and other environmental impacts, as well as disassembly for reuse or recycle potential [21]. In this scenario, the introduction of bio-composite materials and systems can represent a further boost for the building envelope construction market. Indeed, the building envelope is a complex system responsible for separating the outdoor and the indoor environments, which needs to satisfy different requirements from thermal–acoustic–mechanical performances, people's safety, and various technologies' integrability. The introduction of bio-composites must comply with all these requirements. On the other hand, prefabricated façade modules can also contribute to a more circular economy. They have advantages such as reducing CO₂ emissions, assembly time, and production waste, and facilitate disassembly, maintenance, and product durability [18,22]. In the realm of bio-composite façade module systems, it can be stated, based on the current understanding and evaluation of the authors, that the most notable accomplishments in Europe have been documented in the context of the two FP7 European projects—BioBuild [23] and OSIRYS [24]. At BioBuild, the commitment has been to meet the demand for reduced embodied energy compared to conventional methods. The innovative solution involved a panel crafted from a combination of natural fibers and natural resins [25–27]. On the other hand, the OSIRYS project has yielded a diverse array of solutions for external façades in the form of building envelope products that incorporate innovative bio-composite materials [28,29].

The focus of this article is the assessment of the environmental impacts of prototypes of Façade System Modules (FSMs) that have been developed as part of the Basajaun H2020 project (2019–2024; G.A. 862942) [30]. The primary aim of this project is to optimize the utilization of wood forest resources for the purpose of constructing a medium-sized wood-based building. The optimization process involves minimizing the consumption of harvested wood from the forest by leveraging innovative wood-based construction materials (such as bio-composites) and systems (such as custom façade systems). As part of this endeavor, these materials and systems have been upscaled, and a full-scale demo building has been constructed in the village of Le Pian-Médoc (Nouvelle-Aquitaine, France) for the purpose of validation. The design of the façade system has been built partially upon the expertise and achievements of the OSIRYS project (2013–2017). With respect to the experience of it, the Basajaun FSMs have been upgraded by using the same bio-composite profiles for both opaque and vision parts. This optimizes manufacturing during off-site

façade assembly. In addition, a new bio-composite profile has been realized, enabling the design of a new profile shape for the façade system. The male/female transom upgrade has been devised to enhance prefabrication and enable easier on-site installation with higher performance achievement for air and water tightness. The mechanical characteristics of the bio-composite profile have also been improved. Furthermore, the removable external cladding upgrade for the opaque façade system will allow the off-site installation of the external cladding while still providing the opportunity for its removal on-site for maintenance.

Despite its limitations, quantifying the potential contribution of emitted greenhouse gases to global warming is the most commonly used indicator for analyzing façade systems' environmental impacts [20,31]. In addition, the proposed amendment from the European Commission to the "Directive of the European Parliament and of the Council on the energy performance of buildings" can make the calculation of Global Warming Potential (GWP) even more meaningful. As it stands at the time of writing this article, if the amendment will complete the approval process, by 2027, "zero-emissions building" will replace the definition of "zero energy building" as the standard for all new buildings, and for all buildings undergoing transformative renovation from 2030 [32]. For this reason, the quantification of GWP is considered an inescapable duty. Moreover, regarding specifically the façade systems, the Centre for Window and Cladding Technology (CWCT) has emphasized the increasing significance of embodied carbon in façade assessment [33]. Considering these aspects, this article presents the results of an Embodied Carbon Assessment (ECA) conducted to estimate the greenhouse gas emissions from cradle to practical completion (A1–A5) and considerations regarding the circularity of the three experimental bio-composed Façade System Modules (FSMs) developed within the Basajaun H2020 project, emphasizing the significance of innovation and environmental accountability. All the construction requirements for these elements (i.e., acoustic, thermal, mechanical, resistance to weather elements, fire behavior) have been analyzed, simulated, and tested to comply with them. The Basajaun solutions have been developed with the target of design, and the solutions have been validated with a wide utilization and optimization of wood-based materials and bio-based polymers. However, behind the general purpose of the project, more façade-oriented objectives have been investigated, like the implementation of different types of façade systems and industrializing their prefabrication process in factories to make replication and installation easier and safer.

Particularly, the façade-oriented objective discussed in this article is the substitution of critical materials with other bio-composite products that combine bio-based polymers and wood in order to increase wood use and wood-based products in the façade system, reducing the carbon footprint and improving circularity.

2. Materials and Methods

2.1. Façade System Modules and Their Technological Systems

During the Basajaun project, three tailored Façade System Modules (FSMs) were developed. This article focuses on these modules of varying types and functions, along with their respective components, which serve as research materials for the environmental assessment presented in the article. Figure 1 shows a picture of these FSMs during the testing phase. The modules, which are 4.0 m tall and 1.2 m wide, have been defined as:

- Basajaun Glazed Vision FSM: This is a curtain wall module that is primarily composed of glass (about 500 kg in weight);
- Basajaun Opaque FSM: This is an opaque curtain wall module that does not contain any glass. It is typically used for areas of the building envelope that require more insulation or where transparency is not desired (255 kg in weight);
- Basajaun Window FSM: This is a curtain wall module that includes both glazed and opaque elements. The glazed portion allows for natural light, ventilation, and visibility, while the opaque portion, referred to as a spandrel portion, can hide building components or provide additional insulation (385 kg in weight).

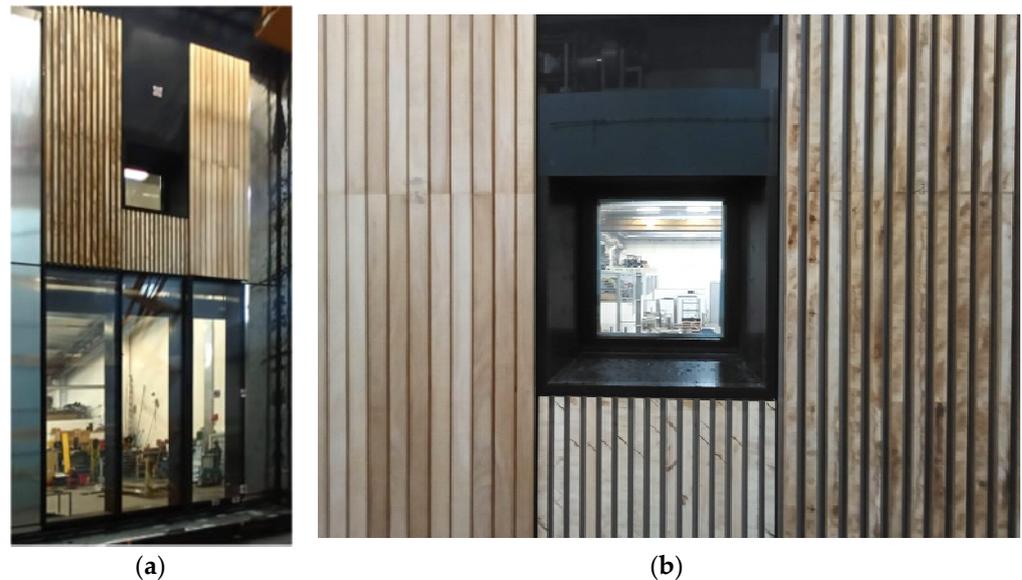


Figure 1. (a) Picture of the Basajaun Façade System Modules performance mock-up; (b) Detail picture of the Opaque and Window modules facing. Frame profiles in bio-composite.

Each module was meticulously crafted with an emphasis on wood-based materials, advanced technologies, and adherence to stringent performance standards. The overarching goal was to create an innovative and environmentally conscious building envelope that aligns with market requirements.

Starting with the Glazed Vision Module, it represents a fusion of aesthetic appeal and functionality. Structurally sealed glass is seamlessly integrated into bio-composite frame profiles. The bio-composite material is a key innovation, featuring a balance of bio-based resin, basalt fibers, and wooden particles. The module undergoes comprehensive mechanical, thermal, and acoustic simulations, affirming its resilience and thermal efficiency. The commitment to energy efficiency is further underscored by a detailed thermal analysis, meeting or exceeding the defined standards.

Moving on to the Opaque Module, the architectural element is marked by an integration of diverse materials and technologies. The internal layer consists of a plywood plate, providing structural integrity combined with the frame of bio-composite profiles (same as in the other FSMs), providing structural integrity as the foundation for subsequent components. Wood fiber insulation panels, with a minimum of 80% wood content, contribute to thermal efficiency. Membrane and sheathing systems, such as the plywood panels, eschew traditional aluminum cladding. The module undergoes thorough mechanical and thermal simulations, ensuring optimal performance under varying conditions. The incorporation of steel plates for connections is necessary to enhance stability and facilitates maintenance and disassembly.

The Window Module integrates a window block with a shading system through an external roller shutter. The façade frame introduces the new bio-composite profile, aligning with the commitment to sustainable materials. The utilization of wood-based insulation and membranes in sealing systems enhances the thermal efficiency while reducing the environmental impact.

The three FSMs incorporate the increased use of wood-based components and a novel bio-composite material in three key technological systems: the frame profiles, the insulation equipment, and the seal system. The subsequent sub-sections unveil the alternative solutions that have been devised for each system.

2.1.1. Bio-Composed Frame Profiles

The façade module's frame profiles are carefully crafted to complement the architectural design. The vertical mullions and horizontal transoms are strategically composed to

withstand mechanical stresses, adhere to module dimensions, and uphold the moment of inertia [34]. The Basajaun project entails the meticulous crafting of pultruded custom bio-composite profiles. Pultrusion technology is a continuous process where reinforcing fibers, such as fiberglass, are impregnated with resin and then pulled through a series of dies and cured to form a continuous profile. It is employed for manufacturing, ensuring a constant section composite with high mechanical strength [35]. On the other hand, extrusion, which is used for the crafting of an aluminum profile (most commonly used for FSMs), involves forcing a material through a die to form a profile with a constant cross-sectional shape.

The Basajaun bio-composite profiles feature a blend of components, primarily composed of a bio-based resin system and basalt fiber reinforcement. With a meticulous material ratio, the reinforcement accounts for 55%, comprising endless roving fibers and various types of woven roving. The resin system, constituting 45% of the composite, is a complex amalgamation of elements. Notably, 30% of the base resin is bio-based, incorporating succinic acid instead of conventional orthophthalic or isophthalic acid and recycled components. The bio-based resin system is enriched with a range of additives, including a shrinkage reducer, internal mold release agent, accelerator, catalyst, color paste, and air bubble remover additive. Additionally, 3% of the resin system is comprised of wooden particles, all of which are bio-based. The bio-based content is calculated by taking into consideration the proportion of the bio-based resin and the wooden particles. The resulting bio-based quantity stands at approximately 11.5% of the total mass. Numerous tests were conducted to ensure that the bio-composite profile meets the necessary requirements as a façade profile. This article will not delve into the specific characteristics of the material, but some test results will be provided to facilitate a better understanding of it. According to UNE EN ISO 527-4:1997 [36], the axial tensile strength of the profile is 409 MPa, and the axial modulus of elasticity (E_f) is 24,900 MPa. Additionally, results from axial compression strength tests according to UNE-EN ISO 14126:2001+AC:2002 [37] show a modulus of elasticity of 34,600 MPa, a compressive strength of 443 MPa, and a deformation in compressive strength of 1.8%. The thermal conductivity is 0.58 W/mK, assessed by the manufacturer within the project development. It is worth noting that even if durability analyses of the material were not conducted during the project, aging tests were conducted to evaluate the tightness of tapes and sheets. The Basajaun bio-composite profiles are depicted in Figure 2.



Figure 2. (a) Picture of the Basajaun bio-composite pultruded mullion profile; (b) Picture of the bio-composite frame of a Basajaun mock-up module.

2.1.2. Wood-Based Insulation Equipment

Insulation plays a pivotal role in enhancing the performance of the entire façade system [17]. Its primary function is to maintain the indoor temperature, and it also significantly

contributes to the energy efficiency of the building [38]. In the Basajaun Façade System, the insulation is entirely wood-based. The wood fiber insulation panels used are crafted from a combination of base and ancillary materials, ensuring a high-performance solution. The primary constituent is wood, with a minimum content of 80%, predominantly sourced from pine and supplemented by some hardwood. Notably, a minimum of 70% of the wood used is certified by the Program for the Endorsement of Forest Certification (PEFC) attesting to sustainable forestry practices [39]. Binding fibers contribute to the structural integrity of the panel, comprising 3–8% of the composition. The incorporation of these fibers enhances the material's overall strength and durability. Additionally, the panel contains water in the form of wood moisture, ranging from 4–8%, and ammonia phosphate, constituting 6–8% of the material. The material possesses specific characteristics as per the established required standards. The noteworthy characteristics are the gross density (as per EN 1602 [40]), which is 55 kg/m³, the thermal conductivity (as per EN 13171 [41]) of 0.038 W/(mK), and the water vapor diffusion resistance factor (as per EN 12667 [42]), which is 5. The wood fiber insulation placed in a mock-up module is depicted in Figure 3.



Figure 3. Picture of the wood fiber insulation panel placed in a Basajaun mock-up module.

2.1.3. Seals and Gaskets

Ensuring the building's envelope is protected from moisture and weather damage is a complex process that depends on various factors [43]. Thus, properly sealing a building's façade with non-combustible materials is critical for fire safety. Therefore, sealing the interfaces of the FSMs helps prevent the spread of fire by restricting airflow and flames. The Basajaun Façade System limits the use of aluminum sheets and silicon in façade modules.

The Basajaun FSMs incorporate three distinct sealing products used to enhance their functionality and performance. The first sheet features a reflective fire reaction vapor barrier screen, comprising an upper layer of aluminum film and a lower layer of fiberglass fabric. The second sheet is a highly breathable reflective membrane; its composition includes a protective layer of perforated aluminum film, an intermediate layer of functional PE film, and a bottom layer of fiberglass fabric. The third element, a double band, consists of layers that contribute to robust adhesion and reinforcement. It involves a separating layer of silicone-coated paper, solvent-free acrylic dispersion adhesive, a reinforcement grid made of polyester, and another layer of solvent-free acrylic dispersion adhesive. These diverse sealing products collectively contribute to the product's versatility, combining reflective properties, breathability, fire resistance, and robust adhesion for a comprehensive and effective solution.

On the other hand, the plywood panels' primary component is wood, constituting about 84%. This wood content encompasses a balanced selection of quality wood materials, contributing to the panel's overall strength and stability. To enhance the structural cohesion of the panel, 11% of the composition is resin, 0.16% is mastic, and 0.16% is additives. For

additional reinforcement, the panel features hardener and water, accounting for 5%, and glued tapes and composing glue, comprising 0.04% of the composition. Tapes, membranes, and plywood placed in a mock-up module are depicted in Figure 4.

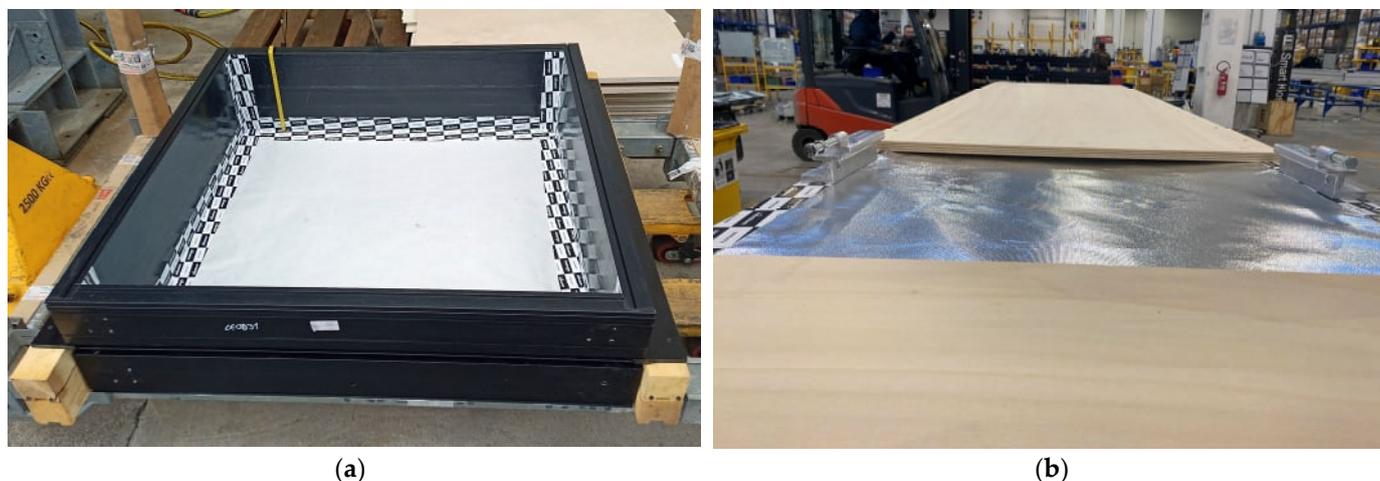


Figure 4. Picture of tapes, membranes (a), and plywood manels (b) placed in a Basajaun mock-up module.

These technological systems work together to ensure the FSMs are safe, functional, and efficient, contributing to the overall performance of the building.

2.2. Environmental Assessment Methodology

In order to be able to make more precise assessments regarding the environmental impact of these façade systems, the Global Warming Potential (GWP) of the modules was quantified. This was achieved by performing an Embodied Carbon Assessment (ECA) of all three FSMs considering a boundary from cradle to practical completion. During the calculation of the embodied carbon, the Centre of Window and Cladding Technology's method indications were considered [44]. With reference to the life cycle assessment (LCA) method defined by ISO EN 14044 [45,46]. After the goal and scope definition phase, defining the reasons for applying this methodology to the project, the other two phases of the ECA as defined by the norm were applied.

2.2.1. Life Cycle Inventory (LCI)

This phase involves calculating the input and output flows throughout the entire supply chain, based on the LCA methodology. This includes measuring quantities of components and materials, assuming their waste generation, and their consequential greenhouse gas emissions. Once the reference system flows are defined, the impacts are calculated using various stages defined by the standard. The presented study stages from cradle to practical completion have been considered (A1–A5). These stages include collecting quantitative project data on materials and components, as well as environmental data from primary (foreground) and secondary (background) sources.

2.2.2. Embodied Carbon Assessment Results

This last phase involves the final assessment by associating the LCI results with the environmental factors. The results presented are focused on GWP, the best known and most requested impact assessment category. Considering the limitations of this methodology when applied to bio-based materials [47] and that GWP is one of several categories of environmental impact, the results were analyzed considering biogenic carbon sequestration as emitted carbon dioxide during raw material supply.

3. Results

To better understand the environmental impact of the Basajaun Façade System Modules (FSMs), their Global Warming Potential (GWP) was quantified through an Embodied Carbon Assessment (ECA). Given the Basajaun H2020 project context, one of the goals is to assess the environmental performance of the façade modules from their raw material extraction to installation on the construction site. To that aim, the Embodied Carbon Committee of the Centre for Window and Cladding Technology (CWCT) published a report in 2022 that presents a peer-reviewed methodology for assessing the embodied carbon of façades [44]. This procedure focuses on the GWP environmental impact indicator and aligns it with whole-life carbon assessment documents from other construction industry bodies. The methodology is also aligned with the life cycle assessment (LCA) method, as defined by ISO EN 14044 [45,46], and considers the life cycle boundary as defined by EN 15804 and EN 15978 [48,49]. However, while designers and assessors should ideally consider as many life cycle modules as possible, CWCT has identified the minimum life cycle stages that should be included in a façade assessment. These stages include the product stage (A1–A3), construction process stage (A4–A5), replacement stage (B4), and end-of-life stage (C1–C4). The study presented herein has placed a particular emphasis on the A1–A5 stages due to a dearth of foreground data pertaining to the stages subsequent to practical compliance.

This methodology was applied to the three FSMs developed within the Basajaun project. Then, in order to establish a benchmark reference for the analysis and interpretation of the results, an ECA A1–A5 of parallel FSMs conceived as conventional was conducted, assuming the use of conventional materials and common practice solutions for the curtain wall façade for the different technological systems that met the same design requirements. Each technological system was then examined to identify alternatives that provided the same mechanical, thermal, and sealing performance as the Basajaun system. This led to the consideration of aluminum frame profiles in comparison with bio-composite profiles according to their mechanical characteristics and thermal resistance, mineral wool insulation in comparison with wood fiber according to their conductivity and density, and traditional sealing systems with gaskets and silicones in comparison with tapes and sealants according to their water and air tightness, as well as the use of aluminum sheets instead of plywood panels. No alternative glazing was considered due to its unique functionality. Other components, such as screws, nuts, and surface treatments, were assumed to be identical in both Basajaun and benchmarking versions, as their negligible mass and negligible CO₂ emissions made them inconsequential to the overall GWP comparison. Additionally, based on BS EN 15978 Section 9.4.3 and BS EN 15804 Section 6.3.6, components that do not exceed 1% of the façade system mass could have been excluded from the GWP calculation [48,49].

By emulating the process in a conventional manner, the aim was to assess the GWP consumption patterns of Basajaun FSMs against an abstraction of how they would have been as conventional. This approach not only provides a more comprehensive understanding of the unique characteristics of the custom design but also facilitates comparison by highlighting deviations from traditional practices.

3.1. Life Cycle Inventory

The technical information related to the manufacturing of the FSMs has been produced after completing the design stage. A comprehensive bill of supplies detailing all the necessary materials and components, along with technical drawings outlining the assembly steps and machining procedures, has been drafted for each module. Considering them, once the reference system flows have been defined as related to energy consumption, consumption of raw materials or waste, or greenhouse gas emissions, their GWP was calculated through the A1–A5 life cycle stages defined by the standard EN 15978 [49]. This inventory step requires: (1) the collection of quantitative project data on materials and components used and (2) the collection of environmental data (i.e., carbon factors) from primary (foreground) and

secondary (background) sources to evaluate the impact of the project. To ensure accuracy and reliability in analyzing the as-conventional module quantitative project data related to material composition and consumption, they were adjusted using conversion factors selected based on manufacturer information and research. This approach ensured that the virtual representation of the as-conventional modules reflected the anticipated material quantities that would be utilized in a common construction scenario. The sources of the data used in the ECA are indicated in Table 1, about the project data, and in Table 2 about the environmental data.

Table 1. Summary of the project data sources.

A1	
Modules' materials and components	Bill of components, products' datasheet, company's PLM and ERP, technical drawings, BIM model.
A2	
Materials and components' shipping information	Geographical position of the suppliers, company's PLM, ERP, and departments' worksheets, DDT.
A3	
Module manufacturing	Production plans.
A4	
Transport to the construction site	Geographical position of the construction site, shipping plans, company's PLM, ERP, and departments' worksheets, DDT.
A5	
Machine or plant usage on site due to modules' installation	Production and construction company.

Table 2. Summary of the environmental data sources (i.e., carbon factor sources).

A1		FU
Frame profiles		
Aluminum profiles	European Aluminum. Environmental Profile Report [50].	kg
Bio-composite profiles	Eco Impact Calculator for composites v.1.1.1 [51], primary data from the manufacturing company, and Azrague et al. [52].	kg
Insulation equipment		
Rock wool	Average from EPDs of panels with similar density and thermal conductivity.	m ³
Wood fiber	Used product EPD.	m ³
Seals and Gaskets		
Aluminum sheet	Aluminum Sheet European avg. Environmental Profile Report [50].	kg
Plywood	Used product EPD.	m ³
Tapes and sealants	Average from EPDs of products with similar characteristics.	m ²
EP and vulcanized seal	Ecoinvent v.3.7.1: Synthetic rubber [53].	kg
Other components		
IGU	Generic values CWCT [33].	m ²
Roller shutter	Average from EPDs of products with similar characteristics.	m ²
Finishing	Ecoinvent v.3.7.1: Powder coat, steel [54].	m ²
A2–A4		
Transport	Ecoinvent v.3.7.1: Transport, freight, lorry EURO5 {RER} avg 3 to >32 metric tons [55].	kg _{tran.ted} · km

Table 2. Cont.

A1		FU
A3		
Assembly off-site A3 waste rate	Primary data from the manufacturing company. How to calculate the embodied carbon of façades: a methodology; CWCT [44].	WRi = 3%
A5		
Energy consumption A5 waste rate	Report of emissions per kWh of the regions of the construction sites. How to calculate the embodied carbon of façades: a methodology; CWCT [44].	WRi = 3%

Given the significance of the implementation of bio-composite profiles in this study and the noteworthy interest surrounding them, it is deemed pertinent at this point to expound on the outcomes derived from the compilation of data pertaining to these innovative profiles.

Based on the composition outlined in Section 2.1.1, percentages were assigned to the mass unit relative to its contents, with 55% of the composite of reinforcement and 45% of the resin system. Every effort was made to attribute a carbon factor to each content, with a focus on foreground factors. However, the suppliers of the FSM components could not provide primary data about their impact; as a consequence, secondary data was utilized. To estimate their carbon factor, the Eco Impact Calculator for composites 1.1.1 was utilized. This digital tool enables the calculation of the environmental impact of composite products, from cradle to gate, as provided by the European Composites Industry Association (EuCIA). The background datasets for this tool are sourced from the SimaPro 9.3.0.3 software, and it is supplemented by industry data obtained through completed questionnaires [51]. However, it appears that there is still a lack of specific data regarding the content of the bio-resin system in the given quantities, as well as the reinforcement basalt fibers. As a result, it has been necessary to make assumptions about their carbon factors assuming one related to polyester resin and glass fibers, respectively. As a result, the carbon footprint calculated by the software of 1 kg of Basajaun profile is equal to 2.98 kgCO₂eq/kg. However, based on a thorough review of the relevant scientific literature to identify more specific carbon factors, revised calculations were carried out. In light of the carbon factor reported by Azrague et al. for a comparable basalt fiber reinforcement content [52] and more precise calculations regarding the consumption of the pultrusion process, the new calculations were conducted. Upon careful consideration, it has been determined that the carbon dioxide equivalent emissions associated with the retrieval of raw materials for one kilogram of the bio-composite developed in the Basajaun project amount to 1.67 kgCO₂eq/kg. Afterwards, when it comes to estimate pultrusion-related emissions, which is claimed to be one of the most cost-effective and competitive approaches to obtaining constant section composites [56,57], the operational parameters are critical in determining energy consumption. The pulling equipment used, according to the machine technical datasheet, requires 13 kW of unit power, while about 6 kW is allocated for heating the production dies. This is assuming 2/3 of the maximum heating power of 9 kW as, in the context of series production, maintaining a consistent level which is imperative and the exothermic heat generated during the process aids in heating up the die. Therefore, when calculating the energy used in one hour of the pultrusion process, the total reaches 19 kWh. The average pulling speed ranges from 0.25 to 0.30 m/min, which translates to 15 to 18 m/hour, and 180 to 216 kg of profiles. Consequently, the energy consumption per kilogram of the pultruded main profile is estimated to be between 88 and 105 Wh/kg. Considering the green carbon factor of the pultrusion plant region, of 215 gCO₂eq/kWh, it has been assumed a carbon factor for the pultrusion process of the Basajaun bio-composite profile of about 0.021 kgCO₂eq/kg. On the other hand, in the extrusion realm, average pulling speeds range from 3 to 12 m/min, requiring 45 to 90 kW of power, with an output

ranging from 150 to 250 kg per hour. That means applying the same green carbon factor as the pultrusion plant would achieve 0.072 kgCO₂eq/kg. Despite the bio-composite profiles, which have been specifically designed for the structural frame (as the one depicted in Figure 2), exhibiting a notable weight of 12–15 kg/m. It has been determined that a conventional extruded aluminum profile, when subjected to identical loads and tension, would weigh approximately 7 kg/m. However, it is important to note that these values are approximate, as precise measurements have not been conducted during the design and production.

The article refrains from specifying additional data assumptions for other technological systems, owing to the fact that they are composed of materials that are more prevalent and conventional in the market. As indicated in Table 2, Environmental Product Declarations (EPDs) have been made available for insulation and plywood panels.

3.2. Embodied Carbon Assessment Results

The last stage involves the final assessment by associating the collected data in the ECA results. It is important to note that the impact of phase A1 should be understood as the impact of the components of the façade module. Therefore, the A1 impact of a component belonging to an FSM does not solely refer to the extraction of its raw materials but also to their pre-processing in other plants. For example, in the study presented here, item A1 of a bio-composite profile corresponds to the extraction of its raw materials, its transportation to the plant where it was pultruded, and the impact of the pultrusion.

Furthermore, prior to presenting the results, it is crucial to highlight that the findings regarding the influence of transportation in the supply chain do not represent a typical supply chain. This is because the modules being analyzed are part of a European initiative (Basajaun project) involving industrial partners located across the continent, such as Italy, Spain, and Hungary. Consequently, the impacts related to transport (A2 and A4) are probably higher than what they would be in a typical supply chain.

In the subsequent sub-sections, the outcomes of both the Basajaun FSMs and the as-conventional FSMs have been expounded through a series of explanatory graphs. These graphs have been categorized based on the three FSMs, namely Glazed Vision FSM (Figures 5–7), Opaque FSM (Figures 8–10), and Window FSM (Figures 11–13).

3.2.1. Glazed Vision FSM

Each FSM sub-section includes a histogram that compiles the GWP results from the five stages of the module life cycle. The first column displays results from the as-conventional module (light blue), while the second column shows results from the Basajaun module (green). The values from different stages have been merged in different manners to better understand their impact on the total. The values represent the impact of the entire façade modules, which are 4.0 m tall and 1.2 m wide (kgCO₂eq) or they are normalized to m² (kgCO₂eq/m²) depending on the bar description in the histogram. The mass of the modules differs depending on the FSM type; it is about 500 kg for the Glazed Vision FSM, 385 kg for the Window FSM, and 255 kg for the Opaque one.

In all three cases, the stage causing the highest emissions is A1 due to the complexity of the components of the façade modules. According to the findings, the A1 stage of the bio-composite version yields 9.64×10^2 kgCO₂eq (2.01×10^2 kgCO₂eq/m²), whereas the as-conventional version results in 1.15×10^3 kgCO₂eq (2.39×10^2 kgCO₂eq/m²). Furthermore, the factory responsible for assembling the components is powered by photovoltaic panels, and the site operations are confined to module installation and sealing operations. As a result, the environmental impact of these stages is remarkably low if compared to A1. A3 values are invariant across both versions, yielding a result of 1.14×10^1 . This is attributed to the assumption of an equal assembly process for all the FSMs. A5 values differ slightly between the as-conventional and Basajaun versions. In the as-conventional version, the A5 value is 4.59×10^{-2} kgCO₂eq, whereas in the Basajaun version, it is 5.05×10^{-2} kgCO₂eq due to the increased weight.

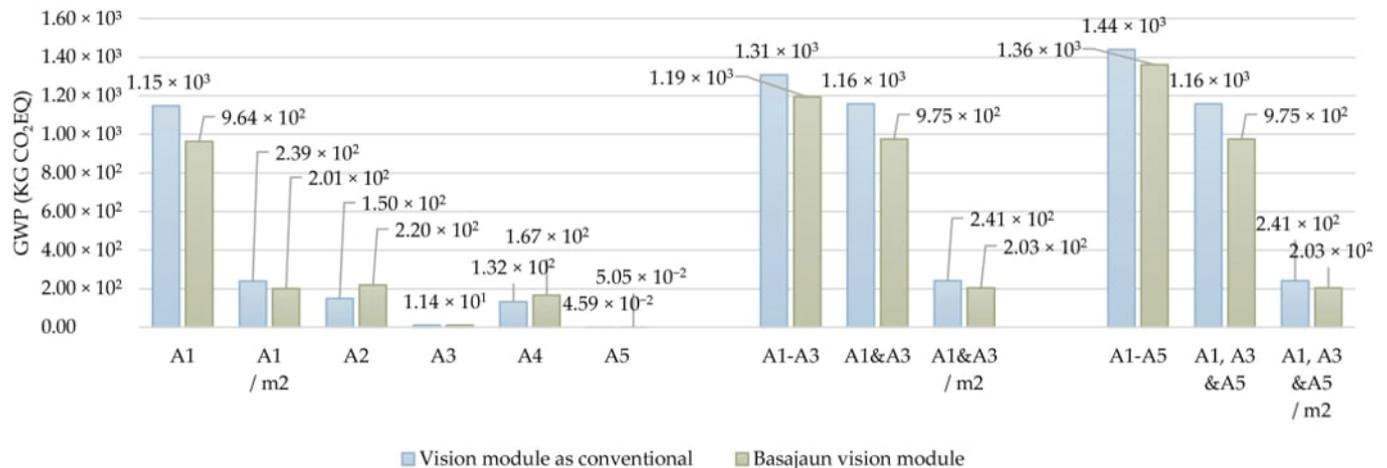


Figure 5. Comparison of the Basajaun and as-conventional Glazed Vision FSM results: A1–A5 GWP.

The second histogram displayed in each FSM section provides a more detailed analysis of the impact of individual technological systems, as previously presented in Section 2.1.1. The GWP values encompass all components of the FSM.

These are the only charts where the impact considering the carbon included in the wood-based products is presented, referred to as “Basajaun—Considering biogenic carbon stored in the materials.” Biogenic carbon is derived from biological sources and is associated with the carbon stored in the biomass. When conducting an ECA or an LCA, the carbon in these products is usually considered separately from fossil carbon, which comes from non-renewable sources. Trees absorb carbon dioxide during growth and store it in their biomass. When harvested and used to make products, this stored carbon contributes to a negative value in the GWP. This carbon sequestration aspect is a key reason why wood products are considered environmentally beneficial, as they can help offset carbon emissions. Although there is no consensus on the assessment of biogenic carbon in LCA, different methodological choices and assumptions can lead to opposite conclusions [58]. For this reason, it is important to clearly state how this is considered. In the presentation of the findings, the discounting of biogenic carbon dioxide was considered valuable to ensure a more effective comparison of the proposed solutions despite the narrow boundary. In the A1 values displayed, the biogenic carbon is then considered as actual emissions. Nonetheless, given its significance, a bar has been included to reflect the results of the Basajaun module in the event that it is taken into account (Figures 6, 9 and 12).

Specifically, Figure 6 pertains to the Glazed Vision module that lacks a spandrel portion and therefore has no insulation-related impacts. Notably, the “other components” category presents high values due to the inclusion of glass, which comprises the major surface and mass of the module. Finally, since bio-composite profiles have a limited wood-based component and since there are no plywood panels, the reductions given by biogenic carbon are not significant.

In each FSM section, the final figure provides a more precise breakdown of A1’s GWP, detailing each component type within the analyzed module. The left side displays graphs related to the as-conventional module, while the right side displays graphs related to the Basajaun-developed module. Components and materials assumed as unchanged between the two versions are represented in grayscale, while components belonging to different technological systems are shown in color to aid in comparison. The histograms display absolute values for the entire module, while the pie charts illustrate the components’ perceptual impact on the total A1 GWP. The height of the bar and the corresponding value above it reflect the outcome derived from the primary environmental data gathered during the LCI phase. Conversely, the error bar signifies

the potential variance in results that could arise from utilizing secondary data from external databases or considering alternative suppliers.

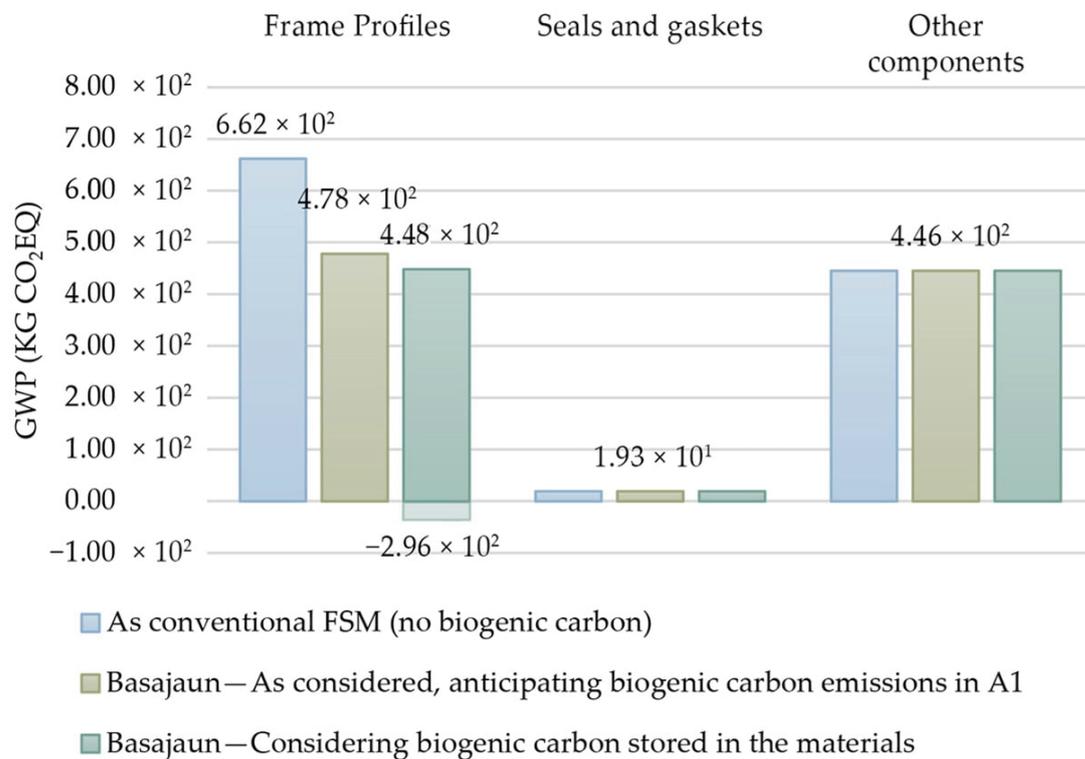


Figure 6. Glazed Vision FSM technological systems comparison of A1 GWP.

The figure related to the Glazed Vision FSM is Figure 7; it reveals that the primary contributors to emissions of this FSM are the frame profiles and glass components. It is notable that the Glazed Vision system demonstrates a reduction in the GHG emissions only regarding the structural profiles, benefiting from bio-composed materials with respect to aluminum profiles. The item labeled as ‘Extruded profiles’ in the two diagrams, which also appears in the following FSM sections, encompasses all the connection elements that are integrated into the module. These elements had to be made of either stainless steel or aluminum due to structural safety considerations.

The comprehensive error bar observed in the aluminum profiles—which, as pointed out, represents possible alternative outcomes by assuming different data—is due to the variability of GWP among similar aluminum-extruded products in the market. The values used for evaluating aluminum profiles in the as-conventional FSM are obtained from the Environmental Profile Report [50], whereas profiles containing 36% recycled aluminum are indicated as the European average. However, some exceptional products available in the market contain 75% recycled content and possess environmental certifications that attest to GWP per kg values that are 45% lower than the values used in this analysis [59]. Conversely, some international databases report values that are up to four times higher than the values used in this study [60]. These factors contribute to the large error bar observed in the graph for aluminum profiles. Then again, the error bar pertaining to the profiles in bio-composites is representative of the value that would have been obtained had the result been derived from the Eco Impact Calculator for composites 1.1.1 from EuCIA.

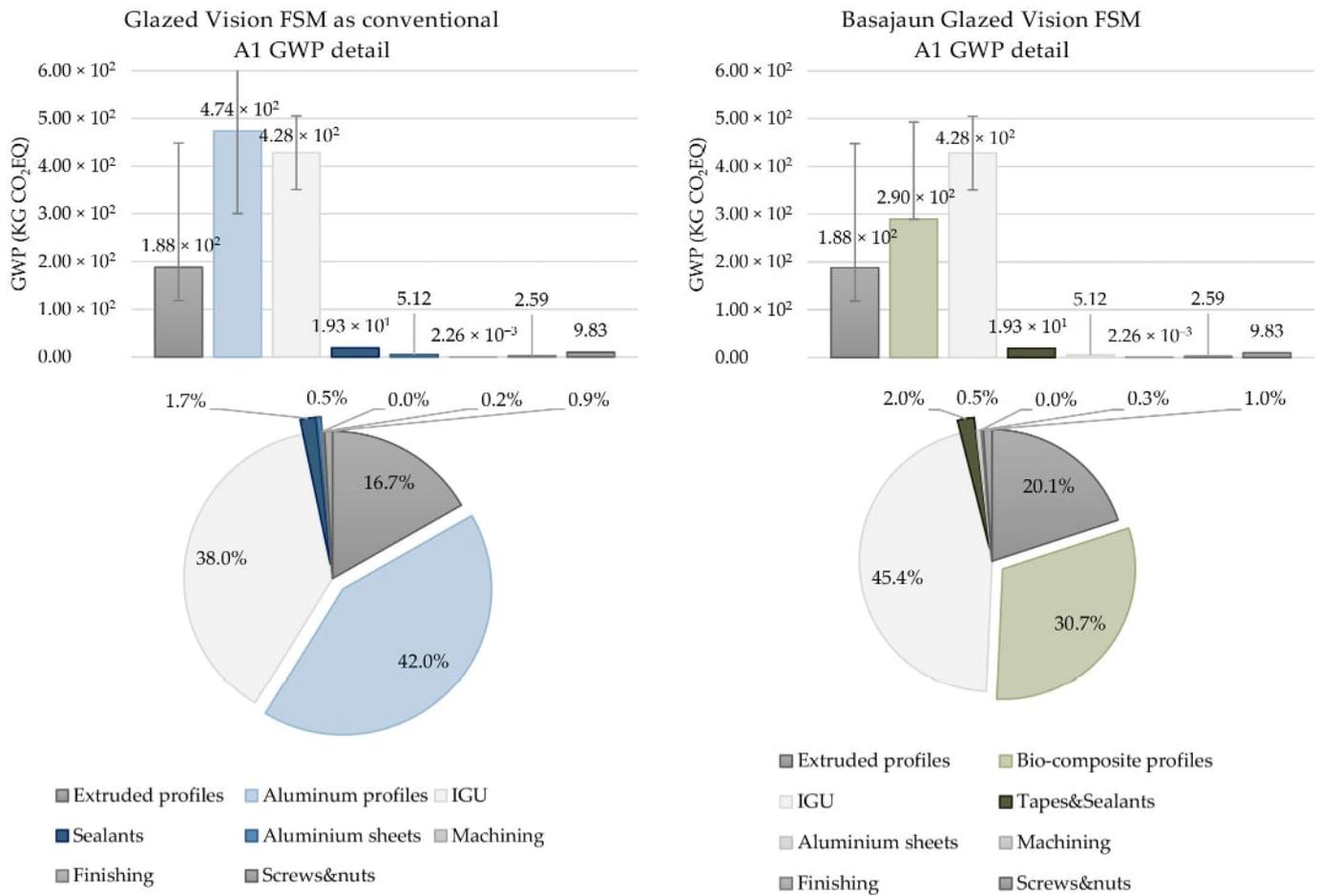


Figure 7. Comparison of the Basajaun and as-conventional Glazed Vision FSM results: A1 GWP detail.

3.2.2. Opaque FSM

As for the previous FSM section, the first figure, Figure 8, displays a comprehensive cross-section of the results obtained from the different GWPs analyzed in various stages. As for the Glazed Vision module, the impacts of A3 and A5 are relatively inconsequential compared to the other factors. The GWP of A1 for the Basajaun Opaque module is 6.38×10^2 kgCO₂eq (1.33×10^2 kgCO₂eq/m²), while that of the as-conventional module is 8.60×10^2 kgCO₂eq (1.79×10^2 kgCO₂eq/m²).

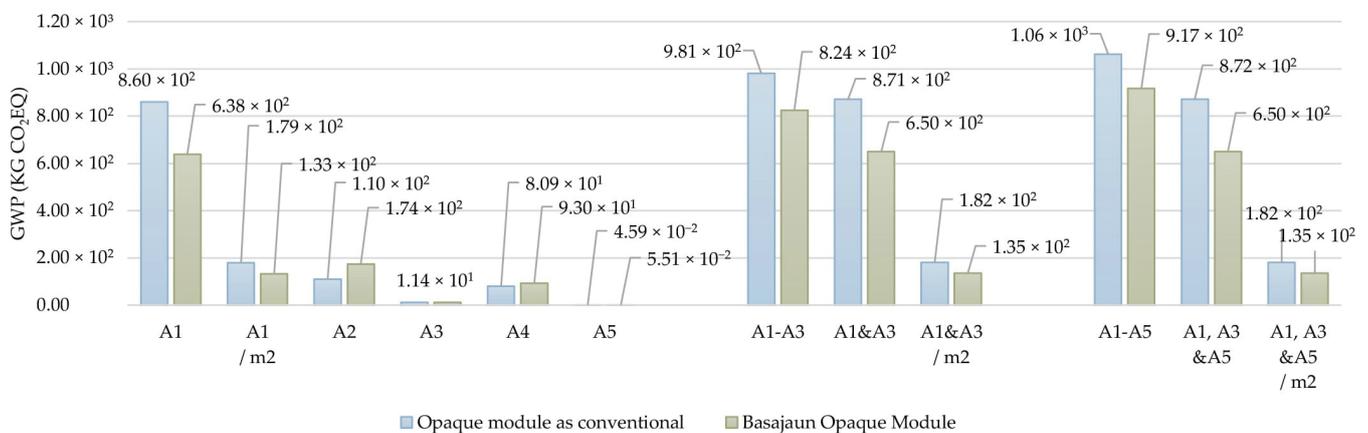


Figure 8. Comparison of the Basajaun and as-conventional Opaque FSM results: A1–A5 GWP.

In Figure 9, a closer look at A1 GWP is presented. Since it is about Opaque FSM, the impact of insulation equipment and the part about sealing and related aluminum sheets or plywood panels appear in the graph. When comparing the results of the as-conventional FSM, it becomes evident that the impact related to the aluminum-extruded profiles is higher than the impact of insulation and seals equipment. However, with the Basajaun FSM, the impact of various factors is more evenly balanced and lower overall. It is worth noting that when considering biogenic carbon in the Basajaun modules, the items related to insulation and sealing exhibit significant variation. Specifically, with wood fiber panels, the majority of GHG emissions are associated with the release of embedded carbon during end-of-life disposal.

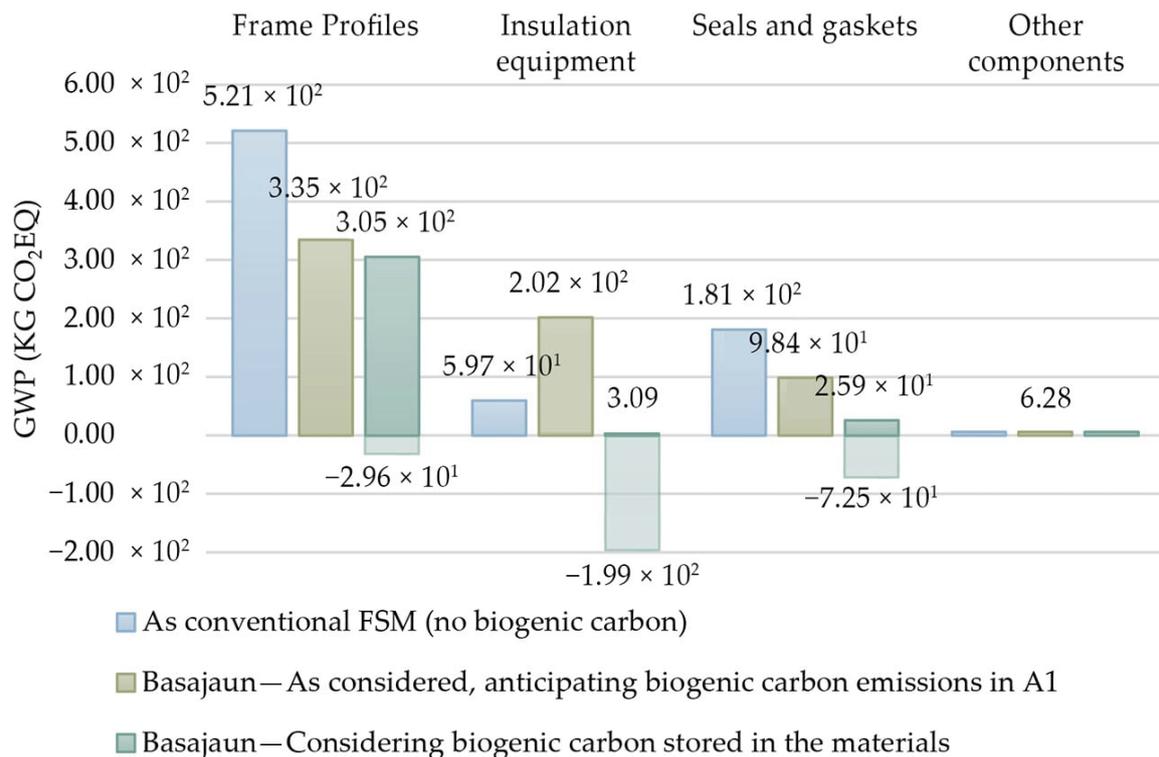


Figure 9. Opaque FSM technological systems comparison of A1 GWP.

Figure 10 presents detailed graphs of the impact of stage A1 on the Opaque modules, revealing insights. The as-conventional module shows that almost all of its impact is attributed to extruded profiles and aluminum sheets, which account for 94.9% of the total. In contrast, the Basajaun module balances this percentage with a combination of extruded and pultruded profiles (55.6%) and plywood (11.8%), due to the significant impact of wood fiber insulation (31.5%). It is important to note that biogenic carbon was considered in this graph as emitted in A1.

One can also observe the significant error bars of the insulation equipment in both versions. The EPD of the products used in making the mock-up was used for the analysis, and the histogram bar represents its value. However, the error indicates the result that could have been obtained with other similar products available on the European market whose EPD was public.

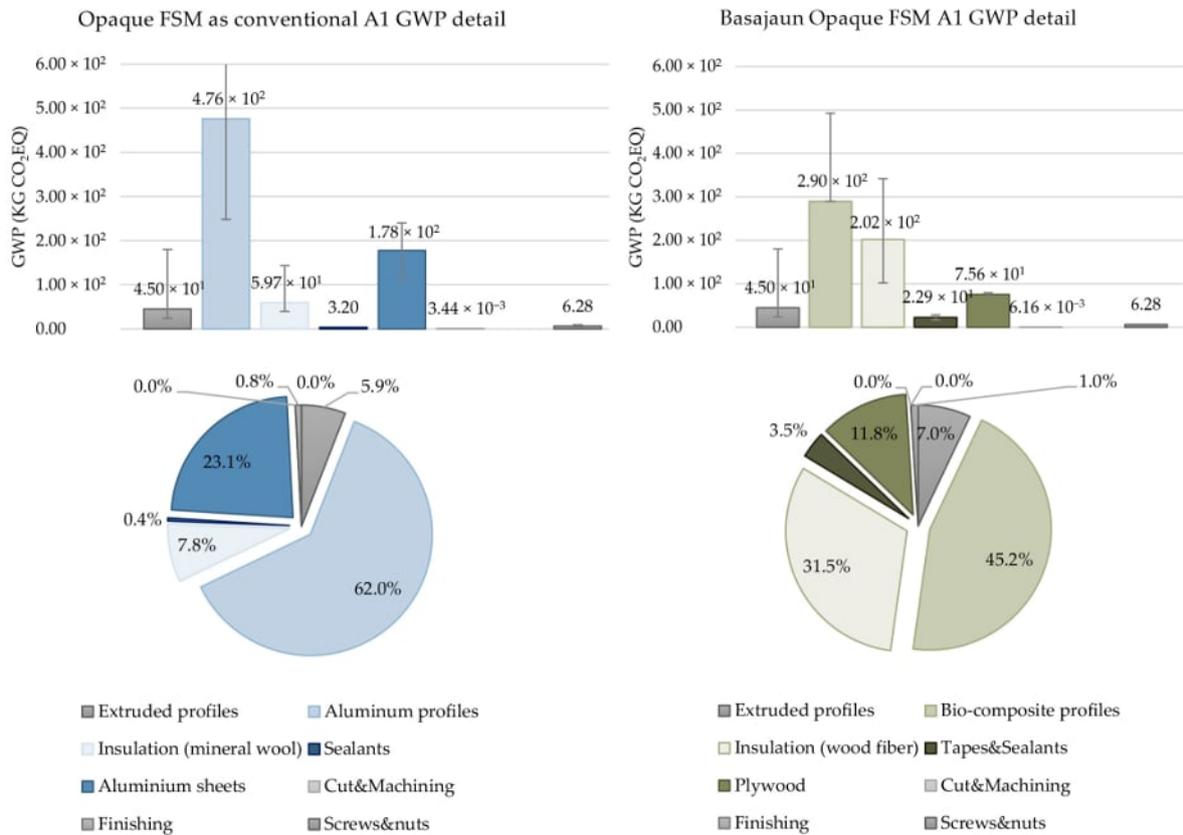


Figure 10. Comparison of the Basajaun and as-conventional Opaque FSM results: A1 GWP detail.

3.2.3. Window FSM

After analyzing the three FSMs, it was observed that the Window module had a more elevated impact compared to the other two. The data reveals an A1–A5 GWP of 1.52×10^3 kgCO₂eq (3.16×10^2 kgCO₂eq/m²) for the Basajaun model, whereas if it had been designed as conventional, 1.71×10^3 kgCO₂eq (3.56×10^2 kgCO₂eq/m²). The detailed results are presented in Figure 11.

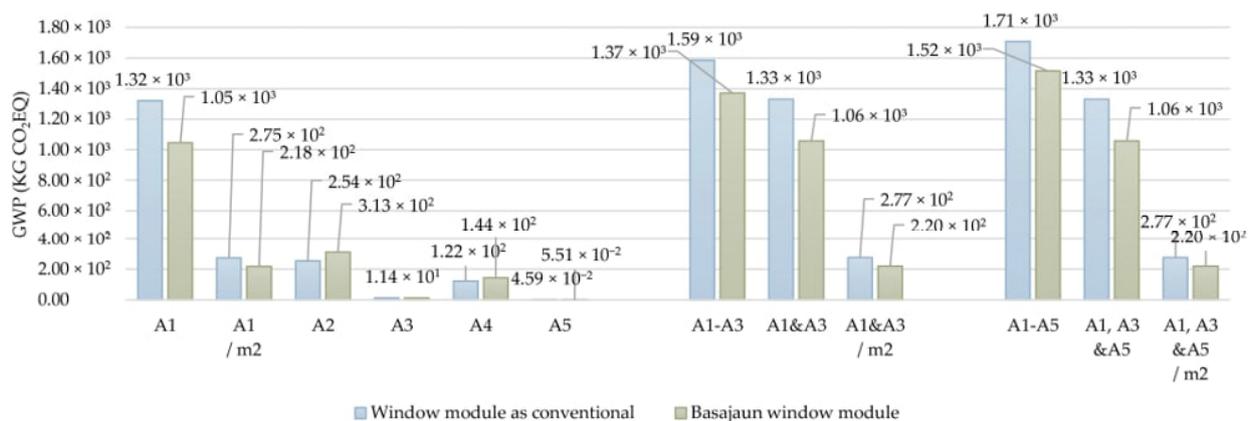


Figure 11. Comparison of the Basajaun and as-conventional Window FSM results: A1–A5 GWP.

The assessments pertaining to Figure 12 mirror those of Figure 9. Nevertheless, it is worth noting that the frame profiles exhibit a higher GWP value owing to their added responsibility of accommodating an opening window, thereby requiring more and larger sections. The “other materials” category also shows an increase due to the inclusion of the window glass.

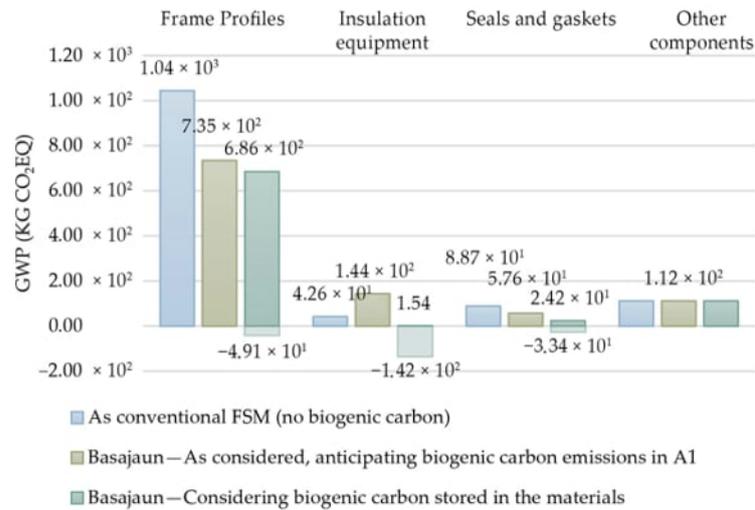


Figure 12. Window FSM technological systems comparison of A1 GWP.

Analogous to the other sections within the FSM, the final figure in this series illustrates the specifics of the results for A1 GWP, as seen in Figure 13. The profiles carry a greater weight, resulting in a more pronounced indicator for them. In contrast, the glass component holds less weight compared to the Glazed Vision FSM, since it only covers a smaller surface area of 1.1 m^2 .

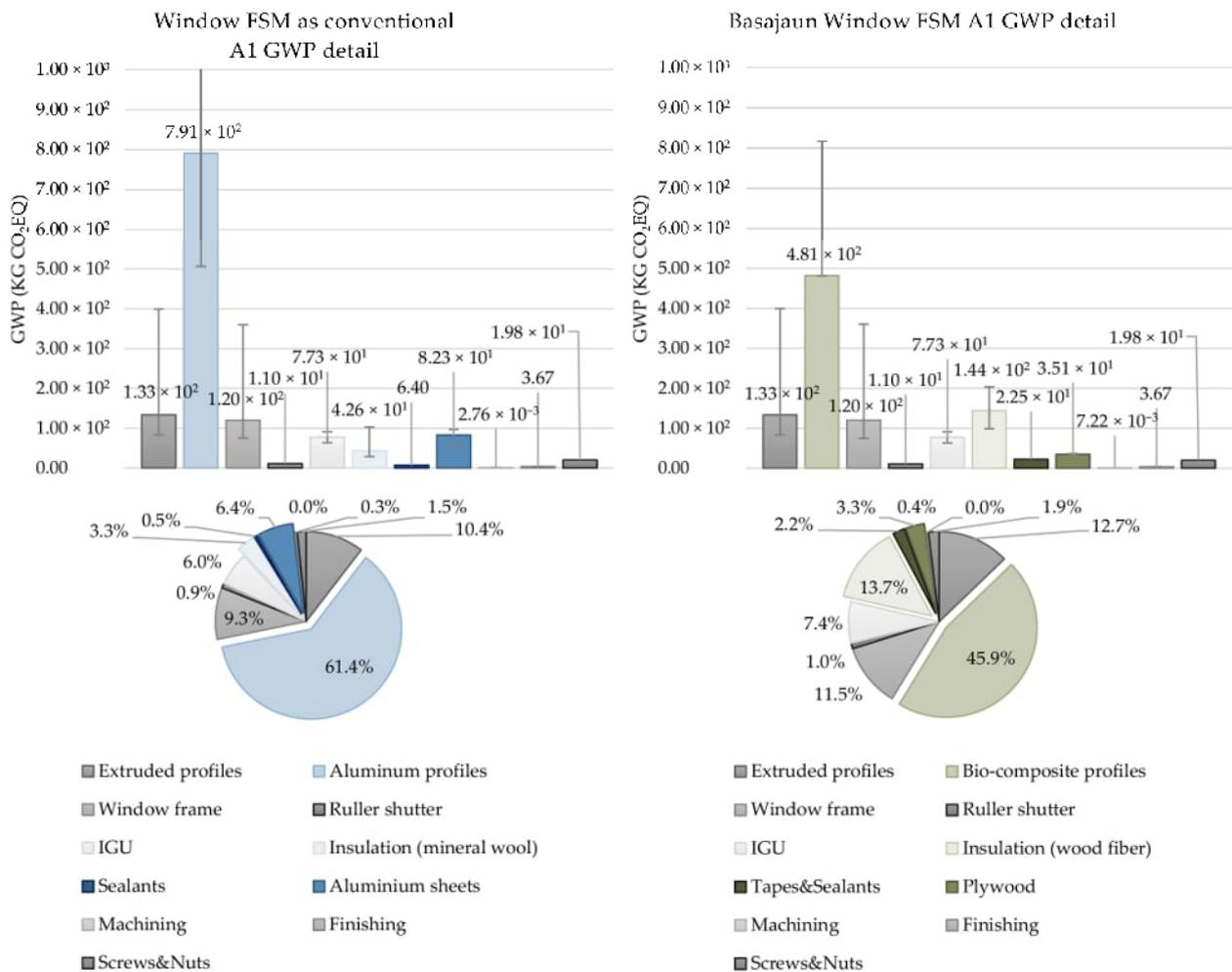


Figure 13. Comparison of the Basajaun and as-conventional Window FSM results: A1 GWP detail.

4. Discussion

This section will synthesize the key discussions about the Basajaun project objective related to Façade System Development described in the introduction. It will explore how the implementation of different façade typologies, industrialized manufacturing processes, and the use of bio-composites converge to create innovative building envelope solutions with lower emissions. The objective was to design a façade system that substitutes currently used materials with the highest wood-based and bio-composite contents while maintaining system performance and reducing carbon footprint.

Regarding the reduction in CO₂ emissions, the Embodied Carbon Assessment (ECA) performed for stages A1–A5, yielded results that align with the predicted carbon footprint reductions across all three Façade System Modules (FSMs) designed. Table 3 provides a summary of the analysis results and the corresponding percentage decrease in Global Warming Potential (GWP) for each FSM.

Table 3. Summary of the GWP reduction thanks to the Basajaun approach in the three FSMs.

	Glazed Vision FSM		Opaque FSM		Window FSM	
	kgCO ₂ /Module	kgCO ₂ /m ²	kgCO ₂ /Module	kgCO ₂ /m ²	kgCO ₂ /Module	kgCO ₂ /m ²
A1 as-conventional	1.15×10^3	2.39×10^2	8.60×10^2	1.79×10^2	1.32×10^3	2.75×10^2
A1 Basajaun	9.64×10^2	2.01×10^2	6.38×10^2	1.33×10^2	1.05×10^3	2.18×10^2
	reduction:	16%	reduction:	26%	reduction:	21%
A1, A3, and A5 as-conventional	1.16×10^3	2.41×10^2	8.72×10^2	1.82×10^2	1.33×10^3	2.77×10^2
A1, A3, and A5 Basajaun	9.75×10^2	2.03×10^2	6.50×10^2	1.35×10^2	1.06×10^3	2.20×10^2
	reduction:	16%	reduction:	25%	reduction:	21%
A1–A5 as-conventional	1.44×10^3	3.00×10^2	1.06×10^3	2.21×10^2	1.71×10^3	3.56×10^2
A1–A5 Basajaun	1.36×10^3	2.84×10^2	9.17×10^2	1.91×10^2	1.52×10^3	3.16×10^2
	reduction:	5%	reduction:	14%	reduction:	11%

The results of the ECA for these Façade System Modules revealed that the materials with the highest CO₂ emissions were the frame profiles and glass due to their quantity and characteristics, confirming the literature findings [61–63]. As a result, the modules with larger quantities of profiles, such as the Opaque FSM (with a 26% reduction in A1 GWP) and the window FSM (with a 21% reduction in A1 GWP), saw the greatest benefits from substituting critical materials with those made from forest-based and bio-composite sources. However, it is fundamental to recognize that the potential contribution of greenhouse gas emissions to global warming does not provide a comprehensive view of the overall environmental impact of an object, with other aspects like energy consumption, resource depletion, toxicity, and water footprint being essential to guarantee a broader range of environmental impact categories, giving a more holistic understanding of sustainability. To analyze these aspects, other assessments like a complete LCA would be needed. Moreover, the study delves into the A1–A5 life cycle stages, which encompass raw material extraction to façade practical completion. Developing end-of-life plans for a prototypical product is intricate, and one can only rely on assumptions based on prior knowledge.

Moving forward with the considerations of the results, a point should be made on the insulation equipment. Even though wood fiber insulation is often considered to have lower embodied carbon than mineral wool insulation [64], this analysis revealed a rise in CO₂eq emissions due to the implementation of wood fiber insulation equipment when compared to the alternative due to considering its biogenic carbon as actual emissions in A1. This could be attributed to the EPDs referenced in the analysis, which exhibited a significant variance in values based on the chosen product used as a reference. Nonetheless, when the biogenic carbon within the material is taken into account as compensation, the

overall GWP of this technological system could be considered significantly reduced. It is pertinent to note that the biogenic carbon, as discussed in this study, was reported as having been emitted to the atmosphere in A1 instead of C3. This approach, if not specified, could potentially lead to misunderstandings.

The benefits of factory-based manufacturing are widely recognized, including cost efficiency, quality control, scalability, and advanced automation technologies [65,66]. Through economies of scale, factories can produce goods in large quantities, distributing fixed costs across a greater number of units and reducing the cost per module [67]. Standardized processes and automated machinery ensure consistent product quality, while scalability allows manufacturers to quickly respond to changes in demand. Incorporating prefabricated modules assembled in line is a crucial element for product sustainability. Nevertheless, in order to achieve a sustainable transition, the utmost consideration must be given to limiting the production of new materials only to cases where other, more virtuous principles of the circular economy can no longer be applied. This approach will significantly contribute to the preservation of our natural resources and help mitigate the negative impacts of industrial activities on the environment.

When it comes to pultrusion and extrusion technologies, extrusion is known for its ability to create intricate shapes and lighter profiles. This process operates within the thermoplastic domain, while pultrusion works with thermosetting materials. Extruded profiles are generally lighter, allowing for the production of more profiles from the same amount of raw material. Though pultrusion has some advantages in energy consumption per unit weight (kW/kg), with the bio-composite profile reducing energy consumption by about 70% compared to aluminum profile extrusion, it is difficult to make a direct comparison due to the fundamental differences in technology, output characteristics, and material properties. It is important to take into account that a Basajaun pultruded profile measuring one meter in length weighs nearly twice as much as an equivalent aluminum profile with comparable structural properties. Extrusion is versatile in creating complex shapes and lighter products [68], while pultrusion excels in producing stiffer and more durable profiles [35].

The considerable weight of bio-composite profiles also affects negative aspects concerning atmospheric emissions resulting from their use. Their more significant weight and cross-sections compared to conventional structures increase the impact of transporting FSMs of this type, because the mass of the load transported is directly proportional to the emissions of the transporting vehicle. Moreover, it might happen that due to its slightly larger volume, the system design causes fewer modules that can be loaded on a single truck, resulting in more trips. However, this last specific condition did not happen during the Basajaun project. Also, during the construction phase, these features require greater amounts of consumed energy and could also adversely affect the timing of the on-site installation process. The use and maintenance phase of the life cycle is also outside the domain of analysis presented in this research; however, it could have highlighted how the developed bio-composite profiles seem to require lower maintenance than metal or aluminum profiles. Despite these drawbacks, the results describe them as a lower-emission solution than a corresponding conventional profile. However, another crucial concern regarding the profiles that is not within the scope of this analysis pertains to the building's structural system. With their increased mass, these profiles may necessitate an oversizing of the load-bearing structure supporting the façade system. As the structure is a major contributor to the embodied carbon of a building [69,70], these factors could have significant implications for the GWP of the building, particularly in the case of tall structures. However, this was not evaluated in this particular presented analysis.

It was claimed already that bio-based wall panels are a first step in integrating a circular economy approach in the construction sector, using renewable resources, carbon sequestration potential, and high-quality suitability for reuse and recycling [71]. However, regarding aspects related to the circular economy, further analysis of the FSMs developed in Basajaun is necessary. While prefabrication of the modules in the factory offers advantages

such as easier disassembly at the end of life, it is not yet possible to confidently state that the Basajaun's façade system is more circular than a conventional system. By examining alternative technological systems individually, it becomes clear that specific insights are required to test the recyclability of bio-composite profiles. While reuse could be evaluated only at its disposal, the fibrous materials from which it is composed would likely require at least surface treatment and may not guarantee adequate characteristics for reuse with the same function, necessitating a downcycle. Chemical recycling methods, such as conventional pyrolysis, solvent, and dissolution recycling, are viable options that aim to transform plastic waste into its original components or beneficial products [72]. These methods can be considered feasible alternatives for recycling the bio-composite profiles. Conventional pyrolysis emerges as a widespread thermal process operating in the absence of oxygen, thermally degrading the resin matrix into oil, gases, and solid products [73]. This method, typically executed between 400 °C and 700 °C, yields fibers, char on the fibers, and fillers from the solid products, offering a promising route for recycling. However, challenges include the need for high temperatures and the potential for energy-intensive processes [74]. Moreover, solvolysis, a prevalent chemical recycling process, involves dissolving the polymer matrix with chemicals like acids, bases, and solvents. While mechanically shredding and grounding solid fiber-reinforced plastic waste, solvolysis provides uniformity and higher fiber lengths without imposing high mechanical and thermal forces. However, the use of chemicals and solvent recovery steps pose challenges, environmental concerns, and process complexities. Lastly, the dissolution process introduces an innovative concept where a carefully chosen solvent selectively dissolves the polymer matrix, allowing for polymer recovery. This process, classified into superheated solvent dissolution, enables the separation of polymers from composite waste, offering energy-efficient precipitation of the polymer through flash evaporation. Each of these recycling techniques presents opportunities for the recycling of the bio-composite components, contributing to a broader approach to circular materials' management. However, the trade-offs involve chemical use, solvent recovery, and energy considerations. A careful evaluation of these methods shall contribute to a comprehensive approach to construction. Wood fiber insulation, being of organic origin, can be considered a circular material. It can be biodegradable and it can come from the recycling of waste wood from sawmills [64], but its end-of-life use options are still the subject of much scientific research. Mineral wool insulation, provided as an alternative in the proposed conventional module, can be recycled or reused, making it a sustainable alternative to current mortars made from composite materials [75]. Lastly, the sheathing and taping provided to ensure seals are composed of several layers that cannot be separated and are therefore unable to be recycled.

5. Conclusions

The presented prefabricated Façade System Modules (FSMs) developed within the Basajaun H2020 project represent a pioneering venture into incorporating bio-based materials into sustainable and operational building envelope systems, aiming to reduce the environmental impact of façade systems through innovative design, material choices, and manufacturing processes.

The comprehensive Embodied Carbon Assessment (ECA) conducted from cradle to practical completion (stages A1–A5), provided valuable insights into the environmental performance of the FSMs. Another ECA was conducted by replicating the assessment as per the same FSMs but designed as-conventional prefabricated façade modules to establish a benchmark reference for analysis. This approach provided a more comprehensive understanding of the unique design characteristics.

While some EPDs are available for certain components used in the facade modules analyzed, obtaining primary data for assessing environmental impact categories has proven difficult or even impossible. Moving forward, it is essential for the construction industry to increase the amount of data available to properly evaluate the environmental impacts of materials and components. Suppliers play a crucial role in this endeavor by raising

awareness among manufacturers and purchasers, paving the way for virtuous networks in the construction industry. This approach encourages sustainable practices and promotes demand for eco-friendly materials.

The results demonstrated that substituting critical materials with forest-based and bio-composite sources can reduce CO₂ emissions. The frame profiles, identified as the primary contributors to emissions, showed significant GHG emission reductions when replaced with the pultruded bio-composite profiles developed within the project. Consequently, the Opaque FSM and Window FSM, with larger quantities of profiles, exhibited substantial reductions in A1 GWP, witnessing reductions of 26% and 21% in A1 GWP, respectively, and highlighting the potential for impactful carbon footprint reduction in façade systems.

While the benefits of reducing emissions in frame profiles were apparent, challenges arose with wood fiber insulation. The analysis revealed a rise in CO₂eq emissions compared to the mineral wool alternative, underscoring the relevance of considering biogenic carbon in the evaluation.

Factory-based manufacturing processes proved advantageous, aligning with industry-recognized benefits such as quality control and scalability. The comparison between pultrusion and extrusion technologies highlighted the need to consider each method's strengths and limitations carefully. Extrusion's versatility in creating intricate shapes and lighter profiles demonstrates advantages in specific contexts. Pultrusion proved valuable for bio-composite applications thanks to its reduced energy consumption per kg of profile (9.77×10^{-2} kWh/kg). However, the considerable weight of bio-composite profiles can introduce challenges during transportation and installation on-site. While the analysis confirmed a lower overall environmental impact than conventional alternatives, the weight considerations necessitate careful planning to mitigate potential structural implications. While further analysis is required to assess bio-composite profiles' recyclability and determine their end-of-life, there are various methods of chemical recycling, such as pyrolysis, solvent, and dissolution recycling, which have the potential to convert bio-composite material waste into its original elements or useful products.

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Article

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/m² and a typical load of 1.5 kN/m², the weighted sound reduction index obtained is $R_w = 44$ dB, and the thermal transmittance of the vision façade is 0.74 W/m²K while that of the entire opaque façade is 0.27 W/m²K (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 CO₂ 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 characterization 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 Low tolerance during the pultrusion	Maximum façade height is 4 m 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 Expensive mold creation A simple mold shape is required	Unique mold for multiple profiles and accessories for transoms and connection 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 $R'w \geq 30$ 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 (q_{50}) 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 $1.56 \text{ m (b)} \times 3.85 \text{ m (h)}$. 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: $25 \text{ kN/m}^3 \times 0.029 \text{ m} \times 1.56 \text{ m} \times 3.85 \text{ m}/2 \text{ supports} = 2.18 \text{ kN}$ at 1/10 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): $1.35 \text{ self-weight load} + \text{wind load (suction)} \times 1.5 + \text{horizontal live load} \times 1.5 \times 0.7$.
- ULS2 (Ultimate State Limit): $1.35 \text{ self-weight load} + \text{wind load (suction)} \times 1.5 \times 0.6 + \text{horizontal live load} \times 1.5$
- SLS1 (serviceability limit state): $\text{self-weight load} + \text{wind load (suction)} + \text{horizontal live load} \times 0.7$.
- SLS2 (serviceability limit state): $\text{self-weight load} + \text{wind load (suction)} \times 0.6 + \text{horizontal live load}$.

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 kgCO₂eq/mL, while the bio-composite pultruded profile has 26.80 kgCO₂eq/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 kgCO₂eq/m³, while the wood fiber insulation used in Basajaun has an A1–A5 GWP of 1.63 kgCO₂eq/m³ (biogenic carbon = 261.00 kgCO₂eq/m³) 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 kgCO₂eq/m² for an opaque façade module, while the membranes, tapes, and plywood implemented have an estimated embodied carbon of about 5.41 kgCO₂eq/m² of an opaque façade module (biogenic carbon = 15.10 average kgCO₂eq/m²).

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.

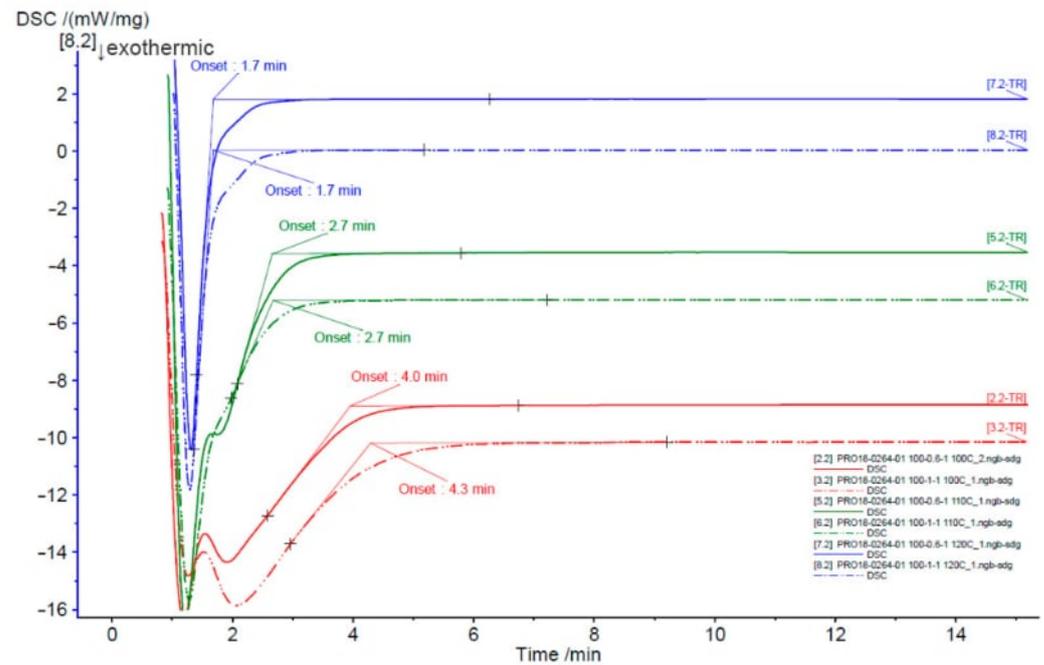


Figure 1. DSC isotherm studies were conducted to study polymerization. The graph with the same color continues, and the striped lines represent repetitions.

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.	[×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/cm³; 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 cm².

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

Description	Rovings		Mat or Fabric			Fiber			Occupied Section (cm ²)
	Tex (gr/km)	No. of Threads or Layers	Grammage (g/m ²)	Effective Width (m)	Weight (g/m)	Density (g/cm ³)	Volume (cm ³ /m)	Fraction V. Local	
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.

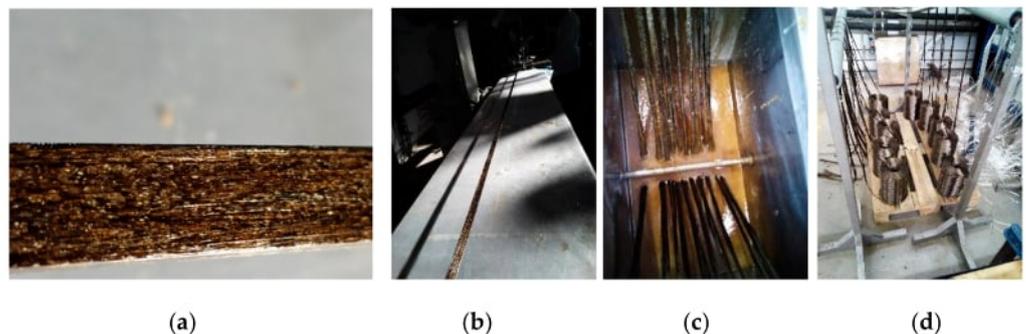


Figure 3. Optimized bio-based polyester and basalt fibers profile obtained by pultrusion (13 yarns of basalt fiber). Samples manufactured in AIMPLAS' facilities. Bio-based profiles pultrusion (a); bio-based profiles pultrusion (b); basalt fiber in the resin (c); basalt rovings (d).

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 cm² (Figure 4).

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

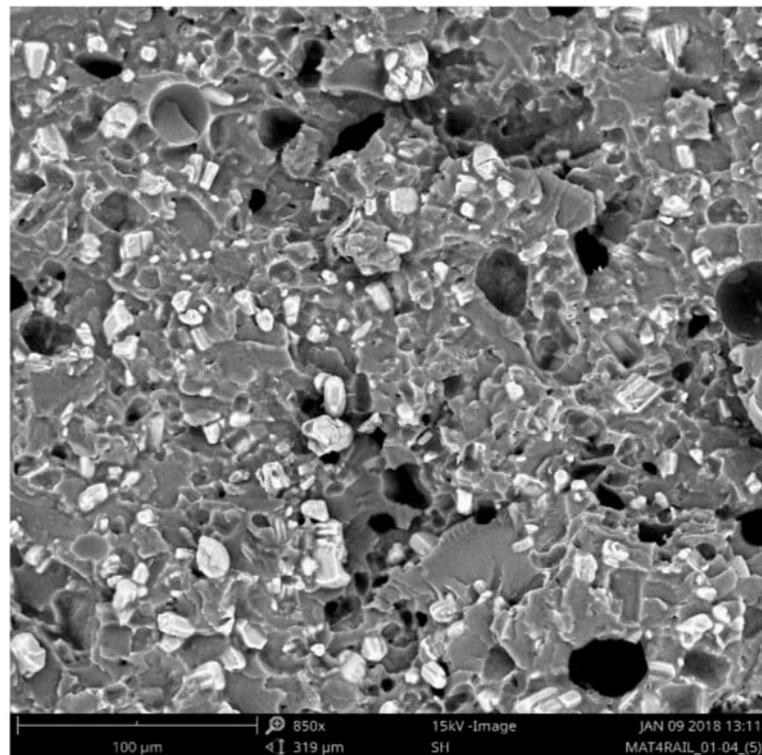
Description	Rovings		Mat or Fabric			Fiber			Occupied Section (cm ²)
	Tex (gr/km)	No. of Threads or Layers	Grammage (g/m ²)	Effective Width (m)	Weight (g/m)	Density (g/cm ³)	Volume (cm ³ /m)	Fraction V. Local	
Fabric (Glass Fiber)		2	500	0.1	100	2.55	39.22	0.28	500
Roving (Basalt Fiber)	4800	80			384	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.

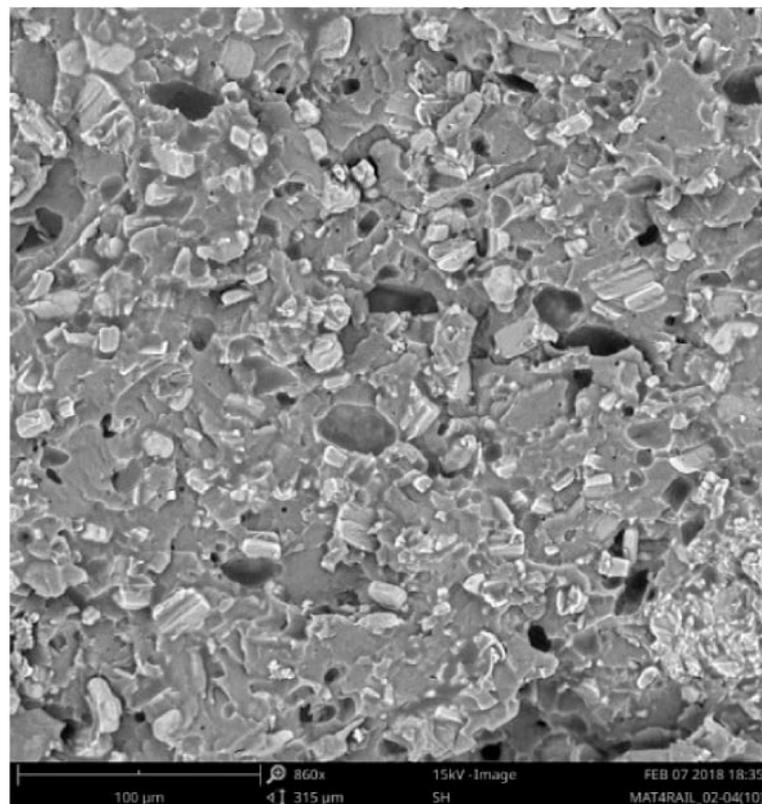
First, flame retardancy (FR) trials on this polyester system were conducted by dispersing two different halogen-free flame retardants. An optimal dispersion of the flame retardant into the polyester matrix is a key requirement to obtain a resin with good processability for any process. Two dispersion 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/m² at 380 s (T-1-2) and 163 kW/m² at 440 s (F-1-2) while the uncoated sample achieved a higher heat emission (403 kW/m²) in a shorter time period (160 s); the peak rate of the heat release was 354 kW/m² at 360 s (T-1-2) and 305 kW/m² at 420 s (F-1-2) while the uncoated sample achieved a higher heat release (759 kW/m²) in a shorter time period (140 s); the peak of the smoke production rate was 11 m²/s at 310 s (T-1-2) and 10 m²/s at 400 s (F-1-2) while the uncoated sample achieved a higher smoke production (20 m²/s) in a shorter time period (120 s).

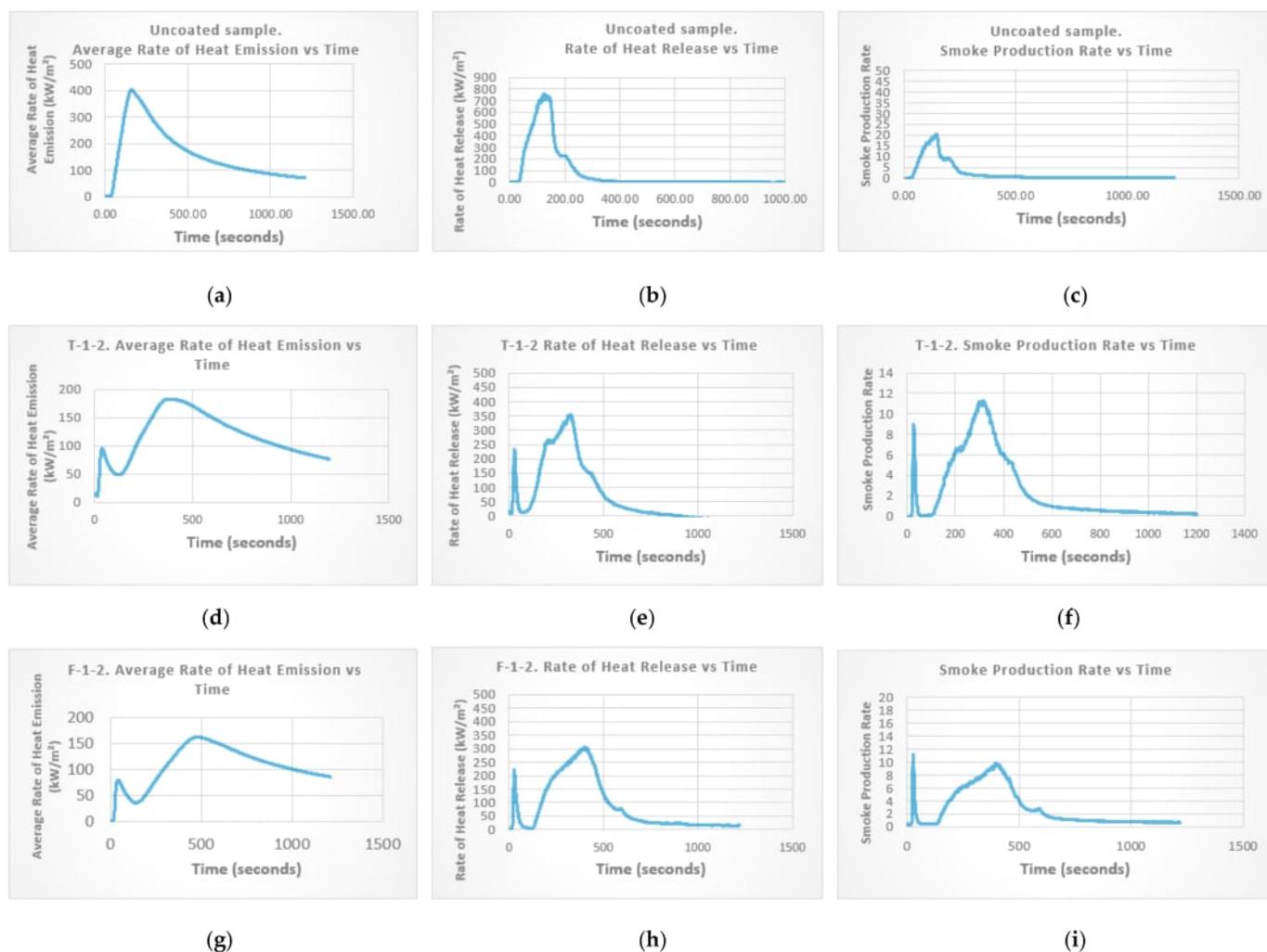


Figure 6. Cone calorimeter tests of the resin were performed using two types of coatings. Average rate of heat emissions for uncoated sample (a); rate of heat release for uncoated sample (b); smoke production rate for uncoated sample (c); average rate of heat emissions for T-1-2 sample (d); rate of heat release for T-1-2 sample (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/m² and a Peak Heat Release Rate of 759 kW/m². 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	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.

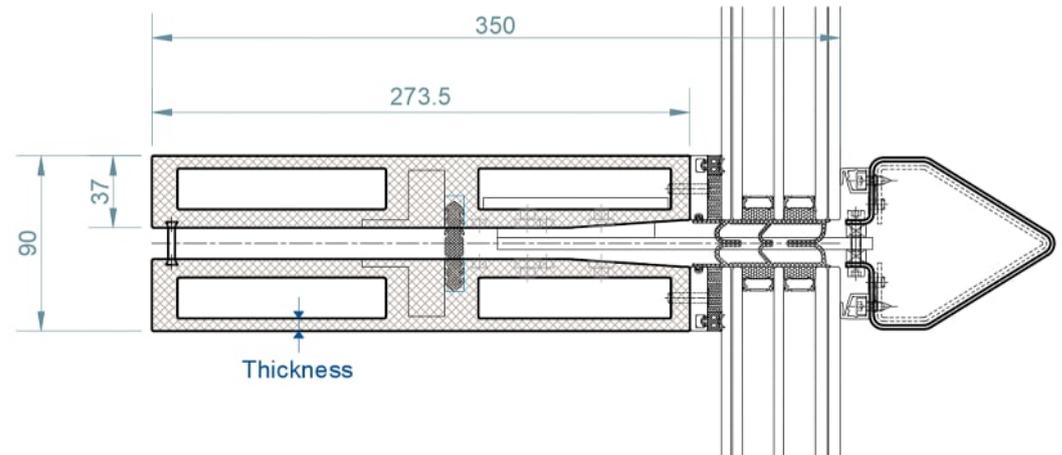


Figure 7. Preliminary bio-composite profile for mechanical characterization.

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	
<u>Loads:</u>	
$WL = 2 \text{ kN/m}^2 \times 0.79 \text{ m} \times 7.65 \text{ m} =$	12.1 kN
$WL_{ult} = 1.5 \times 12.1 =$	18.13 kN
$E = 1 \text{ kN/m} \times 0.79 \text{ m} =$	0.79 kN
$E_{ult} = 1.05 \times 0.79 \text{ kN} =$	0.83 kN
$E2 = 1 \text{ kN/m} \times 0.79 \text{ m} \times 0.7 =$	0.553 kN

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

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

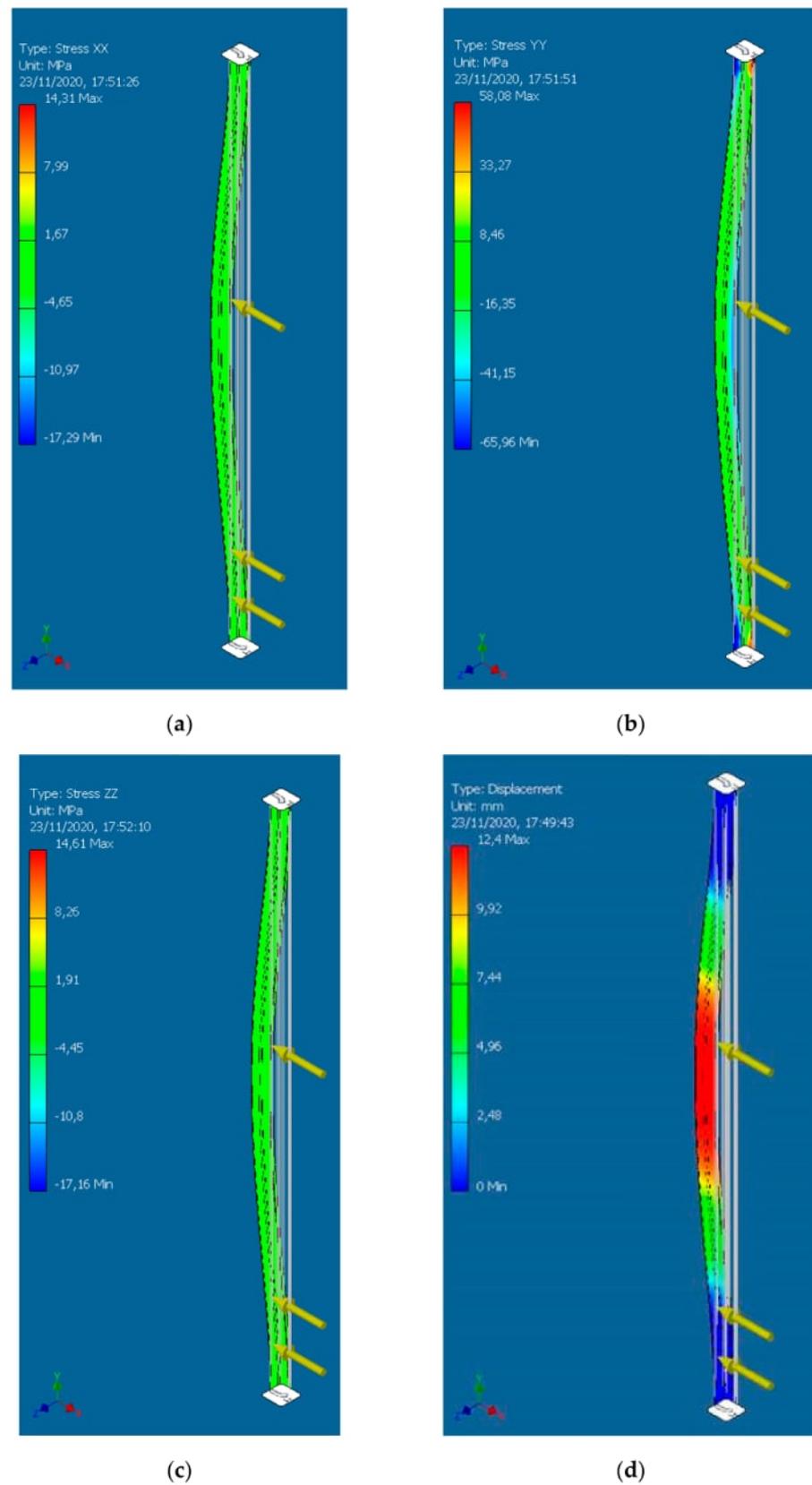
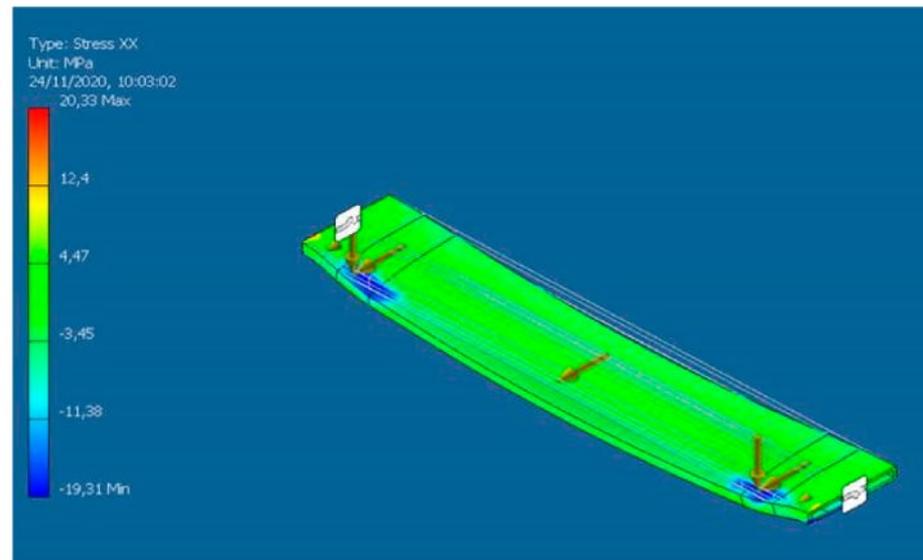
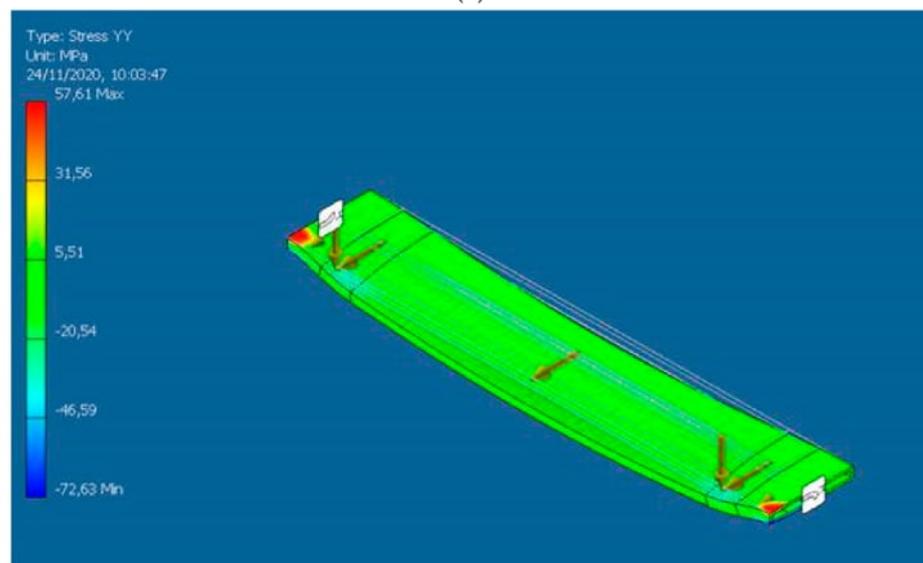


Figure 8. Stress XX is a max of 14.31 MPa with permissible stress: 75 MPa (a); Stress YY is a max of 58.08 MPa with permissible stress: 185 MPa (b); Stress ZZ is 14.61 MPa with permissible stress: 75 MPa (c); displacement max is 12.4 mm with permissible deformation $<7650/250 = 30.6$ mm (d). The arrows 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.

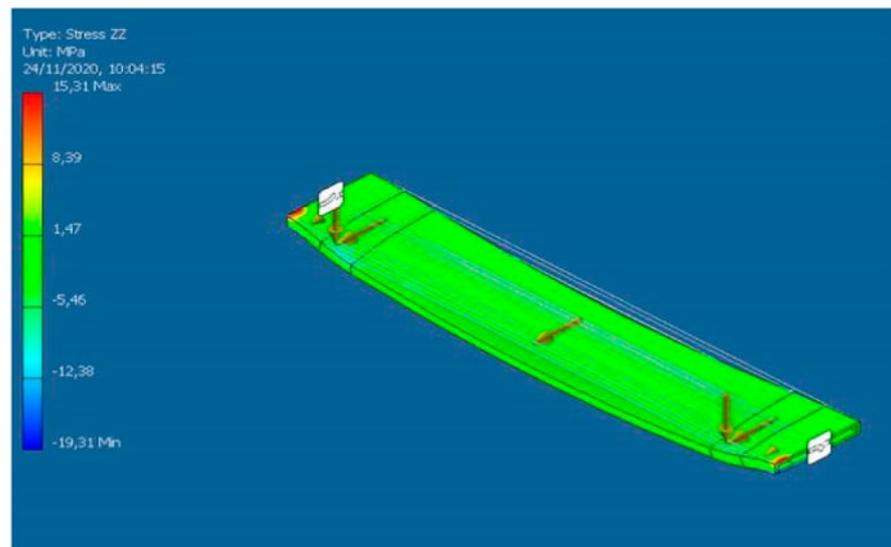


(a)

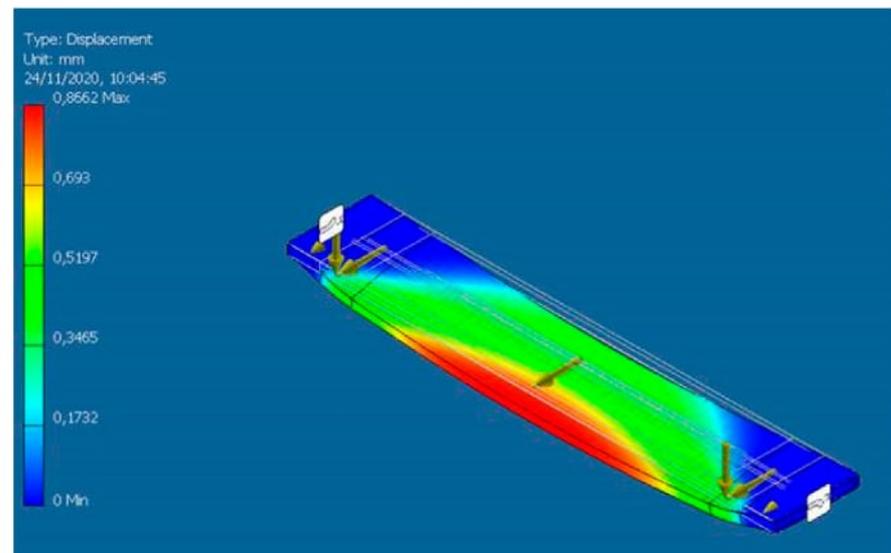


(b)

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.

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 Basajaun	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 Basajaun	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.

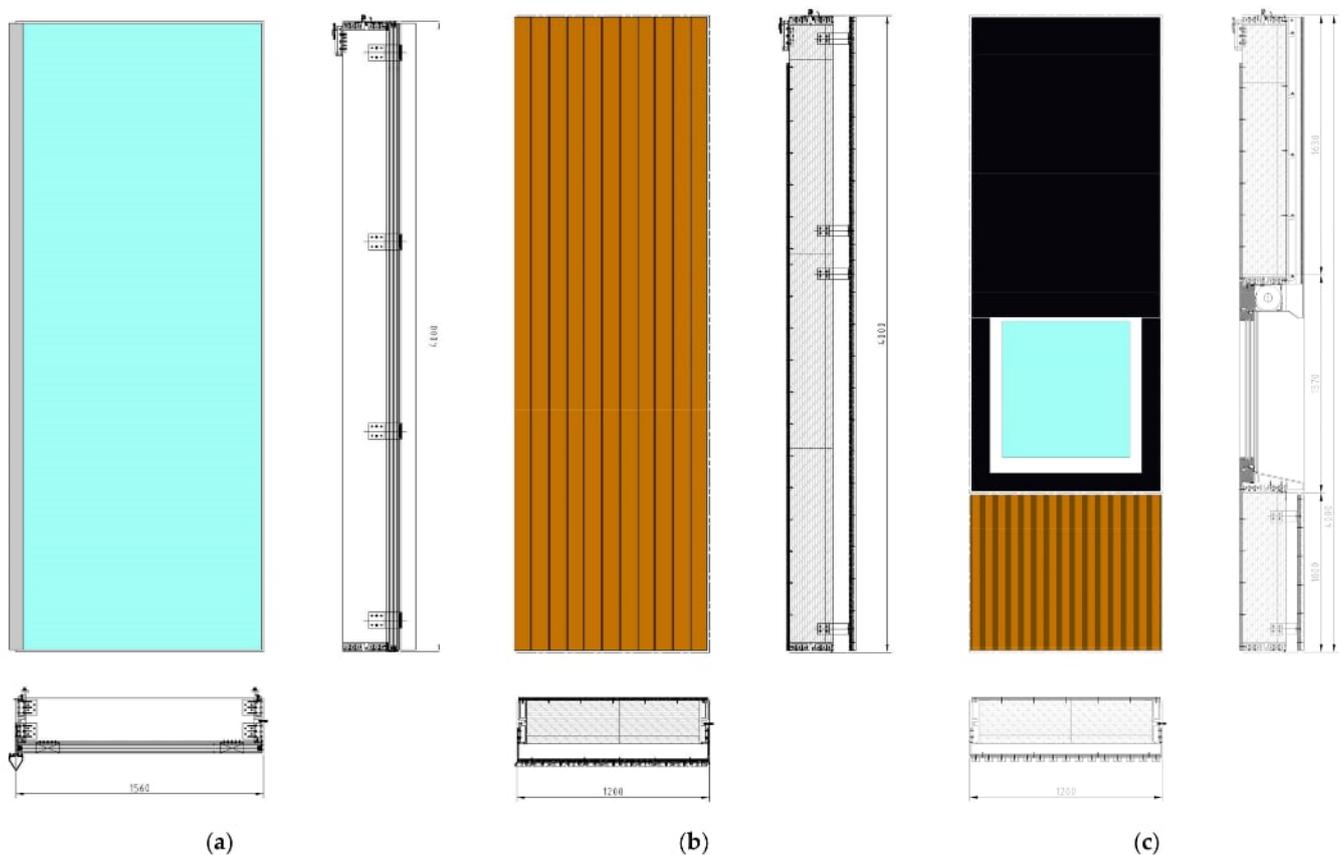


Figure 11. Drawings of façade modules (elevation, vertical section on the right, horizontal section at the bottom): vision façade module (a); opaque façade module (b); window façade module (c).

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.

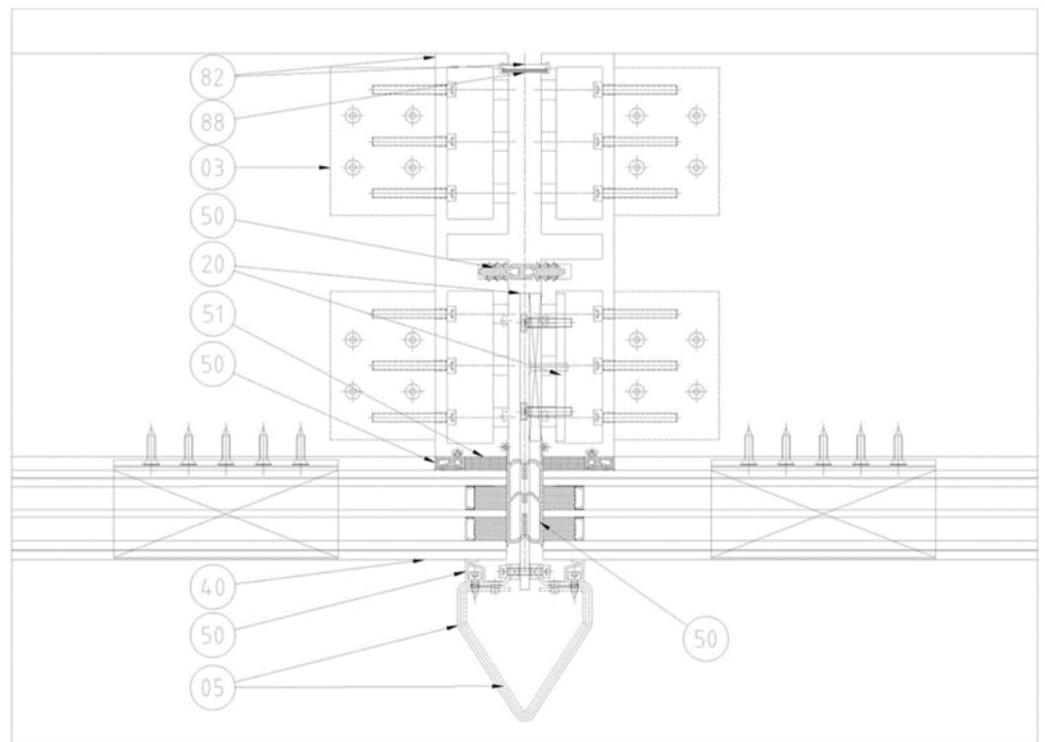


Figure 12. Final solution: horizontal section of Basajaun vision façade module. The numbers for the components' identification refer to Table 17.

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.

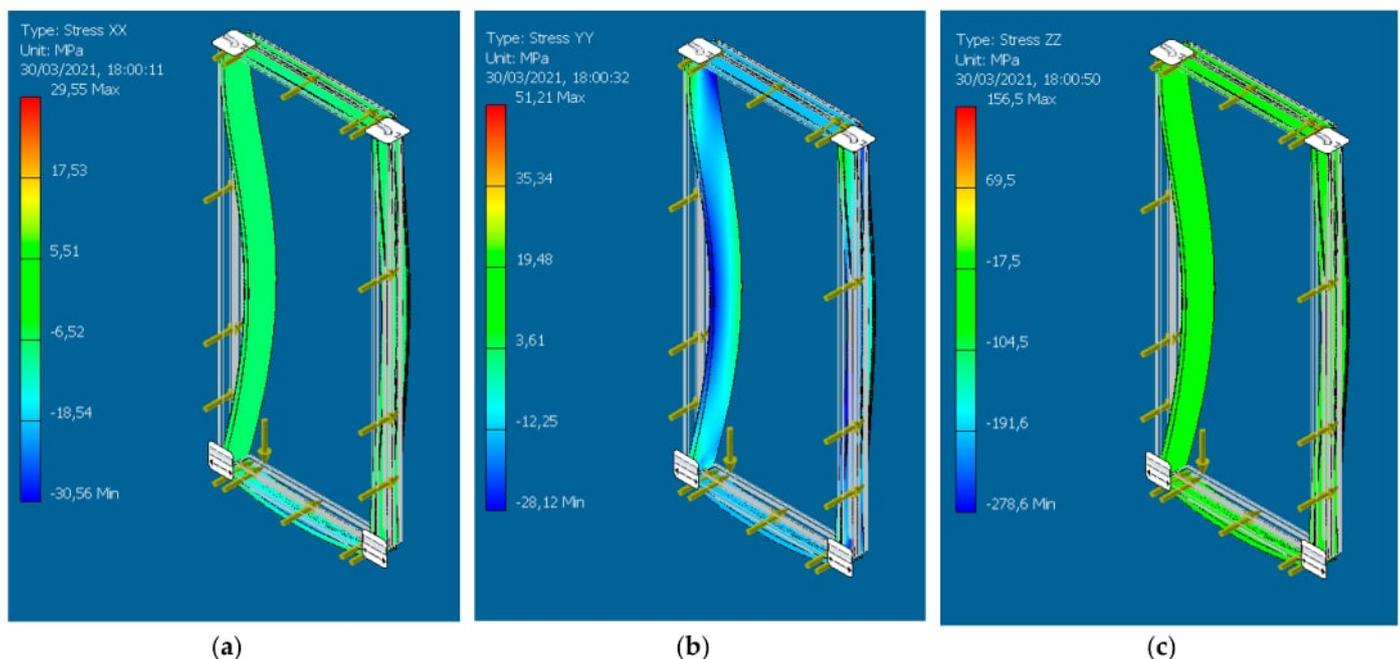


Figure 13. Perimeter structure stress analysis: stress XX is 29.55 MPa with permissible stress 38 MPa (a); stress YY is 51.21 MPa with permissible stress 125 MPa (b); stress ZZ is 156.5 MPa with permissible stress 38 MPa (c). The arrows depicted in the figures represent the resultant of the load, and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

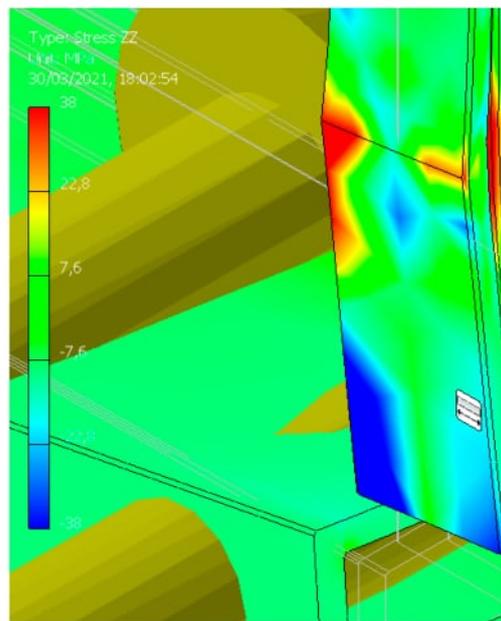


Figure 14. Mechanical simulation results: the cross-member connection stress analysis with the maximum stress ZZ is exceeded in a small area; the profile is considered adequate.

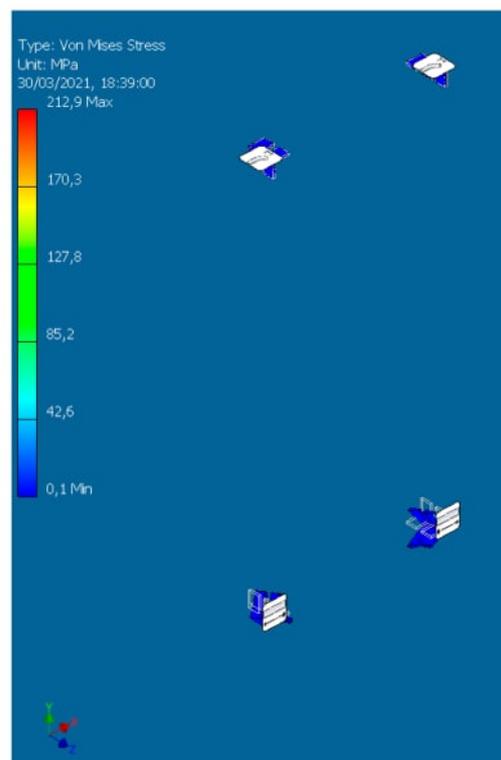


Figure 15. Mechanical simulation results for cross-member connection stress analysis: max stress is 212.9 MPa with a permissible stress of 227 MPa.

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.

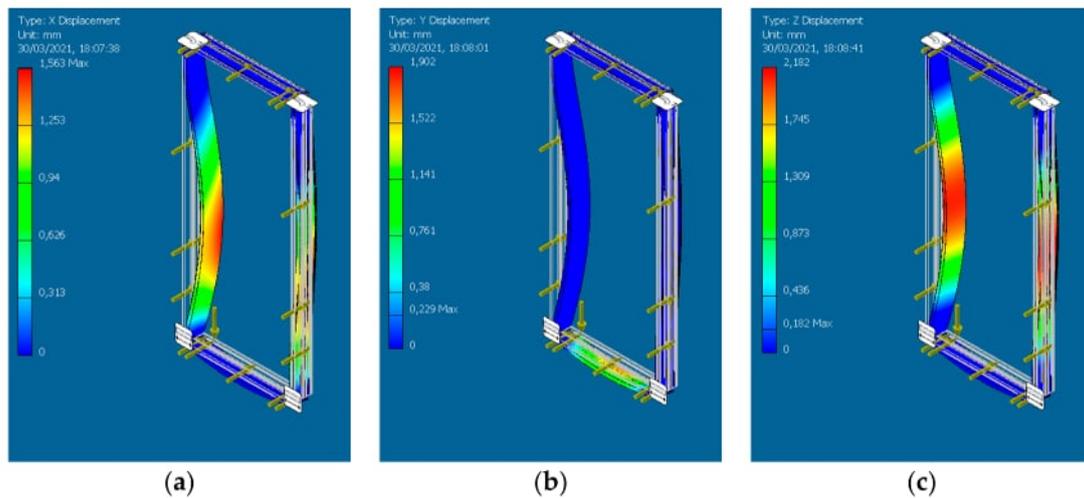


Figure 16. Perimeter structure deflection analysis: X deflection is a max of 1.56 mm with permissible deformation $< 3850/300 + 5 = 17.83$ mm (a); Y deflection is a max of 1.90 mm with permissible deformation $< 1560/500 = 3.12$ mm (b); Z deflection is a max of 2.18 mm with permissible deformation $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

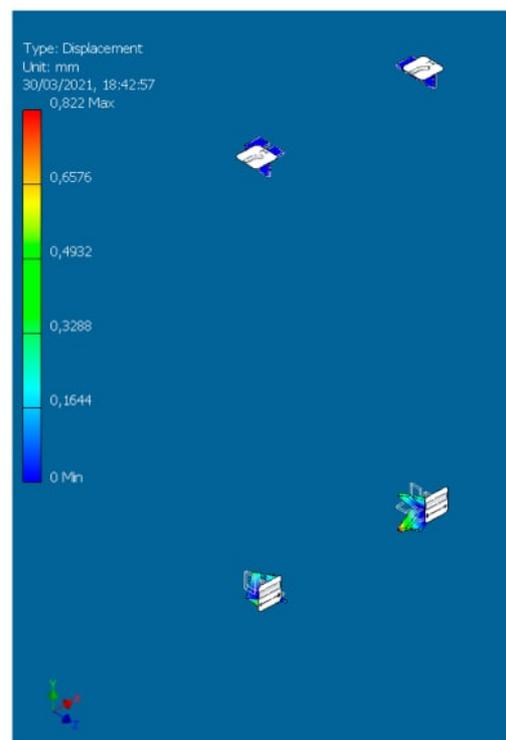


Figure 17. Cross-member connection deflection analysis has a max of 0.82 mm deformation with permissible deformation < 1 mm.

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 $0.74 \text{ W/m}^2\text{K}$, satisfying the verification criterion of being less than or equal to $1 \text{ W/m}^2\text{K}$. 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.

$$U_{cw} = \frac{\sum (U_g \times A_g) + \sum (U_s \times A_s) + \sum (UTJ \times ATJ)}{\sum A_g + \sum A_s + \sum ATJ} \quad (1)$$

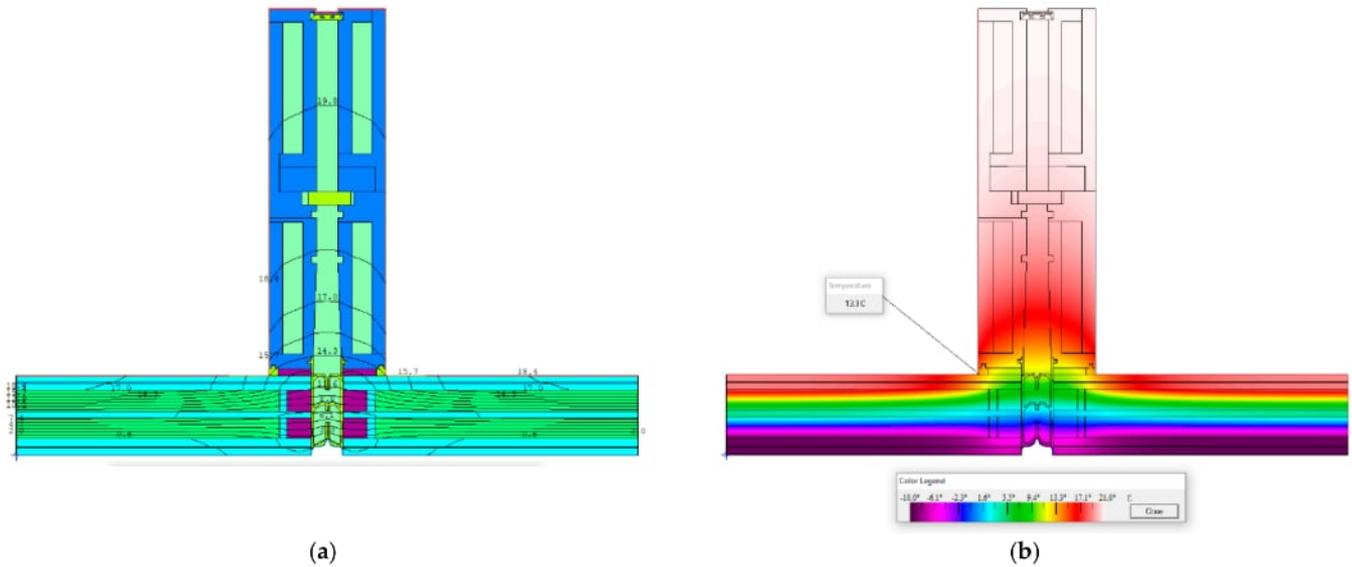


Figure 18. Vision façade module nodes' thermal simulations for "Node 1 mullion-mullion": node transmittance analysis with $U_{TJ} = 2.253 \text{ W/m}^2\text{K}$ (a); condensation analysis with $T_{\text{simin}} = 13.3 \text{ }^\circ\text{C}$ $\geq 10.2 \text{ }^\circ\text{C}$ is verified (b).

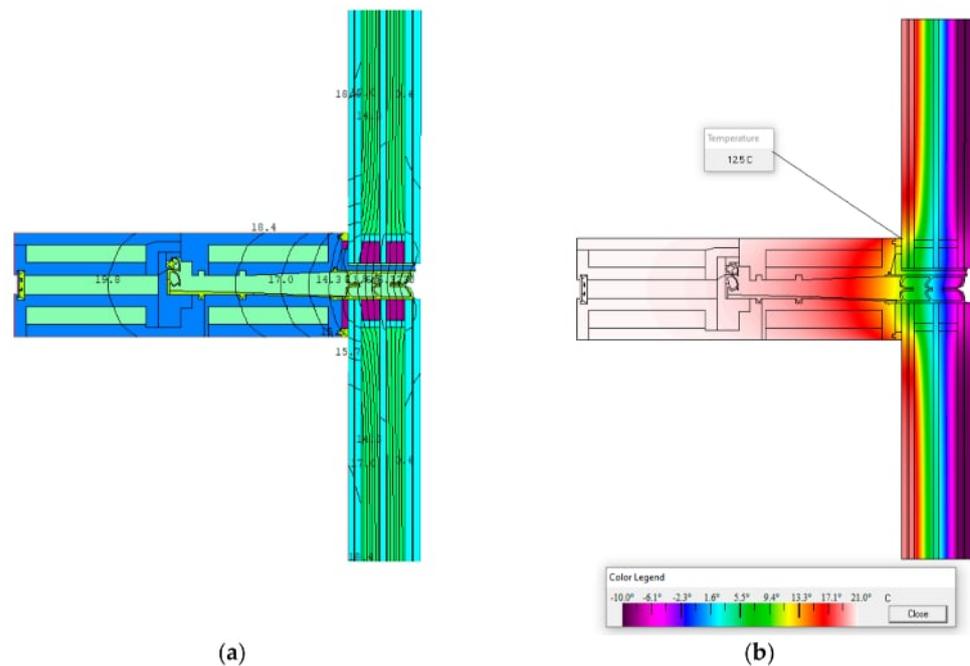


Figure 19. Vision façade module nodes' thermal simulations for "Node 2 male transom-female transom": node transmittance analysis with $U_{TJ} = 2.331 \text{ W/m}^2\text{K}$ (a); condensation analysis with $T_{\text{simin}} = 12.5 \text{ }^\circ\text{C}$ $\geq 10.2 \text{ }^\circ\text{C}$ is verified (b).

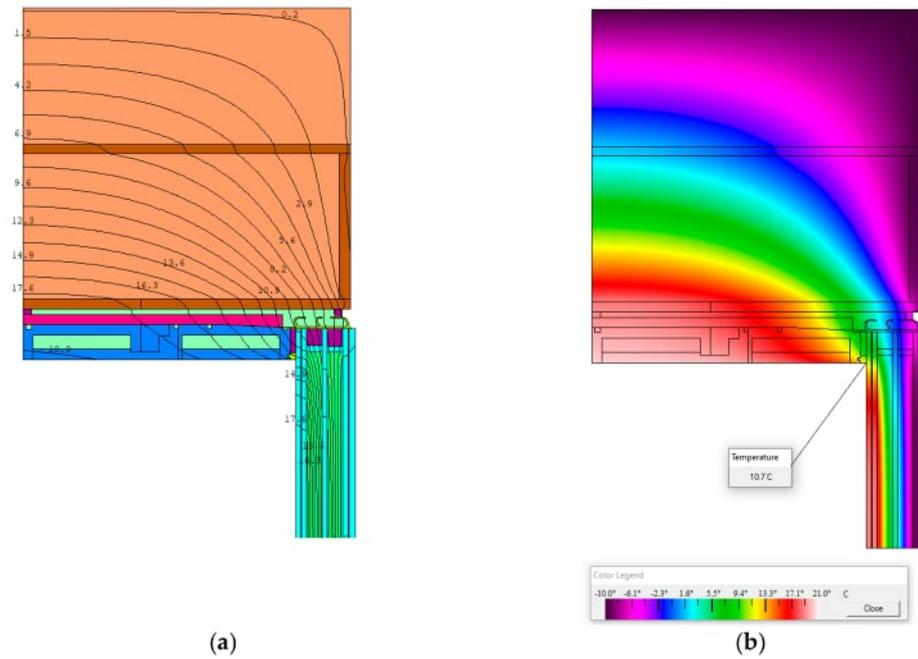
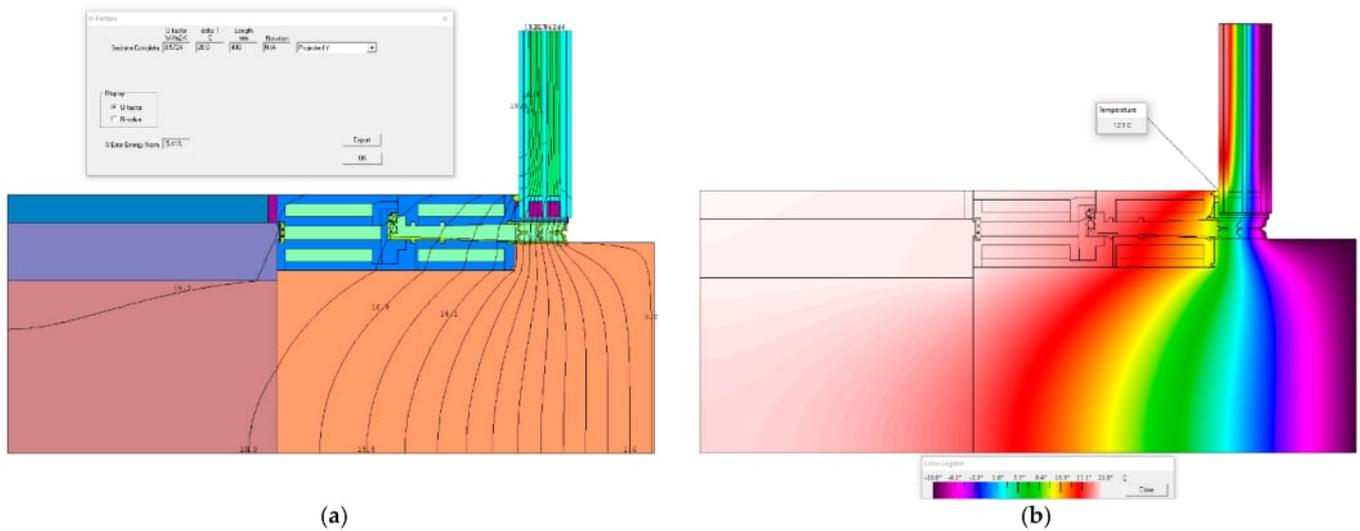


Figure 20. Vision façade module nodes’ thermal simulations for “Node 3 mullion-roof”: node transmittance analysis with $U_{TJ} = 0.556 \text{ W/m}^2\text{K}$ (a); condensation analysis with $T_{\text{simin}} = 10.7 \text{ }^\circ\text{C}$ $\geq 10.2 \text{ }^\circ\text{C}$ is verified (b).



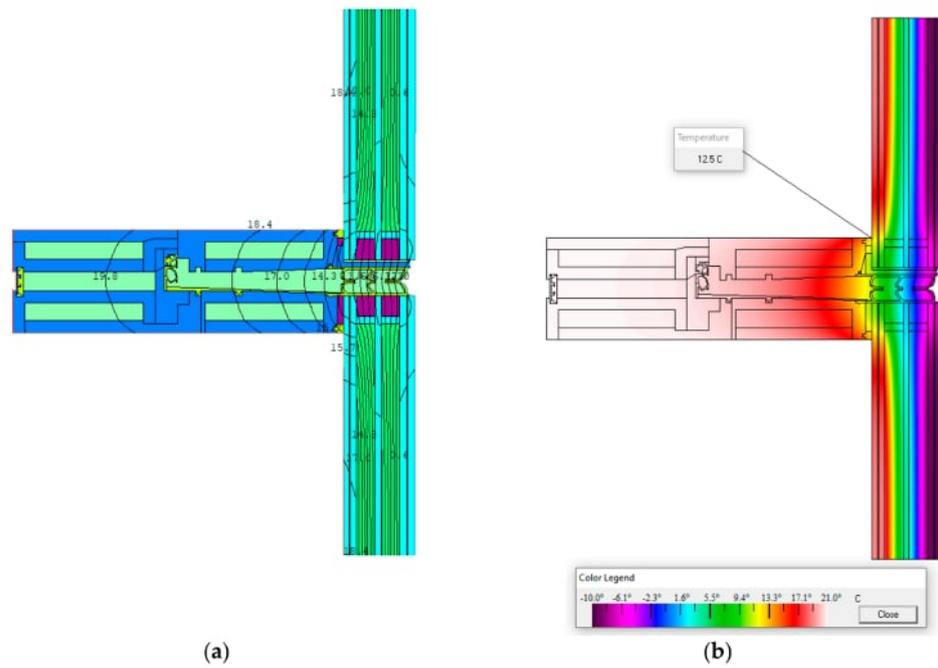
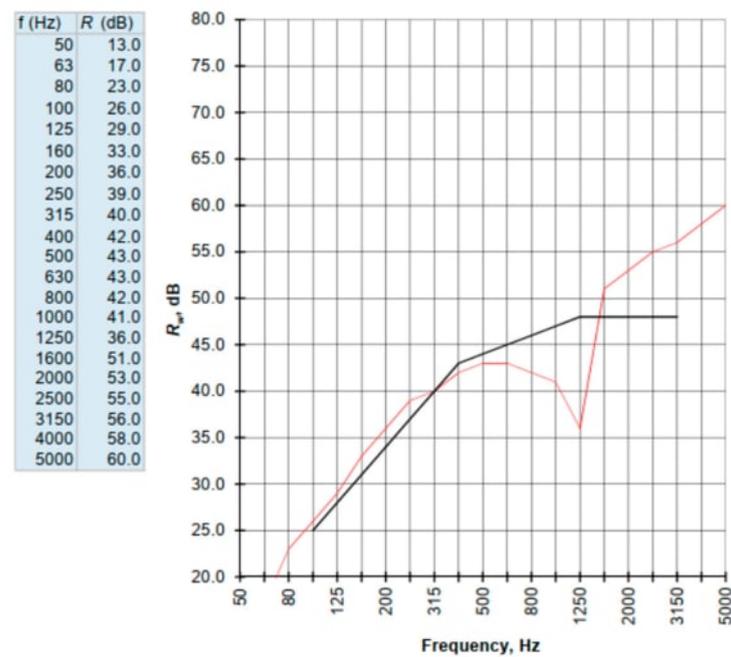


Figure 22. Vision façade module nodes thermal simulations for “Node 5 male transom-female transom”: node transmittance analysis with $U_{TJ} = 2.331 \text{ W/m}^2\text{K}$ (a); condensation analysis with $T_{\text{simin}} = 12.5 \geq 10.2 \text{ [}^\circ\text{C]}$ is verified (b).

For what concerns the acoustic simulation, the result for the vision module façade system is reported in Figure 23 with an insulation of $R_w = 44 \text{ dB}$.



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 $R_w = 44 \text{ dB}$. — 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.

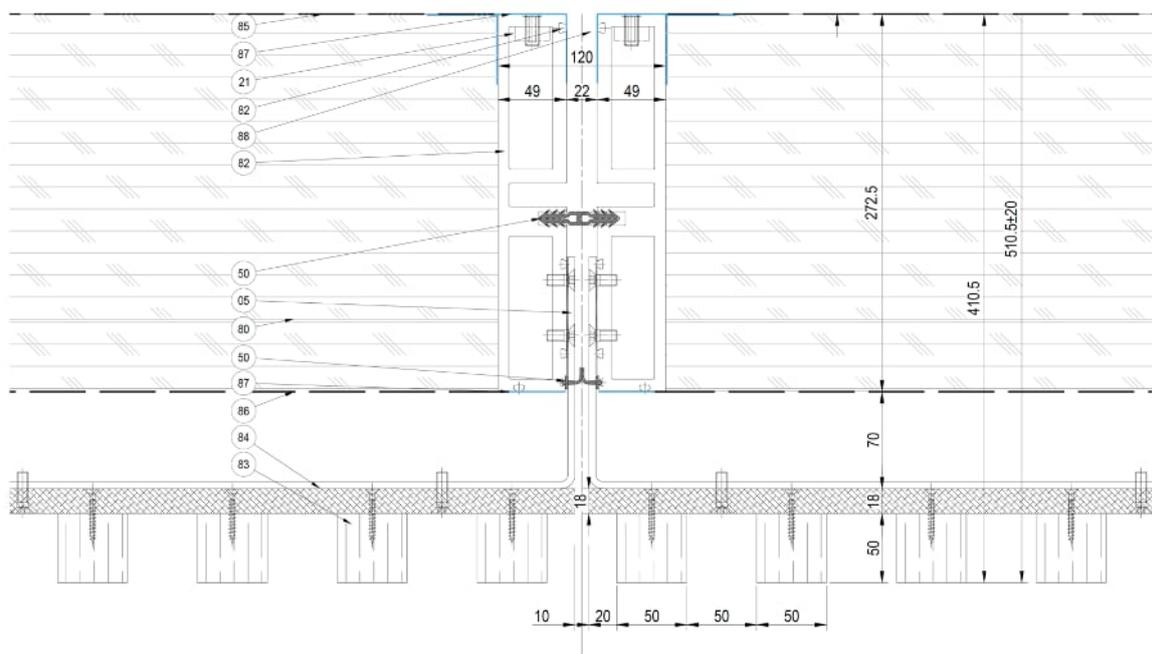


Figure 24. Final solution: horizontal section Basajaun opaque façade module. The numbers for the components' identification refer to Table 19.

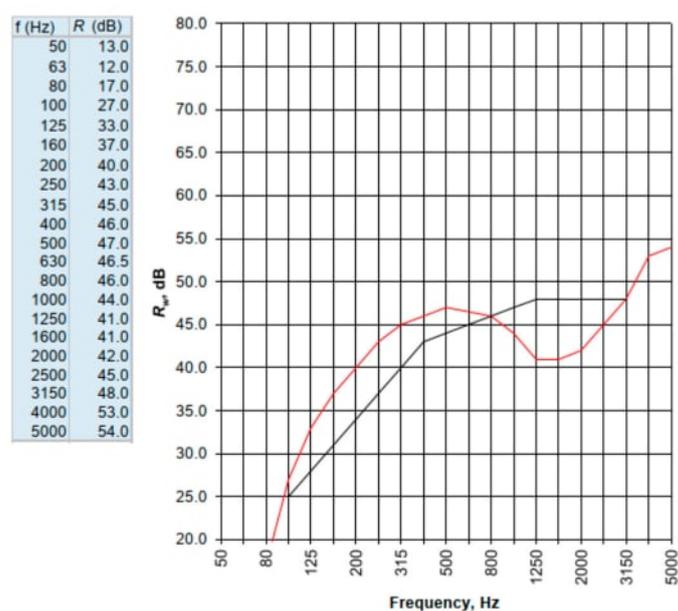
For the mechanical simulation, the opaque façade module was verified because the loads on the façade were lower than those on the vision façade module already discussed in the related paragraph.

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 $0.27 \text{ W/m}^2\text{K}$, which was higher than the $0.20 \text{ W/m}^2\text{K}$ requested by the French regulation and even more for the Finnish requirement of $0.17 \text{ W/m}^2\text{K}$. 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 plaster board. The thermal transmittance for the opaque façade plus the interior wall achieved $0.17 \text{ W/m}^2\text{K}$, 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 ² K 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.



SS-EN ISO 717-1

R_w	44 dB	C	=	-1 dB
max. dev.	7.0 dB	C_{tr}	=	-3 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.

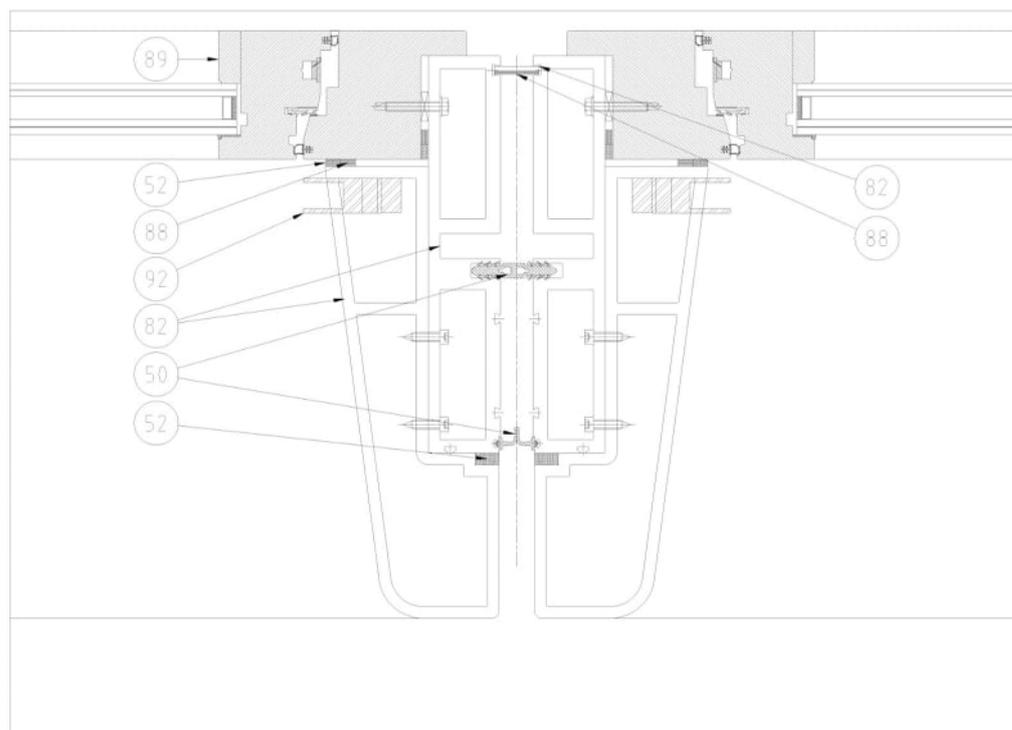


Figure 26. Final solution: horizontal section Basajaun window façade module. The numbers for the components' identification refer to Table 20.

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 $\pm 0.3/0.4$ 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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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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Testing Activities for Technological and Normative Validation of Bio-Based Components in Façade System Modules

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Abstract: This research explores the development and validation activities of a bio-based façade system within the Basajaun H2020 project, focusing on enhancing the utilization of bio-based components within building envelopes to replace conventional solutions with eco-friendly alternatives. This paper reports the methodologies employed to detect requirements and outline the testing protocols undertaken to validate the façade system design devised within the project, focusing on the original façade components as the biocomposite profile. Vision and opaque façade modules are prototyped and tested following curtain wall standards for performance (EN 13830:2015) and acoustic assessments (EN ISO 717-1:2020) to showcase the efficacy of the developed solution. The conducted tests demonstrate the feasibility of integrating bio-based components as alternatives to conventional materials into building envelopes, aligning with project expectations and prevailing standards for curtain wall façade solutions. Notably, the designed façade system meets technical conditions and research objectives. Nevertheless, the paper underscores the need for further refinements to facilitate solution industrialization and explore broader market applicability focusing on the biocomposite profile.

Keywords: bio-based products; curtain wall façade; prefabrication; sustainable construction; validation; testing activities



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1. Introduction

The construction sector contributes to 30% of raw material utilization, nearly 40% of greenhouse gas emissions [1,2], and up to 40% of solid waste generation [3]. Consequently, integrating bio-based materials into the construction industry has emerged as a focal objective within EU policies, aimed at fostering sustainable practices across the entire value chain [4,5] and throughout a building's lifespan to reduce the carbon emissions [6,7] as well as contributing to reducing pollution and resource consumption [8–12].

The integration of bio-based components presents more than just an environmental advantage; it offers a gateway to reimagining building products through the synergy of bio-economy and circular economy concepts [13,14]. This approach has the potential to not only enhance environmental sustainability but also to optimize industrial-scale production value chains. Therefore, by investigating renewable and biodegradable resources, bio-based materials offer a compelling solution to mitigate the ecological footprint associated with building envelope façades [15].

The building envelope represents an important building component, since it serves as a multifaceted system tasked with delineating outdoor and indoor environments while meeting stringent criteria and integrating diverse technologies encompassing thermal,

acoustic, and mechanical performance [16,17], ensuring indoor comfort [18] and energy performance [19]. The current benchmark for curtain wall façades is represented using aluminum components, glazed panels, and mineral wool as insulation, which is a mature technology within the market. The growing demand for bio-based materials in building envelopes stems from their versatility, compatibility with modern design, and ability to address technological requirements [20–22]. Moreover, the prefabrication process involved in curtain walls enhances the design of eco-conscious façade systems, contributing to sustainable buildings. Paramount considerations include factors such as disassembly, reuse, and recycling, as well as efficiency in manufacturing, waste production, and maintenance [23–25].

In this context, the Basajaun H2020 project (G.A. 862942) [26,27] represents a boost in the adoption of bio-based materials for the building envelope sector. It plays an important role in the research and innovation sector; indeed, its objectives are to integrate wood-based materials into building product systems, thereby fostering increased acceptance and utilization of biomaterials within the construction market. Within this activity, this paper presents the results of the prototyping and testing activities conducted in line with normative market requirements to validate the façade system modules developed within the Basajaun project in the designing phase. The research is also based on a previous VII Framework Programme project (Osirys—G.A.: 609067) [28,29] where a first version of the use of a biocomposite profile was developed and protected under a patent (EP3628790).

In addition, within the Basajaun H2020 project, the study highlighted the sustainability benefits of integrating bio-based solutions into façade systems, investigating their environmental impact through an Embodied Carbon Assessment (ECA). The results showcased reduced embodied emissions by substituting conventional materials with wood-based components and novel biocomposite frame profiles, which is particularly evident in the decreased carbon footprint associated with replacing aluminum frame profiles [30].

This article aims to demonstrate the effectiveness of using bio-based and alternative components as substitutes for conventional materials within prefabricated façade systems through iterative methodologies. Therefore, it investigates and reports multifaceted considerations and decision-making processes underlying the development and integration of environmentally sustainable products within façade system modules. In particular, this article's objectives are to investigate and provide contributions in the scientific field in the validation of bio-based curtain wall façade systems, regarding the façade manufacturability and the normative compliance to testing in an accredited laboratory, focusing on the original façade components as the biocomposite profile. Indeed, the research validates the manufacturability of the biocomposite profile in pultrusion lines and the relative cutting and machining phase in Computer Numerical Control (CNC) machines. Moreover, the research aims to assess the manufacturing of bio-based façade system modules while defining the prototypes' weak points and the industrialization issues in the off-site manufacturing process to meet industrial needs for a wide replication in the market.

The paper is structured as follows: Section 2 outlines the methodology applied and materials used for the validation and testing phase. Section 3 presents the outcomes from the manufacturing and testing activities of the components and the overall prototyping of the façade system modules. Section 4 reports the results obtained during the validation and testing phase, and defines the successful aspects of integrating bio-based and alternative components in the façade. In this section, the issues which emerged during the manufacturing stages and gaps identified due to research and test limitations are declared and reported. Section 5 summarizes the main achievements related to the paper's goal of analyzing the opportunities for bio-based façade system modules.

2. Materials and Methods

The methods applied in the research comprise the following three stages:

1. Identification of validation activities—based on designing validation and desk simulation conducted in the designing phase, a list of testing is defined to demonstrate the

feasibility of manufacturability and integrability of the components in the façade system modules. Indeed, based on the research objectives and the defined test activities, the standards to be addressed were identified.

2. Prototyping and testing activities—testing activities for manufacturing and normative validation of bio-based façade system modules are conducted to align with product requirements and expected outcomes to collect data and analyze the results achieved. Therefore, in this phase the test procedure and standard compliance for system validation is defined, focusing on the performance and acoustic tests. This stage allows to validate modules against requirements, identifying weaknesses, and implementing improvements. This step is divided into: (i) the test preparation phase—the norms and therefore the method statements, and the facilities for each test are defined; (ii) design and manufacturing—the Basajaun modules are designed for each test and manufactured; and (iii) tests and performances achieved—the tests are conducted, and the results collected.
3. Analyze the obtained results—this stage aims at identifying weaknesses and opportunities for bio-based façade system modules based on the test results. Indeed, a specific focus is given to gaps and barriers to challenge for market introduction by identifying weak points and improvement opportunities for further activities. The materials for the research activity are:
 - Façade system design defined in Basajaun project—more detailed insights derived from the development of the Basajaun façade system are presented in Pracucci et al. [31] offering the methodology applied for the designing phase. Figure 1 shows the final design configuration of three façade typologies while Figure 2 depicts a zoomed in image of the horizontal section of the opaque façade module.

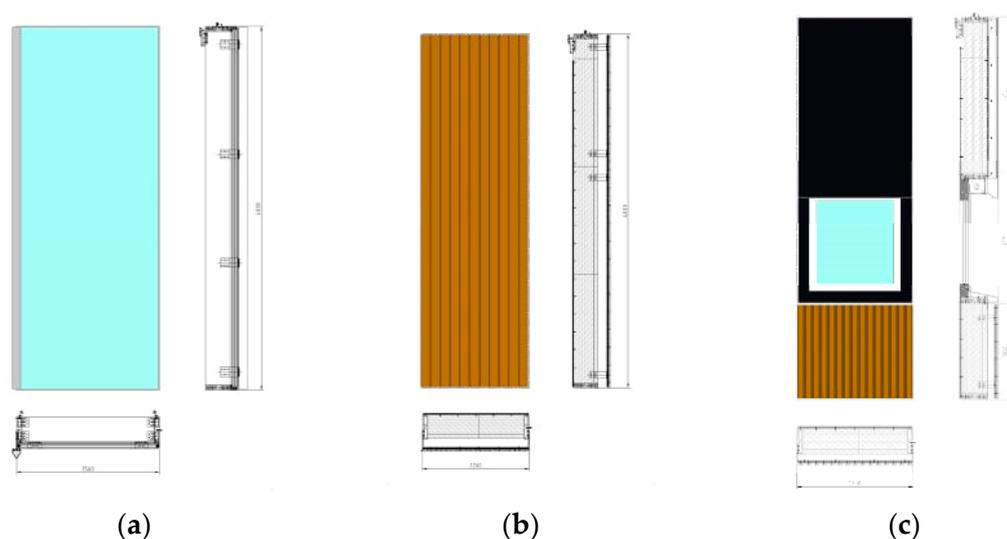


Figure 1. Drawings of façade modules (vision on the left, opaque in the middle and window modules on the right): vision façade module (a); opaque façade module (b); window façade module (c).

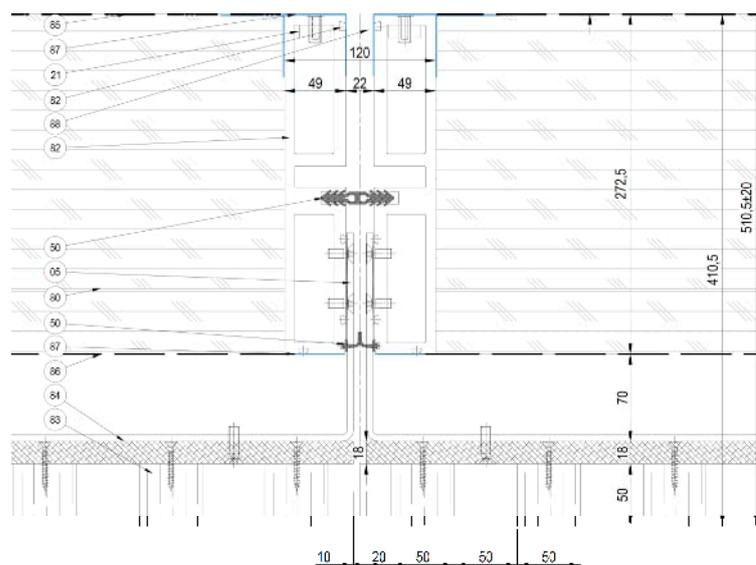


Figure 2. Final solution: horizontal section of the Basajaun opaque façade module.

Important to mention are the technologies integrated within the façade system to replace the standard components:

- Insulation—the conventional material in curtain wall façades is mineral or rock wool. In the Basajaun façade system, an insulation material of comparable thermal resistance composed of wooden fibers has been selected. The choice of wooden fibers over synthetic alternatives underscores a commitment to eco-friendly design [32] with the aim to demonstrate the balance between aesthetic, ecological, and technical performances. The selected insulation has a thickness of 220 mm and 50 mm, gross density of 55 kg/m^3 , and thermal conductivity of $0.038 \text{ W}/(\text{m}^2 \times \text{K})$.
- Frame profile—Biocomposite profiles feature a blend of components, primarily composed of a bio-based resin system and basalt fiber reinforcement. Within the material ratio, the reinforcement accounts for 55%, comprising endless roving fibers and various types of woven roving. The resin system, constituting 45% of the composite, is a complex amalgamation of elements. Notably, 30% of the base resin is bio-based, incorporating succinic acid instead of conventional orthophthalic or isophthalic acid and recycled components. The bio-based resin system is enriched with a range of additives, including a shrinkage reducer, internal mold release agent, accelerator, catalyst, color paste, and air bubble remover additive. Additionally, 3% of the resin system is comprised of wooden particles, all of which are bio-based.
- Membrane and tapes as tightness and wooden plywood as stiffness layers—these technologies replace the conventional aluminum sheets. The selected membrane is in aluminum/PE and glass fiber, with a thermal conductivity of $0.0007 \text{ W}/(\text{m}^2 \times \text{k})$, water impermeability Class W1, and fire classification (EN 13501-1 [33,34]) class A2-s1, d0. The stiffness layer supports the assembly structurally, distributing loads and resisting deformation. For the Basajaun façade, 18 mm-thick plywood panels are employed as a bio-based alternative in wood-based façade system modules.
- In the design, the selected insulation and tightness layer are on-market technologies, while the biocomposite profile is an original product developed within the project.
 - Also included is the method statement for testing activities conducted in a laboratory environment to validate façade system modules, based on EN 13830:2015 [35] and EN 14019:2016 [36] for curtain walling—impact resistance—and performance requirements and local norms for thermal behavior. These European standards specify the requirements for lightweight façades intended for use in the building envelope to provide weather protection, safety in use, energy savings, and heat

retention. The performance test sequence is reported in Table 9. In addition, for the acoustic validation, the tests are performed by following the EN ISO 717-1:2020 (IN-OUT test) standards [37].

3. Results

The Basajaun façade system is defined based on requirements and market standards for both vision and opaque typologies of curtain wall façade systems. Applying the Basajaun façade in demonstration buildings serves as the initial validation in real-world settings with stakeholders. The target for each demo is to have an innovative product that complies with all the requested outcomes for the façade. The EN 13830:2005 standard is used as the norm of reference for the testing activities and the requirements to be achieved, while also complying with those defined by the demo buildings and those to be further described.

Additionally, particular emphasis is placed on validating the implementation of bio-composite materials within the Basajaun façade system. While curtain façade technology with aluminum profiles is well-established in the market, the utilization of pultrusion materials constitutes a novel contribution to building envelopes, necessitating careful consideration of specific requirements. The research explores the feasibility of incorporating pultruded bio-based components by testing their performances and characteristics.

The following paragraphs present the validation of the final design of the bio-based façade system resulting from the previous evolutions, requirements, and considerations.

3.1. Identification of Validation Activities

Based on the identified requirements during the designing phase of the project, a set of validation tests during the integration of the components have been defined at different stages of the development of the façade systems. Table 1 reports an outline of the activities deployed for validation.

Table 1. Testing activities to validate the integration of alternative components into curtain wall façade.

Validation	Test Conducted	
Biocomposite properties	EN 13706:2002	Lab test
Structural silicone compatibility and adhesion with bio-based profiles	Compatibility test ASTM C1087 and ETAG002 (5.1.4.2.5) Adhesion test ASTM C794 or ETAG 002 (8.3.2.4(6))	Lab test
Tape and membranes adhesion with biocomposite profile	EN12316-2:2013 and EN12317-2:2011	Lab test
Bio-based profiles cutting and machining	CNC machining center	CNC machining center
Façade manufacturing	Mock-up manufacturing	Mock-up manufacturing
Watertightness of joints	EN ISO 13830:2005 curtain wall façade—CE for façade	Performance mock-up (PMU)
Wind load resistance	EN ISO 13830:2005 curtain wall façade—CE for façade	Performance mock-up (PMU)
Acoustic attenuation	EN ISO 10140-2	Opaque acoustic mock-up (AMU)
Acoustic attenuation	EN ISO 10140-2	Vision acoustic mock-up (AMU)

3.2. Façade Prototyping and Testing Phase

The following chapter reports the tests conducted to validate the developed façade system design. It begins with the validation of the properties and characteristics of the biocomposite profile. Subsequently, adhesion and compatibility tests were conducted among the biocomposite profile and façade components to ensure proper integration. Finally, the façade systems were manufactured, and performance and acoustic tests were conducted.

3.2.1. Bio-Based Profile Testing

The bio-component pultruded profile for the façade module system has undergone various tests to ensure its suitability for inclusion in the system. It is important to note that this material, although based on wood, has been configured as a composite by mixing resins and fibers to create a plastic composite. Through an iterative manufacturing process involving adjustments to the pultrusion process velocity and curing temperature, the results obtained align with the expected profile design. Figure 3 shows the first pultruded profile demonstrating the effectiveness of the material properties and the design. Indeed, these tests confirm the compatibility of the material and its configuration within the system.



Figure 3. Image of the bio-based pultruded profile tested.

Based on the standard “EN 13706-2:2002 Reinforced plastics composites—Specifications for pultruded profiles—Part 2: Methods of test and general requirements” [38], the first tests were conducted, and the results were compared with the values tabulated in the UNE-EN 13706-3 standard [39] (Table 2), obtaining the highest classification you can have.

Table 2. Minimum properties regarding EN 13706-2:2002.

	Properties	Unit	Test Method	Minimum Requirements	
				E23	E17
1.1	Modulus of elasticity	GPa	Annex D, EN 13706-2:2002	23	17
1.2	Tensile modulus longitudinal	GPa	EN ISO 527-4 [40]	23	17
1.3	Tensile modulus transverse	GPa	EN ISO 527-4	7	5
1.4	Tensile strength longitudinal	MPa	EN ISO 527-4	240	170
1.5	Tensile strength transverse	MPa	EN ISO 527-4	50	30
1.6	Pin-bearing strength longitudinal	MPa	Annex E	150	90
1.7	Pin-bearing strength transverse	MPa	EN 13706-2:2002	70	50
1.8	Bending strength longitudinal	MPa	EN ISO 14125 [41]	240	170
1.9	Bending strength transverse	MPa	EN ISO 14125	100	70
1.10	Shear strength longitudinal	MPa	EN ISO 14130 [42]	25	15

Table 3 shows the tests conducted by each specific standard, and demonstrates the good properties obtained for this bio-component pultruded profile for the façade module system. The tests that do not appear were not made for the dimensions of the profile and therefore cannot provide standard test specimens.

Table 3. Properties of bio-based profile according to specifications EN13706-2:2002.

Test	Standard	Reference Document	Properties	Main Value (SD)	Requirement	Classification
Tensile properties (axial)	EN ISO 527-4:1997 [43]	EN 137063:2003	Modulus of elasticity (MPa)	27,100 (1100)	E23 GRADE \geq 23,000; E17GRADE \geq 17,000	E23
			Tensile strength (MPa)	409 (39)	E23 GRADE \geq 240; E17GRADE \geq 170	E23
Pin-bearing strength (axial)	EN 13706-2, Annex E EN ISO		Pin resistance (MPa)	310 (13)	E23 GRADE \geq 150; E17GRADE \geq 90	E23
Flexural properties (axial)	14125:1999+ ERRATUM:2002 + 1M:2011 [44]		Flexural strength (MPa)	630 (28)	E23 GRADE \geq 240; E17GRADE \geq 170	E23
Interlaminar shear strength (axial)	EN ISO 14130:1999		Apparent interlaminar shear strength (MPa)	25.0 (0.8)	E23 GRADE \geq 25; E17GRADE \geq 15	E23

In order to increase the performance of the profile and, above all, to assess how it could behave against aggressive agents, the Table 3 shows the results of mechanical tests carried out in addition to those described above and physical tests to evaluate its properties (Table 4).

Table 4. Mechanical tests.

Test	Standard	Properties	Main Value	Test	Standard	Properties	
Tensile properties (axial)	EN ISO 527-4:1997	Poisson ratio (μ)	0.33 (0.03)	Compression strength (axial)	EN ISO 14126:2001 + AC:2002 [45]	Modulus of elasticity (Mpa)	34,600 (1500)
		Tensile strain at tensile strength (%)	1.7 (0.1)			Compressive strength (Mpa)	443 (15)
		Stress at break (MPa)	409 (39)	Deformation in compressive strength (%)		1.8 (0.3)	
		Strain at break (%)	1.7 (0.1)	Modulus of elasticity (Mpa)		17,300 (500)	
Flexural properties (axial)	EN ISO 14125:1999+ ERRA-TUM:2002 + 1M:2011	Modulus of elasticity (Ef) (MPa)	24,900 (1700)	Compression strength (transverse)		Compressive strength (Mpa)	90.3 (3.4)
		Flexural strain at the maximum point stress (%)	17 (2)			Deformation in compressive strength (%)	0.74 (0.08)
Interlaminar shear strength (axial)	EN ISO 14130:1999	Apparent interlaminar shear strength (MPa)	25.0 (0.8)	Tensile properties (axial) after 1200 h of Xenon aging test simulating one year of aging	EN ISO 527-4:1997	Poisson ratio (μ)	0.29 (0.08)
		Apparent interlaminar shear resistance (MPa)	21.5 (1.1)			Modulus of elasticity (MPa)	28,000 (2200)
Interlaminar shear strength (transverse)	EN ISO 14130:1999	Apparent interlaminar shear strength (MPa)	5.66 (0.65)			Tensile strength (MPa)	388 (25)
		Apparent interlaminar shear resistance (MPa)	5.17 (0.58)			Tensile strain at tensile strength (%)	1.42 (0.08)
Impact resistance Charpy (axial)	EN ISO 179-1:2011 [46]	Break type	No break			Stress at break (MPa)	388 (25)
Impact resistance Charpy (transverse)		Impact resistance (kJ/m ²)	19 (3)			Strain at break (%)	1.42 (0.08)

Based on these results, including tensile properties before and after aging tests, it can be confirmed that crucial mechanical properties such as tensile properties remain

unaffected by aging. The material maintains its rigidity (27.1 GPa before aging and 28 GPa after), tensile stress (409 MPa before aging and 388 MPa after), and tensile strain of 1.7% compared to 1.4%. These values are consistent, considering the standard deviation shown in each test. Moreover, the latest test conducted on the profiles indicates improved flexural properties compared to previous ones, with a 25% increase in elasticity modulus and a 35% increase in flexural strength, as shown in Table 5. As a result, the performance of both the profiles and the system surpasses the expectations set by the mechanical calculations.

Table 5. Improvement of the flexural strength and the flexural modules with the last tests conducted on the material.

	Calculus Made	Real Element	Variation
Flexural strength (MPa)	409	630	35%
Flexural modulus (MPa)	18,800	24,900	25%

Regarding the physical assets (Table 6), a battery of tests was conducted to validate the properties and compare them with commercial profiles. Table 6 reports all the results which are very promising, showing a performance equal to or superior to commercial profiles in some tests.

Table 6. Physical and optical properties.

Test	Standard	Properties	Main Value	Test	Standard	Properties	Main Value
Fiber content by weight	EN ISO 1172:1999 Method A [47]	Glass fiber content (%)	61.21 (0.72)	Color difference/color coordinates after chemical resistance (H ₂ SO ₄) and water absorption	EN ISO 11664-4:2020 [48]	L*	11.85
Thermal expansion (axial)	ISO 11359-2:2021 [49]	Thermal expansion (axial) (K-1)	10×10^{-6} (2×10^{-6})			a*	−0.56
Thermal expansion (axial)		Thermal expansion (axial) (K-1)	51×10^{-6} (3×10^{-6})			b*	−2.12
Barcol hardness	EN 59:2016 [50]	Barcol hardness	49 (3)	Color difference/Color coordinates after chemical resistance (NaOH) and water absorption		L*	15.25
Chemical resistance	EN ISO 175:2011 [51]	Chemical resistance NaOH mass loss (%)	0.018 (0.008)			a*	−0.48
		Chemical resistance NaOH mass loss (%)	−0.001 (0.001)			b*	−2.53
Water absorption	EN ISO 175:2011	Water absorption (%)	1.58 (0.026)	Density	EN ISO 1183-1:2019 [52]	Density (g/cm ³)	1843 (0.002)

Beyond the specific results about bio-component pultruded profiles, tests were conducted to validate the compatibility between the biocomposite profile and other façade materials. In particular, the following tests were conducted:

- The opaque façade's technological systems (Figure 4) were tested for exposure to damp heat, water spray, and a salt mix under ISO 4611:2011 [53] to assess:
 - The internal vapor barrier technological system composed of tape, membrane, double tape, and the biocomposite profile.
 - The external wind-air tightness and wind load resistant technological system composed of tape, membrane, double tape, and the biocomposite profile.
- The vision façade system, particularly the technological system composed of structural silicone and biocomposite profile, was tested for adhesion and compatibility.

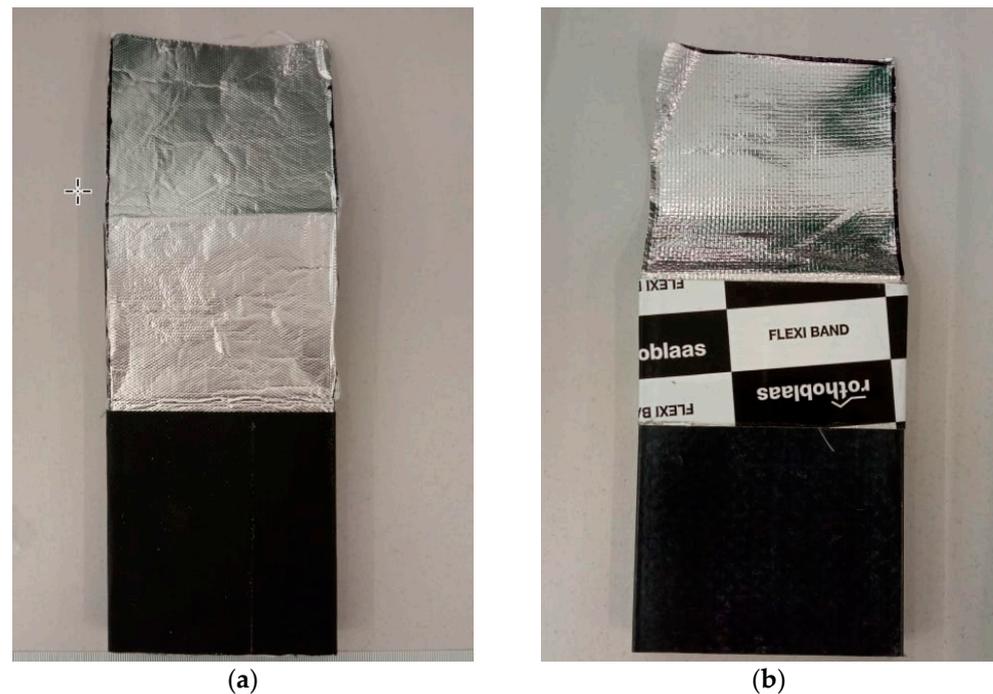


Figure 4. Samples for opaque façade technological system tests: air, water tightness, and wind load-resistant technological system (external side) (a); vapor barrier technological system (internal side) (b).

For both systems, peel and shear tests were performed before and after aging in specific conditions. Peel tests were performed based on UNE EN 12316-2:2013 [54] with specimens with a width of 91 mm. Shear tests were performed based on UNE EN 12317-2:2011 [55] with specimens with a width of 91 mm and a total length of 200 mm, with a width of the joint in the middle of the specimen of 50 mm. The tests performed in each system were:

- Internal technological system:
 - Shear test of the reference (procedure based on UNE EN 12317-2:2011)
 - Peel test of the reference (procedure based on UNE EN 12316-2:2013)
 - Shear test of the samples after an aging of 168 h at 50 °C and 70% RH
 - Peel test of the samples after an aging of 168 h at 50 °C and 70% RH
- External technological system:
 - Shear test of the reference (procedure based on UNE EN 12317-2:2011)
 - Peel test of the reference (procedure based on UNE EN 12316-2:2013)
 - Shear test of the samples after aging of 14 days at $(23 \pm 2) \text{ }^\circ\text{C}/(50 \pm 10)\%$ RH + 4 days at $(70 \pm 2) \text{ }^\circ\text{C}$ + 24 h at $(23 \pm 2) \text{ }^\circ\text{C}-(50 \pm 10)\%$ RH + UV aging according to Annex C UNE EN 13859-2:2014 [56] (336 h of UV cycle phase)
 - Peel test of the samples after aging of 14 days at $(23 \pm 2) \text{ }^\circ\text{C}/(50 \pm 10)\%$ RH + 4 days at $(70 \pm 2) \text{ }^\circ\text{C}$ + 24 h at $(23 \pm 2) \text{ }^\circ\text{C}-(50 \pm 10)\%$ RH + UV aging according to Annex C UNE EN 13859-2:2014 (336 h of UV cycle phase, a total of 403 h)

Results of the peel tests are reported in Table 7.

Results of the shear tests are reported in Table 8.

Table 7. Results of the peel tests.

	Average Force (N/50 mm) (SD)	Maximum Force (N/50 mm) (SD)	Failure Mode
Internal technological system—reference	81 (4)	86 (4)	A—Peeling of the joint
Internal technological system—168 h at 50 °C and 70% RH	79 (3)	83 (4)	A—Peeling of the joint
External technological system—reference	92 (1)	102 (1)	A—Peeling of the joint
External technological system—after aging *	78 (8)	104 (5)	A—Peeling of the joint

* 14 days at $(23 \pm 2)^\circ\text{C}/(50 \pm 10)\%$ RH + 4 days at $(70 \pm 2)^\circ\text{C}$ + 24 h at $(23 \pm 2)^\circ\text{C}-(50 \pm 10)\%$ RH + UV aging according to Annex C UNE EN 13859-2:2014 (336 h of UV cycle phase, a total of 403 h).

Table 8. Results of the shear tests.

	Shear Strength—Maximum Force (N/50 mm) (SD)	Failure Mode
Internal technological system—reference	253 (51)	In the material, outside of the joint
Internal technological system—168 h at 50 °C and 70% RH	175 (13)	In the material, outside of the joint
External technological system—reference	337 (26)	In the material, outside of the joint
External technological system—after aging	296 (26)	In the material, outside of the joint

Structural silicone (test description)—as mentioned above, a series of tests were conducted to guarantee the compatibility and adhesion behavior between the biocomposite profile with structural silicone and other sealants to be used in façade manufacturing (vision façade module) and in the installation stage (tightness sealing for the curtain wall façade) by the silicone supplier.

- Compatibility—performed in accordance with the adapted ASTM C1087 [57] and ETAG002 paragraph 5.1.4.2.5 [58]. Seven test pieces were produced and conditioned at a temperature of $(60 \pm 2)^\circ\text{C}$ and $(95 \pm 5)\%$ relative humidity, five for 28 days and the remaining two for 56 days.
- Adhesion—performed in accordance with the adapted ASTM C794 [59] or ETAG 002 Paragraph 8.3.2.4(6) [58]. The test assessed three pieces in immersion in water $(95 \pm 2)^\circ\text{C}$ for 24 h, three test pieces in immersion in water at $(23 \pm 2)^\circ\text{C}$ for 7 days, and three test pieces in an oven at $(100 \pm 2)^\circ\text{C}$ for 7 days. The pieces were then conditioned for (48 ± 4) hours at a temperature of $(23 \pm 2)^\circ\text{C}$ and $(50 \pm 5)\%$ relative humidity. The conditioned test pieces were then subjected to tensile tests to rupture.

Cutting and machining—an important phase is the cutting and machining, which involves the precision cutting and shaping of the biocomposite profile to meet specific design requirements. This process typically includes tasks such as sawing, milling, drilling, and tapping to create precise dimensions and features. Overall, the cutting and machining phase is essential for transforming raw profile bars into functional components ready for assembly in the production line. Preliminary tests were conducted on the biocomposite profile sample for cutting and machining activities with the aim to investigate its behavior, and to identify the best equipment to use to identify the most suitable tool for the biocomposite material (Figure 5). The tests revealed good properties for cutting, allowing the operation to take place without provoking any cracks or damage. However, the standard equipment

used for aluminum is not suitable for the biocomposite due to the hard properties of basalt fibers, which ruined the machining during the activities. Therefore, different tools and systems need to be used. Moreover, due to the amount of resin included in biocomposite materials, a fully equipped vacuum system is needed for the generated dusts, as illustrated in Figure 6.

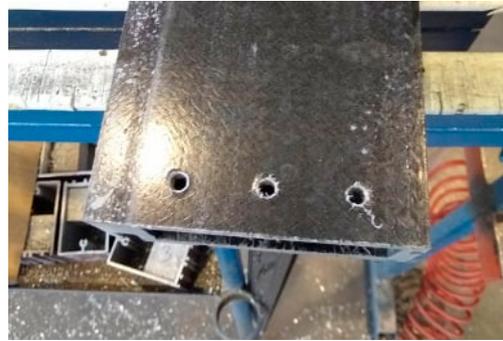


Figure 5. Preliminary drilling activities.



Figure 6. Dust removal after the machining phase.

The Basajaun biocomposite profiles after the cutting and machining process are depicted in Figure 5.

3.2.2. Façade Manufacturing

The manufacturing of prototypes for the Basajaun façade involves both vision and opaque modules. This comprehensive approach aims to showcase the design's effectiveness and test the entire façade system. The primary objectives are to demonstrate the façade system design effectiveness and to identify potential weak points, aiming to provide valuable insights for enhancement. Therefore, the testing phase not only serves to validate the Basajaun façade system but also aligns with the norms set by the curtain wall façade (EN 13830). This demonstration emphasizes the correct design and manufacturing processes for the module, ensuring compliance with industry standards. Below, a sequence of manufacturing processes is reported; Figure 7 for vision modules and Figure 8 for opaque modules, while Figure 9 shows the three components which replaced conventional technologies: biocomposite profiles (a), membrane and tape application (b), and wooden fiber integration with the façade (c).

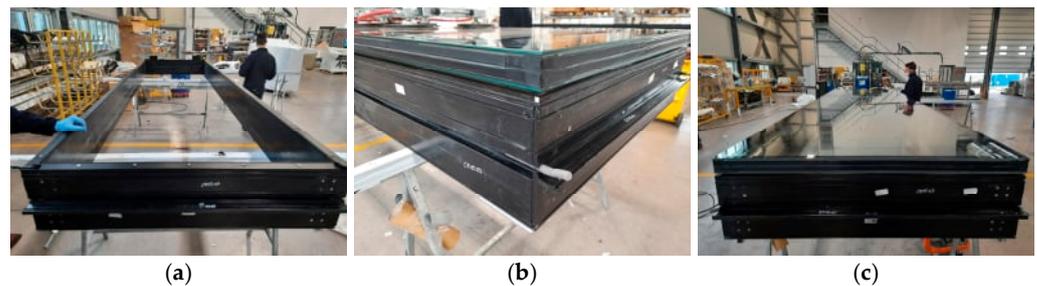


Figure 7. Vision façade module prototype manufacturing: biocomposite profile frame and aluminum plate assembly (a); glass detail (b); glass on the biocomposite profile frame before the sealing (c).

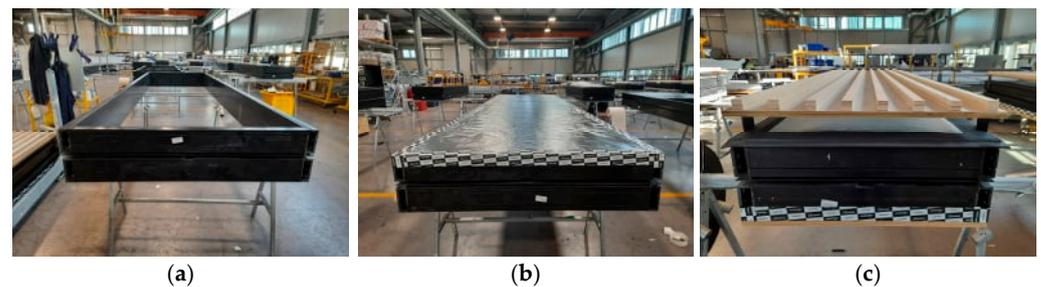


Figure 8. Opaque façade module prototype manufacturing: biocomposite profile frame assembly (a); membrane and tape positioning (b); and cladding installation (c).

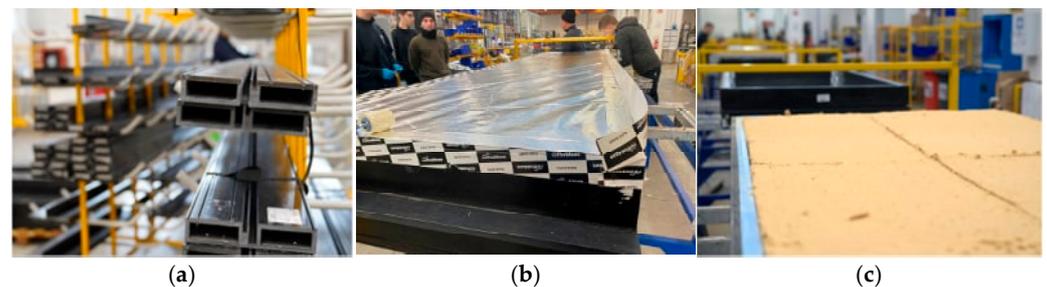


Figure 9. Bio-based profile preparation for façade prototypes after cutting and machining phase (a); membrane and tape application within the façade; (b) and wooden fiber insulation integration (c).

3.2.3. Performance Test

The Basajaun PMU has been designed considering the most relevant unit typologies and the material used in the demo buildings. Therefore, the units have been positioned on two different floors to be able to test all the possible junctions. For this reason, the n°3 vision module was positioned on the ground floor, while on the first floor two opaque units (n.1 with wooden cladding for the French demo and n.1 with the one for the Finnish demo) with a n°1 window typology were positioned. The Basajaun façade constitutes a unitized system, necessitating validation of its performances in accordance with EN 13830 standards for curtain wall façades. The conducted test, specific to this technological product, entails a comprehensive analysis of norms to discern the extent to which this façade facilitates elevated building performances. Accredited testing facilities, authorized to furnish official test reports for the acquisition of CE certification under EN 13830, have executed the test. The method statement delineating the testing procedures has been meticulously defined, and the sequential arrangement of the tests has been stipulated as follows:

1. Air permeability, water penetration resistance, and wind resistance test sequence.
2. External and internal impact test sequence for impact with the double tires.
3. Deflection gauge verification—based on façade mechanical simulation, the correspondence between the value from the simulation and the one from the test is compared to confirm the theoretical component. The complete list of conducted tests is in Table 9.

Table 9. Method statement of laboratory environment tests—performance tests.

Sequence	Test	Activity—Range Values
1A	Air permeability	Test Pressure: ± 75 Pa
1B	Air permeability infiltration/exfiltration	Test Pressure: ± 600 Pa
2	Static water penetration resistance	Test pressure: $+600$ Pa
3	Wind resistance serviceability	Test pressure: ± 1350 Pa
4	Air permeability infiltration/exfiltration	Test Pressure: ± 600 Pa
5	Static water penetration resistance	Test pressure: $+600$ Pa
6	Wind resistance safety	$\times 1.5$ wind design pressure. Test pressure: ± 2025 Pa
7	Impact test—double tire	343 J (700 mm height)

Figure 10 shows the façade installed, three vision modules on the ground floor, and three opaque modules on the first floor (a), and one of the impact tests performed with the double tire on a glass surface (b).

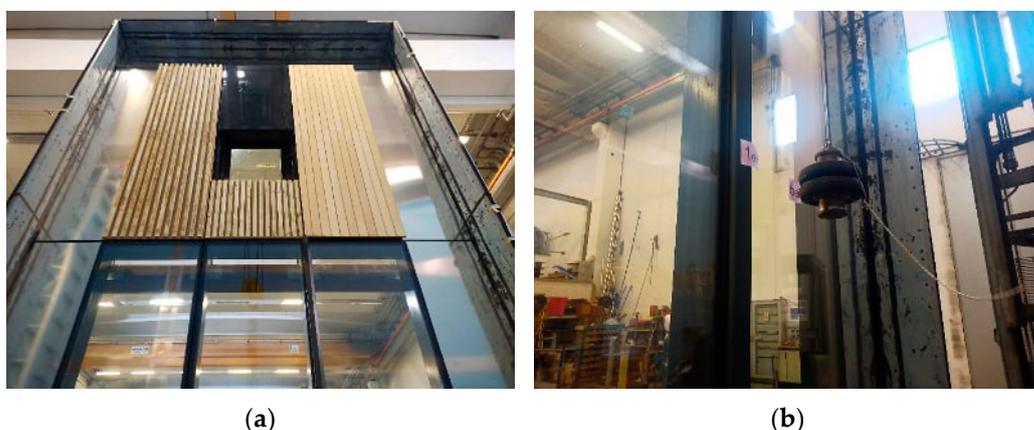


Figure 10. Performance mockup test: mockup installed in lab environment before testing activity (a); impact test against vision façade module (b).

The result achieved by the PMU test accomplished all the requirements according to the EN ISO 13830:2005, as shown in Table 10.

Table 10. Results achieved during EN 13830 testing activities.

Activity	Test Reference	Classification Reference	Class
Air permeability through fixed parts	Related to overall area	EN 12153 [60]	A4
	Related to fixed joint lengths	EN 12152 [61]	A4
Watertightness	EN 12155 [62]	EN 12154 [63]	R7
Resistance to wind load under design load $+1350$ Pa and -1350 Pa	EN 12179 [64]	EN 13116 [65]	Pass
Internal impact resistance	EN 14019	EN 14019	I2
External impact resistance	EN 14019	EN 14019	E5

3.2.4. Acoustic Test

The purpose of the acoustic mock-up was to demonstrate the Basajaun façade acoustic insulation performance under the norm EN ISO 717-1:2020 (IN-OUT test). The acoustic mock-up has been designed by considering the dimensions of the acoustic chamber set up in the Tecnia laboratory where the test was conducted. Four façade modules, each

800 × 2760 mm, were installed into a prefabricated concrete frame 40 cm thick with interior dimensions of 2800 mm high by 3600 mm long, with a surface of wood cladding oriented to the source test room. The gap, in the lateral part, between the acoustic chamber frame and the façade modules was filled by a brick wall with gypsum plasterboard and mineral wool lining on both sides. The test mock-up was mechanically fixed to the perimeter by means of a steel profile and the gap was sealed mainly by mineral wool and joint sealing. Figure 11 shows the vision module acoustic chamber while Figure 12 shows the opaque modules.



Figure 11. Vision façade picture of test specimen in the test rooms.



Figure 12. Opaque façade pictures of the test specimen in the test rooms.

The test was conducted in horizontal transmission rooms, which consisted of a source room and a receiving room. The receiving room comprised two separate concrete boxes, each with a thickness of twenty and ten centimeters respectively, designed for acoustic isolation. Conversely, the source room was constructed with a double box featuring a metal frame and gypsum board, also for acoustic isolation. The mobility of the source room facilitated the positioning of the test specimen externally, as well as its subsequent installation between the test rooms. The test's objective was to obtain the rating according to EN ISO 717-1:2020. Therefore, it was necessary to obtain the sound reduction index, R , for the one-third-octave band from 100 Hz to 5 kHz, according to EN ISO 10140-2:2021 [66]:

$$R = L_1 - L_2 + 10 \times \log S/A \quad \text{where} \quad S: \text{test specimen area}; A = 0.16 \times V/T$$

- The average sound pressure level in the source and receiving room, L_1 and L_2 , were measured using a moving microphone with a sweep radius of 1 m and a traverse period of 16 s during 32 s of measure. Background noise in the receiving room was measured according to the same measurement process of the sound field in the receiving room.
- The equivalent sound absorption area, A , in the receiving room was evaluated from the reverberation time measured in the receiving room, T , and from the receiving room

volume, V . Reverberation time was determined by using two positions of the sound source and three fixed microphone positions for each source position distributed at 120° in the microphone path. The measurement chain was verified just before and after the execution of the test.

- The rating according to EN ISO 717-1:2020 was calculated from the sound reduction index curve obtained according to EN ISO 10140-2:2021.
- For the vision modules the test was conducted following the EN ISO 10140-2:2021, and the results obtained are (rating according to EN ISO 717-1:2020):
- R_w (C; Ctr): 42 (−2; −6) dB.
- $RA = R_w + C_{100-5000}$: 41 dB.
- $RA, tr = R_w + C_{tr,100-5000}$: 36 dB
- While for the opaque modules the results obtained are (rating according to EN ISO 717-1:2020):
- R_w (C; Ctr): 44 (−2; −7) dB.
- $RA = R_w + C_{100-5000}$: 43 dB.
- $RA, tr = R_w + C_{tr,100-5000}$: 37 dB

4. Discussion

This section synthesizes the key discussions and interconnections regarding the Basajaun project objectives outlined in Section 1. The results obtained during the validation phase revealed that the façade system design aligns with the research objective and expectations mentioned in the introduction. These results demonstrate the effectiveness of implementing various façade typologies, industrialized manufacturing processes, and the use of biocomposites, which converge to create sustainable and innovative building envelope solutions. Regarding the biocomposite profile developments:

- All the conducted tests confirmed a successful outcome—the profile could be a valuable alternative to conventional materials such as aluminum in curtain wall façades. Indeed, considering the production process of the frame profiles, pultrusion consumes less energy per unit weight compared to aluminum profile extrusion, with the biocomposite reducing energy consumption by about 70%. However, Basajaun pultruded profiles weigh nearly twice as much as aluminum profiles with comparable structural properties. At the same time, the assembly of the façades did not show significant variations during the analysis. More detailed insights derived from the sustainability analysis of the façade systems are presented in Morganti et al. [30], offering indicators toward circular, environmentally conscious, and bio-composed building envelopes.
- For the adhesion test between the sealants and biocomposite profile, the aim was to use structural silicone in direct contact with the biocomposite profile to reduce the number of system components. While the test did not fail, for safety reasons and for future building lifespans, the manufacturing has been conducted with an aluminum profile integrated with the bio-component profile to have certainty of the adhesion of structural silicone with glass.
- For the adhesion test between the membrane and biocomposite profiles, the results confirm that the solution may be considered valuable for utilization in the façade, not having achieved failure mode. Conducting durability tests on these systems over an extended period, considering the diverse support structures to which they were affixed, has been a fundamental step. Such evaluations are crucial for ascertaining the long-term effectiveness of these systems as well as their suitability for practical implementation.
- Cutting and machining—due to their characteristics, the biocomposite profiles can be cut and machined by changing the equipment tool, in comparison to the aluminum profiles. However, for further developments a substantial weight reduction needs to be considered to enhance overall economic efficiency.

Regarding the development of bio-based curtain wall façade:

- The Basajaun system tests confirm successful outcomes, including manufacturability of panels, validation of design accuracy with minor adjustments, definition of possible performance levels, adherence to current curtain wall façade standards, and demonstration of the effectiveness of the Basajaun systems in addressing prefabrication challenges while meeting high-performance standards.
- The performance test (PMU) demonstrates that the façade can support the wind load in pressure and suction, and guarantees air permeability and watertightness based on tests according to the standard provided. Table 11 reports the results obtained and the result analysis.
- AMU—The results of the acoustic mock-up are useful to define the acoustic insulation provided by the Basajaun project. Both typologies were validated by in situ tests. Table 12 shows a comparison of the obtained results.
- The results of the acoustic mock-up, according to EN ISO 717-1:2020, R_w ; C; Ctr; C100–5000; Ctr,100–5000, are necessary to estimate the acoustic behavior of the rooms of a building, R'_w . Once the building is executed, an in situ test is carried out to validate R'_w against the established requirement. Table 11 shows that the in situ measured results improve the simulation results and are much higher than the requested requirements.
- It is very important to have reliable data of enclosures, especially in new systems, to obtain adequate estimation data and be able to satisfy the established requirements.

Table 11. Discussion of test results.

Test	Minimum	Result	Discussion
Air permeability—EN 12153:2002	A1	A4–A4	A4: Classified under pressure/suction of 600 Pa
Watertightness—EN 12155:2002	R4	R7	R7: No water entrance under 600 Pa
Resistance to wind load, fitness for use—EN 12179:2002	1350 Pa	+1350 Pa et –1350 Pa	The test wind load was repeated after the air permeability and the watertightness. The façade demonstrated that the joints of the systems work properly. Indeed, after the application of the wind load pressure and suction, there was no reduction of functionality and performance.
Safe impact/break resistance (interior)—EN 14019:2016	I1	I2	Results from I1 to I5 (it is not tested higher than I2 to not have the possibility to break the sample before the end of the test)
Safe impact/break resistance (exterior)—EN 14019:2016	E1	E5	Results from E1 to E5: obtained the highest classification

Table 12. Comparison among the results obtained for acoustic tests in different phases.

Typology	Results to be Achieved	Results Obtained during Simulation	Result Obtained During the Test
Vision module	$R'_w \geq 30$ dB	$R'_w \geq 44$ dB	$R'_w \geq 42$ dB
Opaque module	$R'_w \geq 31$ dB	$R'_w \geq 44$ dB	$R'_w \geq 44$ dB

However, further activities need to be conducted with the aim to investigate additional characteristics and implement the façade system:

- Sealant test—once defined, the finishing of the window (architectural choice ongoing by UNSTUDIO and demo partner); a final approval on dark finish (T17 EBANO) for the wooden frame is pending.
- Implementation of Basajaun façade typologies—the activities conducted during the Basajaun façade system demonstrate that the system could be adapted for different façade module typologies to be used in a demo building. The next activities regarding the Basajaun façade will be to develop the demo detail design and Basajaun façade

manufacturing. In addition, to have the possibility to install the system in the demo building in France (Bordeaux), it was requested by the local architects to fulfill an ATEX procedure (Appreciation Technique d' experimentation) of the entire façade system. All these tests were used as part of this validation process conducted by the CSTB (Centre Scientifique et Technique du Bâtiment) with reference number: 3047_V1.

- Prefabrication process industrialization—the goal of advancing the prefabrication manufacturing process lies in its industrialization to address the construction industry's needs. This segment looks into assessing the benefits of factory-based manufacturing, encompassing aspects such as cost efficiency, quality control, and scalability. One aim is to decrease both the weight and thickness of the façade system with a targeted approach towards optimizing biocomposite profiles, resulting in improved resource efficiency and cost savings. Indeed, Basajaun pultruded profiles weigh nearly twice as much as aluminum profiles with comparable structural properties.

5. Conclusions

The above-mentioned activities demonstrated that the Basajaun façade system design is successfully aligned with the stipulated objectives and requirements of the research, demonstrating accomplishments in several key areas. The validation phase highlights that the designed Basajaun façade system is in line with current building envelope standards for curtain wall façade solutions. Indeed, the results obtained addressed all the assessing criteria defined by the curtain wall standards, demonstrating the feasibility of replacing standard components with bio-based ones. These results represent an important achievement in taking a step further in the introduction of bio-based materials in the construction sector.

Moreover, the focus on industrialization allows for off-site manufacturing, with on-site installation limited to brackets and base profiles, ensuring scalability and reproducibility as well as reducing the construction site time and costs.

The prototyping and testing activities validated these outcomes and explored the broader applicability of the Basajaun façade within wood-based products in the construction value chain.

Beyond the achievements obtained by the Basajaun façade system, further steps could be made with the aim to improve the façade system and its marketability:

- To further validate the Basajaun façade system design and demonstrate its applicability in pilot buildings (located in France and Finland), we will develop the pilot detail design to investigate its impact on real-case manufacturing,
- To tackle all the defined weak points,
- To enhance 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,
- To develop the market validation which is missing and should be conducted once the bio-based profile is able to reduce its manufacturing costs.

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