Implementation of a multifunctional Plug-and-Play façade using a set-based design approach

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Abstract
An immediate paradigm shift is needed to transform the deep renovation market for improved building performance and expanded energy efficiency horizons. The financial, social, and sustainability challenges of the EU targets suggest research towards reliable, inter-compatible, and interoperable solutions aiming at combining different energy conservation measures. This work proposes the implementation of a lightweight Plug-and-Play (PnP) building system for façade renovation using a set-based design approach. The PnP module, based on a main structure in the form of a Light Steel Frame (LSF) and a metal-faced sandwich panel, is combined with various market-ready components. The efficient integration of these third-party products is highlighted by defining and demonstrating the design process, implementing a solution driven by the reach of a highly industrialised solution, easy to assemble and install, customizable, scalable, and adaptable to the existing buildings. With the set-based design matrix, different integration scenarios are investigated through virtual prototypes. Moreover, to facilitate the shift from design to construction of the integrated PnP module, the study proposes three prototyping levels to demonstrate the efficiency of the design integration methodology and the technical feasibility of both the various module's configurations and the overall module, exploring them through the realisation of preliminary, full-scale façade and actual environment-applied prototypes.

Keywords
plug-and-play façade, off-site construction, set-based design, integrated design, building renovation

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1 INTRODUCTION

In the framework of the European Green Deal (European Commission, 2020), the construction sector is acknowledged as the second-largest responsible for greenhouse gas emissions (Haigh et al., 2021). With the launch of the Renovation Wave, the European Union (EU) identifies the upcoming years as crucial for the transition to a carbon-neutral future. The EU gave a strong signal towards changing the building industry with modifications to the Energy Performance of Buildings Directive (European Commission, 2018), highlighting the importance of buildings' performance. Within this context, the need for forward-thinking strategies toward the improvement of the overall construction process in building renovation interventions has seen off-site construction techniques gaining interest from researchers in light of the industrialisation of the construction process toward the improvement of the construction rate (Correia Lopes, Vicente, Azenha, & Ferreira, 2018). Certainly, given the diverse range of commercial solutions in the market and the utilization of disparate criteria and inconsistent semantics among the prevailing categorization and classification systems for construction products, there persists a crucial requirement for standardization concerning the principal Prefabricated Enclosure Wall Panel Systems (PEWPS).

The construction sector is now shifting in a direction that has already been taken in other industries like automotive, design, and shipbuilding, where products' subparts are preassembled off the main assembly line, producing high-quality, optimised, and specialised products (Kieran & Timberlake, 2004). Although the renovation practice is increasing, according to the 2022 Global Status Report for Buildings and Construction (United Nations, 2022), the progress of the building sector is far from the targets set. As a result, the trends of recent research projects supported by the EU also confirm the rising interest in off-site and multifunctional construction technologies for the building envelope (D'Oca et al., 2018) and particularly Zero Energy Renovation Kits, which are considered pivotal to accelerating the Renovation Wave (Van Oorschot, Di Maggio, Op 't Veld, & Tisov, 2022) and potentially overcoming the existing technical, financial and social obstacles (D'Oca et al., 2018). In this context, there is significant opportunity and room for improvement of Plug-and-Play (PnP) solutions (Piaia, Turillazzi, Longo, Boeri, & Giulio, 2019). The term "plug and play" is widely known in the computer industry, referring to the ability to easily implement an existing system without manual intervention. In the last years, the term has also been used in the construction sector (Sebastian et al., 2018). PnP solutions are primarily off-site components, which, due to standardisation and ease of on-site assembly, contribute to (i) speeding up the renovation time by up to 50%, (ii) avoiding the disturbance of people, (iii) reducing the overall cost, allowing at least 15% savings, (iv) increasing performance and resource efficiency in both energy and material terms, and (v) the possibility for urban mining and re-use of building materials (D'Oca et al., 2018; Op't Veld, 2015; Piaia et al., 2019).

Although the goal of this work is not to provide a state-of-the-art of off-site and industrialised technologies developed within the EU-funded programs, many research projects deepened the topic (Li & Chen, 2022). The projects focus on improving building energy, thermal, and environmental performance, emphasising façade retrofitting, which accounts for 20-30% of energy consumption (Dall'O', Galante, & Pasetti, 2012). One of the possible measures to address façade retrofitting is to adopt Energy Conservation Measures (ECMs) (Sarihi, Mehdizadeh Saradj, & Faizi, 2021). Various ECMs to renovate buildings that adhere to the standards established by the most recent European and international directives can be developed: (i) passive ECMs aim to reduce building energy consumption by increasing thermal resistance, replacing windows, and using bioclimatic strategies, (ii) active ECMs replace Heating, Ventilation and Air Conditioning (HVAC) components with energy-efficient sources, (iii) renewable energy source ECMs, like solar panels, photovoltaic panels, and wind turbines, and (iv) control ECMs optimise energy supply technologies, rationalising fossil fuel use (Sarihi et al., 2021). However, the application of each ECM will allow only certain improvements in the building performance; thus, recent studies focus on the combination of ECMs in the same system (D'Oca et al., 2018), investigating multifunctionality.

In considering the combination strategies, the MEEFS project, launched in 2012, focused on multifunctional façade modules with composite materials and renewable energy sources. Although the integration of renewable energies in the façade's modules is of common interest (Du, Huang, & Jones, 2019), many other projects deepen mainly the integration of active and passive technologies, such as high-performance lighting systems and energy-efficient HVAC. The E2VENT project proposed a comprehensive strategy for the retrofit of residential buildings employing a cutting-edge ventilated façade with heat recovery units, solar cells, and envelope insulation technologies and a latent system integrating Phase Changing Materials (Basso, Mililli, Herrero, Sanz, & Casaldiga, 2017). Furthermore, several projects investigated the manufacture of industrialised solutions in terms of process and product optimisation. The MORE-CONNECT project suggested process and product innovation for prefabricated modular façade elements, combining multifunctional components for temperature control, energy savings, building physics, aesthetics, and developing PnP connections (Veld, 2015). Consistently, the BERTIM project improved a prefabricated wood-based module integrating windows, balconies, insulation, collective HVAC systems, and renewable energy systems, addressing the complexity and multidisciplinarity of the multifunctional building envelope.

Although the projects focused on the application of both products and renovation methodologies, new concepts, such as building envelope adaptability, have expanded in recent years. There has been a renewed emphasis on improving energy efficiency, overall sustainability, and cost-effectiveness of off-site technologies in the last five years, proposing fast PnP façade solutions, including implementation within the BIM environment (D'Oca et al., 2018). The P2ENDURE project focused on prefabricated PnP solutions that are ready to use, scalable, adaptable, and effective, implementing prefabricated and multifunctional façade integrating windows, water ducts, and pipes, air supply and/or even ventilation ducts, heating, and cooling functions. On the same page, project 4RinEU also developed a prefabricated multifunctional façade integrating active components, proposing a risk evaluation method to address the effectiveness of the proposed technologies and implementations (D'Oca et al., 2018).

Even though research has shown that off-site façades for building renovation are cutting-edge in terms of sustainability, energy, and environmental efficiency (Capeluto, 2019), the literature identifies obstacles to their advancement. One of the main barriers is the lack of knowledge and experience among architects, engineers, and contractors in designing and constructing off-site façades. Moreover, the high initial costs associated with implementing these technologies compared to traditional construction techniques (D'Oca et al., 2018) form a bottleneck. Although many concepts have been created, only a few have reached market maturity and are now being used in building renovations (Capeluto, 2019). As a result, another method consisted of making these systems more competitive by merging several market-ready components. For example, the project BRESAER developed an innovative and adaptable industrialised system combined with a lightweight and versatile structure, using market-ready products, thus allowing the study of the mutual interaction between the components (Capeluto, 2019).

In light of the above, industrialisation is recognised as fundamental towards upscaling these solutions (Capeluto, 2019), highlighting the need for mass production strategies to boost them.
In addressing the complexity of the new technological solutions, industrial manufacturers will be key players in upscaling the solutions through industrialisation (Torres et al., 2021). On the one hand,

there is a need to implement innovative paradigms to design flexible and effective multifunctional complex construction systems (Simões et al., 2019), also considering that different stakeholders might be involved and, on the other hand, that there is the need for new holistic methods to evaluate and design renovation interventions (Colajanni, Rotilio, Di Santo, & Marrone, 2022). Although it might seem that prefabricated elements allow for limited adaptability, if the system is conceived as a combination of different components and implemented according to the demand, the possibilities are significant (Negrão, Godinho Filho, & Marodin, 2017).

This work uses a set-based design methodology to implement a PnP façade module for deep renovation. The PnP façade module's core is made by lightweight industrialised technologies, particularly Light Steel Frame (LSF) and sandwich panels. The role in the optimisation of resource use and reduction of building's embodied energy allowed by industrialised lightweight construction technologies which effectively use less material is generally recognised (Gervásio, Santos, Da Silva, & Lopes, 2010; Marrone, Sesana, & Imperadori, 2023).

Considering the need to shift towards more resilient and sustainable design, the main aim of this study is to offer a paradigm shift to transform the market of deep building renovation technologies by defining and demonstrating a design and production process of a PnP façade module which relies on the integration of industrialised products, avoiding commitment to a particular design and instead generating and assessing sets of design alternatives. In following such aim, the current research has two main objectives. The first objective is to explore the use of set-based design principles (Singer, Doerry, & Buckley, 2009) to investigate different levels of prefabrication, thus improving a multifunctional lightweight PnP façade system for deep renovation interventions. The second objective is to show the viability and benefits of the set-based design methodology in facilitating the exploration of various scenarios, in a virtual environment, which facilitates collaboration between companies for product development. This methodology allows for identifying potential design conflicts and optimising the system's performance before physical prototypes are created. The demonstration phase of the design methodology is discussed, providing three levels of full-scale prototyping. According to the objectives, the manuscript proceeds as follows: Section 2 describes the methodology used to implement innovative façade solutions. The results of the applied methodology are presented in Sections 3 and 4; the first dealing with the outcomes of the set-based design method to the design phase of the implemented PnP module; the latter presenting the outcomes of the PnP module's demonstration phase through full-scale prototypes. Section 5 reports the conclusion and further research developments.

2 METHODOLOGY

The PnP module has been implemented and integrated using interoperable and interconnected third-party products (TPP) available in the market to provide a highly industrialised off-site solution through a set-based design methodology. This section describes the methodology adopted. The first part gives an overview of the PnP module and provides the classification of the TPPs to be integrated into the module. In the second part, the set-based design methodology is presented, highlighting how it has been applied in this study.

2.1 THE PLUG-AND-PLAY FAÇADE MODULE

2.1.1 Module design

The façade module object of the study is a PnP complex system composed of different layers which can be integrated and varied depending on the project needs. The PnP concept applied to the façade is connected to a high level of prefabrication; thus, the façade design incorporates a certain degree of standardisation for fast on-site assembly and user-friendliness to reduce human intervention. Therefore, the implementation of the PnP module includes market-ready components which are already tested and validated in different scenarios, complying with regulations. The final design of the PnP façade module has been developed by an Italian company with expertise in industrialised steel-based products such as LSF structures and metal-faced sandwich panels. The main core of the module is composed of metal-faced sandwich panels assembled on an LSF structure. The modules are produced off-site and installed as a single element on the existing building through a flexible anchoring system fixed to the LSF, allowing movements in three directions. Flexibility is assured, on the one hand, by the anchoring system, which allows interventions to a wide range of existing buildings and, on the other hand, by the adaptability of the PnP module. The modularity of the design allows the PnP to be customised in terms of dimensions, with heights ranging from 2.5 to 4 meters and widths ranging from 1.30 to 3 meters. Depending on the project requirements, the module's thickness can range from 20 to 35 centimetres, while from an energy performance perspective, the system enables achieving U-values below 0.2 W/m^2K. To streamline the layers that constitute the PnP module, its composition can be simplified into five main layers as represented in FIG 1.

Starting from the outside, the PnP module is composed of a ventilated façade (Layers 1 and 2). The first layer will be addressed throughout the work as the "External layer" and refers to the exterior finish of the façade, while the second layer is defined as "Air gap & substructure" and consists of the air cavity inherent to ventilated façades, including aluminium profiles for the exterior finish. The third layer is the main core of the module and will be addressed as "Structure and sandwich panels". It is constituted by the metal-faced sandwich panels attached to the LSF structure made of vertical and horizontal cold-formed steel profiles 3 millimetres thick. Metal-faced sandwich panels consist of a core layer of polyurethane or mineral wool skinned with two steel sheets. The sandwich panels provide thermal insulation, air and water tightness, acoustic insulation, and a good reaction to the fire. The sandwich panels allow the installation of the ventilated façade through anchoring elements installed on the ribs of the sandwich. The fourth layer is addressed as the "Air gap and anchoring system". It consists of the anchoring systems for the installation of the module on the existing envelope, thus creating a non-ventilated air gap in between.

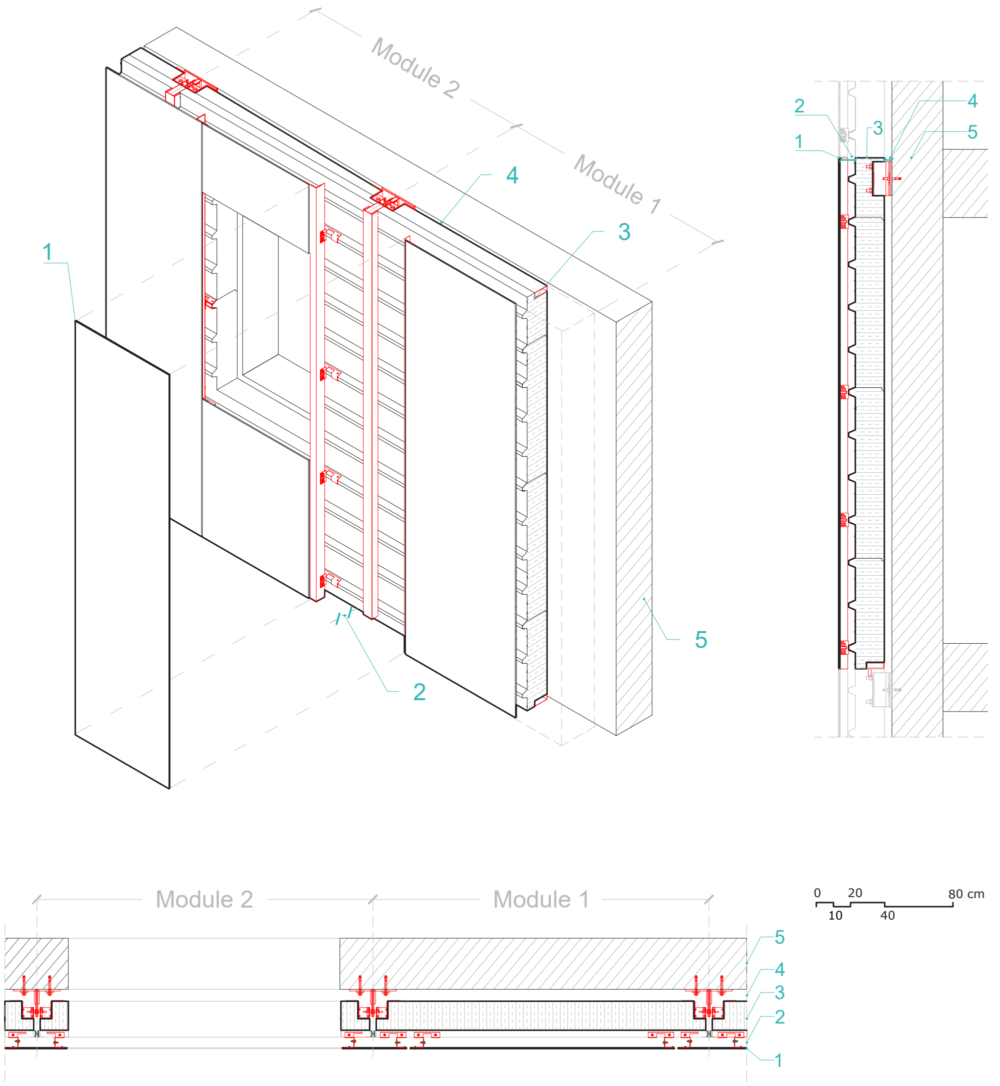


FIG. 1 Representation of the PnP module's details: a) 3D representation; b) Vertical section; c) Horizontal section.
1. External Layer | 2. Air gap & Structure | 3. Structure & Sandwich panel | 4. Air gap & Anchoring System | 5. Existing Envelope

The fifth layer is intended to be the structural element of the building and is not part of the PnP module but constitutes the complete envelope. The PnP module can accommodate pipes and other services in the Air gap and substructure (layer 2). The object of the study is the implementation of this basic PnP module with selected TPPs already available in the market through the set-based design approach described in section 2.2.

2.1.2 Integration of third-party products

According to the state of the art of PnP systems, it is necessary to propose fast and adaptable solutions to boost this market. As the demand for building renovation continues to grow, it is essential to keep exploring new solutions and technologies. In this context, the interoperability of TPPs needs to be studied in detail, focusing on already market-ready products. The products integrable in the PnP module have been selected using a structured protocol (Batallé, Masip, Ràfols, Lupi, & Donnerup, 2022) to ensure interoperability and inter-compatibility between components.

The protocol outlines six principles that the TPP must follow: industrialisation, customisation, compatibility and interoperability, circularity, open information exchange, and adherence to certification and regulation requirements. By adhering to industrialisation and customisation principles, the selected product allows off-site assembly, ease of installation, and adaptability to various architectural geometries and aesthetics, thus enhancing the overall easy and time-saving installation of the PnP module. Besides the variety of innovative and established solutions in the building renovation market, efforts have mostly focused on two main concepts: the reduction of energy demand and the optimisation of energy production through the combination of different ECMs, which include passive, active, and energy production systems. Passive systems are those methods that help the building perform the function of heat transfer and storage with no assistance from energy sources. These systems include external cladding, high-performance windows, and solar protection. On the other hand, active systems maintain demanded environmental conditions within a space. The energy production systems consider all technologies integrated into the building that can produce energy, such as photovoltaic panels. The technologies considered in this paragraph are those that can be integrated into the façade according to the protocol: comfort and salubrity (Demand-Controlled Ventilation, DCV) and energy production (Photovoltaic panels, PV). The integration of a heating and cooling system has been discarded since any TPP meets the PnP protocol. The TPPs identified to be integrated into the module are listed in Table 1.

TABLE 1 TPPs potentially integrable into the PnP façade module.

Third-Party Products (TPP) potentially integrable into PnP module	
Passive systems	1. External Cladding
	2. High-performance windows
	3. Solar Protection or Sun Shading
Active systems and energy production	4. Demand Controlled Ventilation (DCV)
	5. Photovoltaic (PV) panels

2.2 A SET-BASED DESIGN MATRIX FOR PNP FAÇADE DEVELOPMENT

This section describes the methodology used to implement the PnP module with TPPs. The design of such complex systems and their product development means that different parties must collaborate to deliver the expected outcome, highlighting the need for a structured methodology. Considering the integration of TPPs in the PnP façade module, this work investigated the application of the set-based design methodology to address the complexity of the problem.

Among other design methodologies, set-based design (Sobek & Ward, 1996) allows resilient design solutions; thus, it is one of the main methods adopted in product development. Known as a pillar of lean thinking, set-based design is a structured approach which allows the exploration of a wide range of possible alternatives to gradually converge to the best possible solution while handling the uncertainties typical of the early design stages (Sobek & Ward, 1996). The main characteristic of the approach is keeping design freedom in the earliest phases of design, conversely to a point-based approach (Singer et al., 2009). The traditionally used design practice tends to consider engineered design as an iterative process which, step by step, reaches the final solution without any guarantee that the solution will be the best one (Inoue, Takahashi, & Ishikawa, 2013).

Although the approach with its hybrid applications has been used in designing different products, structural building solutions, construction management, and BIM environments (Serugga, Kagioglou, & Tzortzopolous, 2020), to the authors' best knowledge, it hasn't been explored widely in the technical implementation of off-site building façades.

In this paper, the authors propose a design method for implementing an industrialised façade for building renovation using the set-based design method as the main theoretical framework to develop a set-based design matrix to investigate inter-compatible and interoperable sets of design alternatives. Although the set-based design has been consistently used in product development, according to the literature, there is a need to develop its knowledge-based environment through techniques able to increase the comprehension and application of the methodology, such as prototyping and testing. The development of an innovative industrialised PnP building system, potentially upgradeable, is a complex task that has been further investigated by enriching the set-based design methodology with a prototyping phase developed with three different levels of detail. The proposed methodology assesses the decision-making in developing the PnP modular façade, allowing both the main developer and the third-party companies to collaborate in a virtual environment and integrate their products, exploring an open set of design solutions. In this study, the authors focused on the feasibility of the façade module integration with existing TPPs to attempt to boost the industrialised production process.

Considering that the set-based design methodology highly depends on the object of the study, the boundary conditions and the design phase, the literature cannot outline a specific set of actions to apply it (Parrish, 2009). Although there is a different complexification according to each project, the key concepts to implement a set-based design methodology have been synthesised: (i) understand the design space considering a wide range of design alternatives, (ii) specialists have to be allowed to think about the problem from their perspective, and (iii) the intersection of many sets may be used to enhance a design and determine its feasibility before committing to it.

Starting from breaking down the design problem into smaller and manageable components, this study suggests the application of set-based design methodology according to the following phases: (i) identification of the main layers of the façade module, (ii) identification of potential integrable TPPs, (iii) identification of the possible scenarios of TPPs integration, (iv) demonstrate the scenario in a virtual environment, (v) develop technical design alternatives for each scenario, (vi) prediction of future performance requirements according to the technical constraints, (vii) demonstration of the selected options through prototyping at different levels of detail, and (viii) validation phase through different performance tests to qualify the final product. Although the validation phase is considered necessary to allow the market readiness of the solutions, this phase has not been included in this study.

To commit to the definition of all the possible TPP integration scenarios into a PnP façade module and the technical requirements, a set-based design matrix has been outlined. The matrix provides the designer with the visualisation of several scenarios assisting the exploration of the possible effect on the façade module in terms of technical requirements and feasibility. Particularly, the set-based design matrix presents three different inputs: the TPPs selected, the PnP modular façade's layers, and hypothesized performance requirements. The reading process of the matrix is reported in Table 2.

TABLE 2 Example of the set-based design matrix's reading process and identification of a possible scenario.

[2]

[1]

[3]

			PNP MODULE'S LAYERS						
			1	2	3	4	5		
			External Layer	Air gap & Substructure	Structure & Sandwich Panel	Air gap & Anchoring System	Existing Envelope		
TPP potentially integrable into the PnP module	N	Name	-	-	Scenario N1 ☑	-	-		Technical requirements of each scenario
			R_n	R_n	R_1, R_2, ...	R_n	R_n	R_n	
	X	Name	-	-	-	Scenario X2 ☑	-		
			R_n	R_n	R_n	R_1, R_2, ...	R_n	R_n	

The integration of the TPP into the PnP module involves identifying scenarios where it can be effectively incorporated. The two factors that define a scenario are, from one side, the TPP potentially integrable into the module (arrow [1]) and the layer of the PnP module in which the TPP is installed (arrow [2]). Once a potential scenario is identified, a list of requirements (arrow [3]) that must be fulfilled is proposed to ensure smooth integration and functionality across the various layers in which the TPP is installed. The requirements, identified and numbered subsequently as "Rn", can involve not only the specific layer in which the TPP is integrated but also the adjacent layers, which can be potentially influenced by the TPP integration. Thus, the matrix may present requirements in multiple layers at once, influencing different layers. Each scenario is studied and technically implemented within a virtual environment by the PnP module designers and the third-party companies which provide the product to be integrated. To fast-track the deep renovation, the possible solutions of integration are successively prototyped and demonstrated at three different levels: a preliminary prototype, a full-scale prototype, and a real environment prototype on a case study building. This method allowed the collaboration between the different companies towards the industrial production of a complex PnP façade system incorporating different ECMs.

3 DESIGN SOLUTION SET FOR PLUG-AND-PLAY MODULE: APPLICATION OF THE SET-BASED DESIGN MATRIX

The main objective of the set-based design methodology is to guide the technical development of the PnP module by integrating existing technologies available in the market through the exploration of different scenarios. Moreover, it is considering the technical requirements and the feasibility of its integration. However, this means that to fulfil a correct integration of a TPP into the PnP, the requirements presented in this paper should be met. Table 3 offers a summary of the possible scenarios identified for the TPPs integration into the PnP module. To clarify the scenarios along with their list of requirements (addressed as Rn and numbered progressively), the following paragraphs will describe each case.

TABLE 3 Overall matrix of the scenarios identified to integrate potential TPPs into the PnP module.

TPP potentially integrable into the PnP module		PNP MODULE'S LAYERS					Technical requirements of each scenario
		1 External Layer	**2** Air gap & Substructure	**3** Structure & Sandwich Panel	**4** Air gap & Anchoring System	**5** Existing Envelope	
A	External Cladding (3.1)	**Scenario A1** ✓	-	-	-	-	
		$R_1, R_2, ...$	R_n	R_n	R_n	R_n	$\mathbf{R_n}$
		-	**Scenario A2** ✓	-	-	-	
		R_n	$R_1, R_2, ...$	R_n	R_n	R_n	$\mathbf{R_n}$
B	High performance windows (3.2)	-	-	**Scenario B1** ✓	-	-	
		R_n	R_n	$R_1, R_2, ...$	R_n	R_n	$\mathbf{R_n}$
		-	-	-	-	**Scenario B2** ✓	
		R_n	R_n	R_n	R_n	$R_1, R_2, ...$	$\mathbf{R_n}$
C	Solar Protection or Sun Shading (3.3)	-	**Scenario C1** ✓	-	-	-	
		R_n	$R_1, R_2, ..$	R_n	R_n	R_n	$\mathbf{R_n}$
		-		**Scenario C2** ✓		**Window** –	
		R_n		$R_1, R_2, ...$		R_n	$\mathbf{R_n}$
D	Demand Controlled Ventilation (3.4)	-	-	**Scenario D1** ✓	-	-	
		R_n	R_n	$R_1, R_2, ...$	R_n	R_n	$\mathbf{R_n}$
		-	-	-	-	**Scenario D2** ✓	
		R_n	R_n	R_n	R_n	$R_1, R_2, ...$	$\mathbf{R_n}$
E	PV or ST Panels (3.5)	**Scenario E1** ✓	-	-	-	-	
		$R_1, R_2, ...$	R_n	R_n	R_n	R_n	$\mathbf{R_n}$
		-	**Scenario E2** ✓	-	-	-	
		R_n	$R_1, R_2, ...$	R_n	R_n	R_n	$\mathbf{R_n}$

3.1 EXTERNAL CLADDING

The integration of TPPs in the external layer of the PnP module affects the part of the envelope in contact with the exterior, i.e., the ventilated façade, which directly involves the external layer (1) and its substructure (2). The cavity between the external layer and the sandwich panel is a ventilated gap. The integration of the external cladding deals with the capability to offer different types of geometries and aesthetic finishes, in other words, providing a high degree of customisation. Two possible scenarios have been identified for this integration. The first scenario, named A1, sees the TPP adapting their system to the basic substructure of the PnP module. In this case, the main challenge is to ensure a secure union between the substructure and the external cladding.

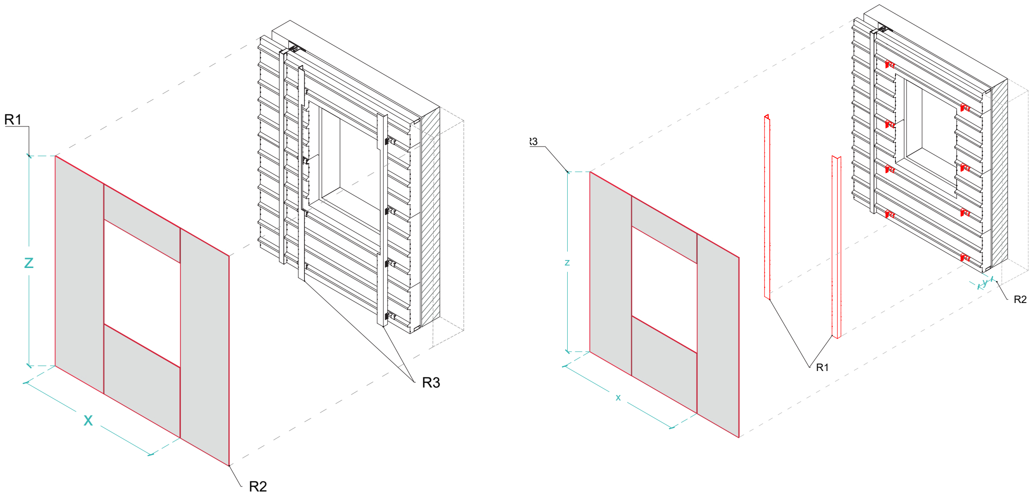
The second scenario, named A2, explores the case in which the TPP provides its own substructure for the ventilated façade. In this case, a reliable anchoring system is necessary to ensure the structural stability and safety of the façade. The installation of the substructure to the ribs of the sandwich panels is guaranteed by a flexible anchoring system with the capability to integrate different substructures, thus allowing these two scenarios.

As can be seen in Table 4, a list of requirements to be fulfilled by the TPP to be integrated into the modules is provided. Regarding scenario A1, the first requirement (R_1) highlights the need for the external cladding's dimensions to be between 2.5 and 3 metres to be adaptable to the PnP envelope size, ensuring the correct transportation and the assembling process. The second requirement (R_2) is the compliance of a maximum weight, which is related to the mechanical and load-bearing capacity of the façade, while the third (R_3) requires the adaptability of the system to the existing substructure.

TABLE 4 Set-based design matrix for the integration of external cladding as TPP in the PnP module

		PNP MODULE'S LAYERS					
		1	**2**	**3**	**4**	**5**	
		External Layer	**Air gap & Substructure**	**Structure & Sandwich Panel**	**Air gap & Anchoring System**	**Existing Envelope**	
A	**External Cladding**	**Scenario A1** ☑	-	-	-	-	
		R_1: The external cladding should be adaptable to PnP envelope size between 2,5 - 3 mt and different configurations.	R_3: Anchoring system adaptable to the existing substructure.				R_n
		R_2: The external cladding elements should not be heavier than 60 kg/m^2					
		-	**Scenario A2** ☑	-	-	-	
		R_3: Adapt to PnP envelope size specifications.	R_1: The provided substructure should be attached either to the sandwich panel or the brackets.				R_n
			R_2: The anchoring system must fit in the ventilated facade air gap.				

The main objective of the PnP module is to be able to offer third parties the option to integrate their products without limitations. It should be mentioned that the sandwich panel can also be placed vertically, opening a wide range of possibilities.



a *Scenario A1*   *b* *Scenario A2*

FIG. 2 Representation of integration scenarios and relative requirements (Rn) - Scenario A1: Integration of TPP external cladding in the external layer of the PnP module; Scenario A2: Integration of TPP external cladding in the air gap and structure layer of the PnP module through a provided substructure.

3.2 HIGH-PERFORMANCE WINDOWS

TABLE 5 Set-based design matrix for the integration of high-performance window as TPP in the PnP module.

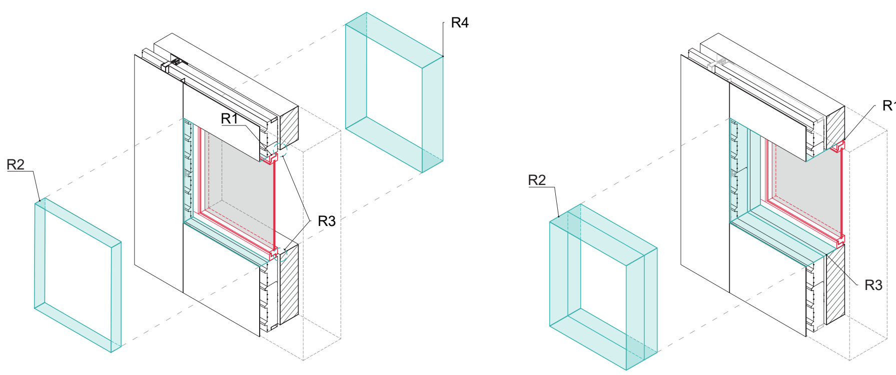
		PNP MODULE'S LAYERS					
		1	**2**	**3**	**4**	**5**	
		External Layer	**Air gap & Substructure**	**Structure & Sandwich Panel**	**Air gap & Anchoring System**	**Existing Envelope**	
B	**High performance windows**	**-**	**-**	**Scenario B1** ☑	**-**	**-**	
		R_2: The installation of a perimetral frame is needed to seal the window hole.		R_1: The substructure of the window must be compatible with the sandwich panel.	R_3: The air chamber should be sealed.		**R_n**
					R_4: The installation of a perimetral frame from the interior is needed to provide an optimal interior finish.		
		-	**-**	**-**	**-**	**Scenario B2** ☑	
		R_2: The installation of a perimetral frame is needed to seal the window hole. A double frame should be provided.				R_1: The existing building must allow the window frame installation.	**R_n**
				R_3: The continuity of the isolation layer should be solved, otherwise the implementation would present thermal bridges.			

High-performance windows are decisive elements that complement the building's envelope, providing natural light and ventilation while also contributing to aesthetic and thermal properties. The integration of high-performance windows depends on the bioclimatic strategy and the solar orientation of the building. Table 5 offers an overview of the identified scenarios and relative requirements to be fulfilled to ensure correct integration of the TPP in the PnP module.

Scenario B1 considers the window's installation within the sandwich panel, thus substituting the windows installed in the existing building, while scenario B2 explores the hypothesis in which the window is kept or substituted in the existing envelope. The location of the windows also affects the placement of other components, such as sun shading systems.

Diving deeper into the main features of scenario B1, it can be said that it assures the continuity of the thermal envelope throughout the façade plane. However, the integration of a window frame in an industrialised component, such as the sandwich panel, is an issue that highlights the need for compatibility between the two products. Moreover, the placement of the window in the third layer of the PnP module is possible if considering the installation of a perimetral frame and sealing the air gap between the existing building and the PnP module. Another detail related to scenario B1 is the need to complete the module installation with an interior frame to ensure an aesthetic internal finishing. This action must be carried out on-site, accommodating the tolerances of the building.

Scenario B2 describes the situation in which the installed windows to be renovated are left in their location. In this case, the technical solution proposed is the integration of a perimetral frame to seal the opening made in the PnP module corresponding to the window. In this case, a double frame or a frame that allows both thermal and mechanical movements should be integrated into the PnP module. The technical detail adopted in the installation of this frame could help ensure the continuity of the insulation layer to avoid thermal bridges. This second scenario allows the potential integration of solar protection systems in the PnP module, which will be discussed in the next paragraph.



a *Scenario B1*

b *Scenario B2*

FIG. 3 Representation of integration scenarios and related requirements (Rn) - Scenario B1: Integration of TPP high-performance window in the structure and sandwich panel layer of the PnP module; Scenario B2: Integration of TPP high-performance window in the existing envelope.

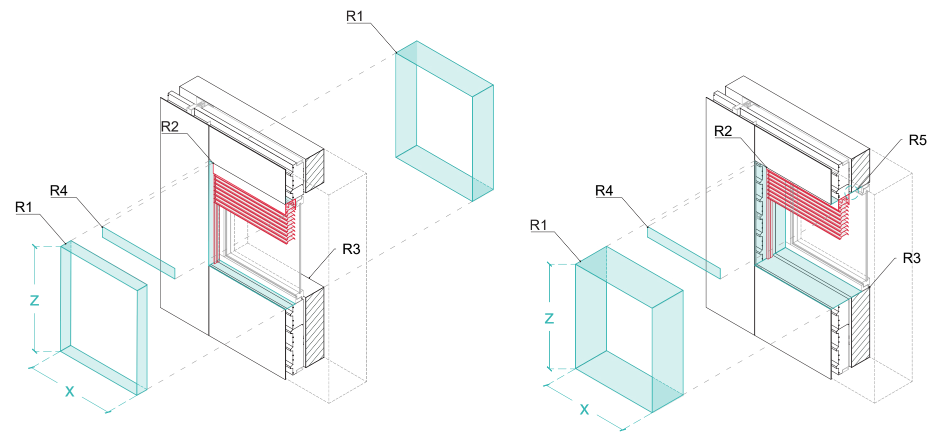
3.3 SOLAR PROTECTION | SUN SHADING

Solar protection and sun shading are crucial elements in the building envelope since they must be implemented depending on the climate analysis and the building's location and orientation. These features must be designed aiming at the user's comfort; thus, every situation is different. For example, buildings in hot and sunny climates benefit from external shading devices such as solar blinds or shades, while buildings with less sun exposure may benefit from internal shading devices such as blinds or curtains. The integration of solar protection or sun shading systems into the PnP façade module, if correctly designed, can significantly contribute to reducing the cooling demand of a building by limiting the solar gains. Additionally, by lowering glare and heat accumulation, sun protection systems can increase building occupants' comfort. Although there are various types of solar protection systems and sun shadings, their implementation within the PnP module is related to the window location. When it comes to integration, solar protection or sun shading installation can be made directly onto the metal frame installed in the window opening, already described in the previous paragraph, thus making the integration process relatively straightforward. Table 6 provides the set-based design matrix of solar protection and sun shading integration within the PnP module, highlighting two possible scenarios and the relative technical requirements, addressed in the figures and tables as "Rn".

While scenario C1 considers the integration of the solar protection and sun shading systems when the window is installed within layer 3 of the PnP module, scenario C2 explores the integration of the TPPs when the window is in the existing envelope.

TABLE 6 Set-based design matrix for the integration of solar protection or sun shading as TPP in the PnP module.

		PNP MODULE'S LAYERS					
		1	**2**	**3**	**4**	**5**	
		External Layer	**Air gap & Substructure**	**Structure & Sandwich Panel**	**Air gap & Anchoring System**	**Existing Envelope**	
C	**Solar Protection or Sun Shading**	**-**	**Scenario C1** ☑	**Window**	**-**	**-**	
		R_4: The structure of the Sun shading needs to be covered by an external layer.	R_1: The TPP should provide a system adaptable to a frame sheet. R_2: Dimensions of the Sun shading should be compatible with building dimensions.		R_3: Installation for the sun shading control should be solved.		R_n
		-		**Scenario C2** ☑		**Window**	
		R_4: The structure of the Sun shading needs to be covered by an external layer.	R_1: The TPP should provide a system adaptable to a frame sheet. R_2: Dimensions of the Sun shading should be compatible with building dimensions.		R_5: The continuity of the thermal envelope should be solved in this layer. Otherwise, the implementation of the window would have thermal bridges.	R_3: installation for the sun shading control.	R_n



a *Scenario C1* *b* *Scenario C2*

FIG. 4 Representation of integration scenarios and relative requirements (Rn) - Scenario C1: Integration of TPP solar protection when the window is installed in the structure and sandwich panel layer of the module; Scenario C2: Integration of TPP solar protection when the window is in the existing envelope.

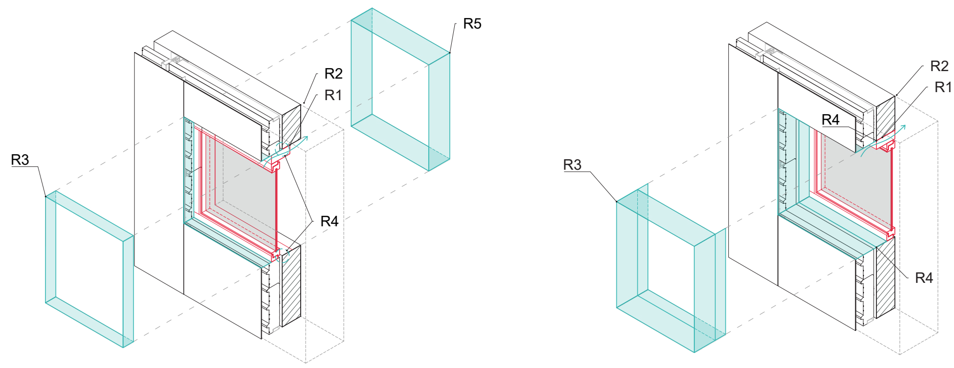
3.4 DEMAND CONTROLLED VENTILATION

TABLE 7 Set-based design matrix for the integration of the DCV as TPP in the PnP module.

		PNP MODULE'S LAYERS					
		1	**2**	**3**	**4**	**5**	
		External Layer	**Air gap & Substructure**	**Structure & Sandwich Panel**	**Air gap & Anchoring System**	**Existing Envelope**	
D	**Demand Controlled Ventilation**	-	-	**Scenario D1** ☑ **Window**	-	-	
		R_3: The installation of a perimetral frame is needed to seal the window hole. A double frame should be provided.		R_1: The DCM system should allow the physical installation on the PnP module through the window system.	R_4: The air chamber should be sealed.		**R_n**
				R_2: The connection with the electrical facilities should be solved.			
					R5: The installation of a perimetral frame from the interior is needed to provide an optimal interior finish.		
		-	-	-	-	**Scenario D2** ☑ **Window**	
		R_3: The installation of a perimetral frame is needed to seal the window hole. A double frame should be provided.				R_1: The existing envelope must allow physically the installation of DCM.	**R_n**
			R_4: The continuity of the thermal envelope should be solved, otherwise the implementation could present thermal bridges			R_2: The existing envelope must allow/provide the electrical facilities.	

A smart ventilation system adjusts ventilation rates in a building to one or more of the following parameters: occupancy, temperature, and air quality conditions. The main purpose is to ensure efficient air filtration in the interior spaces. Table 7 provides the set-based design matrix of a DCV integration within the PnP module, highlighting two possible scenarios.

The integration of DCV in the module is related to the window location; thus, the two scenarios have been identified according to the scenarios identified for the window integration (paragraph 3.2, scenarios B1 and B2). The identified technical requirements, addressed in the figures and tables as "Rn", are related to scenarios B1 and B2 but include the electrical connection of the DCV system.



a *Scenario D1* *b* *Scenario D2*

FIG. 5 Representation of integration scenarios and relative requirements (Rn) - Scenario D1: Integration of DCV system when the window is in the structure and sandwich panel layer; Scenario D2: Integration of DCV system when the window is in the existing envelope.

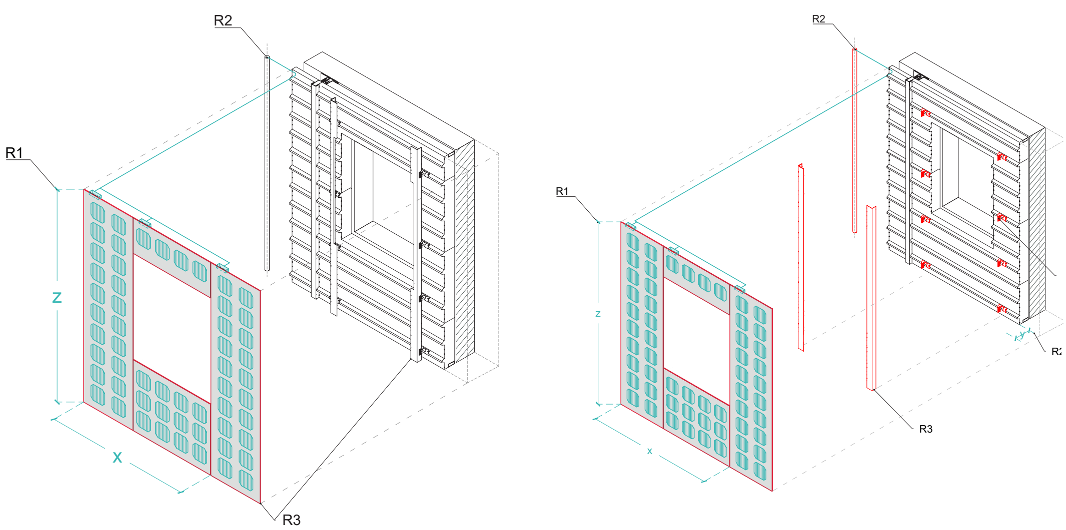
3.5 PHOTOVOLTAIC PANELS

The integration of photovoltaic panels (PV) into the PnP module contributes to reducing the energy consumption of the building. Although the amount of electricity generated by a PV panel depends on several factors, installing PV panels in the façade is a topic of growing interest, considering that the panels are becoming more efficient and affordable due to technological advancements. Table 8 shows the set-based design matrix, which identifies two main scenarios

Scenario D1 represents the case in which the TPP can adapt its system to the existing substructure. Scenario D2 investigates the case that the TPP system provides its own substructure or anchoring system. The integration of PV panels into the PnP module has been validated by various companies; thus, it is considered reliable especially due to the presence of a ventilated gap. On the one hand, the presence of the ventilated gap helps dissipate heat generated by the PV panels, preventing any potential damage or decrease in efficiency due to overheating. On the other hand, the available space allows the allocation of the technical connection and facilities of the panel, ensuring easy installation, maintenance, and accessibility.

TABLE 8 Set-based design matrix for the integration of PV panel as TPP in the PnP module.

		PNP MODULE'S LAYERS					
		1	**2**	**3**	**4**	**5**	
		External Layer	**Air gap & Substructure**	**Structure & Sandwich Panel**	**Air gap & Anchoring System**	**Existing Envelope**	
E	**PV or ST Panels**	**Scenario E1** ☑	-	-	-	-	
		R_1: Adapt to PnP envelope size specifications.	R_2: Ground wires R_3: The anchoring system of panels must be compatible with PnP module's substructure.				R_n
		-	**Scenario E2** ☑	-	-	-	
		R_1: Adapt to PnP envelope size specifications.	R_2: Ground wires R_3: The substructure must be compatible with the brackets or attachable to sandwich panel. R4: The anchoring system must fit into the air gap of the ventilated façade.				R_n



a *Scenario E1*   *b* *Scenario E2*

FIG. 6 Representation of integration scenarios and relative requirements (Rn) - Scenario E1: Integration of PV Panels when the TPP can adapt their system to the existing structure; Scenario E2: Integration of PV Panels when TPP provides a new substructure or anchoring system.

4 FULL-SCALE DEMONSTRATION

One of the main objectives of this work is to practically demonstrate the feasibility of the scenarios previously explored in a virtual environment through the set-based design methodology. To eliminate the weakest solutions in the set and thus concentrate on the design options which can ensure flexibility, discovery, and innovation, the set-based design approach uses prototypes to facilitate successful product development. According to the literature, one of the aspects that require more evaluation in future research is both virtual and physical prototyping, which is considered necessary to allow an informed convergence process (Toche, Pellerin, & Fortin, 2020).

Considering the above, this section presents the demonstration phase of the solution set explored with the set-based design methodology. If the virtual modelling represented a preliminary level of investigation serving as feasibility prototypes, the physical demonstration was implemented to streamline the transition from research to real-scale applications. The methodology used in the prototyping phase allows the demonstration of the integrated PnP systems in real scenarios considering three levels of investigation: preliminary level, demonstration level, and final level. The three levels of prototyping aim at exploring various aspects respectively.

The first level of prototyping consisted of investigating the PnP module at a preliminary level, diving deeper into a portion of the module to study the interfaces between various TPPs. The second prototype intends to demonstrate a full-scale façade made of six complete PnP modules. The third prototype demonstrates the shift from design to construction of a real façade solution applied on a real case study building.

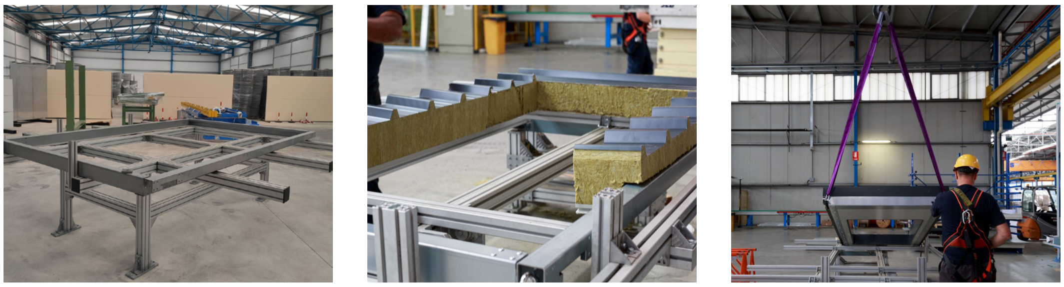
a b c

FIG. 7 Full-scale demonstration of the PnP module at three levels. a) preliminary module prototype; b) full-scale façade prototype; c) façade prototype in a real environment.

The prototyping phase is a physical demonstration of the scenarios virtually explored with the set-based design matrix. Hence, for reasons of space, the TPP integration validation addressed in this study are the external cladding, high-performance windows, and solar protection. During the prototyping phase, an active collaboration between technology providers was established to reach the best technical solution. Particularly, the three demonstrators investigated the inter-compatibility of (i) a ventilated façade system developed by a sandwich panel producer: the system enables the integration of different finishes such as perforated sheets, HPL, WPC, wood, and composites through visible or concealed fastening, (ii) a high-performance window composed of aluminium profiles developed by a company specialised in façades and curtain wall manufacturing, and (iii) an aluminium folding shutter developed by a company specialised in the production of solar protection solutions. The shutter can be oriented from 0° to a maximum of 115° and can be moved up and down until achieving total closure. The results of the prototyped TPP integration in the PnP module are reported in the following paragraphs.

4.1 FIRST LEVEL OF DEMONSTRATION: THE PRELIMINARY PROTOTYPE

The first level of prototyping aimed at addressing the feasibility of the set of solutions investigated in a virtual environment following the set-based methodology. This phase has been a crucial step to deepen the inter-compatibility between the TPPs and components, solving many technical issues. Only a portion of the PnP module has been used to focus mainly on the interface between the substructure and sandwich panel, with first the high-performance window and then the sun shading system. The physical dimensions of the PnP module were 1.3 meters in width and 2.2 meters in height. The LSF structure and the sandwich panel have been assembled on a horizontal working station, as shown in FIG 8.



a b c

FIG. 8 Preliminary prototype: a) LSF structure on horizontal working station; b) Assembling the PnP module on the horizontal working station; c) Lifting of the module vertically once preassembled.

The first TPP integration consisted of prototyping the window allocation in the structure and sandwich panel layer (Scenario B1). A designed aluminium frame attached to the steel sheets of the sandwich panel made it easy to install the high-performance window since the sandwich panel's technical characteristics allow the window's load. The second TPP integration prototype consisted of the integration of the sun shading system. Here, some shortcomings were identified. One major issue was the lack of information about the main production and workability features of each TPP. Without this information, the design team was unable to detect potential technical incompatibilities between the different components, given that the goal was to produce the PnP module in an industrialised manner. The first attempt supposed the integration of the sun shading system in the structure and sandwich panel layer (Scenario C2). Although the connection was possible, the aesthetic and functional result was deemed insufficient. Particularly, it was impossible to easily hide the blinds inside the sandwich panel when they were not all the way down, thus impacting the quantity of light entering the existing building's window. This issue highlighted the need for a more thorough analysis of the TPP integration process to ensure seamless compatibility between the technologies. Additionally, it emphasised the importance of considering both functionality, aesthetics, and feasibility in the integration of TPP in the PnP module to smooth the industrialisation process and meet the desired standards.

Considering the above, the integration of the sun shading system inside the air and substructure layer has been addressed with a second prototype (Scenario C1). This prototype successfully achieved the desired aesthetic and functional results by allowing for easy concealment of the blinds when they are not in use. However, there was the need to study an anchoring system for the sun shading system to ensure compatibility with the sandwich panels' ribs; such a system was not available in the market. The need to study an anchoring system for the sun shading system suggests that the TPPs selected should allow modifications or at least be flexible in case some adjustments are needed. The exploration of these three scenarios revealed the significance of close collaboration between the design team, manufacturers, and suppliers of TPPs. The more accurate the technical information on the TPPs, the more precise the integration into the PnP modular system. When the 3D drawings were not detailed enough, some critical intersections had to be solved during the prototypation phase. By involving all stakeholders early in this process, technical constraints have been addressed, leading to more effective solutions and smoother integration of the different products.

a *b* *c*

FIG. 9 Preliminary prototype: a) Integration of aluminium folding shutter in PnP module; b) Integration of high-performance window in PnP module.

4.2 SECOND LEVEL OF DEMONSTRATION: FULL-SCALE FAÇADE PROTOTYPE

While the first level of demonstration has been used for the decision-making process in the early TPP integration attempts in the PnP module, the second level of prototyping aims at deepening both the production phase and the installation phase of a PnP module with a higher integration level, including three TPPs. Six complete PnP modules, integrated with high-performance windows, an aluminium folding shutter sun shading system, and an external cladding in HPL, have been produced to be installed on a sample structural frame which simulates an optimal condition for an existing building. This prototype aims to identify the potential issues and challenges that may arise during the production, transportation, and installation phases of a complete PnP module. This is crucial to enable necessary adjustments for a smoother industrial implementation and allow upscaling of the solution.

a b c c

FIG. 10 Demonstration prototype: a) Assembly of TPP in the PnP using a vertical working station; b) Movement of the PnP module using a crane; c) Final asset of the prototype; d) Detail of window and sun shading integration.

Regarding the production phase of the modules, some shortcomings have been identified. During this activity, the workers found it uncomfortable to assemble the module on a horizontal working station since it was impossible to easily view the whole module assembly at once, resulting in poor aesthetic quality. Moreover, the horizontal assembly of the integrated PnP module and the following repositioning to place it on the transportation frames, again followed by installing it on the building in two modules, caused misalignments of the external cladding. Despite the difficulties listed above, the installation of the PnP modules with the anchoring systems on the existing structure was smooth, and the six modules were installed in three hours without any major issues.

The main outcome of this phase was the validation of strategies to enhance efficiency in module assembly by developing a new vertical working station on which the entire module can be assembled to streamline the process and favour the industrialisation of the PnP module (see FIG. 10 a). Moreover, to speed up the installation phase, the definition of design limitation dimensions of the modules as 2.5 metres in width and 3.7 metres in height was validated. However, an optimisation strategy must be developed to limit unnecessary movements and prevent potential damages during the installation phase. Overall, this initial prototype has provided valuable insights into simulating at an early stage the real production and installation conditions. Further refinement and demonstrations of the installation process are required to minimise any potential difficulties that may arise through a complete full-scale building application of this new technology on a large scale.

4.3 THIRD LEVEL OF DEMONSTRATION: PROTOTYPE IN A REAL ENVIRONMENT

The last demonstration level is the final prototype, which implies the installation of the PnP system on a real case study application, a kindergarten in Budapest in need of deep renovation. In this study, the objective is to highlight the transition from the design of the system to its construction, addressing mainly the benefits and shortcomings identified in the production and installation phases. The case study building was chosen to showcase the adaptability of the PnP module in interacting with the existing large windows left in the existing building envelope. By selecting a building with a high ratio of transparent and opaque parts, the study aimed to evaluate how well the module could seamlessly integrate with existing geometry.

a b c

FIG. 11 Final prototype: a) Placement of the anchoring system on the existing building structure; b) Transportation and installation of the PnP module; c) Final façade configuration after the renovation with the PnP module.

Additionally, this comprehensive analysis allowed for an assessment of the time required to produce a high number of modules, thus providing valuable insights in terms of time and technical feasibility of the technology's scalability and its industrialisation process. For the renovation intervention, 38 PnP modules have been produced to cover a façade area of 200 m^2. According to the façade's characteristics, the PnP module has been designed with different dimensions, varying from 1.3 m and 2.5 m in width and from 2.6 m and 3 m in height due to dimension limitations in the transportation phases. The production phase of the modules lasted three weeks, considering the off-site production of the sandwich panels and light steel frame structures and the assembly of the complete integrated module by a working team of six people. One of the outcomes of this stage is that the developed vertical working station for module production requires specialised workers able to handle lifting platforms and install ventilated façade technologies.

In this context, the transportation phase strategy has been tested as well. The modules have been placed on a wooden structure designed to carry two modules at a time, already placed vertically and ready to be lifted for the installation. The placement of the module allowed a smooth transportation phase in terms of space used for the shipment in the truck, ensuring a safe and time-efficient delivery of the modules. During the prototyping phase in a real environment, a deep study of the A1 and B2 scenarios mentioned above has been done. Besides the integration of an HPL cladding in the PnP module (scenario A1), there was a need to investigate the scenario involving the direct interaction between a new prefabricated façade system and a window left in the existing building (scenario B2). This scenario is one of the most challenging to address in terms of its implementation since the objective is to prevent thermal bridges and air infiltrations, which can compromise the thermal efficiency of the PnP module. In this specific case, the window intradoses were not industrialised and had to be resolved on-site. The fitting between the dimensions of the current window openings and those of the PnP module was difficult in this case. Considering this, it is essential for the success of the renovation intervention that the technology provider and the architects work together to develop a shared solution to avoid additional costs and on-site time.

Regarding the installation phase, the importance of a preliminary geometry definition of the existing building must be highlighted. An architectural survey plays a crucial role in ensuring the measurements of the existing building. It helps identify potential obstacles or irregularities in the existing geometry that may impact the installation process. By combining the data from the laser scanning and architectural survey, a comprehensive understanding of the site's conditions can be achieved, enabling a seamless and efficient installation of the modules.

5 DISCUSSION AND CONCLUSIONS

An instant paradigm change is required to commit to the urgent energy efficiency frontiers with affordable solutions that can revolutionise the deep renovation market. In this context, the role of industrialised systems is recognised as a key towards the upscaling of the solutions. The deep renovation solution presented in this study is a Plug-and-Play (PnP) façade module which integrates existing third-party products (TPPs) already available in the market. This strategy aims at providing a solution which relies on high-level industrialisation, resulting in an off-site façade system whose configuration can be customized according to the project's requirements. However, while significant progress has been made in the development of PnP façades, their complexification due to the integration of many energy conservation measures has hindered products being available on the market.

Considering the above, the study proposes the application of a set-based design methodology to facilitate and coordinate the design phase of a PnP module integrated with TPPs already available in the market. The integration of TPPs in the PnP module is investigated with a scenario approach through a set-based design matrix. The set-based design approach aims to investigate and understand the inter-compatibility between different TPPs, thus minimising feasibility issues by predicting technical requirements and 3D models. Once a set of design solutions has been explored during the theoretical phase, the study proposes a further step to demonstrate the effective feasibility of the designed solutions by realising the three levels of prototypes.

Starting from a core technology of the PnP module, composed of a light steel frame structure, a sandwich panel, and an anchoring system, the proposed methodology sets solid bases for smooth TPP integration. The set-based design methodology allows the exploration of TPPs integration scenarios, including external claddings, high-performance windows, sun shading systems, PV panels and demand-controlled ventilation systems. The evidence from this proposed application of the set-based design approach suggests effective possible customisation through a wide set of different configurations that are easy to assemble. With this objective in mind, the set-based design methodology was used as a tool to improve the coordination and sharing of knowledge between different companies and developers of building components, facilitating the detection of potential technical limitations already in the design phase.

The demonstration phase of the proposed set-based design approach suggests that successful integration of TPPs in the PnP module requires an effort in the early stage of technology selection. To allow easy and industrial-oriented production of the integrated PnP module, the selected TPPs should allow modifications or at least be flexible in case some adjustments are needed. The exploration of different scenarios of TPP integration through iterations on preliminary prototyping revealed the significance of precise technical details as well as the importance of close collaboration between the design team, manufacturers, and suppliers of TPPs towards a smoother integration of the different products. While the first level of demonstration was used for the decision-making process in the early TPP integration attempts in the PnP module, the second level of prototyping deepened the production and installation phase of the designed integrated module. Further refinement and demonstrations of the installation and production process have been reached through the development of the prototype in a real environment, highlighting the transition from the design to construction. The case study building was chosen to showcase the adaptability of the PnP module, simulating some scenarios identified in the set-based design matrix, allowing a better understanding of how the PnP module can be integrated into different architectural designs, validating its potential for widespread use in construction projects.

Although the study aims to boost the renovation wave in the European context by demonstrating a PnP façade system as a result of a broad research-based design study, further considerations for future research are needed. To allow the market breakthrough and the boost of these technologies, the authors want to focus the reader's attention on two main topics: performance assessment and economic evaluations. The final validation of such complex systems must include testing their mechanical, fire, air and water tightness, acoustic, and thermal performances to permit qualification and commercialisation. As the combination of different components cannot be studied by harmonised testing procedures, this verification must be part of the process to ensure the safety and reliability of the systems. Considering their market position, other parameters must be quantified as well in comparison with existing building technologies for renovation. Further studies are recommended to evaluate the costs related to the design, production, and installation phases of the PnP modules in comparison with traditional construction systems are suggested.

Starting from this methodology as a theoretical background, more TPPs could be integrated into the PnP module and tested in building demonstrators to further develop the set-based design methodology. Based on this work, the constitution of a "technology-provided consortium" will be proposed in collaboration with producers of third-party technologies that complement the PnP module. The consortium aims to enhance the interaction between third-party providers to develop modular solutions. Additionally, it might offer a mutually advantageous arrangement for prominent technology producers, enabling them to provide their customers with direct access to a comprehensive array of solutions while simultaneously promoting an open innovation environment for the technological advancement of off-site building envelopes. Considering the evidence of this study, further research should deepen the application of set-based design methodology in an informed environment. Through more detailed digital models of the integrable TPPs, the design integration process could be seamlessly implemented and validated in a BIM environment, allowing the exchange not only of geometrical information but also performance ones, opening the perspectives for the application of PnP integrated modules in new buildings.

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