A matchmaking approach for identifying effective modular prefabricated solutions in different contexts

Giulia Paoletti[1*], Ana Sanchis Huertas[2], Vera Valero Escribano[2], Stefano Avesani[1,3], Riccardo Pinotti[1]

* Corresponding author: giulia.paoletti@eurac.edu
1 Eurac Research, Institute of Renewable Energy, Italy
2 Instituto Valenciano de la Edificación, Spain
3 EcoLoop, Italy

Abstract

This article presents an innovative matchmaking approach to identify the most effective modular prefabricated solutions, innovative digital technologies, and circularity criteria across different contexts. Developed with the aim to boost the retrofit rate of existing buildings, our methodology addresses critical energy retrofit needs, aligning with the European Union's ambitious climate-neutrality objectives. Modular and prefabricated solutions can speed up renovations, offering benefits in terms of indoor quality, aesthetics, environmental impact, and cost. The matchmaking approach, developed within the scope of the EU-LIFE BuildUPspeed project, capitalises on best practices (such as prefabricated modular solutions, circularity criteria, and digital technologies) across five contexts (Austria, France, Italy, Spain, and the Netherlands), considering local needs and capacities. A "catalogue" of retrofitting building products was compiled, including guidelines for product implementation (a technical requirements checklist). An extensive mapping of ecosystem characteristics was conducted, considering the construction market's capacities and social, cultural, technological, and economic shortcomings that limit the use of innovative technologies. Using collaborative dialogue, developers, building experts, and local players were involved in several actions to promote, capitalise on, and identify the most effective prefabricated solutions tailored to different ecosystems. The results obtained can be used to promote targeted investments and customized retrofitting solutions for specific contexts.

Keywords

Prefabricated solutions, modular construction, renovation lacks, circularity

DOI

http://doi.org/10.47982/jfde.2025.331

1 INTRODUCTION

The EU aims to become a climate-neutral continent by 2050, with key strategies focused on reducing greenhouse gas emissions across sectors, including construction. To support this transition, and enhance energy efficiency in buildings, the EU has presented top-down initiatives, like the European Green Deal (2019), Renovation Wave (2020), REPowerEU (2022), and EU directives, such as the Energy Efficiency Directive (EED, 2023), and the Revised Energy Performance of Buildings Directive (revised EPBD, 2024). These efforts tackle particularly the challenge posed by the European building stock, nearly 85% of which was constructed before 2000, with 75% performing poorly in terms of energy efficiency ("Energy Performance of Buildings Directive," 2025). To achieve the EU's goal of reducing greenhouse gas emissions by 55% by 2030, the building renovation rate must increase from the current 1% (Renovate Europe, 2023) to 3%. Although national plans are already in place, the annual deep renovation rate of existing buildings remains below the target: in 2021, it was only 0.2% (BPIE, 2021). To accelerate building retrofits, it is essential to prioritise innovative and inclusive approaches to address the challenges of the European continent. Innovative technologies, such as modular prefabricated and industrialised products, can be solid solutions for decarbonising the building stock leading the way towards a more circular construction sector, and providing benefits in environmental quality (e.g., reducing impacts, construction waste, and used of materials), in social and economic terms (Navaratnam et al., 2022) (Aghasizadeh, Tabadkani, Hajirasouli, & Banihashemi, 2022) (Rocha, Ferreira, Pimenta, & Pereira, 2022) (Du, Zhang, Castro-Lacouture, & Hu, 2023).

Prefabricated construction is a broad, increasingly adopted method in industrial construction, characterised by the use of standardisation and lean principles to improve efficiency and reduce waste. Prefabrication offers a viable alternative to traditional construction, serving as an effective strategy to scale up decarbonization of the building stock, increase productivity, and minimize on-site construction time (Konstantinou & Heesbeen, 2022). Prefabricated construction is the manufacturing of components in an off-site factory, where industrialised components (units or parts of buildings) designed with different levels of modularity can be assembled and seamlessly integrated into a structure (e.g., a prefabricated façade) (Ofori-Kuragu, Osei-Kyei, & Wanigarathna, 2022). In the building market, there is a huge range of prefabricated solutions with different levels of standardisation, from entire modular residential buildings to single components for the building envelope and technical systems, modular fabricated façades realised with different materials (e.g., concrete, wood, steel), and building integration of active systems such as photovoltaic panels (BIPV). At the European level, the Prefabricated Construction Market is growing due to rising demand for prefabricated options in residential construction (Research & Research, 2024). The Netherlands leads Europe with a 47% adoption rate of prefabrication, incorporating some form of pre-assembled building components (Hoogenboom, 2025). The opportunities provided by such solutions are numerous and applicable to all stakeholders (building owners, experts, suppliers, companies, investors, building workers, and public authorities). Nevertheless, the adoption of prefabricated construction depends on several context-specific factors, ranging from climate conditions to the maturity of the building market. These factors include local policies, economic incentives, the level of industrial development, and the availability of technical expertise and cultural readiness (Lu, Chen, Xue, & Pan, 2018; Steinhardt & Manley, 2016). However, the use of prefabrication in construction can be limited by deficiencies in benefits, design, and knowledge of prefabricated construction (Navaratnam et al., 2022).

Considering the benefits and constraints of prefabricated construction, the article presents reviews existing industrialised and modular prefabricated solutions, already available on the European building market in different contexts. The method proposed aims to guide the building retrofit choices toward a selected number of innovative products, processes, and solutions (e.g., prefabricated, industrialised, and digital technologies and circularity criteria). The matchmaking approach supports i) building owners (demand side) to increase acceptance of innovative products by showcasing successful prefabricated solutions implemented by early adopters; (ii) building professionals (supply side such as architects, engineers, manufacturers, construction companies, etc.), providing existing ready-to-use solutions and technical support; and (iii) investors, construction companies, and manufacturers to direct future investments toward innovative products by providing an overview of the most suitable solutions for different markets, based on the specific building requirements and barriers of the local building context.

The validation of the matchmaking approach was carried out within the EU-LIFE BuildUPspeed (BUPS) project across five contexts (Austria, France, Italy, Spain, and the Netherlands). Using an inclusive Integrated Design Process (Paoletti, Lollini, & Mahlknecht, 2013), different stakeholders (such as building professionals, local experts, construction companies and manufacturers, representatives of homeowners, public authorities, and academic institutions) were involved in the two-phase approach. In the preparatory phase, stakeholders participated in i) the selection of innovative products (output: a catalogue of industrialised prefabricated solutions and innovative technologies already developed in EU projects) and ii) building market profiling (output: contexts' barriers identification). Successively, they were involved in co-working activities centered on mutual support and continuous knowledge sharing. This collaborative process enabled the identification of the most suitable and innovative prefabricated solutions for various contexts and evaluated a list of technical requirements necessary for adopting these products across diverse settings.

2 STATE OF THE ART

The decarbonised building stock targeted for 2050 (revised EPBD, 2024) includes reductions in greenhouse gas emissions, improvements in indoor environmental quality, and improved health and design. Implementing retrofit building solutions based on prefabricated and industrial technology is a complex task, especially compared to traditional ones. It involves different stakeholders (with different competences) to work together from the early design stages, and presents challenges in technological expertise, market readiness (Shahpari, Saradj, Pishvaee, & Piri, 2019), and increasingly complex logistics and transportation constraints (Tavares, Soares, Raposo, Marques, & Freire, 2021) (Anaç, Ayalp, & Erdayandi, 2023). On the other hand, it offers a wide range of solutions developed in safer conditions (Manzoor et al., 2025) with quality guarantees for the final product that can vary from a single element to a multi-component system, whether for building envelopes' components (e.g., façade, roofs) or technical systems (e.g., heat pumps, photovoltaic panels) or both. The use of Design for Manufacturing and Assembly (DfMA) optimises prefabricated construction by integrating manufacturing and assembly constraints, reducing costs, and enhancing producibility (Fan, Chen, & Chen, 2024). Prefabricated modules are designed for the type of assembly process: "offsite and transported," "transported and assembled on-site," or a mix of both.

Digital technologies are widely seen as a catalyst for innovation and productivity in the construction industry (Wang, Wang, Sepasgozar, & Zlatanova, 2020). They offer real support to the building sector during all phases, in the design (e.g., better visualisation, improved data sharing, etc.), production (e.g., automation), construction, demolition (e.g., reduced construction waste), and logistics (e.g., blockchain for supply chain transparency for quality control or guarantee) (Manzoor, Othman, & Pomares, 2021). Digital technologies drive the transformation of the construction sector, introducing innovation in data analysis and acquisition (e.g., through sensors and 3D scanning), process automation (with 3D printing technology, drones, and robotics), and digital information and analysis technologies (such as Building Information Modeling and 3D virtuality). In this framework, digital technologies can boost the use of industrialised concepts (Founti, Avesani, & Elguezabal, 2023). Building Information Modeling (BIM), as a digital representation of the physical and functional characteristics of a building system, contains extensive facility information and is closely linked to the concept of industrialised building systems (Bataglin, Viana, Formoso, & Bulhões, 2019).

In the building sector, prefabricated, modular, and industrialised solutions offer another important advantage for workers' safety. In 2021, the construction sector ranked first for fatal workplace accidents and third for non-fatal workplace accidents (after manufacturing and human health and social work activities) ("Accidents at Work," 2021). Prefabricated and industrialised technologies can reduce workplace accidents by organising the assembling phase in safer conditions, on the ground, inside a factory, in a sheltered site, reducing outdoor hours, and "work-at-height tasks" (e.g., in scaffolding) (Ahn, Crouch, Kim, & Rameezdeen, 2020). Indoor assembly, commonly used in off-site prefabrication processes, has additional benefits, such as improved material use, limiting the amount of waste produced onsite with the possibility to reuse the remains (Lu, Lee, Xue, & Xu, 2021), and a greater use of natural resources and biomaterials, such as wood, straws etc. (Sutkowska et al., 2024) that are better manageable in environments with controlled climate conditions.

In line with the EU decarbonisation goal, decarbonising the building stock is a priority. Prefabricated construction can offer many environmental benefits in terms of carbon emissions, energy consumption, material consumption, resource efficiency, and construction waste reduction (Y. Wang, Xue, Yu, & Wang, 2020; Rocha, Ferreira, et al., 2022). Tavares, Gregory, Kirchain, and Freire (2021) report that prefabricated buildings have the potential to reduce environmental impact, with a 40% decrease in embodied carbon and a 90% reduction in end-of-life impact. Additionally, Bergmans, Bhochhibhoya, and Van Oorschot (2023) report reductions of up to 50% in embodied carbon emissions achieved by closing material loops through well-considered R-strategies and local reuse of materials. Abuzied, Senbel, Awad, and Abbas (2019) report that the use of design for disassembly (DfD) and disassembly techniques can facilitate disassembly and support the integration of recycling practices. Boer et al. (2019) report that reducing environmental impact at end-of-life by less than 5% and using recycled materials to replace virgin raw materials can reduce overall impact by up to 30%. At the same time, Nußholz, Rasmussen, Whalen, and Plepys (2019) report that the reuse of waste in the building sector has generated new business models and contributed to the creation of innovative and sustainable added value. Tavares et al. (2021) estimate a 20%-50% reduction in construction time for prefabricated solutions compared to conventional construction. Advantages in construction timing also benefit the building tenants (and owners) and, in some cases, can be in-house during the renovation of the building envelope, such as the dismission and installation of new prefabricated façades. Despite these technologies offering potential opportunity for production in lower-cost countries (labour, energy, materials) and export growth (Tavares, et al., 2021), some critical issues found in literature highlight the difficulty for large companies to find qualified employees (Rocha, et al., 2022c) to work in the building retrofit processes and use prefabricated solutions (Lihtmaa & Kalamees, 2023).

The retrofitting choices are guided by the construction market, national/local laws and requirements (Y. Wang et al., 2020), and by social-cultural acceptances. Positive (or negative) feelings often come from personal characteristics and previous experiences (Taherdoost, 2018). Cultural factors (e.g., limited awareness of the benefits and challenges in use and management) can hinder the adoption of innovative technologies, as prefabricated solutions (Dunphy & Herbig, 1995). Awareness-raising initiatives should be undertaken to increase the general knowledge. Early adopters, such as real buildings renovated with innovative technologies, can also demonstrate and validate the benefits of such solutions from an aesthetic point of view ("Demo cases", 2021). The "appeal" of a building plays a crucial role, with its aesthetics being one of the principal aspects of architecture that draw admiration and appreciation (Sandak & Sandak, 2020). Lihtmaa and Kalamees (2023) note that a current limitation of prefabricated solutions is the lack of variety in aesthetic design, an aspect that could soon be overcome as demand increases. In this regard, the collection of early adopter buildings supports the use of prefabricated construction, highlighting benefits in economic, technical risk mitigation, and environmental terms (Katsigiannis et al., 2023).

Against this background, the research aims to respond to the following research gap: What are the "effective" prefabricated modular solutions for the energy retrofitting of an existing building in a data context?

To answer this question, the article presents a matchmaking approach to identify effective innovative products for different contexts, evaluating and considering local characteristics, opportunities, and constraints. The matchmaking approach aims to support the decision-making process for the selection and adoption of innovative prefabricated solutions. It leverages the collective expertise of a broad network of designers and experts, offering a competitive advantage over relying solely on a single design team. It intends to support different stakeholders to overcome knowledge gaps and cultural, technical, and economic barriers through technical requirements derived from real experience. It aims to support the retrofit decision-making process by increasing owners' confidence through early adopter buildings. Additionally, it seeks to enhance the expertise of building professionals, construction companies, and manufacturers through shared experiences and technical specifications. Furthermore, it guides the market by providing insights into the most suitable prefabricated retrofit solutions for various contexts.

3 METHODOLOGY. FROM TRADITIONAL RENOVATION TO INNOVATIVE PROCESSES AND PRODUCTS

Moving towards carbon-neutral buildings, the revised EPBD (2024) goal means significant innovation at all stages of the building life cycle, from design, construction, and management to demolition. Technological innovations, prefabrication, and modular systems are integral to this change and can play a very important role in this transformation. The matchmaking approach is a multi-criteria decision-making process designed to link specific retrofit requirements with appropriate prefabricated solutions.

3.1 MATCHMAKING

The matchmaking is between technological products and contexts, by analysing components and patterns as recurrent and predictable regularities (FIG. 1). These elements are defined to build combinations and sequences that describe industrialised solutions and ecosystems. By identifying similarities, connections, and complementarities within these descriptions, a body of knowledge is formed. This knowledge enables decision-making, and its patterned behaviour, repeated predictably, becomes a certain wisdom for future adaptation.

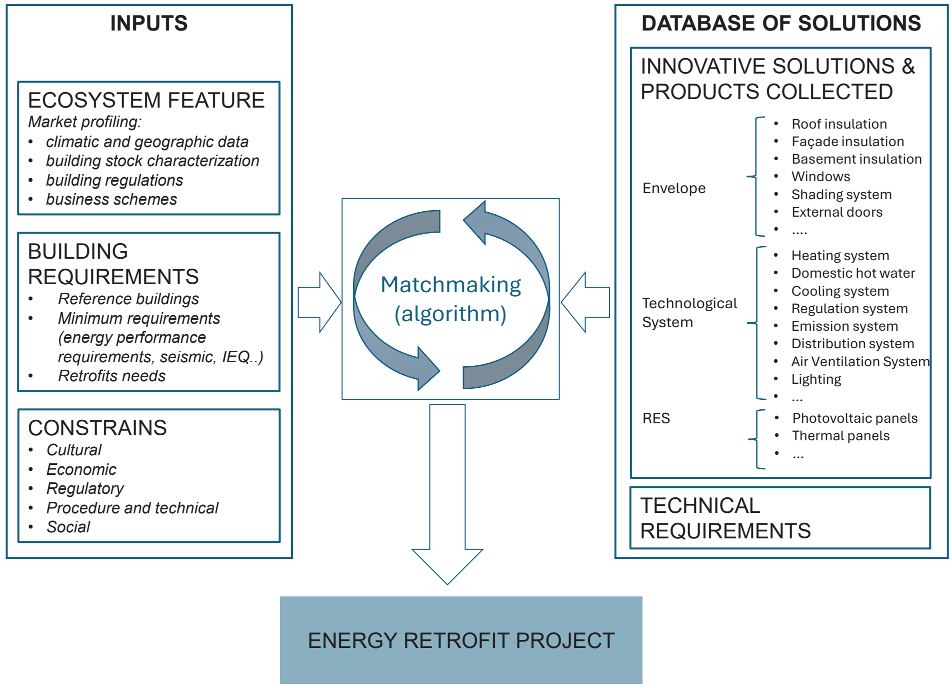

FIG. 1 Matchmaking process between databases of solutions (products/solutions) and Ecosystems (contexts, building retrofit requirements, and gaps)

On the one hand, the approach relies on ecosystem mapping to analyse contextual features such as climate conditions, building stock characteristics and renovation requirements, regulatory frameworks (e.g., energy performance requirements), and market maturity, including the acceptance of innovative products, socio-cultural and technical constraints (Chapter 3.3). On the other hand, a collection of "best practices" was carried out by involving local experts, who shared their knowledge using a common template (see Chapter 3.4). The key characteristics of the best practices are modularity, prefabrication, and integration of advanced technologies. The collected solutions focused on early-adopter buildings, both new and renovated, that utilise prefabricated construction and practically implement industrialized components such as modular façades. Additionally, the collection included other topics necessary for industrialised prefabrication processes such as digital technologies used in the design, manufacturing, and industrialization processes (e.g., data acquisition, modelling, and performance-economic evaluation using tools such as 3D scanners and BIM), as well as the integration of circularity principles, including material reuse and utilisation of recycled resources. Local experts (Chapter 3.2) with knowledge of policies, regulations, local capacities, and practical experience were involved to share their expertise and identify contextual gaps. To facilitate replicability, a database of solutions (chapter 3.4) was developed containing a list of technical requirements that address contextual constraints (such as building and urban planning) and technical feasibility.

The matchmaking approach was tested in the BUPS project in five Ecosystems (Austria, France, Italy, Spain, and the Netherlands). The "bottom-up" approach used aligns with the "New European Bauhaus" (NEB) and the beautiful | sustainable | together criteria. Through a collaborative framework, key ecosystem actors (such as local interested players) contribute to sharing experiences, knowledge, and the difficulties that hinder their widespread implementation. Each Ecosystem was represented by a group of local stakeholders – *Ecosystem Expert Team of BuildUPspeed project (BUPS-team)* – composed of building experts in building stock analysis and energy retrofitting (architects and engineers), prefabricated technologies (manufacturers and construction companies), innovative construction methods (academia), property owners, and new business models (consulting companies). The five BUPS teams were involved in different actions, from data collection on retrofit prefabricated solutions to the identification of relative technical requirements and early-adopter buildings (such as best practices) to identifying local building market gaps (in social, cultural, regulatory, economic, procedural, and technical terms). The validation of the matchmaking approach was made at the Ecosystem level by each BUPS team. Thanks to them, it was possible to identify the most interesting, prefabricated, and market-ready solutions across contexts.

FIG. 2 reports the scheme of the methodology process used to collect, analyse, and organise the i) Catalogue of best practices, including the technical requirements checklist for each product, ii) Ecosystem preference (as technological solutions most interesting for each context), and iii) related constraints that limit their adoption.

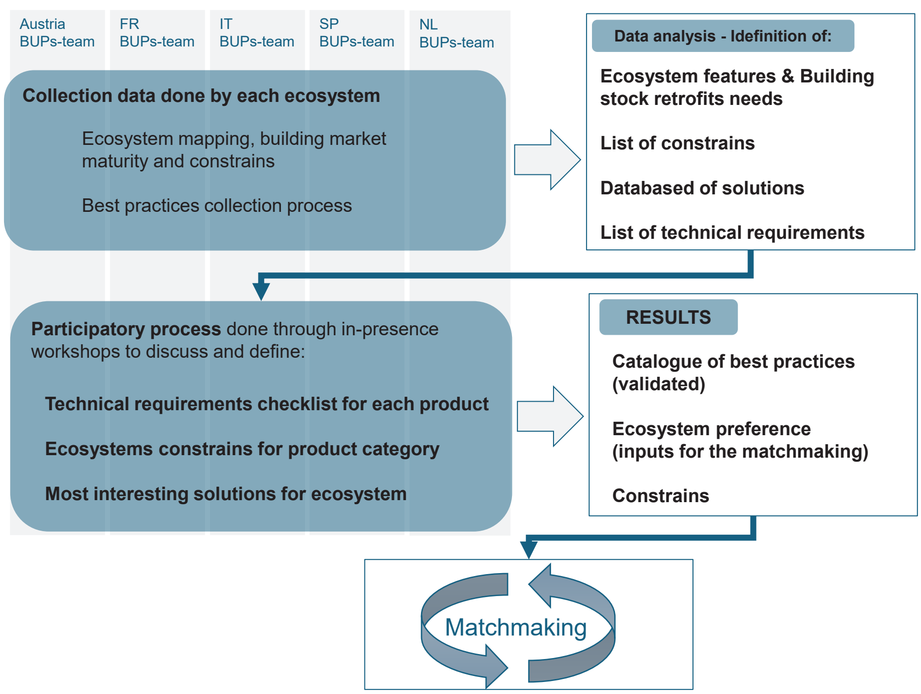

FIG. 2 Scheme of the methodology process.

3.2 ECOSYSTEM EXPERT TEAM (BUPS TEAM)

A participatory process based on Integrated Design Process with multidisciplinary teams composed of local building experts (e.g., architects, engineers, building companies, manufactures, building owners, service providers and researchers) from various EU countries were involved in active and collaborative process to jointly together to identify innovative products, solutions and processes that can be used in the energy retrofits of existing buildings advantages (Paoletti, Lollini, & Mahlknecht, 2013). Five expert teams (BUPS teams), one for each country (AT, FR, IT, SP, NL) were engaged in identifying the local specificities of the building markets, to share experiences on innovative products that they have already used, and help each other to overcome obstacles that prevent the adoption of innovative products (such as limitations due to the architectural culture of a place and traditions, as well as technological, economic, and managerial constraints). Workshops and active dialogues among Ecosystems, representative partners, and local players were organised, generating synergies, expanding knowledge, and developing solutions to fill existing gaps that hindered full market exploitation. The collaborative approach has contributed to improving industrial practices in deep building renovation by identifying the technical requirements necessary for the adoption of innovative solutions. In doing so, the matchmaking approach supports the replication of modular prefabricated and industrialised building solutions across diverse contexts, promoting greater efficiency, scalability, and innovation within the construction sector.

3.3 ECOSYSTEM MARKET PROFILING

The Ecosystems' mapping scope is to provide valuable information for identifying opportunities and overcoming constraints to innovative modular and industrialized solutions. The context investigation evaluates the market potential for integrating innovative prefabricated retrofit solutions, circularity criteria (such as reuse, restoration, or recycling of building materials), and digital technologies (e.g., virtual reality, 3D solutions, etc.). The ecosystem market profiling considers the following parameters:

- Climatic and geographic data, such as temperatures (hot, warm, cold), humidity (arid, dry), and precipitation. The Köppen-Geiger classification was used to compare the Ecosystems' climate.
- Building stock characterisation by reference buildings and traditional renovation packages providing a benchmark of energy renovation measures commonly used in a specific context (Ballarini, Paolo Corgnati, Corrado, & Talà, 2011) (Exner et al., 2016).
- Building regulations (e.g., building codes, national and local policies) that define minimum building requirements (e.g., energy performance, seismic adaptation, waste-circularity requirements) and play a crucial role in the retrofitting process and the identification of the renovation strategy.
- Financial instruments (subsidies, incentives, bonuses, VAT discounts) and business models for energy renovation, seismic adaptation (reinforcement and consolidation action), and waste reduction.

When we look for an ecosystem market profiling, meaning looking for its barriers, challenges, constraints, or definitively their lacks, we do it for either i) addressing un-aware users, so to ask the market conditions about a solution that can be used in that market conditions (changing user consciousness, not market conditions), or ii) addressing aware users (i.e. policy makers & companies) to introduce industrialised concepts and products in this market (changing market conditions, not user consciousness). Ecosystem market profiling, defined as the identification of barriers, challenges, constraints, or systemic gaps, is typically conducted for two main purposes. On the one hand, targeting unaware users allows assessing market conditions, appropriate solutions for that market, and the potential adoption, thus aiming to shift user awareness rather than changing market conditions. On the other hand, addressing aware users (informed stakeholders, such as policymakers and companies) aims to introduce industrialised concepts and products, thus influencing market conditions rather than user awareness. As an example, if parties want to encourage/introduce a specific industrialised solution in a specific market, they must first ask: *Why hasn't this solution been adopted yet? What are the (replication) barriers? How can the existing barriers be overcome?* Depending on the identified barriers, different strategies can be applied: i) If the product is perceived as aesthetically unappealing, a well-designed showroom or virtual simulator can help reshape public perception; if there is a lack of technical expertise (design, assembly, installation) free training programs can be offered; if there is a lack of maintenance culture, users can introduce the product as a service (e.g., maintenance service contracts for elevators).

The objective is to profile markets and then connect them to different industrialized solutions through categorisation and market innovation trends. This approach allows addressing the market positively (for solutions that fit the market) and responding to negative aspects (barriers to overcome) with positive answers (innovations that help to overcome the barriers).

3.3.1 Building market constraints of prefabricated and innovative solutions

Market constraints slow the use of deep energy retrofits. A literature review revealed social, cultural (knowledge-related), economic, policy, procedural, and technical gaps that slow down the retrofits have been investigated (Lassandro et al., 2023), (Brissi, Debs, & Elwakil, 2020), (Ibrahim, Hamdy, & Badawy, 2023) (Zhou, Syamsunur, Wang, & Nugraheni, 2024). Building on these findings, BUPS teams were involved in identifying the key market barriers in each context, with a focus on prefabricated and innovative solutions. The output was a list of market gaps for prefabricated construction (Table 1).

TABLE 1 List of identified market constraints

Cultural (as knowledge)	Lack of knowledge and understanding
	Lack of experience
	Lack of training schemes
	Lack of knowledge on innovative materials.
	Lack of knowledge on circularity criteria (in demolition phase, reused materials…)
Economic	Lack of financial support
	Difficult access to incentives
	Instability of incentivizing schemes
	Higher investments (compared to traditional solutions)
Regulatory	Lack of knowledge on added permissions requests.
	Regulatory approval challenging
	Regulatory protection (heritage building)
Procedure and technical	Risks of warranty validity
	Private intellectual property
	Lack of industry support
	Lack of institutional support
	Low accessibility for inspection and maintenance operations
	Lack of proper procurement procedures of industrialised/prefabricated solutions (e.g., single-multicomponent elements), costs, and criteria.
	Lack of producer responsibility during the dismantling processes (producers are "motivated" to invest efforts in designing it with a more holistic, sustainable life-cycle approach).
Social (as acceptance, feeling, changing habits)	Lack of awareness
	Perception of complexity
	Resistance to implementing changes and innovations

In a second step, by tapping into the BUPS teams' firsthand experiences, they evaluated technical, economic, and procedural shortcomings, alongside social and cultural lacks that hinder broader acceptance of innovative (industrialised and prefabricated) renovation solutions. The outputs might supply various indications for different building stakeholders. Policymakers might streamline administrative procedures and design economic incentives, such as grants or tax breaks, to accelerate the uptake of prefabricated solutions. Industry and training providers might organise hands-on workshops and showcase events to build community acceptance, spark emotional engagement, and drive lasting behavioural change. Building companies and manufacturers might use these outputs to identify where to invest and in which product, to tailor communication campaigns and financial products, and ensure that technical, procedural, and cultural barriers are overcome.

3.4 BEST PRACTICE COLLECTION

The target of the "Best Practices of Innovative Solutions" collection is to promote deep renovation through innovative prefabricated products and industrialised processes that enhance energy performance, indoor comfort, and worker safety, reduce construction time and costs, incorporate circularity principles (such as reduce, reuse, and recycle), and add significant economic and ecological value. A data template was developed to collect information on products, experiences, and early-adopter buildings, including innovative solutions for building envelope retrofits, active systems such as heat pumps, and systems based on renewable energy sources (RES), digital technologies, and monitoring systems. The data was gathered according to the following criteria:

- Prefabricated and industrialised modular technologies.
- Energy performance and indoor Environmental Quality (IEQ) improvements provided by the solution.
- Digital technologies for enhancing an industrialised approach and improving design, production, and implementation processes.
- Innovative processes for cost-optimality and life-cycle cost (LCC) evaluation
- Circularity principles (e.g., reduce, reuse, recycle), applied to maximise resource efficiency.
- Saving potential in specific areas (construction site, labour, transport, costs, and environmental impacts), enhanced by the solution.

For each product or solution collected, the following technical information was gathered: i) General information, including name, brief description, and development context (e.g., European project); ii) Solution category, in relation to the type of products (e.g., report/article, data repository, guidelines, etc.) and building components, for the envelope (e.g., façade, windows, etc.) or technical system (e.g., HVAC, RES, etc.), digital technologies (e.g., database, tool, platform, etc.), along with the source and any identified constraints (e.g., social, economic, or technical barriers); iii) Replicability potential, rated as low, medium, or high; iv) Exploitability and market readiness; and v) Contact details of promoter partners.

All five BUPS teams contributed their experience and know-how to the data collection process by describing implemented products, validated solutions, and practical experiences (such as early-adopter building). Their extensive knowledge acquired through working with innovative processes, products, and their integration into early-adopter buildings represents the added value of the database. During data processing, a checklist of technical requirements was developed to filter the collected information, enhance its usability, and enable replication across different contexts. The collection process is presented in Fig. 3.

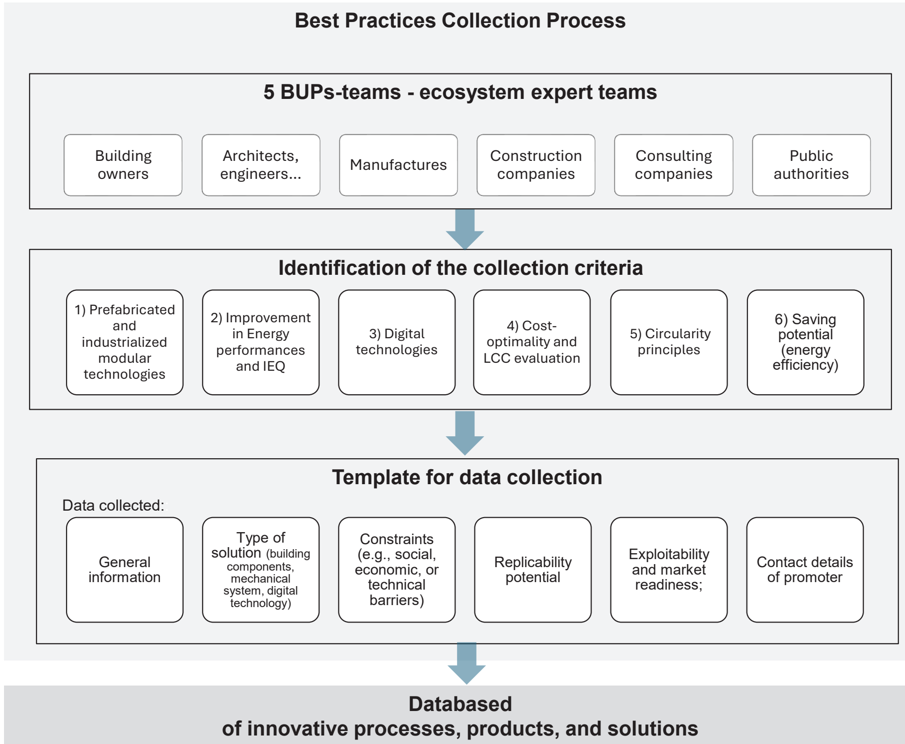

FIG. 3 Best Practices collection process, database of innovative solutions/products, and technical requirements.

3.4.1 Technical requirements checklist for prefabricated modular industrialised solutions

The correct application of innovative prefabricated modular industrialised components and related products is a crucial factor in ensuring quality and achieving successful outcomes. To support feasibility assessments, the technical requirements for each product were collected in the templates used for the “Best Practices collection”. Subsequently, the technical requirements were grouped into a comprehensive list, shown in Table 2.

At a later stage, during an in-person co-workshop, the five BUPS teams were requested to evaluate the most significant barriers for each type of innovative product. The output was a technical requirements checklist for each product category. These checklists might be facilitation tools to support quick feasibility assessments. They might be used, particularly by architects, at the early stages of the retrofit design phase, serving as decision-making aids to verify whether a product meets the necessary technical requirements and can be adopted. This approach simplifies replicating the process across different buildings and contexts throughout Europe.

TABLE 2 List of technical requirements

Building data	Homeowners	Coordination with occupants
		Information and clear communication
	General information	Property Ownership: Single owner or multi-property
		Housing Tenure: Owned or rented
		Building Use: Residential, tertiary, sanitary, sports, etc.
		Building Typology: SFH (Single Family House) / MFH (Multi Family House)
		Year of construction of the building
		NO monumental protection: If the building is not under heritage protection
		NO colour restrictions in architectonic elements, such as façades, roofs, etc.
		Expansion Potential: Possibility to build more floors or increase the useful surface.
	Building-related requirements	Number of Floors
		Number of underground floors
		Dwelling Surface (m2)
		Building height: e.g., free height from street level
		Indoor Height: free height between pavement and ceiling
		Renovation Size: number of m^2 renovated (façades, roof) or number of elements (e.g., windows)
		Structural Type: Material and structure (wall, pillars).
		Structural Capacities of the existing building.
		Technical Room: Existence and size
		Perimetral Wall Length
	Façade-related requirements	Dimension of the façade
		Façade height: e.g., free height from street level
		Co-planar façade geometry (e.g., simple façade geometry)
		Façade Construction System: type of construction/material
		Presence of insulation
		Presence of balconies, terraces, or other elements
		Façade Finish: Type of external finish.
	Window-related requirements	Number of windows to renovate (is there a minimum number of windows to renovate?)
		Openings Layout: Distribution and variety/regular size of openings.
		Openings Size: Window sizes.
	Roof-related requirements	Roof Type: Flat or sloping.
		Roof Size: Dimensions (m2)
		Roof Construction System: Type of construction.
		Shading and obstacles (chimney, antennas...)
	Systems	Electrical Network: Status of the home's electrical network, circuit separation.
		HVAC System: Type of heating, ventilation, and air conditioning system.
		Heating/DHW System: Individual or centralized.
		DHW System: Type of domestic hot water system.
		Existence of thermal or electrical storage systems.
		Existing Renewable Energy Systems
Surroundings side conditions		Façade orientation
		Shadows (on the façade/roof/windows)
		Possibility of crane access from the street
		Free space between the façade to be renovated and the façade of the opposite building (e.g., minimum street width, absence of physical obstructions such as vegetation, utility lines, or other elements that could hinder installation activities)
		Possibility of soil connection next to the façade
		Possibility to install scaffolding

>>>

TABLE 2 List of technical requirements	
Regulatory compliance	Fire
	(national, local)
	Energy efficiency and RES use
	Waste reduction
	Circularity
	Water use restrictions
	Energy sharing/energy community's legislation
	Labour
Process management	Training and expertise, knowledge
	Data monitoring
	Coordination between different actors (e.g., constructor, designer)

4 RESULTS

This chapter reports the outputs of the preparatory phase and the validation of the matchmaking approach, both identified by the BUPS teams' support. The outputs of the preparatory phase are the "Best Practices collection" and the "Checklist of technical requirements," which together form the database of knowledge on solutions, experiences, and know-how of the BUPS teams. The outputs of the matchmaking approach are i) the most interesting solutions (products) for different users in different ecosystems, and ii) market readiness by gap identification. Compared to the traditional process, the matchmaking approach supports the retrofit decision-making process by identifying the most effective prefabricated solutions across various contexts, offering a competitive advantage from the experience of a large group of designers (experts) over a single design team (FIG. 4).

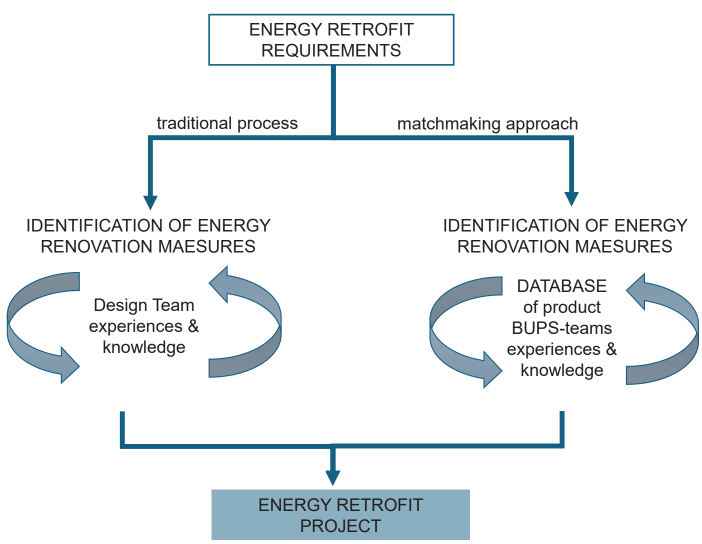

FIG. 4 Matchmaking approach - advantages from a large body of knowledge from a large number of building experts (as designers).

A crucial aspect of the matchmaking approach is the ability to facilitate an effective match between solutions, contexts, and users. First, the strategy focuses on helping the BUPS users to discover and understand the available innovative solutions that transform structured data into meaningful insights. Secondly, the matchmaking results aim to support decision-making by enabling them to compare and assess different options through a product catalogue and a checklist of technical requirements, turning raw data into actionable knowledge. Finally, looking toward the future, the strategy aims to facilitate the gradual adaptation of solutions, markets, and user awareness as industrialisation evolves. This will be achieved by identifying the specific needs of the renovation context and setting out a checklist of technical requirements for each innovative product. This checklist will consolidate and analyse the key data, facilitating the adoption and replication of the products.

4.1 BUPS TEAM COMPOSITION

The BuildUPspeed project enabled engagement with a broad set of local stakeholders, ranging from technically skilled actors (building professionals, construction companies, manufacturers, and academic institutions) to demand-side representatives (such as homeowners and public authorities). This diversity was essential to ensure that the matchmaking approach captured both the technical feasibility of the best practices and the practical constraints of the Ecosystems. Across the five participating EU countries, the BUPS teams brought complementary expertise that shaped the identification and evaluation of innovative prefabricated solutions. Despite different levels of awareness and market maturity, every team (composed of 4-6 experts) contributed by: i) providing detailed descriptions of innovative solutions, products, and processes (later analysed and collected in a database) and ii) supplying key contextual information for building market characterisation, including building stock, retrofit requirements, and local gaps. Their common entry point was location-based analysis, ensuring that each assessment considered the specificities of the ecosystem. The teams' composition highlights the heterogeneity of expertise mobilised:

- Austria: Expertise in prefabricated façade and roof modules (AEE INTEC), edible balconies for retrofits (ESSBAR - Rhomberg Bau), digital innovations and BIM (AEE INTEC), and circularity solutions such as RE-USE-BOX (BauKarussell, Austrian Institute of Ecology).
- France: Circular deconstruction and rebuilding, "Re fair" sustainable redevelopment approach (La Fab -DomoFrance), and low-impact construction and disassembly-dismantling processes (NOBATEK, INEF4).
- Italy: Prefabricated multifunctional façades modules integrating RES systems (Eurac research) and Energiesprong model (Edera).
- Dutch: Prefabricated multifunctional façade modules, biomaterials, PV and heat pumps (Zuyd, WEBO), digital/ BIM technologies (DEMO).
- Spanish: Disassembly/adaptability (DfD/A) tool such as RE10, construction waste and costs estimation tools, BIM catalogue (IVE), and prefabricated systems including CREE and CLT (ACR), supported by digital innovation (PTEC).

This composition not only provided a wide spectrum of technical and organisational perspectives but also influenced the collected data (Chapters 4.2, 4.3), the qualitative outcomes of the matchmaking analysis (Chapter 4.4), and the gaps in replicability (Chapter 4.5), facilitating the tailoring of solutions to local needs and supporting the broader goal of accelerating energy-efficient retrofits across Europe. Countries with more robust markets, for example, in prefabrication, have proposed more mature solutions, which also help other Ecosystems address systemic barriers, knowledge gaps, regulatory constraints, and digital limitations more effectively. Conversely, countries with less developed markets have highlighted challenges and contextual constraints that can inform and refine the solutions proposed by more mature ecosystems.

4.2 CATALOGUE OF THE BEST PRACTICES

The representative of the five BUPS teams contributed to the collection of "Best Practices" by filling in a structured template that collected products and practical experiences, both outcomes from previous EU projects and in-house solutions of BUPS partners, according to six criteria (Chapter 3.4). The analysis of the collected Best Practices showed that many solutions present multiple positive attributes across the six criteria, meaning they often address more than one objective simultaneously. This means that a single prefabricated modular solution can, for example, improve energy performance, enhance indoor environmental quality, support circularity, reduce construction time and costs, and increase worker safety, all at once. To improve usability, the solutions collected in the Catalogue of Best Practices were organised into three categories according to their nature: (i) Methodologies and Guidelines, (ii) Solutions and Technologies, and (iii) Digital Technologies. Appendix A (Table 4) presents the Catalogue of Best Practices, including the category, main topic, solution name, brief description, origin (EU projects and in-house products), and reference source. Subsequently, a data analysis was conducted to structure a database of energy retrofit solutions by identifying criteria that improve the usability of the collected information. This process ensured that retrofit requirements could be effectively linked to the appropriate solutions, allowing users to easily access and filter prefabricated and innovative retrofit options.

4.3 TECHNICAL REQUIREMENTS CHECKLIST

To support feasibility assessments and simplify the adoption of innovative products, the technical requirements of each product category were investigated. The template used in the Best Practices collection included information on replicability potential, exploitability, market readiness, and technical barriers. Once all product data had been collected, the barriers were compiled into a comprehensive list (Table 2). Next, the BUPS teams conducted a follow-up analysis to identify the critical barriers for each product, starting with the comprehensive barriers list. Using five levels of importance (very important, moderately important, important, relatively important, and not important), the BUPS teams defined the Technical Requirements Checklist (Appendix B) for each product. The first two levels of the checklists (very important, moderately important) represent mandatory requirements that must be satisfied for correct implementation, such as the dependence on boundary conditions and installation feasibility. For example, the Technical Requirements Checklist for Prefabricated Façade Modules highlights three clusters of 'very important' requirements:

- *Façade-related requirements* include the surrounding context and regulatory constraints. Key data, such as the "façade dimensions" and "co-planar façade geometry," are critical for assessing replicability. For example, the façade area should exceed 30-40 m^2, as investment below this threshold is typically not economically viable.
- *Surrounding side requirements,* the site must allow for sufficient "crane access from the street" and provide "free space between the façade to be renovated and the façade of the opposite building (e.g., minimum width of the street, absence of physical obstructions, such as vegetation, utility lines, or other elements that could hinder installation activities)".

- *Regulatory compliance:* the prefabricated façade modules must comply with relevant national building codes, particularly those related to "fire safety" and "seismic" performance.
- The "important" technical requirements for prefabricated façade modules include a variety of factors, such as heritage protection constraints, colour restrictions, the type of existing façade materials, the presence of insulation, the number of windows, and the overall building height (i.e., number of floors). While not universally critical, these parameters shape the degree of adaptation needed for each solution and therefore affect the scale-up potential across different contexts.

Overall, the Technical Requirements Checklists function as operational decision-support tools. They are designed to ensure effective implementation across diverse building contexts and to facilitate decision-making by anticipating installation constraints, resolving potential obstacles, and identifying the conditions under which each product can be replicated or standardised. As a result, the checklists promote the adoption of innovative solutions and maximize market uptake by clarifying where technical feasibility is assured, where adaptation is needed, and where replication is limited by context-specific constraints.

4.4 MATCH! INTERESTING SOLUTIONS FOR DIFFERENT USERS IN DIFFERENT ECOSYSTEMS

Drawing on local particularities, such as building stock, energy renovation requirements, and available capacities, each BUPS team implemented the participatory matchmaking approach through an in-person workshop to identify the most promising solutions. Using the Best Practices Catalogue (Appendix A), each team engaged in a structured discussion-based evaluation process to determine the suitability levels of the collected solutions for their specific ecosystem. This assessment considered factors like retrofit needs, building-sector maturity, and priority renovation challenges. During the workshop, the experts evaluated each solution based on technical and material feasibility relative to local construction practices, implementation feasibility (including workforce skills and manufacturing capacity), compliance with national and regional renovation requirements, and anticipated limits to replicability, awareness, or user acceptance. Based on this collective analysis, each team assigned one of three suitability levels: very suitable (xxx), moderately suitable (xx), or potentially suitable (x) using consensus rather than numerical scoring. The evaluation results are reported in Table 3.

These outputs identified the most interesting and promising solutions for each Ecosystem (Austria, France, Italy, the Netherlands, and Spain). They provide valuable insights that clarify which solutions, products, technologies, or digital technologies are suitable for each Ecosystem, according to the building stock characteristics, retrofit needs, and market maturity (e.g., regulatory barriers or other conditions that limit their uptake). Collectively, these insights can inform value-added innovation and guide future investments by various stakeholders, including investors, construction companies, and manufacturers.

TABLE 3 Level of interesting solutions for each Ecosystem: very suitable (xxx), moderately suitable(xx), potentially suitable(x), and not suitable

Product type	Short description	AT	FR	ES	NL	IT
End of Life Manual	Manual deconstruction and dismantling activities	XXX	XXX	X	XX	XXX
Repository of EE and IEQ performance evaluation in EU countries	Repository of energy performance evaluation results for different type of buildings in different type of climate context	XXX	XXX	X	XX	XXX
Advanced window	Solar Window Block	X	XXX	XXX	XX	XXX
	Active Window System	X	XXX	XXX	XX	
	BGTEC smart windows		X	XXX	XX	
	Bloomframe® folding balcony		X	XX	X	X
HVAC component	HVACsystems - air-heat pump -DHW storage - MODULE		XX	XX	XX	
	Energy storage	XXX	XXX		XX	XX
	Micro heat pumps façade-integrated	XXX	XXX	XX	X	X
New envelope component	PAN rooftop retrofitting/ extension module		XXX	XX	X	
Balcony system technologies	Edible balcony gardens for retrofit - Vertical greening technology for the city	XX	XX	XX	XX	
Exterior finishing	3D printing and robotics Source: P2EnDURE	X			X	X
Prefabricated modules for façades & roofs	Prefabricated façade (insulation and PV integrated)	XXX	XXX	XXX	XX	X
	Prefabricated active modules for façades.	XXX		XX	XX	XX
	Prefabricated timber façade integrated with different technologies (e.g., PV, greening)	XXX		XX	XX	XX
	Prefabricated timber façade	XXX	XXX	XXX	XX	XXX
	Multifunctional prefabricated timber façade integrated with other technologies	XX		XX	XX	XX
	Prefabricated concrete panel	X		XX	X	XXX
	Micro-heat pumps façade-integrated	XXX	X	XX	XXX	X
Digital technology for monitoring system	Life Cycle Cost Façade tool	X	XXX	XXX	XX	XXX
	BIM platform	X	XXX	X	XXX	XX
	RE LCC	X	XXX	X	XX	XX
	One Stop Access Platform (OSAP)		XXX		XXX	X
	Building energy performance simulation (BEPS) tools into the BIM platform	XXX	XXX	X	XXX	XX
Digital technology for monitoring system	Monitoring system	XX	XXX		XXX	XX
Digital technologies for circularity, end-of-life, assembly & disassembly	End of Life tool	X	XXX		XXX	XX
	Disassembly and adaptability analysis tool (ISO 20887:2020 standard)	X		XXX	XXX	
	Construction and demolition waste management	X	XXX	XXX	XXX	
Digital technologies for IEQ and Energy-Performance evaluation	BIM platform	X		X	XXX	XX
	Open BIM for analytical model		XX	X	XXX	
	Meta building optimization tool (BIM tool)		X	X	XXX	
	BIM construction solution catalogue		XX	XX	XXX	
	RE energy tool		XX	XXX	XXX	
	PV system platform			XXX	XXX	XX
	One Stop Access Platform (OSAP)		XXX		XX	X
Human comfort	Comfort Eye	X	XXX	XX	XXX	XX
Building site management	RE Onsite		XXX	XX	X	X
	RE Asset management			XX	X	XX
	Online BIM viewer		XX	X	X	

4.5 READINESS OF DIFFERENT ECOSYSTEMS

Once the list of possible cultural, economic, regulatory, and processual and technical gaps was compiled (Table 1), the BUPS teams selected the local constraints from this comprehensive list that could limit the adoption and replication of the innovative solutions and products collected in the Best Practices catalogue. Through a participatory approach, based on an in-person workshop, the 5 BUPS teams discussed and identified the most common local barriers in each context of each product category (prefabricated façade, HVAC, RES technologies, control systems, monitoring systems, building enhancement, database and repository, digital technologies, processing services, platform, and user interaction). Each team assigned a score of 1 for every barrier identified in their local Ecosystem, and a score of 0 (null) when there were no barriers. As a result, each category of product/solution category could accumulate up to 5 points per gap (one for each team), highlighting which gaps are most frequently encountered across all Ecosystems (FIG.5). The figure shows the distribution of the cultural, social, procedural, and technical and financial barriers for each solution category. Notably, social and cultural gaps are the most prevalent obstacles limiting the adoption of innovative technologies. The most common social barrier is *"resistance to implement changes and innovations*", followed by the three cultural barriers *"lack of knowledge and understanding", "lack of experience",* and *"lack of knowledge on circularity criteria (in the demolition phase, reuse of materials)*".

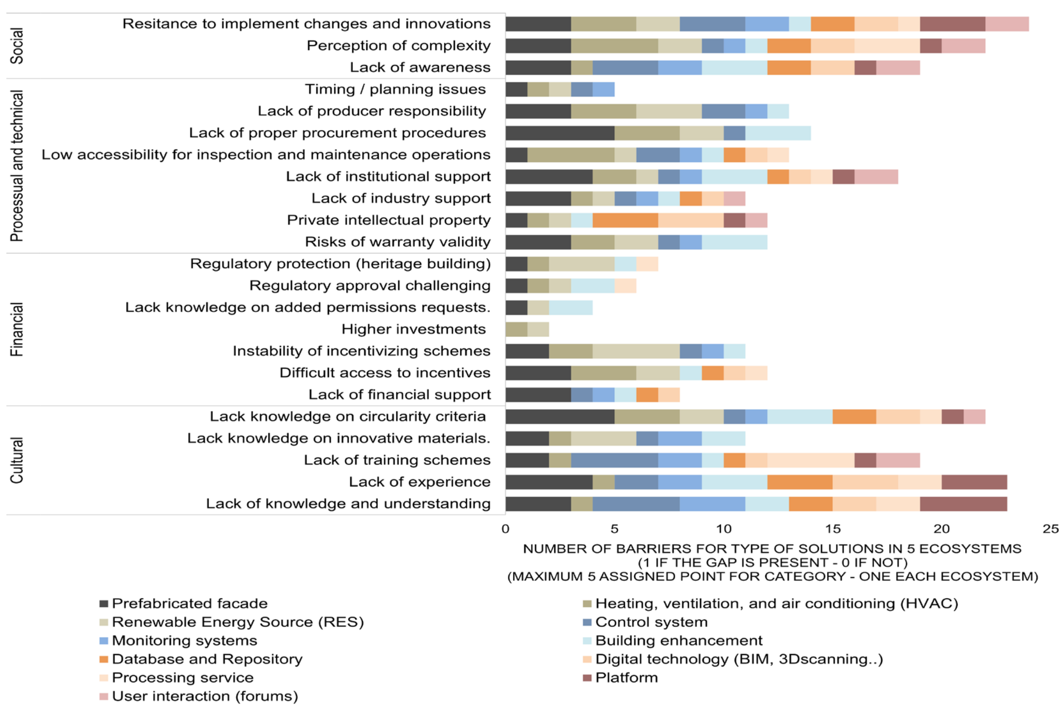

FIG. 5 Distribution of cultural, social, procedural, technical, and financial barriers for each solution category.

In addition, the relationship between the trend in barriers within each Ecosystem and the solution category can be analysed independently. FIG. 6 shows the distribution of the barriers across the five Ecosystems for the "Prefabricated Modules for Façades" category. The most significant barriers to the adoption of prefabricated façade modules across all ecosystems are primarily cultural and processual/technical. Culturally, the "*lack of knowledge on circularity criteria (in demolition phase, reuse of materials)*" stands out as a major obstacle. On the processual and technical side, a key barrier is the "*lack of adequate procurement procedures of industrialized/prefabricated solutions (e.g.,* *mono-multicomponent elements), costs, and criteria*". Recognising these gaps is essential for planning targeted initiatives to reduce barriers and promote the use of such technologies. For example, to address cultural gaps, educational initiatives can include training and workshops, exchange events, and the development of guidelines and modules to promote the use of circularity criteria.

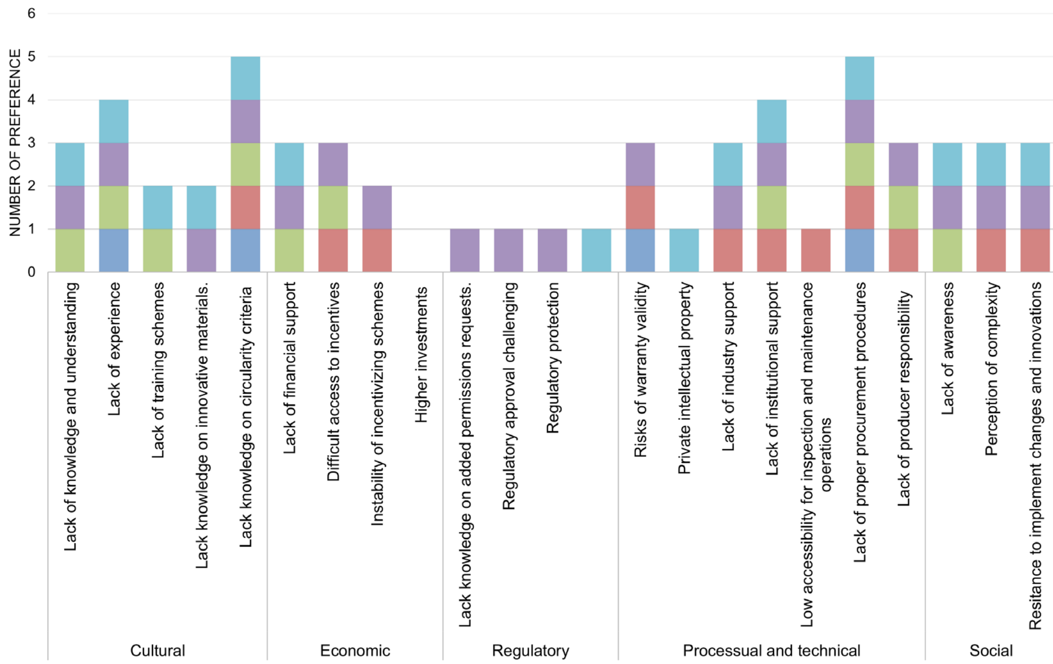

FIG. 6 Distribution of the barriers across the five Ecosystems (FR, NL, AT, IT, SP) for the "Prefabricated Modules for Façades" category.

5 DISCUSSION

The work described presents a qualitative approach for identifying the most interesting and replicable innovative industrialised solutions and products across different contexts. The central challenge addressed is the transition of the retrofit market from traditional renovation solutions to innovative industrialised processes and products. To this end, a matchmaking approach was applied to select the most effective and interesting solutions from a predefined database of products, leveraging the collective expertise of multidisciplinary teams. To ensure contextual relevance, the study mapped several key aspects: geographical climate conditions, building policies and regulations, characteristics of the building stock and deep retrofit packages, retrofit incentives, and local players and capacities. The mapping activities also considered the local experiences with innovative industrialised products and technologies, with particular attention to prefabricated solutions, circular processes, and digital technologies. A core methodological element was the engagement of informed stakeholders (such as building experts, policymakers, building companies, and manufacturers) within the BUPS project framework. Five expert teams (BUPS teams), composed of key actors from five EU countries (AT, FR, IT, NL, SP), shared positive experiences with industrialised prefabricated products and processes. One of the results of this collaborative process was a catalogue of "Best Practice", collecting innovative solutions and products from their professional experience and previous EU projects. In parallel, to facilitate the replication of such innovative products, a technical requirements checklist was developed as a facilitator tool for each product type. At the same time, ecosystem market barriers that limit the uptake of prefabricated and industrialised solutions were identified, highlighting critical constraints related to skills, processes, and market readiness.

From a user perspective, the outcomes of this work are relevant to both aware and less-aware stakeholders, who nonetheless share a common objective: the adoption of industrialised solutions in existing buildings and renovation projects. The entry point is location-related, considering both building stock and market constraints. The limitation of this work lies in the validation phase, which involved a limited number of stakeholders and primarily those already familiar with innovative solutions. To strengthen robustness and generalisability, future validation activities should involve a broader and more diverse group of actors, including less-aware users.

Engaging such users would enable the assessment of acceptance levels and perceptions, both positive and negative, towards industrialised renovation solutions. For example, if there are negative aesthetic perceptions of a specific industrialised solution, it is necessary to involve designers and developers in improvement processes and/or change users' awareness. Raising awareness is crucial for the building sector to shift towards circular construction and sustainable processes (e.g., reuse, recycle, restore). In line with this bottom-up approach, the New European Bauhaus initiative aims to support the green transition by improving well-being and a sense of belonging, guided by three criteria: together, beautiful, sustainable.

6 CONCLUSIONS

This study highlights the potential of a qualitative, context-sensitive matchmaking approach as a strategic instrument to support and accelerate the adoption of industrialised prefabricated solutions across buildings in different ecosystems. By valorising predefined technologies (collected in the catalogue of best practices), the approach acts as a facilitator helping stakeholders to identify modular prefabricated solutions compatible with local building characteristics and boundary conditions, including regulatory frameworks, market conditions, and stakeholder capacities.

In this perspective, the integration of technical requirement checklists represents a key enabling element to reduce uncertainty and support the feasibility assessment of innovative solutions in real renovation contexts. At the same time, identifying local shortcomings is a necessary step to inform future initiatives aimed at overcoming existing constraints. For example, where limited adoption is linked to gaps in technical knowledge or skills, targeted actions such as training programmes or demonstration spaces may be forecasted.

Moreover, the matchmaking approach can be utilised in multiple ways for various purposes by different stakeholders i) as a decision-support tool for design teams operating across diverse contexts; ii) as a feedback mechanism for developers and companies to drive the continuous improvement of products; iii) as a strategic support tool for public authorities and investors to guide strategic planning for incentives and innovative investment models; and iv) as an awareness-raising instrument for building users, aimed at improving understanding and acceptance of these solutions. In this sense, the approach can be further developed and scaled to support more systemic transitions towards industrialised and circular renovation practices.

Author Contributions

Giulia Paoletti: Conceptualization, Methodology, Formal analysis, Investigation, Writing, and Editing. Vera Valero Escribano: Investigation, Review. Ana Sanchis Huertas: Conceptualization, Methodology, and Writing. Stefano Avesani: Review. Riccardo Pinotti: Methodology and Review.

Funding. Grant information

This study was supported by the EU LIFE BUILDUPSPEED project. The BuildUPspeed project has received funding from the LIFE programme of the European Union under Grant Agreement no. 101075843.

Acknowledgements

This study was supported by the EU LIFE BUILDUPSPEED project. For the results obtained a thank you to the BUPS projects partners, Ecosystem teams, and experts involved in the several activities done within Work package 2.

References

3DASH Tool: 3D Automatic Surfaces Handling - REVIT Plug-in. (2020). (EU project No. 820553). *BIM-SPEED Project*. Retrieved from https://www.bim-speed.eu/en/News%20%20Events%20%20Documents/Training%20Material/BIMSPEED_Training_3DASH-tool_CARTIF_v1.pdf

Abuzied, H., Senbel, H., Awad, M., & Abbas, A. (2019). A review of advances in design for disassembly with active disassembly applications. *Engineering Science and Technology an International Journal*, *23*(3), 618–624. https://doi.org/10.1016/j.jestch.2019.07.003

Accidents at work. (2021). Retrieved from https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Fatal_and_non-fatal_accidents_at_work_by_NACE_section,_EU,_2021_(%25_of_fatal_and_non-fatal_accidents)_AAW2023.png

Aghasizadeh, S., Tabadkani, A., Hajirasouli, A., & Banihashemi, S. (2022). Environmental and economic performance of prefabricated construction: A review. *Environmental Impact Assessment Review*, *97*, 106897. https://doi.org/10.1016/j.eiar.2022.106897

Ahn, S., Crouch, L., Kim, T. W., & Rameezdeen, R. (2020). Comparison of Worker Safety Risks between Onsite and Offsite Construction Methods: A Site Management Perspective. *Journal of Construction Engineering and Management*, *146*(9). https://doi.org/10.1061/(asce)co.1943-7862.0001890

Anaç, M., Ayalp, G. G., & Erdayandi, K. (2023). Prefabricated Construction Risks: A Holistic Exploration through Advanced Bibliometric Tool and Content Analysis. *Sustainability*, *15*(15), 11916. https://doi.org/10.3390/su151511916

Ballarini, I., Paolo Corgnati, S., Corrado, V., & Talà, N. (2011). Definition of Building Typologies for Energy Investigations on Residential Sector by Tabula IEE-Project: Application to Italian case studies. *Proceedings of the 12th. International Conference on Air Distribution in Rooms* (Roomvent). Retrieved from https://www.academia.edu/53402676/Definition_of_Building_Typologies_for_Energy_Investigations_on_Residential_Sector_by_Tabula_Iee_Project_Application_to_Italian_Case_Studies

Bataglin, F. S., Viana, D. D., Formoso, C. T., & Bulhões, I. R. (2019). Model for planning and controlling the delivery and assembly of engineer-to-order prefabricated building systems: exploring synergies between Lean and BIM. *Canadian Journal of Civil Engineering*, *47*(2), 165–177. https://doi.org/10.1139/cjce-2018-0462

Bergmans, I., Bhochhibhoya, S., & Van Oorschot, J. (2023). Assessing the circular re-design of prefabricated building envelope elements for carbon neutral renovation. *Journal of Façade Design and Engineering*, *11*(2), 169–196. https://doi.org/10.47982/jfde.2023.2.a4

Bim4Ren. (2022, March 15). Technologies - Bim4Ren. Retrieved from https://bim4ren.eu/technologies/

BIMPlement. (n.d.). Retrieved from https://www.bimplement-project.eu/project/catalogue/

Bloomframe. (2022, October 31). Home - Bloomframe. Retrieved from https://www.bloomframe.com/

Boer, D., Segarra, M., Fernández, A. I., Vallès, M., Mateu, C., & Cabeza, L. F. (2019). Approach for the analysis of TES technologies aiming towards a circular economy: Case study of building-like cubicles. *Renewable Energy*, *150*, 589–597. https://doi.org/10.1016/j.renene.2019.12.103

BPIE. (2021, November). Deep renovation: shifting from exception to standard practice in EU policy. *Buildings Performance Institute Europe*. Retrieved from https://www.bpie.eu/ publication/deep-renovation-shifting-from-exception-to-standard-practice-in-eu-policy/

Brissi, S. G., Debs, L., & Elwakil, E. (2020). A review on the factors affecting the use of offsite construction in multifamily housing in the United States. *Buildings*, *11*(1), 5. https://doi.org/10.3390/buildings11010005

Building management. (2023). Retrieved from https://www.demobv.nl/en/re-suite/building-management

Building management. (n.d.). Retrieved from https://www.demobv.nl/en/re-suite/building-management

Built2Spec. (n.d.-a). Retrieved November 8, 2023, from https://built2spec-project.eu/

Catalogue of constructive elements. (2022). Retrieved from https://www.bimplement-project.eu/project/catalogue/

CYPE Sofware. (2024, August 6). Open BIM Analytical Model. Retrieved from https://info.cype.com/en/software/open-bim-analytical-model/

Deep renovation packages. (2020). (D3.3). *4RinEU*. Retrieved from http://www.4rineu.eu/wp-content/uploads/2021/02/4RinEU_D3.3-4RinEU-Deep-Renovation-Packages_Annex.pdfhttp://www.4rineu.eu/wp-content/uploads/2021/02/4RinEU_D3.3-4RinEU-Deep-Renovation-Packages_Annex.pdf

Demo cases: Report on deep renovation packages as tailored and implemented in the demo cases,. (2021). (D5.3). *4RinEU*. Retrieved from http://www.4rineu.eu/wp-content/uploads/2021/06/4RinEU_D5.3_Deep-renovation-package-in-the-demo.pdf

Du, J., Zhang, J., Castro-Lacouture, D., & Hu, Y. (2023). Lean manufacturing applications in prefabricated construction projects. *Automation in Construction*, *150*, 104790. https://doi.org/10.1016/j.autcon.2023.104790

Dunphy, S., & Herbig, P. A. (1995). Acceptance of innovations: The customer is the key! *The Journal of High Technology Management Research*, *6*(2), 193–209. https://doi.org/10.1016/1047-8310(95)90014-4

Energy Efficiency Directive. (2023). Retrieved from https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/energy-efficiency-directive_en

Energy Matching platform. (2021). Retrieved from https://platform.energymatching.eu/

Energy Performance of Buildings Directive (EU/2024/1275) (2025). Retrieved December 9, 2025, from https://energy.ec.europa.eu/topics/energy-efficiency/energy-performance-buildings/energy-performance-buildings-directive_en#:~:text=85%25%20of%20buildings%20in%20the,decarbonised%20building%20stock%20by%202050.

ESSBAR. (2023). Retrieved from https://nachhaltigwirtschaften.at/en/sdz/projects/essbar.php

The European Green Deal. (2019). Retrieved from https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

EXCESS. (2022). Retrieved from https://positive-energy-buildings.eu/demo-cases/austria

Exner, D., D'Alonzo, V., Paoletti, G., Pascual, R., & Pernetti, R. (2016). Building-Stock analysis for the definition of an energy renovation scenario on the urban scale. In *Green energy and technology* (pp. 33–54). https://doi.org/10.1007/978-3-319-44899-2_3

Fan, J., Chen, L., & Chen, K. (2024). Digitalizing Industrialized construction projects: status quo and future development. *Applied Sciences*, *14*(13), 5456. https://doi.org/10.3390/app14135456

Founti, M., Avesani, S., & Elguezabal, P. (2023). Multifunctional façades for renovation through industrialization. *Journal of Façade Design and Engineering*, *11*(2), V–VI. https://doi.org/10.47982/jfde.2023.2.00

Hoogenboom, D. (2025, February 18). The Netherlands leads Europe in prefabrication adoption. Retrieved from https://www.usp-research.com/insights/news/the-netherlands-leads-europe-in-prefabrication-adoption

Ibrahim, A., Hamdy, K., & Badawy, M. (2023). Overall barriers to the prefabricated construction industry: a Fuzzy-SEM. *Research Square (Research Square)*. https://doi.org/10.21203/rs.3.rs-3487126/v1

INFINITE: Infinite Building Renovation - Industrialised Envelope Solutions. (2023). Retrieved from https://infinitebuildingrenovation.eu/

Katsigiannis, E., Gerogiannis, P., Atsonios, I., Manolitsis, A., & Founti, M. (2023). SmartWall. *Journal of Façade Design and Engineering*, *11*(2), 029–050. https://doi.org/10.47982/jfde.2023.2.t2

Konstantinou, T., & Heesbeen, C. (2022). Industrialized renovation of the building envelope: realizing the potential to decarbonize the European building stock. In *Elsevier eBooks* (pp. 257–283). https://doi.org/10.1016/b978-0-12-822477-9.00008-5

Lassandro, P., Devitofrancesco, A., Bellazzi, A., Cascardi, A., De Aloysio, G., Laghi, L., & Malvezzi, R. (2023). Facing the constraints to the deep energy renovation process of residential built stock in European markets. *Sustainability*, *16*(1), 294. https://doi.org/10.3390/su16010294

Legnattivo. (2019, January 1). Retrieved from https://www.eurac.edu/it/institutes-centers/istituto-per-le-energie-rinnovabili/projects/legnattivo

Lihtmaa, L., & Kalamees, T. (2023a). Emerging renovation strategies and technical solutions for mass-construction of residential districts built after World War II in Europe. *Energy Strategy Reviews*, *51*, 101282. https://doi.org/10.1016/j.esr.2023.101282

Lihtmaa, L., & Kalamees, T. (2023b). Emerging renovation strategies and technical solutions for mass-construction of residential districts built after World War II in Europe. *Energy Strategy Reviews*, *51*, 101282. https://doi.org/10.1016/j.esr.2023.101282

Lu, W., Chen, K., Xue, F., & Pan, W. (2018). Searching for an optimal level of prefabrication in construction: An analytical framework. *Journal of Cleaner Production*, *201*, 236–245. https://doi.org/10.1016/j.jclepro.2018.07.319

Lu, W., Lee, W. M., Xue, F., & Xu, J. (2021). Revisiting the effects of prefabrication on construction waste minimization: A quantitative study using bigger data. *Resources Conservation and Recycling*, *170*, 105579. https://doi.org/10.1016/j.resconrec.2021.105579

Manual deconstruction and dismantling activities. (2024). Retrieved from https://www.baukarussell.at/wp-content/uploads/2023/12/BauKarussell_FAQs_re-use-of-building-components.pdf

Manzoor, B., Charef, R., Antwi-Afari, M. F., Alotaibi, K. S., & Harirchian, E. (2025). Revolutionizing Construction Safety: Unveiling the digital potential of Building Information Modeling (BIM). *Buildings*, *15*(5), 828. https://doi.org/10.3390/buildings15050828

Manzoor, B., Othman, I., & Pomares, J. C. (2021). Digital Technologies in the Architecture, Engineering and Construction (AEC) Industry—A Bibliometric—Qualitative Literature Review of Research activities. *International Journal of Environmental Research and Public Health*, *18*(11), 6135. https://doi.org/10.3390/ijerph18116135

Metabuild GmbH. (2025, January 29). About us | Metabuild. Retrieved from https://www.metabuild.de/en/about-us/

Navaratnam, S., Satheeskumar, A., Zhang, G., Nguyen, K., Venkatesan, S., & Poologanathan, K. (2022a). The challenges confronting the growth of sustainable prefabricated building construction in Australia: Construction industry views. *Journal of Building Engineering*, *48*, 103935. https://doi.org/10.1016/j.jobe.2021.103935

Navaratnam, S., Satheeskumar, A., Zhang, G., Nguyen, K., Venkatesan, S., & Poologanathan, K. (2022b). The challenges confronting the growth of sustainable prefabricated building construction in Australia: Construction industry views. *Journal of Building Engineering*, *48*, 103935. https://doi.org/10.1016/j.jobe.2021.103935

Nußholz, J. L., Rasmussen, F. N., Whalen, K., & Plepys, A. (2019). Material reuse in buildings: Implications of a circular business model for sustainable value creation. *Journal of Cleaner Production*, *245*, 118546. https://doi.org/10.1016/j.jclepro.2019.118546

Ofori-Kuragu, J. K., Osei-Kyei, R., & Wanigarathna, N. (2022). Offsite Construction Methods—What We Learned from the UK Housing Sector. *Infrastructures*, *7*(12), 164. https://doi.org/10.3390/infrastructures7120164

P2Endure | PLUG & PLAY SOLUTIONS. (2020). Retrieved from https://www.p2endure-project.eu/en/demonstration/plug-play-solutions

Paoletti, G., Lollini, R., & Mahlknecht, H. (2013). Nearly zero energy target integration in public design tenders. *Proceedings of the Sustainable Building Conference 2013* (November 2013, Vol. ISBN: 978-3-85125-301-6). Verl. der Techn. Univ. Graz. https://doi.org/10.3217/978-3-85125-301-6

Precept. (n.d.). Retrieved November 11, 2023, from https://www.precept-project.eu/

RCD. (2023). Retrieved from https://security.five.es/Identity/Account/Login?ReturnUrl=%2Fconnect%2Fauthorize%3Fclient_id%3D50C94F0D0265919FFA5841C4DA78195F.iveapps%26redirect_uri%3Dhttps%253A%252F%252Fgrcd.f-ive.es%252Flogin%252Fcallback%26response_type%3Dcode%26scope%3Dopenid%2520profile%2520roles%2520offline_access%26state%3D50924cdcb4d44ce7a5485662ec64f9b8%26code_challenge%3DtnJYFciSm2zXd0EccEA_GDpOyX0Ya6Vz-kvlMc4n8_Nw%26code_challenge_method%3DS256%26response_mode%3Dquery

RE onsite. (n.d.). Retrieved from https://www.demobv.nl/en/re-suite/re-onsite

RE suite. (n.d.). Retrieved October 16, 2023, from https://www.demobv.nl/en/re-suite

RE10 | IVE. (2023). Retrieved from https://www.five.es/project/re10/

Renovate Europe. (2023, March 15). Renovation Wave: revision of EPBD and EED - Renovate Europe. Retrieved from https://www.renovate-europe.eu/renovation-wave/

Renovation wave. (2020). Retrieved from https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/renovation-wave_en

REPowerEU. (2022, May 18). Retrieved from https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en

Research, I., & Research, I. (2024, December 14). EUROPE PREFABRICATED CONSTRUCTION MARKET FORECAST 2023-2032. Retrieved from https://www.inkwoodresearch.com/reports/europe-prefabricated-construction-market/?srsltid=AfmBOorE-hVFX_WlkXjeDBrB6I3nzL2lN-PhBDrt_YNDbCQ2_8Ndcp1Jc

Rocha, P. F., Ferreira, N. O., Pimenta, F., & Pereira, N. B. (2022). Impacts of prefabrication in the building construction industry. *Encyclopedia*, *3*(1), 28–45. https://doi.org/10.3390/encyclopedia3010003

Rocha, P. F., Ferreira, N. O., Pimenta, F., & Pereira, N. B. (2022c). Impacts of prefabrication in the building construction industry. *Encyclopedia*, *3*(1), 28–45. https://doi.org/10.3390/encyclopedia3010003

Sandak, A., & Sandak, J. (2020). Aesthetics in architecture. Retrieved from https://bregroup.com/insights/aesthetics-in-architecture-beauty-and-design-inspiring-each-other#:~:text=The%20aesthetics%20of%20a%20building,%2C%20decoration%2C%20culture%20and%20context.

Sebastiani, I., D'Amore, S., Pinotti, R., & Pampanin, S. (2024). Integrated rehabilitation of reinforced concrete buildings: Combining seismic retrofit by means of low-damage exoskeleton and energy refurbishment using multi-functional prefabricated façade. *Journal of Building Engineering*, *95*, 110368. https://doi.org/10.1016/j.jobe.2024.110368

Shahpari, M., Saradj, F. M., Pishvaee, M. S., & Piri, S. (2019). Assessing the productivity of prefabricated and in-situ construction systems using hybrid multi-criteria decision making method. *Journal of Building Engineering*, *27*, 100979. https://doi.org/10.1016/j.jobe.2019.100979

Smart technologies. (2021). Retrieved from https://www.cultural-e.eu/technologies/

Solar window block. (2023). Retrieved from https://www.energymatching.eu/energymatching-solutions/window-block/

Steinhardt, D. A., & Manley, K. (2016). Adoption of prefabricated housing–the role of country context. *Sustainable Cities and Society*, *22*, 126–135. https://doi.org/10.1016/j.scs.2016.02.008

Sutkowska, M., Stefańska, A., Vaverkova, M. D., Dixit, S., & Thakur, A. (2024). Recent advances in prefabrication techniques for biobased materials towards a Low-Carbon future: From modules to sustainability. *Journal of Building Engineering*, *91*, 109558. https://doi.org/10.1016/j.jobe.2024.109558

Taherdoost, H. (2018). A review of technology acceptance and adoption models and theories. *Procedia Manufacturing*, *22*, 960–967. https://doi.org/10.1016/j.promfg.2018.03.137

Tavares, V., Gregory, J., Kirchain, R., & Freire, F. (2021). What is the potential for prefabricated buildings to decrease costs and contribute to meeting EU environmental targets? *Building and Environment*, *206*, 108382. https://doi.org/10.1016/j.buildenv.2021.108382

Tavares, V., Soares, N., Raposo, N., Marques, P., & Freire, F. (2021). Prefabricated versus conventional construction: Comparing life-cycle impacts of alternative structural materials. *Journal of Building Engineering*, *41*, 102705. https://doi.org/10.1016/j.jobe.2021.102705

Wang, M., Wang, C. C., Sepasgozar, S., & Zlatanova, S. (2020). A Systematic Review of Digital Technology Adoption in Off-Site Construction: Current Status and Future Direction towards Industry 4.0. *Buildings*, 10(11), 204. https://doi.org/10.3390/buildings10110204

Zhou, Z., Syamsunur, D., Wang, L., & Nugraheni, F. (2024). Identification of Impeding Factors in Utilising Prefabrication during Lifecycle of Construction Projects: An Extensive Literature Review. *Buildings*, 14(6), 1764. https://doi.org/10.3390/buildings14061764

7 APPENDIX A

Table 4 reports the Best Practices collected, divided by solution type (category and main topic), name, brief description, EU projects, in-house products, and source.

TABLE 4 Level of interesting solutions for each Ecosystem: very suitable (xxx), moderately suitable(xx), potentially suitable(x), and not suitable.

Category	Main topic	Title	Brief description	Project	Source
Guidelines, methodologies	**End of Life**	Manual deconstruction and dismantling activities	Understanding of the added value of the different approach in planning the deconstruction phase.	Social Urban Mining	("Manual Deconstruction and Dismantling Activities," 2024)
	Energy and IEQ Performance Evaluation	Repository of results for performance evaluation	A set of simulations in six European geoclusters applying several renovation packages (always including the prefabricated façade for retrofit) to evaluate the performance of the building after renovation.	4RinEU	("Deep Renovation Packages", 2020)
Solutions and Technologies	**Advanced window**	Smart Window kit	Prefabricated wooden façades with integrated technologies that include green façades, mechanical ventilation units, BIPV, BIST, and smart windows with shading systems controlled by integrated sensors in the DGU.	Infinite	("INFINITE",2023)
		Solar Window Block	An autonomous, multifunctional, and prefabricated window system that integrates an insulating frame, a highly efficient window, a PV module, a shading system, and a decentralised ventilation machine.	Energy-Matching	("Solar Window Block", 2023)
		Active Window System	A modular timber frame system, movable adaptive shading system, integrated decentralized ventilation device, and the interaction between shading, semi-ventilated cavity, and decentralised ventilation device, to exploit the shading cavity ventilation for optimising indoor air quality and energy consumption.	CulturalE	("Smart Technologies", 2021)
		BGTEC smart windows	Smart window with rotating and locking mechanisms that enhance anti-burglary features, with fully integrated electromagnetic locking fully integrated into the frame.	P2ENDURE	("P2Endure | PLUG & PLAY SOLUTIONS", 2020)
	Window – Balcony	Bloomframe® folding balcony	A window-balcony applicable both in new and existing buildings, especially where a regular balcony is not possible or not allowed.	P2ENDURE	("Bloomframe", 2022)
	Innovative Plaster	3D printing and robotics	3D printing is primarily used to create plastering with a special limestone material on concrete walls, ventilation ducts, or water pipes. It provides 3D exterior finishing in combination with painting.	P2ENDURE	("P2Endure | PLUG & PLAY SOLUTIONS", 2020)
	Prefabricated Envelope	Modular prefabricated timber façade	A multifunctional timber façade aiming at a quick installation process for building renovation.	Legnattivo	(Sebastiani, D'Amore, Pinotti, & Pampanin, 2024)
		Multifunctional Prefabricated timber façade	A timber frame multifunctional façade for building retrofit, integrating a ventilation machine, new windows, new shadings, and insulation.	4RinEU	("Demo Cases", 2021)
		Modular prefabricated timber façade	Prefabricated wooden façades with integrated technologies that include green façades, mechanical ventilation units, BIPV, BIST, and smart windows with shading systems controlled by integrated sensors in the DGU.	Infinite	("INFINITE", 2023)
		EASEE Concrete Prefabricated Panel	Two layers of Textile Reinforced Concrete (1.2 cm each) and an insulation core between them made of expanded polystyrene (10 cm) for high thermal performance and high adaptability.	P2ENDURE	("P2Endure | PLUG & PLAY SOLUTIONS", 2020)

Category	Main topic	Title	Brief description	Project	Source
Solutions and Technologies	**Prefabricated Envelope**	PnPprefabH-VACsystems	Air heat pump, storage capacity for domestic hot water (DHW), mechanical ventilation system, expansion barrel, and control systems. The application of smart connectors significantly reduces the on-site mounting time.	P2ENDURE	("P2Endure | PLUG & PLAY SOLUTIONS", 2020)
		Energy storage	Compact seasonal storage system based on novel high-density materials that can supply required heating, cooling, and domestic hot water (DHW) with up to 100% RES.	P2ENDURE	("P2Endure | PLUG & PLAY SOLUTIONS", 2020)
		Microheatpumps façade integrated	Micro heat pumps for gas-phase Out in multi-storey residential buildings within prefabricated façades.	PhaseOUT	
		Prefabricated façade	Prefabricated façade elements with integrated external wall heating and PV.	EXCESS	("EXCESS", 2022)
		Prefabricated façade	Energy active, serial, and multifunctional building envelope elements (Project started in early 2023).	RENVELOPE	
	Monitoring system	aBMS ADAPTABLE BMS	Prefabricated wooden façades with integrated technologies that include green façades, mechanical ventilation units, BIPV, BIST, and smart windows with shading systems controlled by integrated sensors in the DGU.	Infinite	("INFINITE", 2023)
		Monitoring system	Environmental and structural monitoring systems, embedded in prefabricated structural elements.	BUILT2SPEC	("Built2Spec", n.d.)
	Innovative insu-lation-structural panels	Prefab panels composed of two layers of Textile Reinforced Concrete	Prefab panels composed of two layers of Textile Reinforced Concrete and an insulation core between them made of expanded polystyrene	P2ENDURE	("P2Endure | PLUG & PLAY SOLUTIONS", 2020) https://www.p2endure-project.eu/en/demonstration/plug-play-solutions
	Building enhancement	PAN rooftop retrofitting extension module	A flat roof is renovated to new-build standards with the option of individual improvements, such as an extra skylight or your own energy generation.	P2ENDURE	("P2Endure | PLUG & PLAY SOLUTIONS", 2020)
		Edible Balcony gardens for Retrofit - Vertical Greening technology for the city	Edible balcony gardens for retrofit aim to reduce heat-island effects and buffer rainwater peaks during heavy rain events, improving the renovation by greening measures on existing buildings. The ESSBAR project addresses these problems and essential objectives of the tender and aims to demonstrate an affordable, resource-saving and innovative greening solution with edible plants on the vertical surfaces of existing buildings focusing on people's needs for green open space.	ESSBAR	("ESSBAR",2023)
Digital technology	**Life Cycle assessment (Cost / Environ-mental impact/ End-of-Life)**	Life Cycle Cost Façade tool	An LCC tool especially designed to compare façade solutions.	Legnattivo	("Legnattivo2, 2019)
		BIM platform	BIM platform where the building's geometric model is uploaded, and different tools for LCC, LCA, Energy and PV, O&M, and Installation can be accessed.	Infinite	("INFINITE", 2023)
		End of Life tool	End of Life (EoL) tool developed to analyse the waste management plan of the different components and materials included in the technologies developed within the project.	Energy-Matching	

Category	Main topic	Title	Brief description	Project	Source
Digital technology	**Life Cycle assessment (Cost / Environmental impact/ End-of-Life)**	One Stop Access Platform (OSAP)	A set of easy-to-use tools and services for fast and adaptable renovation processes. Data collection, data management (using extended BIM capacities), data-driven design (e.g., indicative primary energy consumption of a real building based on pre-simulated reference models, environmental sustainability tracker, and BIM-based LCA/LCC, automatic BIM from 2D plans).	BIM4REN	("Bim4Ren", 2022)
		Disassembly and adaptability (DfD/A) analysis tool.	The tool analyses each of the twelve criteria set out in the ISO 20887:2020 standard (Versatility, Convertibility, Expandability, Ease of access to components and services, Independence, Reversible connections, Avoidance of unnecessary treatments and finishes, Support for circular economy, Simplicity, Standardisation, Safety when dismantling, Durability), adapting them to residential building renovation.	RE10	("RE10 | IVE", 2023)
		Construction and demolition waste management	The tool generates a document including the estimated measurements of construction waste generated, the specific technical prescriptions for on-site waste management operations, and an economic estimate of these operations.	RCDs Tool	("RCD", 2023)
		RE LCC	BIM-based LCC calculation where open-source files, such as IFC, are required for geometry data extraction, and, with a connection to a cost database, the LCC calculation can be performed for different time periods and different user-defined parameters.	RE Suit	("Building Management", 2023)
	Energy and IEQ Performance Evaluation	PV system platform	Energy Matching Platform. The tool suggests preliminary configurations for the PV system (the capacity and position of the photovoltaic modules, plus the capacity of the electric storage).	Energy-Matching	("Energy Matching Platform", 2021)
		BIM construction solution catalogue	Online application that offers a wide range of construction solutions (façades, roofs, floors, walls, partitions, windows), providing information on their thermal, acoustic, waterproofing, fire protection, etc. performance.	BIM catalogue	("Catalogue of Constructive Elements", 2022)
		Digital twin platform (with 6D BIM model) Building energy performance simulation (BEPS) tools into the BIM platform	A building energy modelling integration into BIM models alongside real-time integration of actual energy performance of the building into a digital model. Data-driven decision making for renovation.	PRECEPT	("Precept", n.d.)
		Open BIM analytical model	Open BIM analytical model is a tool that develops analytical models for thermal and acoustic simulations. It includes options that allow an analytical model to be created directly within the program or automatically generated from BIM models in IFC format.	BIM-SPEED	("CYPE Software", 2024)
		Megabuilding Optimization Tool	AI technology that enables real estate professionals to create better buildings. Based on BIM and building simulations, we explore billions of possible scenarios for each project.	BIM-SPEED	("Metabuild GmbH", 2025)
		RE Energy tool	The tool provides all the essential features to utilise and exploit the benefits of energy-related building information. It allows corporations, housing managers, and consultants to efficiently monitor the energy performance of real estate and acquire/manage energy performance certificates.	RE Suit	("RE Suite," n.d.)
		Comfort Eye	The Comfort eye enables the assessment of thermal comfort and air quality to support residential renovation projects.	BIM-SPEED	

Category	Main topic	Title	Brief description	Project	Source
Digital technology	Energy and IEQ Performance Evaluation	3DASH tool is a plug-in for REVIT	The "3DASH tool" (3D Automatic Surfaces Handling - REVIT plug-in) automatically detects and creates BIM entities (walls for now) from 3D point clouds (PTX, PTS, PLY formats) acquired by laser scanning or photogrammetry systems.	BIM-SPEED	("3DASH Tool", 2020)
	Building site management	Online BIM viewer	Integrated online WebGL viewer for making BIM models available on-site, to access BIM info from the construction site.	BUILT2SPEC	("Built2Spec", n.d.)
		RE Onsite	An app to collect data on existing buildings from inhabitants. The application can be used by anyone involved in a renovation project who needs to collect data on existing buildings to perform needed analysis.	RE Suit	("RE Onsite", n.d.)
		RE Asset Management and RE Maintenance	The tool allows parties to monitor the management process clearly, efficiently, and in real-time. Inspection and surveys can be performed objectively by sending digital data directly from the site without any paperwork in between.	RE Suit	("Building Management", n.d.)

8 APPENDIX B

Technical requirements checklists of different products.

TABLE 5 Technical requirements checklist for prefabricated façades modules.

Prefabricated Façade			
Very important	**Façade feature**	Dimension of the façade	5
		Co-planar façade geometry (e.g., simple façade geometry)	5
	Surroundings	Possibility of crane access from the street	5
		Free space between the façade and the façade of the opposite building	5
	Regulations (national, local)	Fire	5
		Seismic	5
Important	**Homeowners**	Information and clear communication	4
	Building general information	Year of construction of the building	4
		NO monumental protection: If the building is not under heritage protection.	4
		NO colour restrictions in architectonic elements, such as façades, roofs	4
	Building features	Renovation size: number of m^2 renovated (façades, roof) or number of elements (e.g., windows)	4
		Structural type: Material and structure (wall, pillars).	4
		Structural capacities of the existing building.	4
	Façade feature	Façade height: e.g., free height from street level	4
		Presence of insulation	4
	Windows features	Number of windows to renovate (is there a minimum number of windows to renovate?)	4
		Openings layout: distribution and variety/regular size of openings.	4
		Openings size: Window sizes.	4
	Process management	Training and expertise, knowledge	4
		Coordination between different actors (constructor, designer)	4
Moderately important	**Homeowners**	Coordination with occupants	3
	Building general information	Property Ownership: Single owner or multi-property.	3
	Building features	Number of Floors	3
		Dwelling Surface (m2)	3
		Building height: e.g., free height from street level	3
	Façade feature	Façade construction system: type of construction/material	3
		Presence of balconies, terraces, or other elements	3
		Façade finish: type of external finish	3
	Regulations (national, local)	Energy efficiency and RES use	3
		Waste redaction	3
		Circularity	3
		Water use restrictions	3
		Energy sharing/energy community's legislation	3
		Labour	3
	Process management	Data monitoring	3

TABLE 6 Technical requirements checklist for smart-advanced windows.

Smart-advanced windows			
Moderately important	Homeowners	Coordination with occupants	3
		Information and clear communication	3
	Building general information	NO monumental protection: If the building is not under heritage protection.	3
	Windows features	Number of windows to renovate (is there a minimum number of windows to renovate?)	3
	Surroundings	Possibility to install scaffolding	3
	Process management	Training and expertise, knowledge	3
Less Important	Building general information	Property Ownership: Single owner or multi-property.	2
		Housing tenure: owned or rented	2
		Building use: residential, tertiary, sanitary, sports, etc.	2
		Building typology: SFH (Single Family House) / MFH (Multi Family House)	2
		Year of construction of the building	2
	Building features	Number of floors	2
		Structural type: material and structure (wall, pillars).	2
	Façade feature	Co-planar façade geometry (e.g., simple façade geometry)	2
	Windows features	Opening layout: distribution and variety/regular size of openings.	2
		Opening size: window sizes	2
	Surroundings	Façade orientation	2
		Shadows (on the façade/roof/windows)	2
		Possibility of crane access from the street	2
	Regulations (national, local)	Fire	2
		Energy efficiency and RES use	2
	Process management	Coordination between different actors (constructors, designers)	2

TABLE 7 Technical requirements checklist for prefabricated balconies.

Prefabricated Balcony			
Moderately important	Homeowners	Coordination with occupants	3
		Information and clear communication	3
	Building general information	Year of construction of the building	3
		NO monumental protection: If the building is not under heritage protection.	3
	Façade feature	Façade construction system: type of construction/material	3
		Presence of balconies, terraces, or other elements	3
	Windows features	Number of windows to renovate (is there a minimum number of windows to renovate?)	3
Less Important	Building general information	Property ownership: single owner or multi-property.	2
		Building use: residential, tertiary, sanitary, sports, etc.	2
	Building features	Building height: e.g., free height from street level	2
		Renovation size: number of m^2 renovated (façades, roof) or number of elements (e.g., windows)	2
	Façade feature	Façade height: e.g., free height from street level	2
		Co-planar façade geometry (e.g., simple façade geometry)	2
	Windows features	Opening size: window sizes	2
	Surroundings	Possibility of soil connection next to the façade	2

TABLE 8 Technical requirements checklist for prefabricated modular roof systems.

Prefabricated modular roof systems			
Very important	Roof features	Roof type: flat or sloping	5
Important	Homeowners	Information and clear communication	4
	General information	Year of construction of the building	4
		NO monumental protection: If the building is not under heritage protection.	4
	Roof features	Roof size: dimensions (x or m^2)	4
		Roof construction system: type of construction	4
		Shading and obstacles (chimney, antennas)	4
	Regulations (national, local)	Fire	4
	Regulations (national, local)	Seismic	4
Moderately important	Homeowners	Coordination with occupants	3
	General information	Property ownership: single owner or multi-property.	3
		Building use: residential, tertiary, sanitary, sports, etc.	3
		NO colour restrictions in architectonic elements, such as façades, roof	3
	Building features	Renovation size: number of m^2 renovated (façades, roof) or number of elements (e.g., windows)	3
		Structural type: material and structure (wall, pillars)	3
		Structural capacities of the existing building	3
	Surroundings	Possibility of crane access from the street	3
	Process management	Training and expertise, knowledge	3
		Coordination between different actors (constructors, designers)	3

TABLE 9 Technical requirements checklist for modular heat pump systems.

Heat pump			
Important	Homeowners	Coordination with occupants	4
	Building General information	Property Ownership: Single owner or multi-property	4
		Building use: residential, tertiary, sanitary, sports, etc.	4
	Building systems	Electrical network: status of the home's electrical network, circuit separation.	4
		Heating/DHW System: individual or centralised.	4
		DHW System: type of domestic hot water system.	4
	Regulations (national, local)	Energy efficiency and RES use	4
Moderately important	Building systems	Existence of thermal or electrical storage systems	3
	Process management	Coordination between different actors (constructors, designers)	3

TABLE 10 Technical requirements checklist for modular HVAC system.

HVAC			
Important	Building General information	Property ownership: single owner or multi-property.	4
		Building use: residential, tertiary, sanitary, sports, etc.	4
	Building Systems	Electrical network: status of the home's electrical network, circuit separation	4
		HVAC system: type of heating, ventilation, and air conditioning system	4
	Process management	Training and expertise, knowledge	4
Moderately important	Homeowners	Coordination with occupants	3
		Information and clear communication	3
	Building general information	Housing tenure: owned or rented	3
	Building features	Technical room: existence and size	3
	Building Systems	Heating/DHW system: individual or centralised	3
		Existence of thermal or electrical storage systems	3
	Regulations (national, local)	Energy efficiency and RES use	3
	Process management	Coordination between different actors (constructors, designers)	3

TABLE 11 Technical requirements checklist for RES integration.

RES (as BIPV)			
Important	Homeowners	Information and clear communication	4
	Building Systems	Electrical network: status of the home's electrical network, circuit separation	4
	Surroundings	Façade orientation	4
	Regulations (national, local)	Energy efficiency and RES use	4
		Energy sharing/energy community's legislation	4
Moderately important	Homeowners	Coordination with occupants	3
	General information	Property ownership: Single owner or multi-property.	3
	Roof features	Roof type: flat or sloping	3
		Roof size: dimensions (x or m^2)	3
		Shading and obstacles (chimney, antennas)	3
	Surroundings	Shadows (on the façade/roof/windows)	3
	Process management	Data monitoring	3

TABLE 12 Technical requirements checklist for control systems integration.

Control systems			
Important	Building Homeowners	Information and clear communication	4
	Building Systems	Electrical network: status of the home's electrical network, circuit separation	4
	Regulations (national, local)	Energy sharing/energy community's legislation	4
	Process management	Data monitoring	4
Moderately important	Homeowners	Coordination with occupants	3
	Building general information	Property Ownership: Single owner or multi-property	3
	Building Systems	HVAC System: type of heating, ventilation, and air conditioning system	3
		Heating/DHW System: individual or centralised.	3

TABLE 13 Technical requirements checklist for monitoring system integration.

Monitoring systems			
Very Important		Information and clear communication	5
Moderately important	Homeowners	Information and clear communication	3
	Building general information	Property ownership: single owner or multi-property.	3
	Building Systems	Electrical network: status of the home's electrical network, circuit separation.	3
		HVAC system: type of heating, ventilation, and air conditioning system	3
		Energy sharing/energy community's legislation	3
	Process management	Training and expertise, knowledge	3
		Data monitoring	3
		Coordination between different actors (constructors, designers)	3

TABLE 14 Technical requirements checklist for building enhancements through prefabricated and industrialized 3D solutions..

Building enhancement			
Very Important	Homeowners	Coordination with occupants	5
Important	Homeowners	Information and clear communication	4
	Building general information	Property ownership: Single owner or multi-property.	4
Moderately important		NO monumental protection: If the build-ing is not under heritage protection.	3