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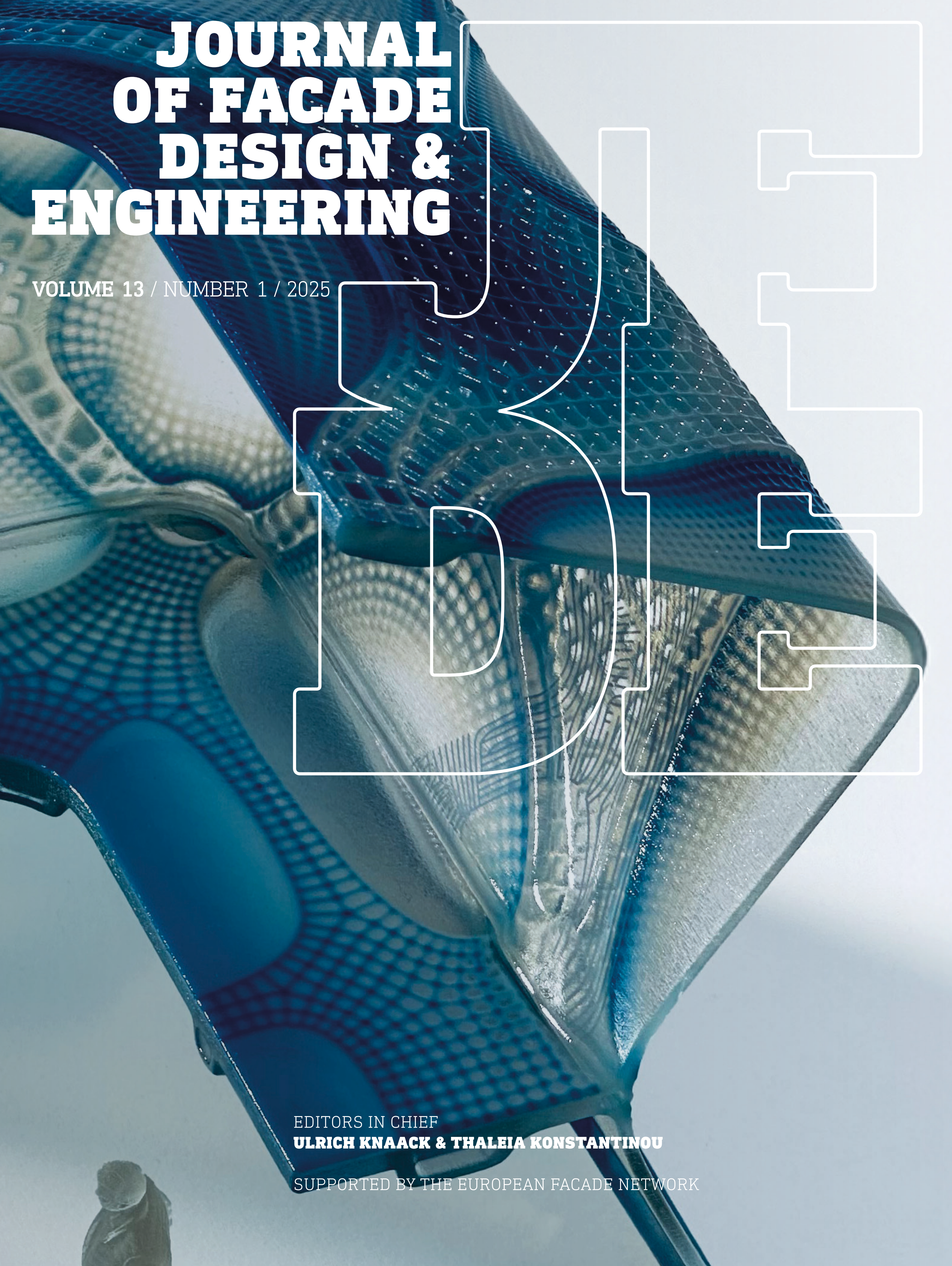

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Contents

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

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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

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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.

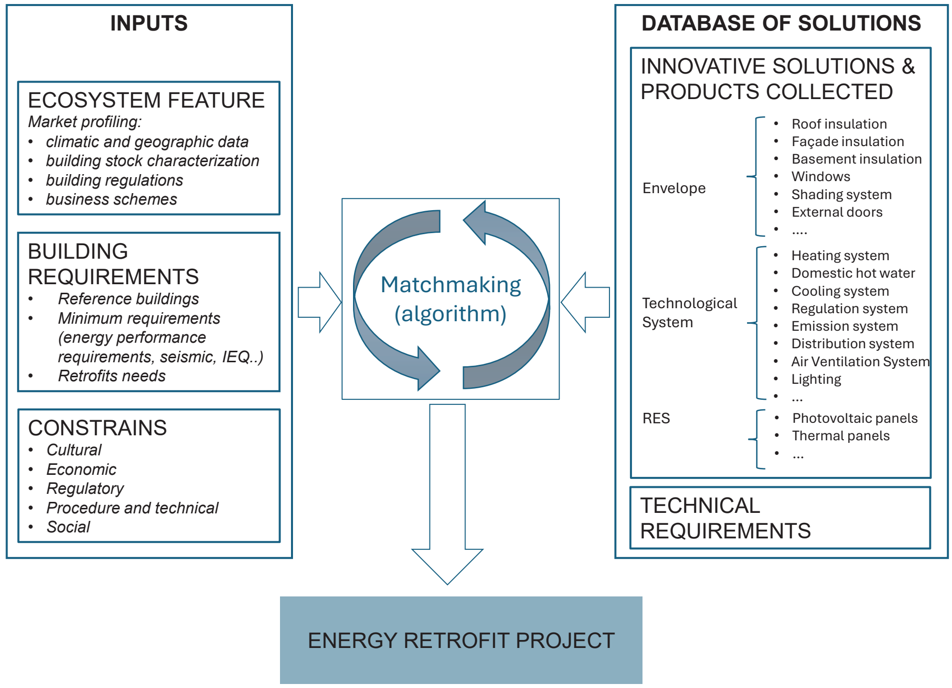

FIG. 1 Matchmaking process between databases of solutions (products/solutions) and Ecosystems (contexts, building retrofit requirements, and gaps)

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.

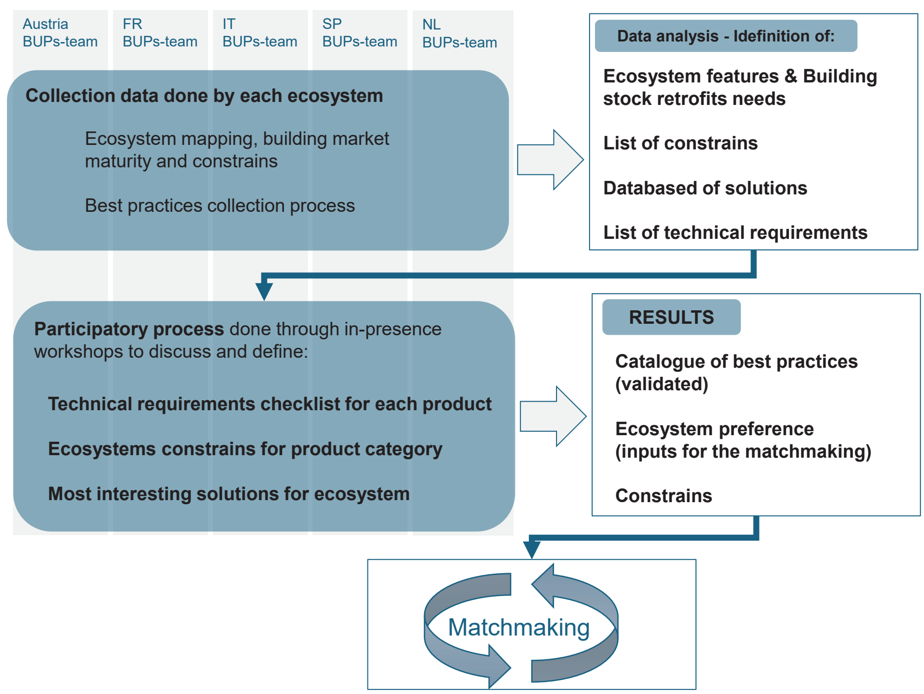

FIG. 2 Scheme of the methodology process.

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.

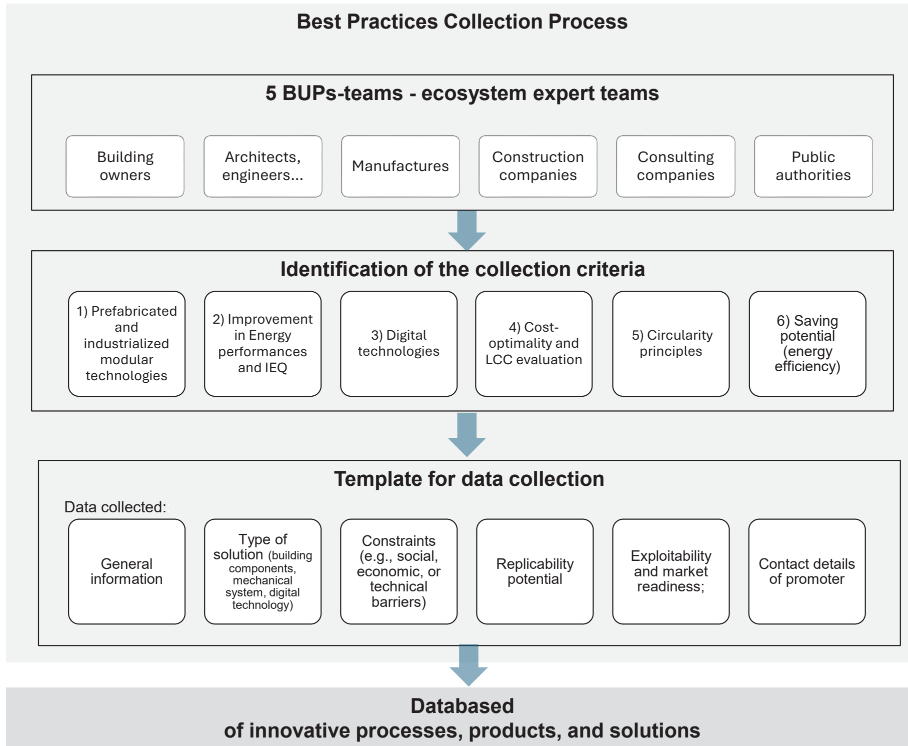

FIG. 3 Best Practices collection process, database of innovative solutions/products, and technical requirements.

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).

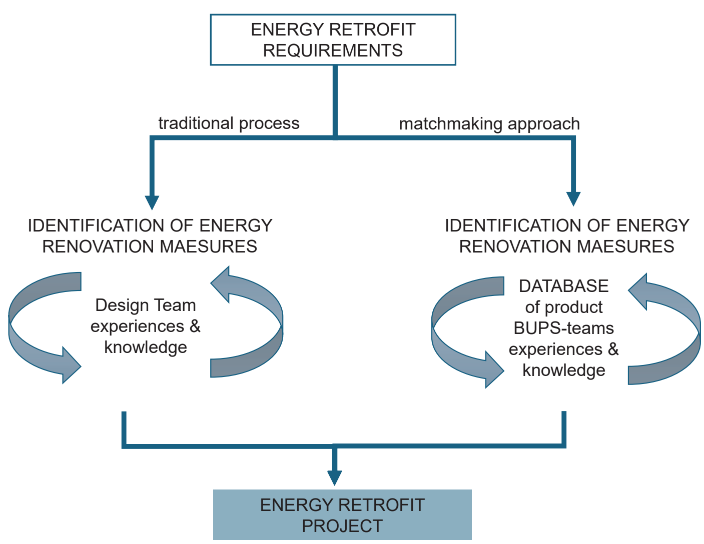

FIG. 4 Matchmaking approach - advantages from a large body of knowledge from a large number of building experts (as designers).

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)*".

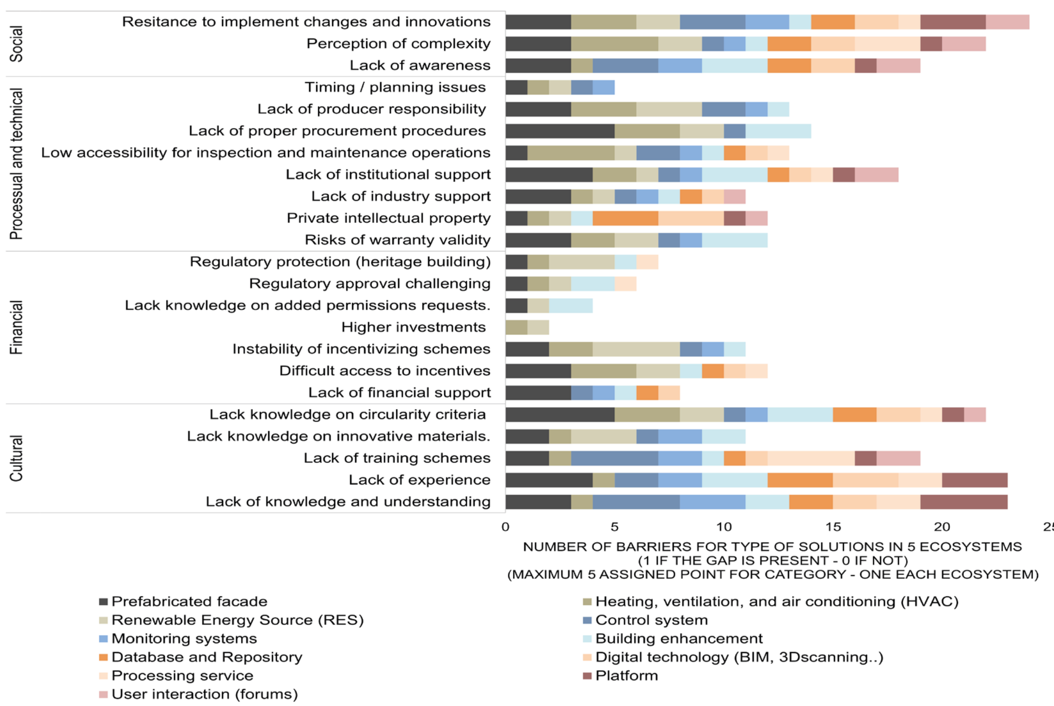

FIG. 5 Distribution of cultural, social, procedural, technical, and financial barriers for each solution category.

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.

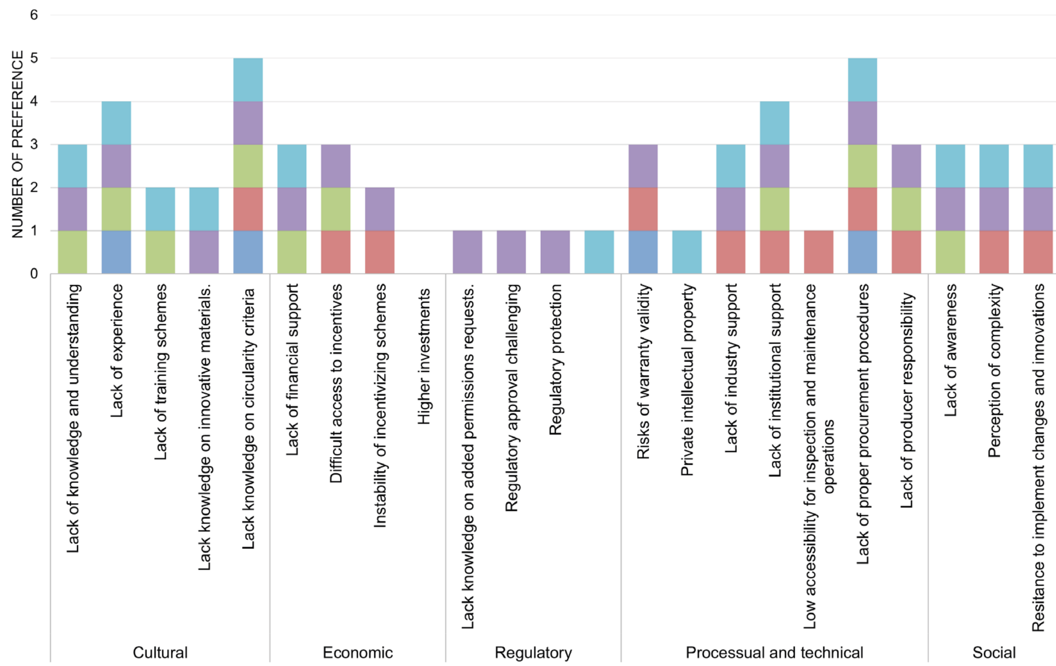

FIG. 6 Distribution of the barriers across the five Ecosystems (FR, NL, AT, IT, SP) for the "Prefabricated Modules for Façades" category.

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.

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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%3Fcli-ent_id%3D50C94F0D0265919FFA5841C4DA78195F.iveapps%26redirect_uri%3Dhttps%253A%252F%252Fgrcd.f-ive.es%252Flogin%252Fcallback%26response_type%3Dcode%26scope%3Dopenid%2520profile%2520roles%2520offline_ac-cess%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 insulation-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 / Environmental 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

Cost-Effective augmented reality tool for enhanced building envelope panel handling: installation and validation

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Abstract

As part of a project aimed at upgrading older, non-renovated buildings by retrofitting their envelopes to meet the European climate targets required by 2050, a low-cost Augmented Reality (AR) tool was developed to facilitate the renovation and maintenance process. Considering that the renovation process involves a large number of different panels, which are assembled like a large puzzle in the building using plug-and-play techniques, traceability remains a challenge. To facilitate the assembly of the panels, which contain digital information, and using AR techniques, the panels will be displayed on the real building in their final position.

In this way, AR tools will bridge the gap between digital information and the real-world environment, allowing users to visualise information about the position to be installed in the real place. Additionally, the tool will have the option to display further information (such as safety instructions or installation details) related to each panel, ensuring that workers have all necessary information on-site. Developed as a web-based Single Page Application (SPA) compatible with standard smartphones and tablets via WebXR, the tool eliminates the need for expensive hardware or software installations.

The tool demonstrates the feasibility of using a cost-effective AR solution to provide necessary information to on-site operators, as well as generating real-time Key Performance Indicators (KPIs) and alerts that managers can consult.

Keywords

Façade, Building Envelopes, Modular Construction, Installation, Verification, AR (Augmented reality), WebXR, Building Information Modelling (OpenBIM), SPA (Single page application)

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1 INTRODUCTION

The European decarbonisation strategy ("2050 Long-term Strategy," n.d.) is closely aligned with the objectives of building rehabilitation, highlighting the crucial role that envelopes play in achieving these goals. Furthermore, the strategy underscores the importance of industrialisation and prefabrication as key enablers of this transformation.

According to the European Commission, 85% of EU buildings were constructed before 2000, and 75% of them exhibit poor energy performance ("Energy Performance of Buildings Directive," n.d.). This fact underscores the urgent need for large-scale, efficient renovations to align the building stock with modern energy efficiency standards.

In this context, the use of prefabricated panels in building retrofits is gaining recognition for its ability to shorten construction times and enhance energy performance. Prefabrication offers multiple benefits, including reduced waste, minimised disruption to occupants, improved efficiency, faster installation, higher quality, increased safety, and greater sustainability. Numerous European case studies have demonstrated the success of this approach in retrofitting projects, highlighting best practices and effective implementation strategies (Callegaro & Albatici, 2023; Loebus, Ott, & Winter, 2014; Sousa et al., 2013). However, several persistent challenges hinder its optimal implementation.

To support the successful execution of panel-based retrofitting, it is essential to perform effective information management during the whole installation and subsequent validation process. The renovation must be carried out with reliable and detailed knowledge of the building to be renovated, along with a sound understanding of the desired result.

Prefabricated panels demand precise alignment and sequencing during installation. In retrofit scenarios—where existing structures may be irregular or poorly documented—this complexity increases the risk of misalignment, leading to costly rework and delays. While Xiao and Bhola (2021) do not focus specifically on retrofitting, they emphasise that the lack of standardised design processes and real-time feedback mechanisms in prefabricated systems often results in inefficiencies and coordination breakdowns.

Since prefabricated components can be manufactured off-site, it is essential to ensure accurate building measurements and precise data exchange between the design, manufacturing, and construction teams. This coordination requires a high degree of accuracy and attention to detail, particularly during the on-site assembly process, to guarantee a seamless fit and ensure that the prefabricated modules meet the required specifications. Li et al. (2023) also state: "We can only significantly improve the construction process and reduce loss and waste if information is shared throughout the design, manufacture, transportation, assembly, construction, and maintenance phases" (p. 3).

The use of Building Information Modelling (BIM) technology has rapidly expanded among AECO (Architecture, Engineering, Construction, and Operations) professionals. However, it remains primarily focused on new designs and faces several challenges, including high equipment and software costs (Azhar, 2024). BIM is used in façade renovation to ensure accurate data flow as it creates a centralised, accurate, and continuously updated model that all stakeholders can access and rely on. In complex renovation projects, information often comes from multiple sources, such as architectural surveys, engineering analyses, and construction site reports. Without a structured system, this data can easily become fragmented, outdated, or inconsistent. BIM provides a solution by integrating all information into a single environment where changes are automatically updated across the model. This ensures that architects, engineers, contractors, and project managers are always working with the latest and most accurate data. As a result, decisions can be made confidently, errors are reduced, and coordination between disciplines becomes smoother. Ultimately, using BIM to manage data flow prevents misunderstandings, rework, and delays, thereby making the renovation process more reliable and efficient.

The versatility of BIM extends beyond renovation projects, offering significant advantages in other construction domains such as modular construction. In this context, Pan and Zhang (2023) argue that integrating BIM with AI and real-time data analytics is crucial for managing the complexity of modular construction. They highlight that event log mining and real-time alerts enable proactive decision-making, which is otherwise hindered by the reactive nature of traditional monitoring systems. "Without real-time data and alerts, managers are unable to make timely decisions, which can lead to inefficiencies, delays, and increased risk" (Pan & Zhang, 2023, p. 1092).

In prefabricated construction, workers often face challenges interpreting digital models or understanding complex installation sequences, especially when they lack prior experience with BIM or AR technologies. According to Azhar (2011), Building Information Modeling (BIM) significantly enhances understanding by allowing users to visualise construction processes in a simulated environment. This not only reduces the need for extensive training but also helps bridge the skill gap between experienced professionals and newer workers, making it easier for them to perform complex tasks accurately and confidently."BIM enables visualisation of construction processes, which enhances understanding and reduces the need for extensive training" (Azhar, 2011, p. 245).

Li and Wu (2021) argue that traditional safety and management systems are insufficient for prefabricated construction due to the shift from on-site casting to off-site manufacturing and on-site hoisting. They emphasise that real-time monitoring of transportation, stacking, and installation is essential to prevent safety incidents and ensure workflow efficiency. The authors propose a BIM-RFID-based system to provide real-time updates and alerts, enabling managers to respond proactively to issues as they arise.

The integration of BIM with complementary technologies is transforming how information is managed and delivered across the construction lifecycle. While BIM ensures centralised and accurate data flow, its full potential is realised when combined with tools like RFID, augmented reality (AR), and artificial intelligence (AI). These integrations address the critical challenge of making complex digital information accessible and actionable on-site.

However, despite these advancements, a significant hurdle remains: effectively delivering BIM-based information to the workplace in a format that is both simple and intuitive. To truly empower on-site personnel, there is a pressing need for systems that can translate detailed digital models into clear, actionable guidance, conveying installation procedures, safety instructions, technical specifications, and final positioning of prefabricated modules in a user-friendly manner.

In this context, the main contribution of the research lies in the creation of a low-cost AR tool for use in the construction field, which guarantees both the reliability of the data presented to the operator and the integration of data generated during its use. To achieve this, the tool overlays digital elements onto the real-world view, providing users with contextual, real-time information about the construction site. This reduces reliance on plans and photographs and enables operators to work more efficiently and safely. BIM model integration is a mandatory requirement to maintain data consistency and comply with various EU standards, such as the EU Directive 2014/24/EU (European Parliament and Council, 2014). The choice of a low-cost device as the platform for demonstrating the tool stems from the goal of making it as affordable as possible, encouraging widespread market adoption.

The objective of this research is to develop a low-cost AR tool to assist in the installation and verification of building envelope panels. Despite its low cost, the tool includes a full suite of augmented reality (AR) capabilities. These include real-time 3D model overlay onto the physical environment, spatial anchoring, interactive data display, and dynamic alignment aids to ensure accurate panel positioning. This tool should deliver detailed information about the panels (safety guidelines, instructions) and display the final placement of the panels on the actual building using AR. The tool will offer three primary features:

- AR-guided installation support: The tool enables operators to visualise the exact final position of each panel directly on the building through augmented reality. By overlaying digital panel models onto the physical structure in real time, the system helps installers align and place components accurately. This reduces reliance on printed plans or manual measurements and minimises the risk of installation errors.
- Real-time data capture and alert generation: During installation, the tool captures status updates and generates alerts based on operator input (e.g., panel accepted or rejected). This information is instantly synchronised with the central system, ensuring that managers receive up-to-date insights from the field.
- KPI monitoring and progress tracking: Managers can access a dashboard that displays key performance indicators such as the number of panels installed, verified, or rejected, along with real-time alerts. This supports informed decision-making and project oversight.

The primary advantage of the tool is its remarkable accessibility, enabling users to operate it without investing in expensive hardware or relying on proprietary data formats. The tool is designed to function on consumer-grade devices such as smartphones or tablets, making the technology widely usable without specialised AR headsets. This accessibility promotes broader adoption and supports more inclusive digitalisation across the construction sector, contributing to efficiency, safety, and sustainability goals. This ensures that even small and medium-sized enterprises can benefit from advanced digital construction technologies without incurring prohibitive costs.

2 STATE OF THE ART AND INNOVATION

AR is increasingly transforming the construction industry by enabling the overlay of digital models onto physical environments. This capability not only enhances real-time visualisation but also facilitates more efficient decision-making on the job site. As Nassereddine et al. said:

> "Respondents were asked to elaborate on their experience and use of the technology and they frequently reported that AR improves project visualisation by allowing owners and contractors to virtually walk through the project, supports decision making on-site by bridging the gap between office and field…". (Nassereddine et al., 2022, p. 11)

In order to make use of the AR, a physical device with the necessary capabilities is required. These devices are currently divided into two types: Head-Mounted Displays (HMDs) and mobile devices. Both vary in cost and performance. HMDs are more expensive due to their specialised technology, including advanced displays, sensors, and processing power. Mobile devices, on the other hand, are more affordable, offering sufficient performance for basic AR tasks, with high-end models providing enhanced features for smoother, more accurate experiences.

HMDs offer a more immersive experience and even allow users to remain hands-free; however, their shorter battery life and ergonomic issues (which may even prevent the use of Personal Protective Equipment (PPE)) make them difficult to use in construction environments. In addition, due to their cost and limited compatibility, their adoption is not widespread, reflecting the current reluctance among construction companies to utilise them (Bressan, Scarpa, & Peron, 2024).

Continuing the focus on HMDs, Dallasega, Schulze, and Revolti (2022) analyse whether AR can overcome the barriers to implementing visual management (VM) in mechanical, electrical, and plumbing (MEP) construction project markup work. As a case study, they performed a MEP installation in a multi-story apartment building, utilising an augmented reality helmet (HMD) to support the marking work. The results showed that the AR can save time and leads to satisfactory levels of accuracy, as well as reducing training effort and resistance to the implementation of VM. The hardware used consists of a high-cost HMD device for use in AR in the construction field. Rankohi et al. (2023) go even further, offering in their book *Applications of Augmented Reality - Current State of the Art*, a review of AR technologies and their applications in architectural, engineering, and construction (AEC) projects. It discusses the challenges of applying AR in these types of projects and includes a case study on the application of AR in a manufacturing plant in Canada. It demonstrates the use of QR markers to make the link between the real world and the virtual world. The device chosen for this case study is HoloLens 2, a niche market device with a high price tag.

The integration of AR in modular construction has been explored through the use of high-cost HMDs (Pan, Chen, Fu, & Lu, 2023). The study discusses the use of a centralised database and multiple profiles for different visualisations. In this setup, the HoloLens, a head-mounted display, is used to bring AR into the construction environment.

In Europe, BIM is increasingly regulated and standardised through several key frameworks. The EU Directive 2014/24/EU (European Parliament and Council, 2014) encourages the use of BIM for publicly funded construction projects across member states. The ISO 19650 standard (International Organization for Standardization, 2018), widely adopted throughout Europe, defines the processes for organising and digitising information about buildings and infrastructure using BIM. Additionally, the EN 17412-1:2020 standard (European Committee for Standardization, 2020) focuses on defining the Level of Information Need in BIM, helping to structure what information is required at different stages of a project. Many European countries, such as the UK, Germany, France, and Italy, have introduced national mandates or roadmaps that align with these broader EU standards and ISO guidelines. Supporting these efforts, the EU BIM Task Group (EU BIM Task Group, 2017) brings together public sector bodies across Europe to share best practices and promote a unified approach to BIM adoption. These collective efforts demonstrate a clear commitment across Europe to harmonise BIM practices, ensuring greater efficiency, interoperability, and innovation within the construction industry.

The integration of AR and BIM is a topic of growing interest and has been the subject of considerable research and practical exploration. Gerger, Urban, and Schranz (2023, p. 3) examine the potential uses of AR in building authority processes, using the city of Vienna as a case study. The article concludes that AR, especially when combined with openBIM, has significant potential to accelerate building authority processes and improve citizen participation, as it cites ''Applications for mAR are often geared towards the design and preconstruction phases, as no exact location or superimposition is necessary.''.

Similarly, Pan and Isnaeni (2024) explore the integration of AR and BIM to improve construction inspection. The authors propose a model that combines these technologies to improve data life cycle management and the efficiency of construction management practices. The AR component was developed using Unity 3D and Gamma SDK, resulting in an .apk file for Android devices. To integrate the BIM file into the app, a conversion is required, meaning the original BIM file is not directly used in the application.

As in the previous case, Chai et al. (2019) study the integration of BIM with AR to improve the applicability of BIM in fieldwork within the construction industry. The authors examine the credibility of the AR-BIM pairing using a case study that replicates the system by combining Unity 3D and C# and a conversion of the BIM file. The results indicate that, although the developed system is still evolving, integrating AR with BIM is feasible, thereby maintaining the benefits of both BIM files and AR.

As shown in the examples above, the integration of AR with BIM is predominantly accomplished through the use of expensive head-mounted display (HMD) devices, the conversion of BIM to other file formats, the deployment of applications that require prior installation on the target device, or a combination of the aforementioned technologies. These approaches, while effective, often present limitations in terms of accessibility, cost-efficiency, and ease of use. Mobile devices, which are capable of delivering AR experiences at a substantially lower cost, offer a viable alternative. Equipped with AR capabilities, these devices provide proven portability, autonomy, and economic efficiency. Moreover, given their widespread use, mobile devices represent a more practical and cost-effective solution, particularly for small and medium-sized enterprises with limited budgets.

In conclusion, the implementation of a low-cost AR tool for the installation and verification of panels in building envelopes represents a practical and accessible solution that enhances efficiency and safety in construction processes. Integrating the BIM asset directly into the application without conversion ensures that we both adhere to and leverage the benefits of various European directives and standards. To take advantage of mobile devices and web technologies, a cross-platform experience can be achieved without the need for native applications, thus eliminating compatibility issues and outdated versions.

3 METHODOLOGY

The development of the tool follows an iterative, user-centred methodology focused on enhancing construction workflows through role-specific functionality and AR integration. Designed for both managers and operators/installers, the tool supports dual operating modes: a non-AR interface for managers to monitor real-time progress and KPIs, and an AR-enabled interface for installers to visualise, install, and verify façade panels on-site.

Installation and validation processes are structured around guided AR workflows. Using a physical reference point, installers align the virtual model with the real building, then scan and assess each panel. The system displays relevant information, such as location, specifications, and safety data, via semi-transparent overlays, allowing continuous situational awareness. Decisions made during installation or verification automatically update the system, generating alerts and adjusting KPIs accordingly. A colour-coded validation system (blue, green, red) helps quickly identify panel status.

Initial testing is conducted using the OpenBIM model of an experimental building, a full-scale facility ideal for iterative development and validation. This controlled environment enables early detection of issues and enables real-time refinement. Following successful testing, the tool will be deployed in real renovation scenarios, validating its performance in diverse European contexts and ensuring practical scalability and operational reliability.

3.1 TOOL WORKING MODES

The tool developed will have dual use, depending on the end user, as shown in Figure 1.

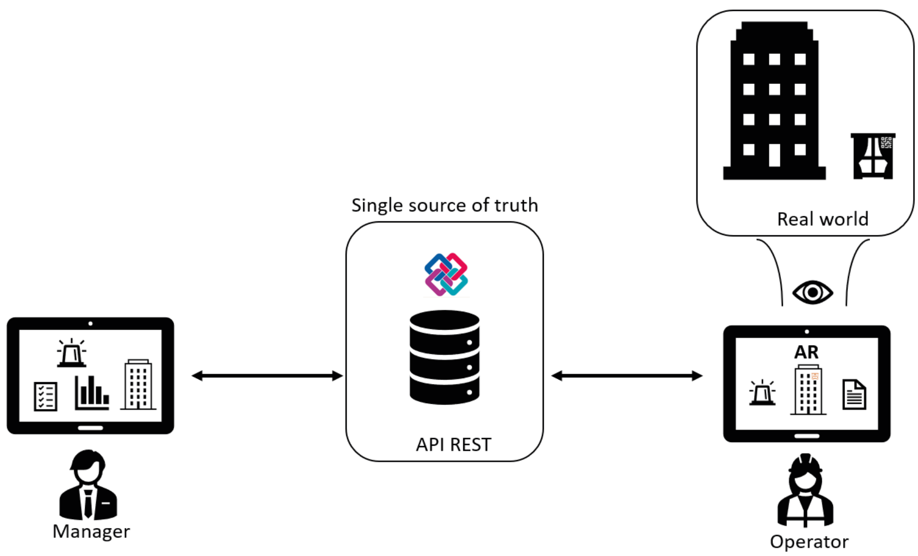

FIG. 1 *Usage possibilities.*

- Manager: No AR capabilities. The interface designed for the manager profile does not incorporate augmented reality functionalities. However, it enables real-time monitoring of the status of individual panels, categorised as idle, installed, invalid, or quality-checked, with dynamic updates as the installation progresses. Additionally, the manager has access to system-generated alerts. This component of the tool is intended to facilitate the tracking of construction progress and overall project status through the use of key performance indicators (KPIs).
- Operator/installer: With AR capabilities. This part of the application will allow the overlay of the virtual building over the real one, enabling the scanning of different panels and displaying their final location as well as information related to their installation and/or security details. When performing both the installation and the verification of the installed panels, the information will flow in real time, generating changes in the manager's part, updating the different KPIs (total number and percentage of the status of the panels, as well as the number of alerts generated).

This dual-purpose approach enhances overall productivity and accuracy within construction workflows.

The tool itself will detect if the device has AR capabilities, and if it does not, it will not allow the operator/installer mode, thus preventing improper operation.

3.2 LINK BETWEEN AR AND REAL WORLD

When using the tool in installer mode and using the AR capabilities, the virtual building is overlaid over the real one. To achieve this, it is necessary to establish a reference and pivot point in the physical environment, which will serve as the basis for accurately aligning the virtual building with the real-world context, as illustrated in Figure 2.

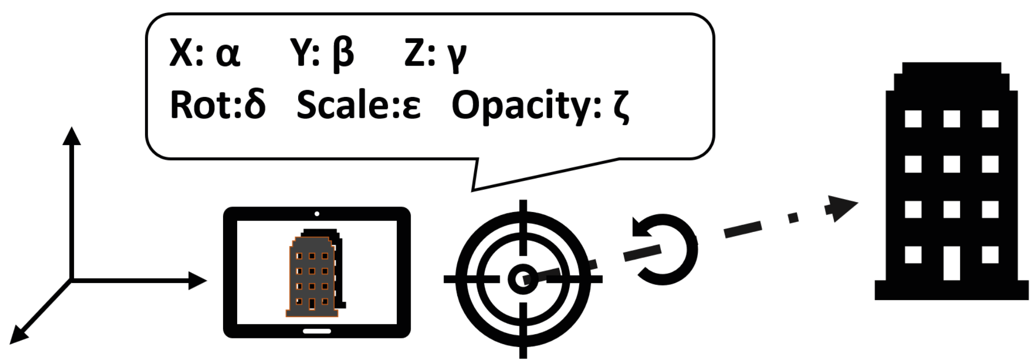

FIG. 2 *Reference and pivot point.*

By identifying the reference point in the physical environment through AR mode, the tool will precisely position the virtual building in its final location. It will use the necessary data from the BIM model, along with the relative positioning information stored within the tool, to ensure accurate placement.

The functionality of being able to move, scale, rotate, and control the transparency in the virtual building will be added, so that changing the reference point does not pose a problem. The visualisation of the virtual world can be adapted to the conditions of the real world (increased luminosity, rain, fog). Once the final position of the virtual model has been modified with respect to the reference point, it is possible to persist it in the tool.

3.3 PANEL INSTALLATION PROCESS

The tool is designed to assist operators with the repetitive task of installing panels on the building. A workflow has been designed to guide the installer through each step required to install the panels using the tool. These steps include identifying the panel, displaying relevant information (such as specifications, instructions, and safety data), and visualising the final installation location in AR. The workflow is depicted in Figure 3.

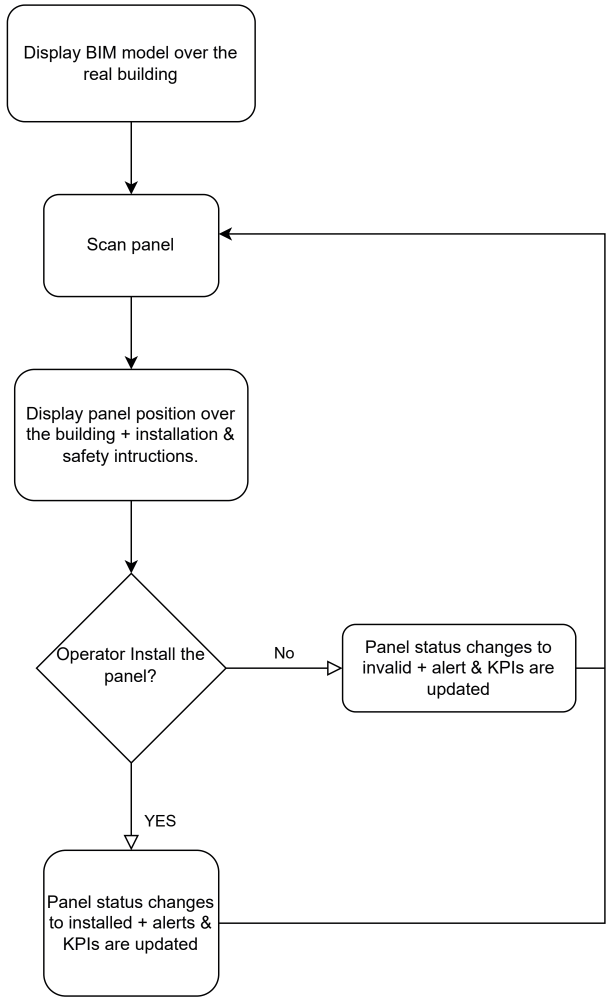

FIG. 3 *Panel installation flow.*

The panel installation process begins as follows: The operator will position the building in its actual location using the reference point, along with the building data, and make any necessary adjustments to fine-tune its alignment to the desired position. Once the virtual building is adjusted, the next steps will be repetitive (the addition of panels), so that there is no need to leave the AR environment.

In the tool, the panel scanning mode will be selected, and the installation of each panel will proceed accordingly. Each panel will be scanned to retrieve the relevant information from the tool, which will then display the panel's final position on the virtual building in AR, along with any associated usage instructions and safety considerations.

The way to display the information in AR will be through a semi-transparent menu, allowing the environment to remain visible at all times. The panel will be highlighted in the building using the black colour, so that focusing with the device towards the building highlights its position.

The operator/installer with the available information will decide whether to install the panel or to reject it (due to panel failure). Both when rejecting the panel and when validating it, the information in the tool will be updated, generating the necessary alerts and automatically updating the KPIs.

3.4 PANEL VALIDATION PROCESS

Once the panel installation is complete, it is possible to verify the panels to ensure that the final positions match the specifications. For this, the workflow will be slightly different from the installation process, as shown in Figure 4.

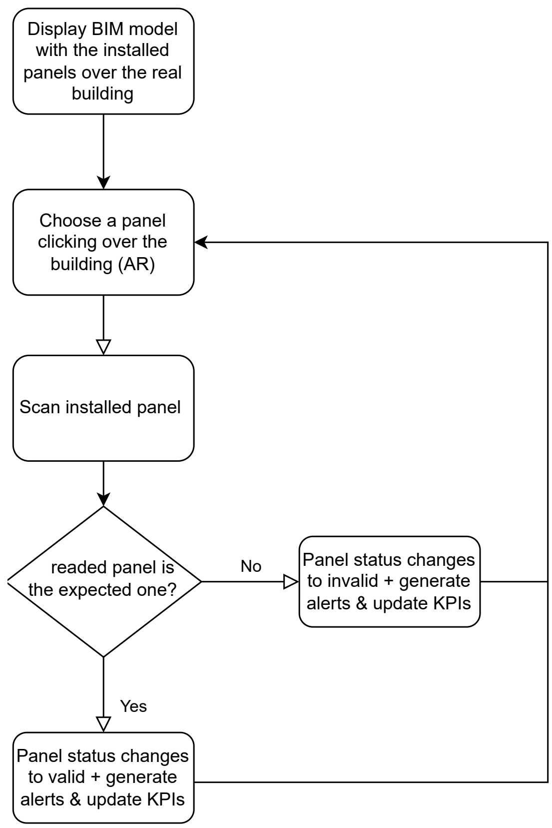

FIG. 4 *Panel installation flow.*

The first step is to load and position the building by reading the reference point and making precise adjustments (position, rotation, scaling, and opacity) if necessary. In the tool, select the verification mode, which will reveal with a colour code the different states of each of the panels:

- Blue colour: Panel installed but not verified.
- Green colour: Panel installed and verified.
- Red colour: Panel installed in the wrong position.

To initiate the verification process, a panel will be selected from the AR building by clicking on it. Once the panel is selected, it will be scanned, and the tool will automatically verify that the selected panel is the correct one. In this process, the information on the tool will be automatically updated, allowing alarms (if any) to be generated and corresponding KPIs to be updated.

In the same way as during the installation process, once a panel has been verified, regardless of the result, the rest of the panels can be verified, as this is done in the same AR session, thus speeding up the whole workflow.

3.5 TOOL MANAGER MODE

The manager mode enables real-time monitoring of construction progress without the use of augmented reality. To support this functionality, a dedicated interface has been developed, allowing users to track the status of individual panels as well as access key performance indicators (KPIs) relevant to project supervision.

In this initial version of the application, KPIs have been implemented to represent the distribution and relative proportions of panels across their installation statuses (idle, installed, invalid, or quality-checked). Additionally, the interface includes a section for visualising system alerts, providing further insight into the ongoing installation process.

Real-time updates will be received, and the interface will display a notification, alerting the manager to the changes that have been made.

3.6 CONTEXT AND EXPERIMENTAL FRAMEWORK

The AEGIR (AEGIR EU Project, 2024) project is a consortium of 30 partners from nine EU countries that focuses on the development of modular, renewable, and industrialised building envelope solutions for low-energy renovation. AEGIR designs scalable and customisable renovation envelope systems tailored to diverse building types, climate zones, social contexts, and occupant needs across Europe.

Figure 5 illustrates the diversity and range of panels that may be involved in an envelope renovation.

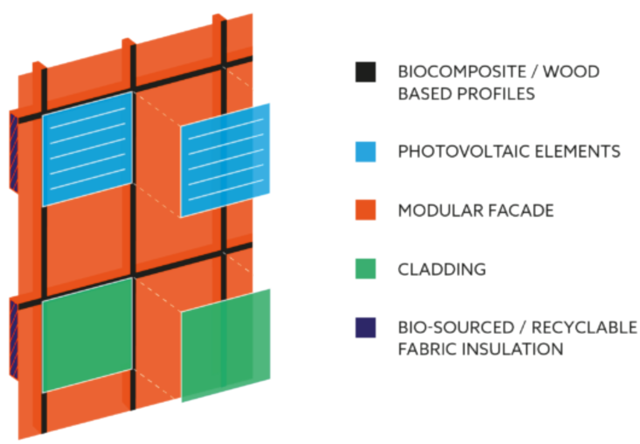

FIG. 5 *Different envelope panels. (AEGIR - EU Project, 2024)*

To carry out the development and testing process, the OpenBIM (IFC) file of the experimental building KUBIK was used, which is located in the Parque Científico y Tecnológico de Bizkaia in Derio, Bizkaia province, Basque Country, Spain (Tecnalia, n.d.). This is an experimental facility created to develop and validate new concepts, products, and services in full-scale tests. The infrastructure comprises a building capable of reconfiguring up to 550 m^2, spread across a basement and three above-ground floors. The building is fully demountable and allows for the reconfiguration of simultaneous scenarios at the construction level by replacing façade, roof, and partition components.

By maintaining a test and development environment that closely mirrors the final use case, the application's various functionalities have been rigorously tested immediately upon implementation. This approach has enabled rapid identification and resolution of issues, ensuring that each feature performs reliably under realistic conditions. It also facilitates iterative development, where feedback from early testing can be quickly incorporated into subsequent updates. Furthermore, the final deployment sites of the AEGIR project will integrate this AR-based technology, transitioning its validation from controlled laboratory settings to real-world renovation scenarios across Europe. This broader deployment not only serves to confirm the robustness and adaptability of the system in diverse environments but also provides valuable insights into its practical utility and user experience in actual field conditions. By bridging the gap between development and deployment, the project ensures that the technology is both technically sound and operationally effective in supporting large-scale energy renovation efforts.

4 RESULTS

4.1 SPECIFICATIONS AND FUNCTIONAL REQUISITES

A Single Page Application (SPA) is a web application that loads a single HTML page and dynamically updates its content as the user interacts with the app, providing a smoother and faster experience without requiring the entire page to reload. The solution will be approached using a SPA-type tool, both because the existing technology allows us to fulfil all the functional requirements described below and because of the advantages of a multi-platform solution without the need for installation, which this research aims to achieve.

- AR capability in a web environment. This capability will be fundamental to carrying out the development of the solution. This will eliminate the need for proprietary hardware, and the solution will be compatible with a wide range of devices.
- Ability to display openBIM elements in an AR environment. It is essential to display both the building and the construction elements in the real environment.
- Ability to store information and distribute updates in real time. For the application to have a significant impact on the operators, a real-time information flow is critical, ensuring that alarms and updates are instantaneous and the information displayed by the application is the latest available.
- Ability to view the overall status of components and different KPIs of the building's condition. The SPA shall be able to operate in an AR environment or in normal web mode, depending on the user's needs, so that the information provided depends on the end user.
- Ability to capture real-world information efficiently. While it is possible to have the operator enter the unique identifier of each panel manually, we can eliminate this step to make the solution dynamic by using image capture, making the whole application flow more comfortable and faster.
- Ability to organise and display information effectively across multiple screen sizes, ensuring a seamless and responsive user experience on devices ranging from smartphones to larger desktop monitors.

4.2 DEVELOPING TOOLS AND TECHNOLOGIES

React is chosen for the development of SPA. React is a JavaScript library used to build user interfaces, particularly those that require efficient and dynamic updates. React allows developers to create reusable components that handle their own state, making it easy to build complex web applications in an organised and maintainable manner.

The creation of the SPA has been carried out considering the principles of responsive design, so it is prepared for a wide range of devices, from PCs to mobile devices. Depending on the device being accessed, the information on the screen will be optimally organised to make the best use of the screen's resources. Figures 6 and 7 show the variability of screen sizes and the corresponding rearrangement of content.

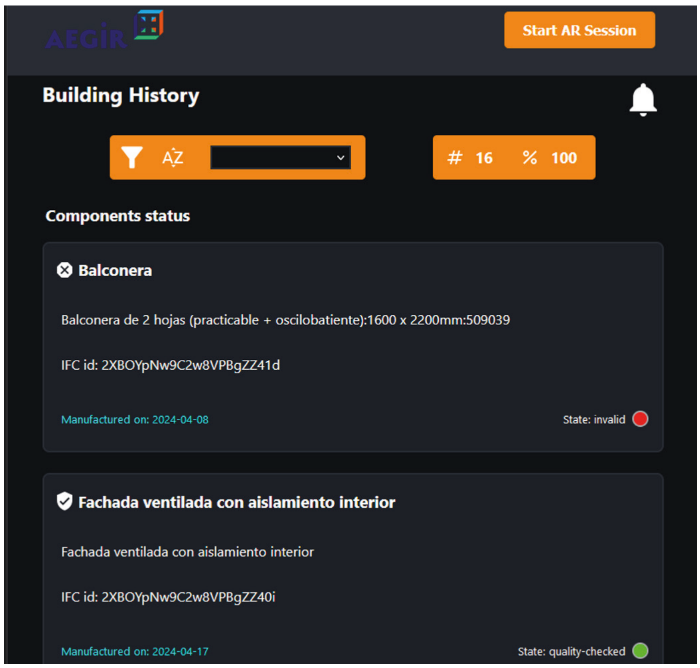

FIG. 6 *SPA on iPad Pro screen.*

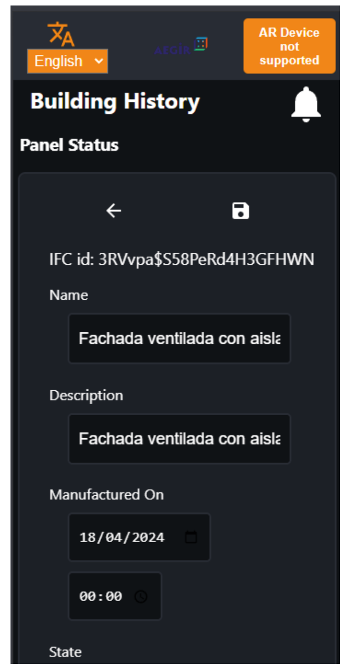

FIG. 7 *Edit panel on Samsung Galaxy S8+ screen.*

Another point to consider when creating the menus is the need to make them usable with a single finger or pointer, so that the operator does not have to type at any time. Thus, all the necessary commands have been translated into elements that can be operated with a single finger (buttons or sliders).

For the 3D viewing capabilities of OpenBIM (IFC) files and the use of AR, the Three.js library has been used ("Three.js – JavaScript 3D Library," n.d.). Three.js is a powerful JavaScript library that simplifies the creation and display of 3D graphics in the browser, leveraging WebGL for rendering. Three.js can be used with IFC files by using libraries designed to interpret BIM data. This compatibility allows the visualisation and rendering of IFC data in 3D directly within web applications. The same library allows the user to colourise, rotate, increase, or hide each of the elements of the 3D environment, so that the information can be displayed as another visual element.

WebXR ("WebXR Device API," 2024) is a technology for obtaining AR in web-based applications due to its cross-platform compatibility, cost-effectiveness, ease of deployment, and real-time interaction capabilities. It builds upon earlier standards, such as WebVR, and extends capabilities to include AR, enabling developers to create applications without the need for specialised hardware or software installations. It enables AR experiences to function across a wide range of devices, including smartphones, tablets, and AR glasses, all through standard web browsers like Chrome, Firefox, and Edge. The technology also supports real-time updates, allowing users to interact with 3D models and digital content as they move or change their perspective, further enhancing user engagement. Furthermore, WebXR integrates seamlessly with existing web development tools and frameworks, such as HTML, JavaScript, and WebGL. Overall, WebXR provides a scalable, accessible, and efficient solution for integrating AR into web applications. In addition, by not requiring a native application, version fragmentation is avoided, as all devices will have access to the latest version hosted on the server. Figure 8 shows the wide range of web browsers that support this capability.

Feature Name	Standardisation	Chrome	Safari on visionOS	WebXR Viewer	Magic Leap Helio	Samsung Internet	Meta Quest Browser	Microsoft Edge
WebXR Core	Explainer Spec MDN	Chrome 79	Behind a feature flag	iOS	Magic Leap Helio 0.98	Samsung Internet 12.0	7.0, December 2019	Edge 87 on Windows Desktop Edge 91 on Hololens 2
WebXR AR Module	Explainer Spec MDN	Chrome for Android, 81		iOS	Magic Leap Helio 0.98	Samsung Internet 12.1	24.0, October 2022	Edge 91. Hololens 2 only
WebXR Gamepads Module	Explainer Spec MDN	Chrome 79			Partially supported on Magic Leap Helio 0.98	Samsung Internet 12.0	7.1, December 2019	Edge 87 on Windows Desktop Edge 91 on Hololens 2
Hit Test	Explainer Spec MDN	Chrome for Android, 81		iOS		Samsung Internet 12.1	25.3, January 2023	Edge 93. Hololens 2 only
DOM Overlays	Explainer Spec MDN	Chrome for Android (Mobile), 83		iOS		Samsung Internet 14.2		

FIG. 8 *Detail of support table for the WebXR Device API ("Immersive Web Developer Home," n.d.)*

Access to and storage of the information is carried out using the STRAPI tool, an open-source content management system (CMS) that allows developers to build, manage, and distribute content efficiently ("Strapi - Open Source Node.js Headless CMS," n.d.). STRAPI features WebSocket technology that enables real-time, two-way communication between client and server. This is essential for applications that require real-time updates, instant notifications, or real-time collaboration. In this way, information can be stored and notifications managed in real time with a single CMS.

For real-world, information-capturing purposes, the chosen option will be the use of QR (Quick Response) codes. The ease of creating them (there are a multitude of libraries and even web pages) and the amount of information they can store make them an ideal candidate. QR codes offer numerous benefits for image capture in a construction environment, streamlining management and providing swift and efficient access to information. QR codes can be easily scanned with mobile devices, streamlining the real-time updating and exchange of data, thereby optimising communication between the various agents involved in construction. This technology also contributes to reducing errors and increasing productivity, as it provides instant access to the necessary information, thereby avoiding wasted time and potential errors that can occur when the user manually enters the information.

Development has been completed using the TypeScript programming language ("JavaScript With Syntax for Types," n.d.). This is an open-source programming language based on JavaScript, which adds optional static typing and other advanced features. Both Three.js and STRAPI support integration with TypeScript, so we will use a single programming language throughout the solution.

The Visual Studio Code IDE has been used as a development environment, and Vite has been used as a compilation tool ("Vite," n.d.). Vite stands out for its flexibility and modularity, allowing developers to choose the tools and technologies that best suit their projects without being limited by rigid configurations.

4.3 DATA ACCESS

The consumption of the information by the SPA will be done through the STRAPI CMS. For this, we will use two different accesses:

- REST API to obtain the details of the elements, such as the installation details of the panels or the geometry of the building.
- WebSocket for obtaining database changes in real-time, such as creating alerts or modifying the status of any panel. Thus, as soon as a change in the database needs to be displayed in the SPA, the necessary actions will be triggered to bring this information to the device.

After evaluating several options, MySQL was selected as the database solution. The general schema of the database is shown in Figure 9, which outlines the structure and relationships between the data elements.

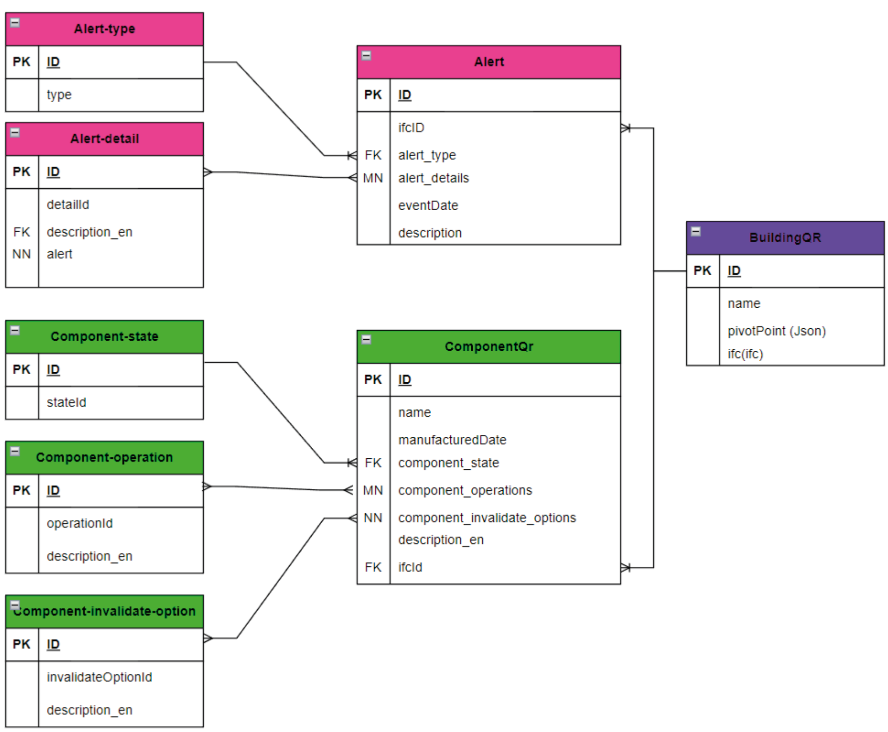

FIG. 9 *Database schema*

As shown in the schema, each panel is identified by its unique ID from the OpenBIM (IFC) file, allowing the tool to link panel-specific information — such as installation details, safety data, and current status (installed, verified) — directly with the corresponding BIM data.

To enhance the user's ability to access information while using the AR component, automatic QR code scanning will be employed. These QR codes will serve two primary functions: first, to define the reference point and retrieve the corresponding BIM file, and second, to capture the panel ID, enabling the retrieval of all relevant information required for the installation or verification process.

The automatic reading of QR codes will significantly reduce the risk of human errors during panel identification, ensuring that each panel is accurately matched with its corresponding data. This streamlined process not only enhances accuracy but also minimises the time spent on manual checks or corrections. By eliminating the possibility of misidentification or oversight, the overall workflow becomes more efficient, leading to faster and more reliable panel installations or verifications. Figure 10 shows an example of 2 QR codes.

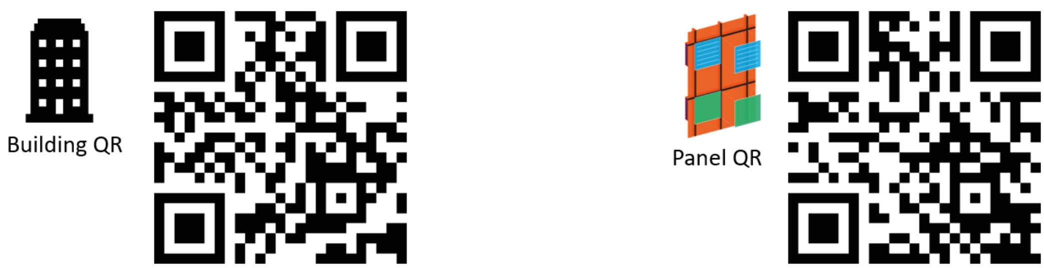

FIG. 10 *QR types.*

4.4 MANAGER MODE

This part of the SPA is the one that the construction manager will use, as it contains the global information about the construction status, and also allows modification of the data that operators/ installers can receive.

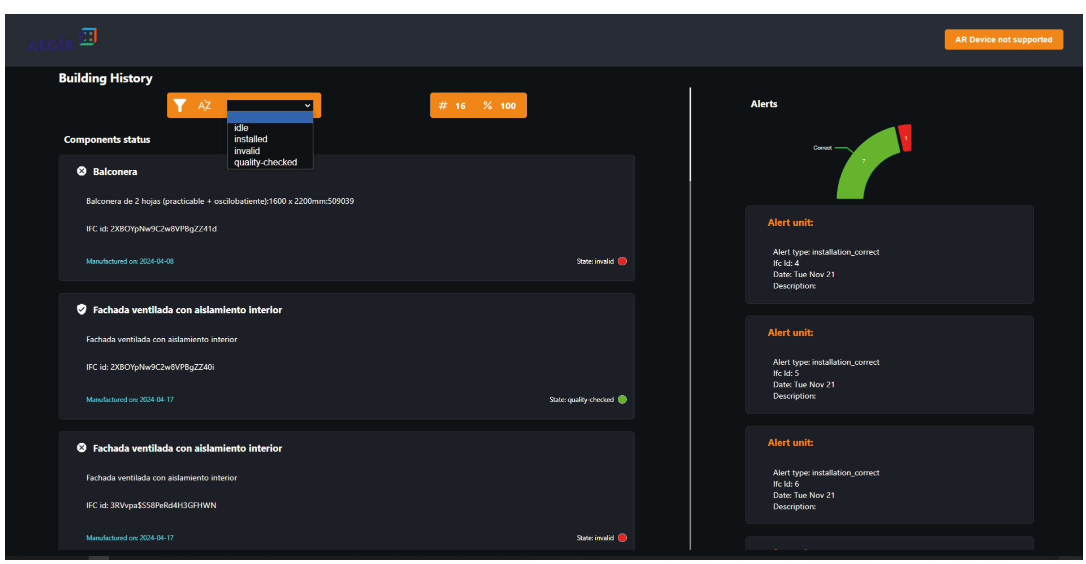

FIG. 11 *SPA in PC(Firefox).*

The interface includes several key features designed to enhance usability and provide comprehensive project monitoring:

- Button to Start AR (Figure 11, top right corner): This button allows users to initiate the AR session, provided the device supports AR capabilities. Activating this feature enables access to operator or installer mode for on-site interaction with the virtual building. The application automatically detects whether the device has AR capabilities, and access to these features will only be available if the device is compatible.
- Building History (Figure 11, centre left section): This section displays detailed information for all panels, including their current status and specific details. The list is fully editable, allowing authorised users to update the status or modify the information of each panel as necessary. Users can filter panels by status and view key performance indicators (KPIs), such as the completion percentage and the total number of panels.
- Alerts (Figure 11, centre right section): This section presents alerts along with detailed information about each issue. It also includes a graphical representation of the various types of alarms received, enabling quick identification of critical problems.

The information presented within the application is continuously synchronised in real time through its connection to the database via WebSocket. This ensures that users always have access to the most recent data regarding panel statuses, alerts, and project progress. Furthermore, each time an item or alert is updated in the system, the application automatically generates a notification, displayed prominently in the upper right corner of the interface. This feature enhances user awareness and responsiveness, ensuring that operators and managers are promptly informed of any changes or critical updates requiring their attention.

In this version of the application, KPIs have been implemented to display both the total number and the relative percentage of panels in each installation status, namely, idle, installed, invalid, or quality-checked. For instance, it may indicate that 60 out of 120 panels have been installed, representing 50%. These metrics provide a clear and immediate overview of the installation progress, enabling stakeholders to monitor performance and identify potential bottlenecks in real time. Furthermore, the application also presents the total number of alerts generated throughout the process, distinguishing between correct and incorrect alerts. This distinction is crucial for assessing the reliability of the alert system and for identifying areas where improvements in detection accuracy may be needed. By consolidating these insights into a single interface, the application enhances operational transparency and supports data-driven decision-making.

Additionally, the KPI dashboard is designed with flexibility in mind, allowing it to be tailored to fulfil the specific needs of different users or teams. Whether it's adjusting the metrics displayed, modifying thresholds, or integrating additional data sources, the system can be customised to align with varying operational goals and user preferences.

4.5 BIM OVERLAY IN AR

If the device is equipped with AR capabilities, the system will prompt the user for permission to access the device's camera when the AR session begins. This access is essential for scanning QR codes, which serve as reference points for positioning and retrieving relevant panel information. Granting camera access ensures seamless integration between the physical environment and the virtual data displayed in the application.

To effectively use the tool, it is imperative to position the virtual building precisely over the physical structure. This is accomplished by scanning the reference point, a QR marker that contains the relevant information. Once that QR code is successfully scanned, the virtual building will be downloaded and integrated into the AR session.

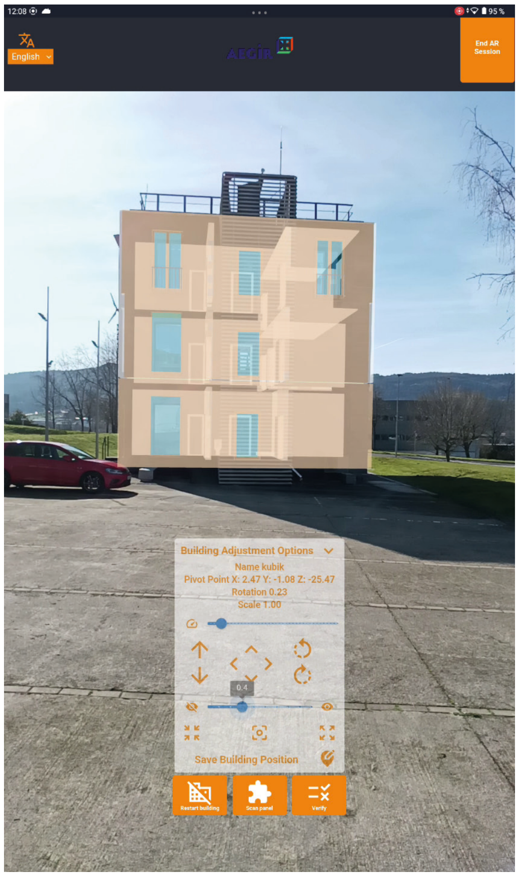

FIG. 12 *Building with edit menu overlay.*

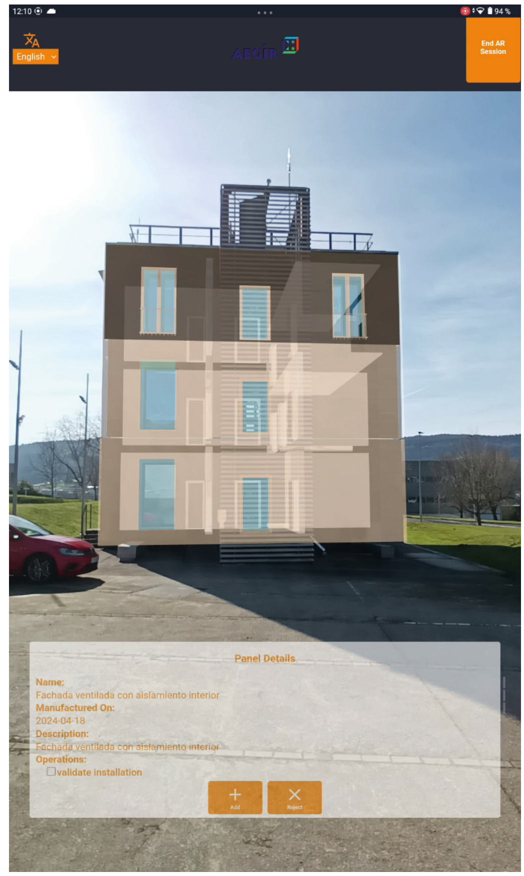

FIG. 13 *Panel placed in the building with the installation details.*

Figure 12 shows the virtual building in its final position together with the superimposed adjustment menu. If needed, its position can be fine-tuned using the menu provided for this purpose.
The decision has been made to make all menus and information available in AR semi-transparent for better integration with the environment.

One of the most helpful functionalities for the integration into the real environment is the control of the virtual building's opacity, allowing the operator or installer to select the appropriate value based on their specific requirements and prevailing environmental conditions.

Once the virtual building has been accurately positioned, the installation or validation of panels can begin by using the options available on the tool's interface.

As the interaction in the application is set up, it is possible to switch between panel installation and panel verification. This facilitates use in changing environments, since it is possible to take advantage of times when installation cannot be performed (e.g., due to adverse weather conditions) to perform validations, or vice versa.

4.6 INSTALLING PANELS

When in panel installation mode, the first action required is to scan the panel's QR code. With the information available in the QR, the tool will access the DDBB and retrieve the panel details. This information will be displayed in AR in two ways, as shown in Figure 13:

- Displaying the panel's position on the building in black: This ensures precise identification of the panel's final placement, eliminating any possibility of error. The operator or installer may freely move around the construction site with the AR session active, allowing them to adjust their viewpoint and obtain a clearer perspective of the panel's location if needed.
- Presenting installation and safety instructions in card format: The relevant information is displayed as overlaid, semi-transparent text, providing clear and accessible guidance without obstructing the user's view of the working environment.

Once we have performed the panel scan, we can proceed with two actions:

- Accept the panel and mark it as installed: This will update the details in the database and the panel will be ready for further verification.
- Reject the panel and mark it as invalid: A list of rejection reasons will be displayed, and after selecting the one that fits the reality, we will be able to reject the panel.

Both actions will update the database, updating the KPIs and generating the corresponding alerts, which will be sent to the manager in real time.

4.7 VALIDATING PANELS

By using the verification mode, the correct placement of the panels will be confirmed, ensuring that each panel is installed in its designated position. All panels subject to verification are displayed on the virtual building, with colour coding to indicate their status: blue for installed, green for verified, and red for rejected, as illustrated in Figure 14.

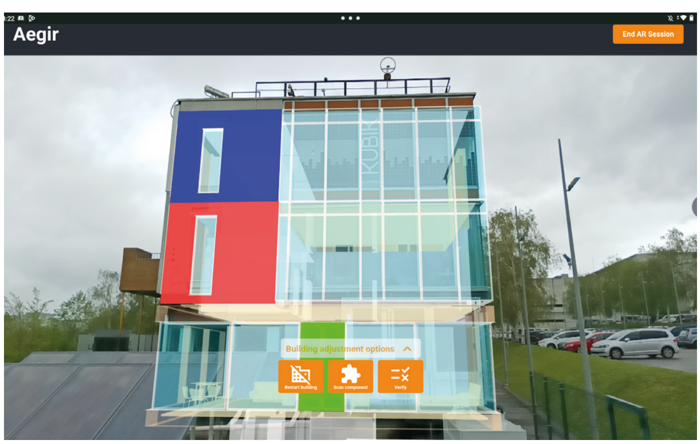

FIG. 14 *Panel placed in the building with colour codes.*

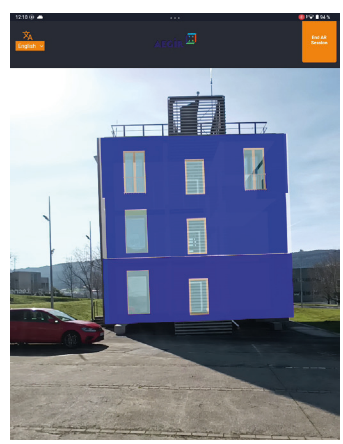
FIG. 15 Panels installed.

The user is required to select a panel and subsequently scan its corresponding QR code to confirm that it matches the information specified in the openBIM file. In Figure 15, all selectable panels are highlighted in blue. This designation indicates that these panels have been installed but have not yet undergone the verification process, meaning they have neither been validated nor rejected. This visual representation helps differentiate the panels that require further inspection or confirmation from those that have already been assessed. Additionally, the interface provides the ability to adjust the opacity of the panels, facilitating clearer visualisation and aiding in the selection process.

After selecting a panel in the verification mode, the user should approach the corresponding physical panel on-site and scan its QR code. Once the tool retrieves the panel information from the database, one of two outcomes will be displayed:

- Valid panel: (Figure 16) The scanned panel matches the designated position and is correctly installed.
- Invalid panel: (Figure 17) The scanned panel does not correspond to the expected position. In this case, the tool will also display the panel that should occupy the selected position, helping to quickly identify and correct any mismatches.

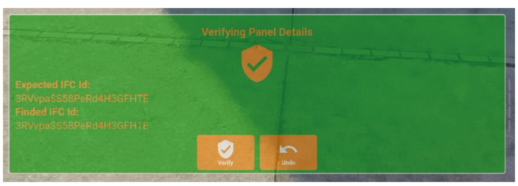

FIG. 16 *Valid panel message.*

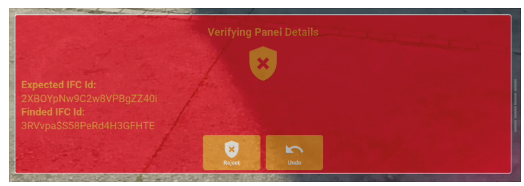

FIG. 17 *Invalid panel message.*

In both cases, whether the panel is valid or invalid, the user will be prompted to confirm the action. Once confirmed, the system will update the DDBB accordingly, automatically refreshing the KPIs and triggering any necessary alerts based on the verification result. Figure 18 shows the coloured digital building with the verified status of the panels. Here, the upper panel is correctly positioned, and the other two are switched.

5 CONCLUSIONS AND FUTURE WORKS

This study presents a practical and accessible solution for enhancing the installation and verification of prefabricated building envelope panels using a cost-effective Augmented Reality (AR) tool. Unlike traditional AR implementations that rely on expensive head-mounted displays and complex BIM file conversions, this tool leverages widely available mobile devices and web technologies (WebXR, Three.js, React) to deliver real-time, on-site guidance without the need for specialised hardware or software installations. The tool eases the repetitive task of installing panels by providing workers with accurate information about the final location of each panel, as well as installation instructions and safety details. This feature helps minimise errors, accelerates the installation and verification process through QR code scanning, and enhances on-site safety.

The tool successfully bridges the gap between digital models and real-world construction environments by overlaying BIM data directly onto physical structures. It supports both installers and managers through dual interfaces, AR-enabled for field operations and standard web-based for project oversight, ensuring synchronised, real-time updates via a centralised database.

FIG. 18 *Verified panels displayed in AR over the building.*

While the tool is designed to streamline workflows, its actual impact on installation and validation time has not yet been quantitatively assessed. However, by reducing manual data entry, enabling continuous AR sessions, and providing real-time visual guidance, the tool is expected to significantly reduce the time required for these tasks. Future studies should include time-tracking metrics to evaluate these potential gains and validate the tool's effectiveness in improving on-site productivity.

The tool, connected to a centralised database via a RESTful API and WebSocket, allows real-time updates on the status of the installation. This improves communication between operators and managers, facilitates tracking of site progress, and enables more informed decision-making.

In the short term, it would be possible to integrate the capture of images of the installation to document the process (both before and after) from the same device that is being used. Another functionality that the WebXR interface allows is to track the device's movement, so that the movements of both the installer and the validator can be monitored. With this data, subsequent analysis (total validation time, average validation time per panel) could be performed, as well as suggestions or alerts on the movements made. Additionally, and to facilitate interaction, it could be practical to use a module for capturing voice commands, which would reduce the need for interaction with the screen.

In the long term, similar tools could expand their functionality beyond panel installation to include other tasks such as plumbing, electrical, or HVAC systems. In addition, the tools could be integrated with other emerging technologies such as robotics or artificial intelligence.

For example, information from the AR tool could be used to guide robots in performing tasks or to enable the AI to detect errors in real time. The use of artificial vision could avoid having to resort to QR codes in cases where elements to be installed would allow it.

In summary, the proposed tool addresses current limitations in AR use within construction by enabling the direct use of BIM files on mobile devices through WebXR, thereby eliminating the need for costly hardware, complex data conversions, and software installations. It provides real-time guidance and verification for panel installation, improves site communication and efficiency, and has potential for future expansion into other construction tasks and integration with robotics, artificial intelligence, and computer vision.

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The OpenBIM (IFC) file of the experimental building KUBIK has been used to carry out the entire process outlined below. The various functionalities of the application have been tested as soon as they have been implemented by keeping the test and development environment as close to the final use case as possible (Tecnalia," n.d.).

References

2050 long-term strategy. (n.d.). Retrieved March 17, 2025, from https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en

AEGIR EU Project. (2024, March 6). Project - AEGIR. Retrieved March 17, 2025, from https://aegirproject.eu/project/

Azhar, S. (2011). Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry. Leadership and Management in Engineering, 11(3), 241–252. https://doi.org/10.1061/(asce)lm.1943-5630.0000127

Bressan, N. M., Scarpa, M., & Peron, F. (2024). Case studies of eXtended reality combined with building information modeling: A literature review. Journal of Building Engineering, 84, 108575. https://doi.org/10.1016/j.jobe.2024.108575

Callegaro, N., & Albatici, R. (2023). Energy retrofit with prefabricated timber-based façade modules: Pre and post comparison between two identical buildings. Journal of Facade Design and Engineering, 11(1), 001–018. https://doi.org/10.47982/jfde.2023.1.01

Chai, C., Mustafa, K., Kuppusamy, S., Yusof, A., Lim, C. S., & Wai, S. H. (2019). BIM integration in augmented reality model. Civ. Eng, 10, 1266-1275.

Cordis, C. (2022, September 21). DigitAl and physical incrEmental renovation packaGes/systems enhancing envIronmental and energetic behaviour and use of Resources. Retrieved March 27, 2025, from https://cordis.europa.eu/project/id/101079961

Dallasega, P., Schulze, F., & Revolti, A. (2022). Augmented reality to overcome visual management implementation barriers in construction: A MEP case study. Construction Management and Economics, 41(3), 232–255. https://doi.org/10.1080/01446193.2022.2135748

Edificio experimental KUBIK | Tecnalia. (n.d.). Retrieved March 17, 2025, from https://www.tecnalia.com/infraestructuras/edificio-experimental-kubik

Energy performance of buildings directive. (n.d.). Retrieved March 17, 2025, from https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en

European Committee for Standardization. (2020). EN 17412-1:2020 – Building information modelling: Level of information need – Part 1: Concepts and principles. Retrieved from https://standards.cen.eu

European Parliament and Council. (2014). Directive 2014/24/EU on public procurement and repealing Directive 2004/18/EC. Official Journal of the European Union. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32014L0024

Gerger, A., Urban, H., & Schranz, C. (2023). Augmented reality for building authorities: A use case study in Austria. Buildings, 13(6), 1462. https://doi.org/10.3390/buildings13061462

JavaScript with syntax for types. (n.d.). Retrieved June 20, 2025, from https://www.typescriptlang.org/

Immersive Web Developer. (n.d.). Retrieved March 17, 2025, from https://immersiveweb.dev/

International Organization for Standardization. (2018). ISO 19650-1:2018 – Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) — Information management using building information modelling — Part 1: Concepts and principles. Retrieved from https://www.iso.org/standard/68078.html

Li, F., Laili, Y., Chen, X., Lou, Y., Wang, C., Yang, H., ... Han, H. (2023). Towards big data driven construction industry. Journal of Industrial Information Integration, 35, 100483. https://doi.org/10.1016/j.jii.2023.100483

Li, J., & Wu, X. (2021). Safety management of prefabricated building construction based on BIM-RFID. In Advances in Intelligent Systems and Computing (pp. 1065–1071). https://doi.org/10.1007/978-981-16-1726-3_131

Loebus, S., Ott, S., & Winter, S. (2014). The multifunctional TES-Façade joint. In Springer eBooks (pp. 31–43). https://doi.org/10.1007/978-94-007-7811-5_3

Nassereddine, H., Hanna, A. S., Veeramani, D., & Lotfallah, W. (2022). Augmented reality in the construction industry: Use-cases, benefits, obstacles, and future trends. Frontiers in Built Environment, 8. https://doi.org/10.3389/fbuil.2022.730094

Pannu, E. S., & Hooda, J. (2025). A comprehensive review on the integration of BIM in modular and prefabricated construction practices. International Journal of Research in Civil Engineering and Technology, 6(1), 101–106. https://doi.org/10.22271/27078264.2025.v6.i1b.85

Pan, N., & Isnaeni, N. (2024). Integration of augmented reality and building information modeling for enhanced construction inspection—A case study. Buildings, 14(3), 612. https://doi.org/10.3390/buildings14030612

Pan, Y., Chen, J., Fu, Y., & Lu, W. (2023). Integrating smart construction objects and augmented reality for onsite assembly of modular construction. Computing in Construction. https://doi.org/10.35490/ec3.2023.178

Pan, Y., & Zhang, L. (2022). Integrating BIM and AI for smart construction management: Current status and future directions. Archives of Computational Methods in Engineering, 30(2), 1081–1110. https://doi.org/10.1007/s11831-022-09830-8

Rankohi, S., Rezvani, M., Waugh, L., & Lei, Z. (2023). Augmented reality application areas for the architecture, engineering, and construction industry. In IntechOpen eBooks. https://doi.org/10.5772/intechopen.1002723

Sousa, J., Bragança, L., Almeida, M., & Silva, P. (2013). Application of prefabricated panels for the energy retrofit of Portuguese residential buildings façades: A case study. Archives of Civil Engineering, 59(3), 337–357. https://doi.org/10.2478/ace-2013-0019

Strapi - Open source Node.js Headless CMS. (n.d.). Retrieved June 20, 2025, from https://strapi.io/

Three.js – JavaScript 3D library. (n.d.). Retrieved June 20, 2025, from https://threejs.org/

Vite. (n.d.). Retrieved June 20, 2025, from https://vite.dev/

WebXR Device API. (2024, October 21). Retrieved March 18, 2025, from https://www.w3.org/TR/webxr/

Xiao, Y., & Bhola, J. (2021). Design and optimization of prefabricated building system based on BIM technology. International Journal of Systems Assurance Engineering and Management, 13(S1), 111–120. https://doi.org/10.1007/s13198-021-01288-4

Integrated Structural and Daylight Optimisation of Variable Transmittance Façades

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Abstract

Traditional fabrication methods for plastic building panels, such as moulding and extrusion, have recently been advanced by large-scale robotic 3D printing (LSR3DP), enabling mass customisation and the production of complex architectural geometries. While existing research on LSR3DP has primarily focused on single-material printing, the exploration of multi-material or multi-property applications remains limited, especially at full architectural scale. This study addresses this gap by developing a performance-driven digital workflow for PETG-based façades that integrates structural efficiency with solar-responsive transmittance gradients. A multiobjective optimisation process using the Non-dominated Sorting Genetic Algorithm II (NSGA-II) generated 16 optimal façade geometries across four orientations (north, east, south, west), achieving up to 14% reduction in summer solar radiation and 26% increase in winter solar gain compared to a conventional vertical façade, while minimising structural displacement. The optimal south-facing solution was selected for detailed daylight performance assessment. A procedural gradient generation workflow was developed to discretise solar-based transmittance values across varying mesh densities and gradient resolutions. The best-performing variable transmittance configuration achieved 46.24% Useful Daylight Illuminance (UDI-a) and 69.21% spatial Daylight Autonomy (sDA), representing a 25.94% improvement in UDI-a over a conventional uniform-transmittance curtain wall. This integrated approach demonstrates LSR3DP's potential to produce unified, materially expressive façades that embed environmental performance directly into form and material logic, eliminating reliance on mechanical shading systems.

Keywords

Computational Design, Multi-property Façade Design, Multiobjective Optimisation, Daylight Performance

DOI

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1 INTRODUCTION

1.1 BACKGROUND

Plastics have been used in façade applications since 1954, initially in the form of glass-fibre-reinforced plastic (GRP) panels enclosing military radar domes (Engelsmann et al., 2010). A few years later, in 1957, the Monsanto House of the Future—designed by Monsanto, MIT, and WED Enterprises—was constructed using large GRP structural sections cantilevered from a concrete core, demonstrating the potential of this new material for building construction. Since then, plastics have been employed in a variety of applications (Engelsmann et al, 2010): *i)* as panels in building envelopes, such as the polycarbonate façade of the Laban Centre in London, UK, and the GRP façade of Terminal V in Lauterach, Austria; *ii)* as structural elements in sculptures, roofs, or pavilions, such as the Hoofddorp Bus Station (Castañeda et al., 2015) in the Netherlands; and *iii)* as both building structure and envelope, as seen in projects like FG 2000 in Altenstadt, Germany, which was constructed from composite GRP and PUR (Polyurethane) foam core structural sections.

In most of these examples, the plastic components were manufactured using injection moulding, casting, or extrusion—traditionally the primary fabrication methods for producing such parts or sections. Today, *Large-Scale Robotic 3D Printing (LSR3DP)* (Milano et al., 2024) has been added to these methods, offering capabilities that extend beyond mass production by enabling greater geometric complexity and adequate cost efficiency. One notable contemporary application of LSR3DP in architecture is the use of ABS (acrylonitrile-butadiene-styrene) plastic panels to clad the steel structure of the east gate at Nanjing Happy Valley Plaza in China (Yuan et al., 2022). The complex, non-repetitive geometry of the structure made a bespoke fabrication method such as LSR3DP particularly suitable, enabling the production of 4,000 unique panels in under two months. This technique is now being increasingly explored as a means of customising the geometry, performance, and finish of façade systems through the fabrication of bespoke, one-off panels.

Additionally, daylight control, typically achieved through mechanical shading devices, can instead be integrated directly using LSR3DP. This is because constructing such shading systems involves a complex assembly process. Another significant issue is “the cost of production and maintenance of sophisticated mechanical systems” (Vazquez & Duarte, 2022). Furthermore, these systems must be fixed to the building envelope using metal components, which introduces weak thermal points due to cold bridging. In contrast, the novelty of LSR3DP lies in its ability to minimise construction complexity, eliminate variability in thermal performance caused by the use of disparate materials and mechanical fixings, and avoid the ongoing maintenance typically associated with kinetic or conventional shading systems.

1.2 STATE OF THE ART

Research into the use of plastics in building façade panels has been ongoing for several years. This work can be divided into mono- and multi-material approaches: the former concerns the use of a single type of plastic across the entire panel, while the latter involves the fusion of plastics of different types, colours, or opacities. Within the mono-material category, sub-themes investigated include ventilation control and thermal heat storage (Mungenast, 2017); thermal performance (Sarakinioti et al., 2018; Piccioni et al., 2020); solar wall design and manufacturing (Tenpierik et al., 2018); and assessments of air permeability, water tightness, wind loads, and impact resistance

(Cheibas et al., 2024). Additionally, Milano et al. (2024) investigate the assembly of 3D printed plastic panels into a complete façade system, focusing on the interfaces between segments.

Of relevance to this study, Cheibas et al. (2023) examine various surface patterns on 3D-printed plastic panels to regulate daylight transmission and distribution, while Taseva et al. (2020) propose the use of circular gradient, truss gradient, and Schwarz P infill geometries in plastic panels for light control. In addition, the engineering practice Eckersley O'Callaghan and design studio Etcetera have undertaken research into "a building enclosure platform that replaces a typical multilayered façade build-up with a *unified* "single-material construction" (Quillet & Rogan, 2022), which is also directly relevant to this article.

Regarding the currently limited multi-material approaches, Grigoriadis (2018, 2019) presented research on design-to-fabrication workflows for a multi-material façade segment using PolyJet materials by Stratasys (Tee et al., 2020). Furthermore, Taseva et al. (2020) showcased a strategy for fabricating polyurethane foam-infilled, functionally graded plastic panels, and Kwon et al. (2019) presented an approach for combining carbon fibre-reinforced thermoplastics with polymers.

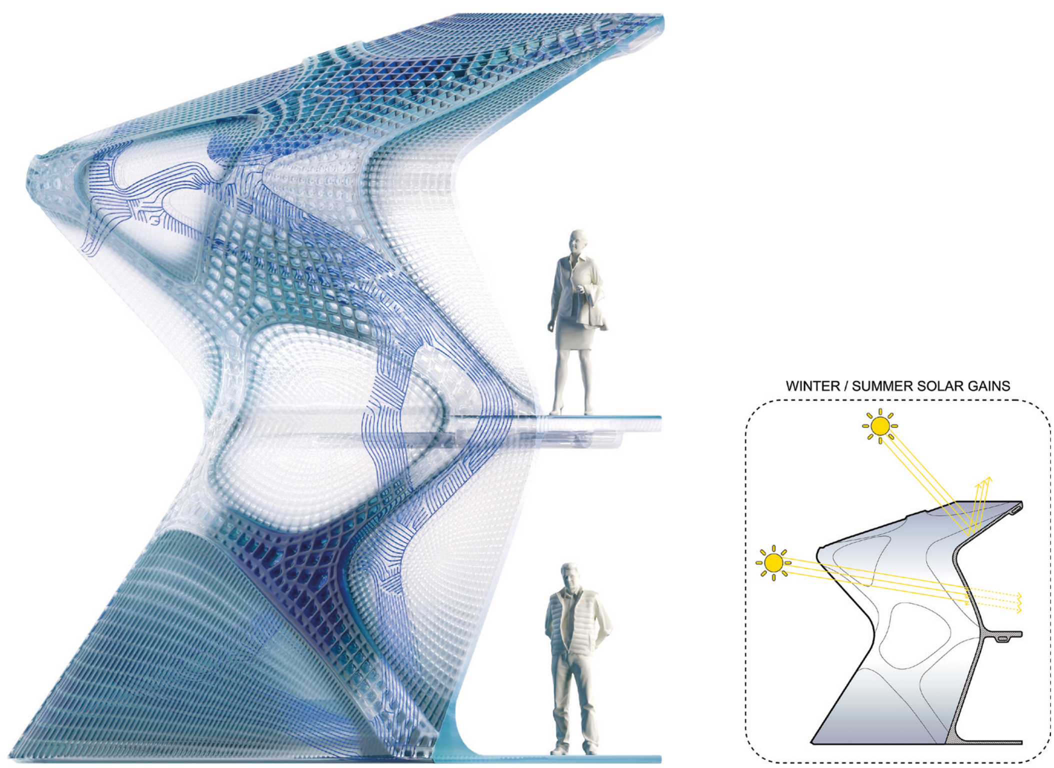

FIG. 1 Side view rendering of the MMIF project, illustrating the distribution of colour and transmittance gradients throughout the façade volume. This project served as the initial basis for the research presented in this paper.

1.3 CONTEXT

The study presented here builds upon the Multi-Material Integrated Façade (MMIF) project, shown in FIG 1 and FIG 2, initially developed by Grigoriadis and Esses and previously summarised in *3D Printing and Material Extrusion in Architecture: Construction and Design Manuals (*Grigoriadis & Lee, 2024). MMIF proposes a component-less building façade, designed and ultimately intended to be robotically fabricated, as a continuous volume characterised by gradual changes in transmittance and colour. In doing so, it effectively introduces a fourth category to those outlined in Section 1.1: the use of multi-properties or multi-materials in *iv*) a self-supporting envelope.

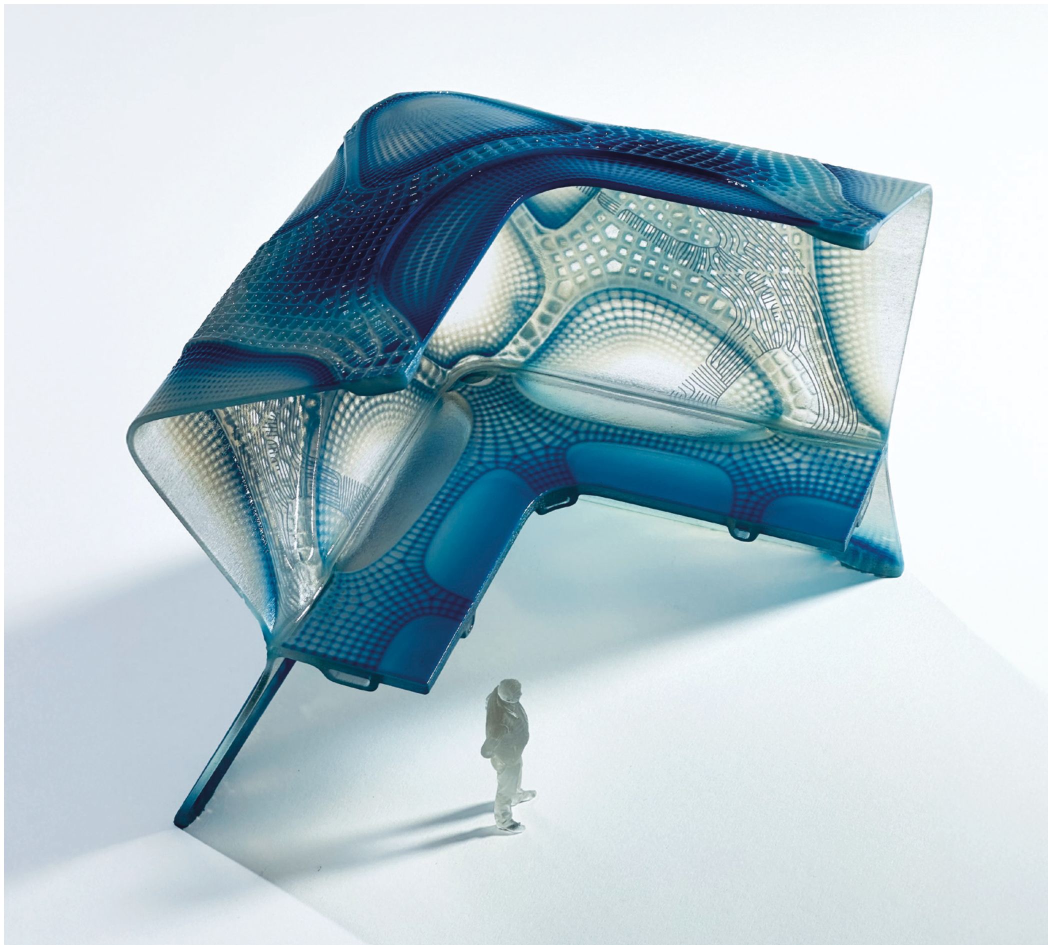

FIG. 2 View of the MMIF scale model printed with PolyJet materials on the Stratasys J835 multi-material 3D printer.

1.4 RESEARCH GAP

Current research on daylight control in 3D-printed façades has predominantly focused on geometric approaches, such as surface patterns, infill geometries, and layer orientation, rather than material-based transmittance gradients. Layered 3D printed geometry has been shown to create anisotropic optical behaviour through variations in layer height, width, and spatial configuration (Cheibas et al., 2023), whilst functionally graded façade elements using minimal surface infill structures have been developed, in which gradient effects emerge from wavelength and amplitude variations controlled by geometric parameters (Taseva et al., 2020). Similarly, research has demonstrated that 3D printing process parameters can tune optical properties from 90% transparency to 60% translucency (Piccioni et al., 2023). However, this tuning occurs through parameters that affect layer deposition rather than through variations in material composition across the façade surface. These studies consistently control light transmission through physical form manipulation rather than through inherent variation in material optical properties.

This article advances this body of research by, for the first time, investigating the distribution and discretisation of continuous transmittance gradients across complex façade geometries to optimise performance. Whilst existing research achieves light control through geometrical articulation, the present work addresses how material properties can be systematically varied across a surface to achieve performance objectives. More specifically, it offers an alternative approach to previous studies (Cheibas et al., 2023; Taseva et al., 2020), focusing on the distribution of transmittance gradients rather than surface texturing or infill geometries. The study addresses two previously unexplored challenges: (1) specifying variable transmittance gradients across freeform geometries based on solar radiation data, and (2) developing discretisation strategies for translating continuous transmittance properties into stepped zones for daylight performance evaluation. This represents a significant gap, as no robust framework currently exists for the performance-driven application and discretisation of gradients, particularly for complex geometries enabled by LSR3DP.

The research that follows adopts a structured, multiobjective optimisation approach to balance summer and winter solar radiation with structural displacement criteria, determining an optimal façade form, illustrated in FIG 3. Multiobjective optimisation processes have typically been applied to the design of façade shading systems (Wagiri et al., 2024; Lin & Tsay, 2024; Fan et al., 2022), relevant to this study, to explore the relationship between glazing types, insulation, window-to-wall ratios, Useful Daylight Illuminance (UDI), and life cycle cost (Shan & Shi, 2016).

Building on this foundation, the optimisation process presented in this article consists of a bespoke workflow that distributes transmittance gradients across the continuous global surface. Daylight metrics analyses accompany this to evaluate the impact of these gradients on interior lighting conditions.

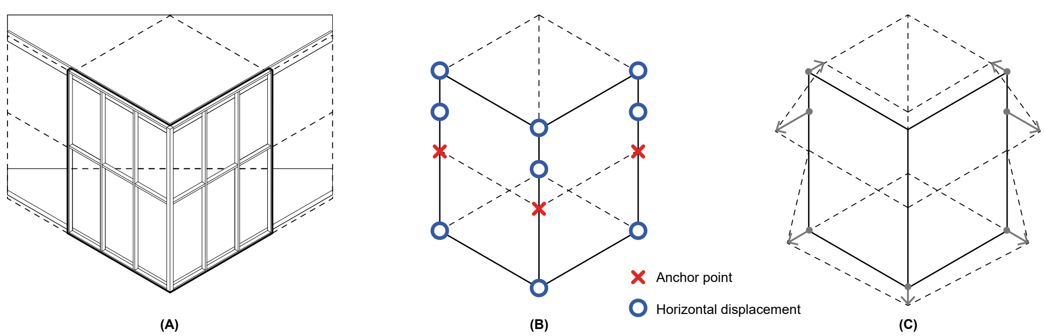

FIG. 3 Diagram of (a) the segment of the virtual building used as the baseline condition for the multiobjective optimisation, (b) the locations allowed to undergo displacement during optimisation, and (c) the geometry after displacement.

Effectively, this article addresses two key research questions:

1. How can multiobjective optimisation be applied to identify façade forms that balance summer solar radiation reduction, winter solar gain maximisation, and structural displacement minimisation?
2. How can solar-informed transmittance gradients be systematically distributed and discretised across façade geometries to achieve comfortable internal daylight levels?

2 METHODOLOGY

The methodological framework of this study comprises two distinct phases: form finding and gradient-based daylight performance analysis. This two-phase approach reflects the hierarchical nature of façade performance optimisation, in which geometric configuration must be established before material properties can be meaningfully assigned.

Phase 1 addresses the first research question by identifying optimal façade forms that balance competing environmental and structural criteria through multiobjective optimisation. This phase focuses on generating façade geometries through parametric modelling, evaluating their environmental and structural performance through coupled analysis, and identifying optimal configurations that balance competing criteria through evolutionary optimisation algorithms.

Phase 2 builds upon the optimised geometry to address the second research question by evaluating how solar-informed transmittance gradients influence interior daylight quality. This phase combines procedural modelling and discretisation techniques with a comprehensive evaluation of daylight performance based on validated simulation metrics.

This integrated approach, summarised in FIG 4, maintains continuity of geometric and performance data across both phases, ensuring that form-finding decisions directly inform the distribution of material properties.

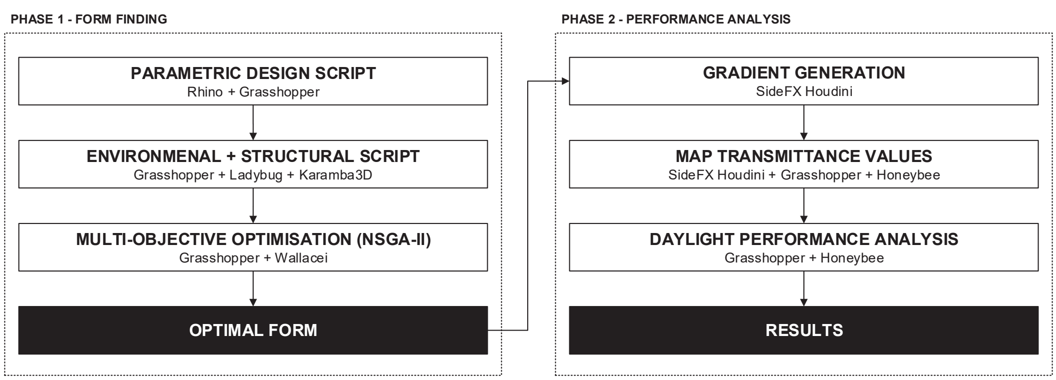

FIG. 4 Diagram summarising the methodology used in this study.

2.1 PHASE 1: FORM FINDING PROCESS

This phase establishes the methodological foundation for performance-driven façade design through parametric modelling, integrated environmental-structural analysis, and multiobjective optimisation. The process systematically explores how geometric variation influences solar exposure and structural behaviour, ultimately identifying configurations that achieve balanced performance across competing criteria.

2.1.1 Parametric Design Script

A parametric design approach was adopted to enable a systematic exploration of façade geometries with varying degrees of self-shading and structural articulation. Rhinoceros (Rhino) (Robert McNeel

& Associates, n.d.) and Grasshopper (Rutten and Robert McNeel & Associates, n.d.) were used to develop the parametric design script. These platforms were selected for their visual programming interfaces and seamless integration with environmental and structural analysis tools. Unlike fixed geometric configurations, parametric modelling allows the simultaneous investigation of multiple design variables and their combinatorial effects on performance, which is essential for identifying optimal solutions within a complex design space.

A corner façade geometry was selected as the case study, representative of typical commercial or office building construction. Eight primary parameters were utilised to articulate the façade with more control points than a typical vertical façade, enabling variations in profile depth, curvature, and corner orientation. These parameters were established to ensure geometric feasibility whilst maximising performance variation across environmental and structural criteria.

2.1.2 Environmental and Structural Analysis

The parametrically generated façade forms were assessed through an integrated environmental and structural analysis workflow within Grasshopper, using Ladybug (Roudsari and Ladybug Tools LLC, n.d.) for environmental analysis and Karamba3D (Preisinger, 2013) for structural analysis. Evaluating both aspects together was necessary, since geometric modifications that improve one criterion often compromise the other. The coupled approach supported the identification of configurations that achieve balanced performance across environmental and structural criteria.

Solar incident radiation was calculated for all façade iterations for summer and winter periods. The seasonal split was critical because effective façade performance requires low summer gains to reduce cooling loads and high winter gains to support passive heating. The analysis was conducted across four cardinal orientations (north, east, south, west), as solar exposure varies significantly with orientation and optimal geometric configurations differ accordingly. Ladybug was used for this analysis due to its validated solar-geometry algorithms and integration with Grasshopper, which enabled real-time feedback during parametric adjustments. The study used London Heathrow EPW data to provide hourly radiation values representative of the UK climate.

Structural displacement was calculated for all façade iterations to assess how each geometry responds to self-weight and applied loads. Displacement served as an indicator of structural efficiency and material use because larger values show higher structural demand that requires additional material or support to maintain stability, which influences fabrication feasibility and cost (Preisinger, 2013; Bollinger et al., 2010). Karamba3D was used for this assessment due to its finite element analysis capabilities and its integration within Grasshopper, which supported the combined environmental and structural workflow used to evaluate the parametrically generated façade forms.

PETG (Polyethylene Terephthalate Glycol) was specified as the façade material due to its demonstrated suitability for LSR3DP applications. PETG offers a favourable combination of durability, flexibility, and printability. It exhibits sufficient structural capacity for self-supporting façades whilst maintaining the flexibility necessary to accommodate thermal expansion and minor deformations without brittle failure (Piccioni et al., 2023a; Sarakinioti et al., 2018). Its optical properties also enable transmittance modulation, essential for Phase 2 of this research.

2.1.3 Multiobjective Optimisation and Pareto Solutions

A multiobjective optimisation process was conducted using Grasshopper and Wallacei (Showkatbakhsh et al., n.d.), employing the Non-dominated Sorting Genetic Algorithm II (NSGA-II) to identify façade geometries that balance competing environmental and structural performance criteria. This approach was necessary because the three performance criteria are inherently conflicting. Multiobjective optimisation enables exploration of the entire trade-off landscape, identifying solutions in which no objective can be improved without degrading at least one other objective (Deb et al., 2002).

Three objectives were selected to address fundamental façade performance requirements: (1) minimising summer solar radiation; reducing cooling demand and overheating discomfort; (2) maximising winter solar radiation; enhancing passive solar heating and reducing heating energy consumption; and (3) minimising structural displacement; ensuring material efficiency and fabrication feasibility, as excessive deformation would require additional material or structural reinforcement, compromising the viability of LSR3DP fabrication.

NSGA-II was employed through the Wallacei plugin for this optimisation process. NSGA-II was selected due to its established effectiveness in generating well-distributed Pareto-optimal solutions for multiobjective problems (Deb et al., 2002). The algorithm uses evolutionary operations such as selection, crossover, and mutation to refine a population of design solutions iteratively, maintaining diversity across the Pareto front while converging toward optimal performance. The optimisation was conducted independently for each cardinal orientation, as optimal façade configurations vary significantly with directional solar exposure.

The optimisation process generated Pareto fronts containing non-dominated solutions. To select a single representative solution from each Pareto front that balances all three objectives, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) was applied (Hwang & Yoon, 1981). TOPSIS is a multi-criteria decision-making method that ranks solutions based on their geometric distance from both an ideal solution (best possible values for all objectives) and a negative-ideal solution (worst possible values for all objectives). The solution with the highest preference score was selected as the TOPSIS-optimal solution for each orientation, providing a systematic approach for balancing competing objectives without arbitrary weighting schemes.

2.2 PHASE 2: DAYLIGHT PERFORMANCE ANALYSIS & TRANSMITTANCE GRADIENT GENERATION

Building upon the previous phase, this process utilises the Solar Incident Radiation data from Phase 1 and the Phase 1 Optimal Geometry (P1OG) as inputs. It follows a procedural workflow using SideFX Houdini (SideFX, n.d.) and further environmental simulations using Grasshopper and Honeybee (HB) (Roudsari and Ladybug Tools LLC, n.d.) to generate a gradient design and evaluate the daylight performance, aiming to establish a methodology for assessing daylight in additive-manufactured multi-property or multi-material façades. Houdini is used for its procedural modelling capabilities, which allow for rapid iteration and precise control over complex geometries and properties, such as colour and transmittance. Custom input/output (I/O) workflows were developed in Python to enable the structured transfer of data between the two platforms for environmental simulation, streamlining the computational process.

2.2.1 Gradient Generation

A procedural gradient-generation script was developed in SideFX Houdini using the P1OG with the associated vertex colours from the solar radiation heatmap generated in phase 1. The P1OG was simplified to three versions, low, medium, and high resolutions, by reducing the number of polygons used to represent the geometry. This was done to compare model complexity with analysis accuracy and runtime during the environmental simulations.

2.2.2 Gradient Discretisation

By discretising the gradient, the mesh was segmented into polygonal zones with shared colour values through attribute-based grouping. Promoting vertex colour attributes to the polygon level allowed polygons to be grouped into discrete model components for data transfer between SideFX Houdini and Grasshopper. This enabled an evaluation of how gradient resolution influences both the accuracy and computational performance of daylight metrics analyses, independent of mesh density. Higher numbers of discrete steps provide a closer approximation to the original continuous gradient. A custom VEX code was written in Houdini to convert the colour gradient into the desired number of discrete steps, summarised in FIG 5. This facilitated assigning stepped transmittance values across the geometry during the environmental simulations.

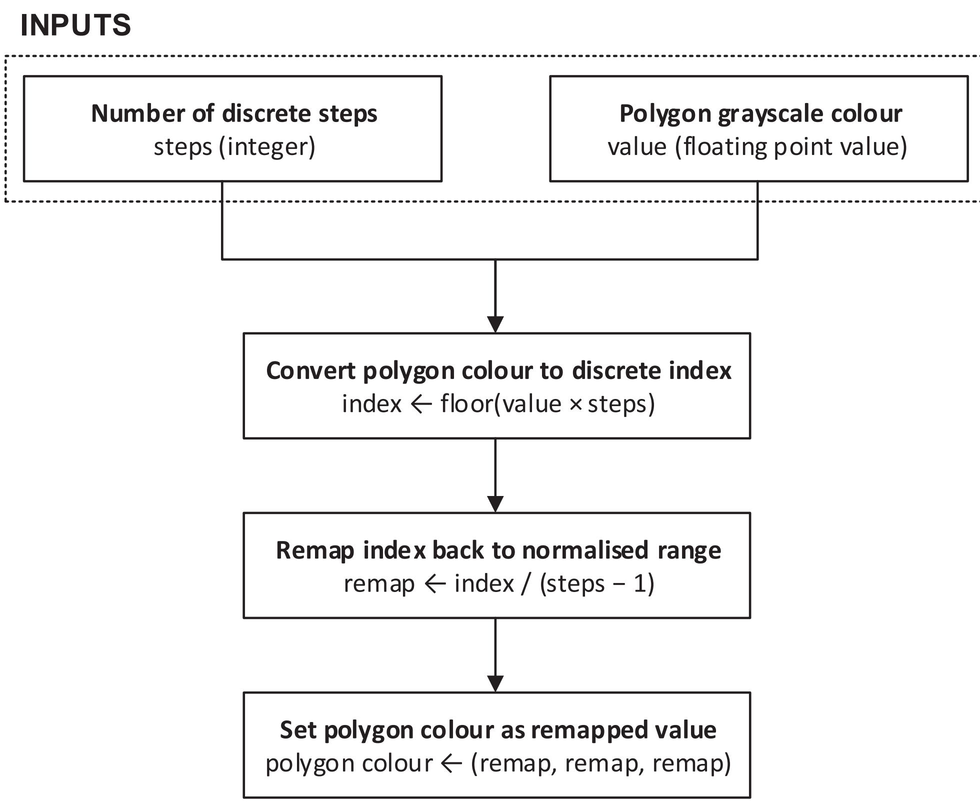

FIG. 5 Diagram of the method used for gradient discretisation.

2.2.3 Environmental Analysis

The output mesh groups were then evaluated within Grasshopper, using HB for environmental analysis. A custom Grasshopper component was developed in Python to construct a sorted list of model components based on their assigned colour values, enabling the mapping of grouped geometry to corresponding transmittance values in HB. Environmental inputs include weather data from the EPW file, the Daylight Autonomy (DA) threshold, and the occupancy schedule, which inform the analysis of DA and Useful Daylight Illuminance (UDI) experienced within the space. The analysis was conducted in two steps. (1) The first step aimed to evaluate the impact of mesh and gradient resolution on daylight analysis accuracy. (2) The second step aimed to identify the optimal range for the variable transmittance model to achieve both high daylight performance and visual comfort. Simulations were conducted on a laptop powered by an AMD Ryzen AI 9 365 processor, featuring 10 cores and 20 threads, with a base clock speed of 2.0 GHz and a maximum boost clock of 5.0 GHz.

3 RESULTS

This section presents the outcomes of the two-phase methodological process developed in this study. Phase 1 focuses on formulating input parameters, evaluating their sensitivity, and identifying optimal solutions based on multiple performance criteria. Phase 2 builds upon the selected geometry from Phase 1 to assess its daylighting performance and generate optimised transmittance gradient models.

3.1 PHASE 1: FORM FINDING PROCESS

This phase presents the form-finding process, summarised in FIG 6. Various form iterations are produced by manipulating the input variables, offering a range of design options for further analysis and optimisation. This consists of 3 key steps: (1) developing a parametric design script that systematically explores façade form options, (2) conducting a sensitivity analysis to test the impact of the building's geometry parameters on the environmental and structural performance, (3) developing a multiobjective framework for optimising the building form in response to the environmental and structural performance.

3.1.1 Parametric Design Script

The foundational geometry is a 6 × 6-meter rectangular footprint, extruded vertically to form a two-storey structure with a total height of 8 meters (4 meters per floor). This basic structure is consistently applied across all iterations, while the parametric flexibility focuses on designing and manipulating the corner wall façade.

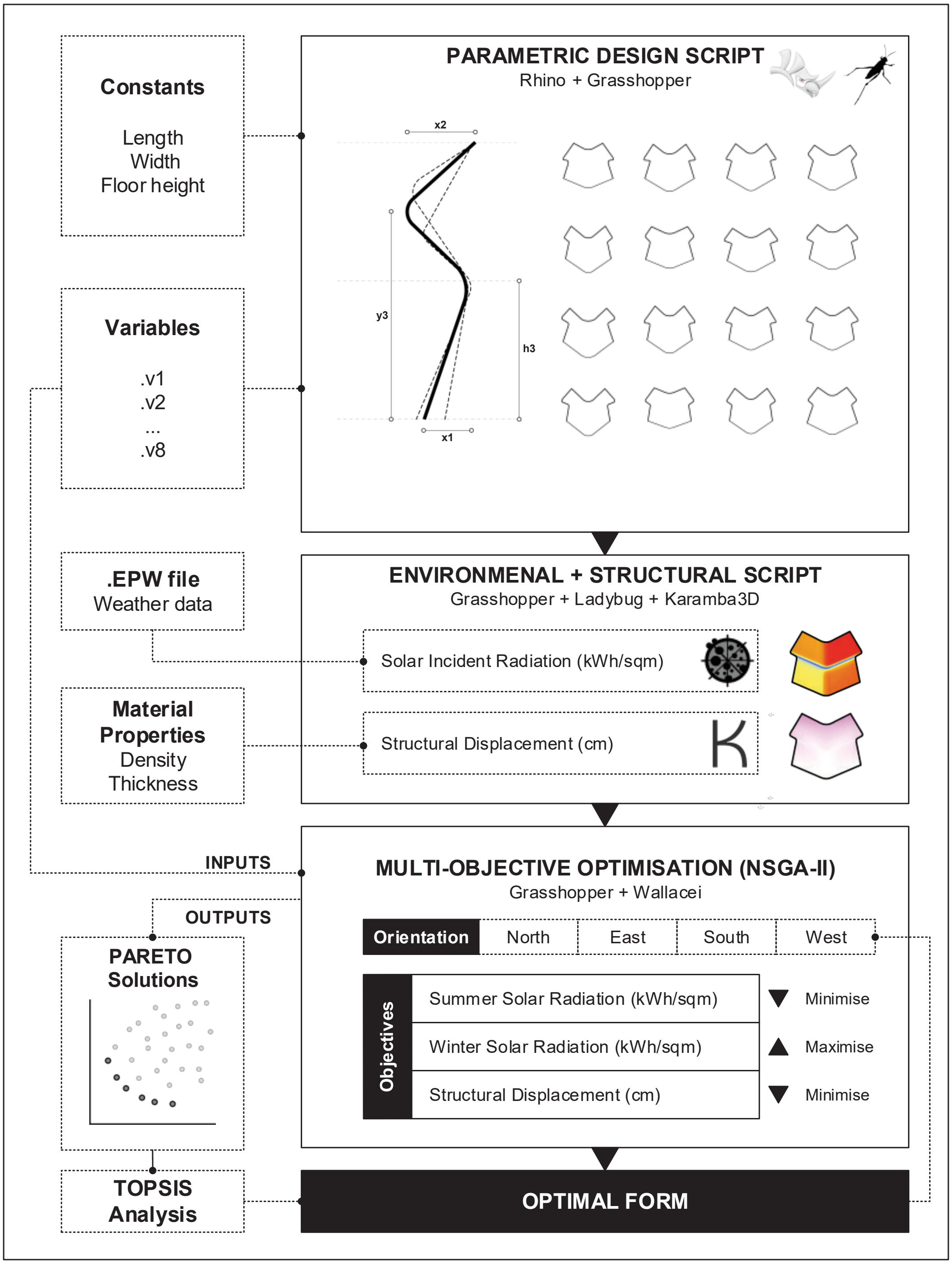

FIG. 6 Diagram summarising the workflow for Phase 1 of the study.

3.1.2 Key Parameters and Structure of the Façade Design

Eight primary parameters drive the generation of the corner wall façade, illustrated in FIG 7, each responsible for different aspects of its geometric configuration:

1. **Profile Articulation**: Six main parameters define the wall's corner profile, breaking the vertical line into three segments marked by four critical points:
   a. *Segment Division*: The vertical profile is segmented at specific points to delineate the ground and upper floors. The lower segment corresponds to the ground floor, while the upper segments represent the upper floor.
   b. *Point Displacements*: Four parameters control the positioning of points 1, 3, and 4 along the Y and Z axes. These points' displacements vary, allowing for a dynamic range of form iterations, each exhibiting unique variations in depth and shape across the façade. TABLE 1 outlines the range of values used for these displacements, enabling a structured yet flexible approach to façade modulation.
   c. *Curvature Control*: To add smoother transitions between segments, two more parameters were added to fillet the corners at points 2 and 3 on the vertical profile. The fillet radii at the points can be adjusted to create tight or loose façade curvature. The different curves of the wall create a sense of continuity along the façade, helping to smooth the transition between the ground and first-floor walls.

2. **Corner Profile Duplication and Orientation**: The main façade profile is duplicated and applied to both adjacent corners of the structure. Each profile copy is rotated by 45 degrees, orienting toward the square's centre, forming a cohesive wrap-around effect at each corner. The positioning of these corner profiles is adjustable through an additional parameter that allows each corner profile to shift either inward or outward relative to the square's corner, creating subtle variations in depth and spatial dynamics along the façade.

3. **Rail Profile Connectivity and Filleting**: Each of the four primary profiles is connected by a continuous rail element that unifies them vertically and horizontally, establishing a smooth transition across the façade segments. The final parameter controls the rail, which adjusts the fillet radius at the corners of the rail. Modifying the fillet creates rounded transitions between profiles, contributing to the façade's overall aesthetic.

4. **Lofting to Create the Façade Surface**: Once all profiles and rails are positioned, they are lofted together to form a continuous façade surface. This lofting operation integrates the profiles and rails into a single, cohesive surface, creating a dynamic façade structure that reflects the unique variations and adjustments defined by the parameters.

By fine-tuning these parameters, this workflow (FIG 8) generates a comprehensive array of façade iterations (FIG 9), each aligned with the core 6 × 6-meter building module, yet showcasing unique façade articulations for further analysis.

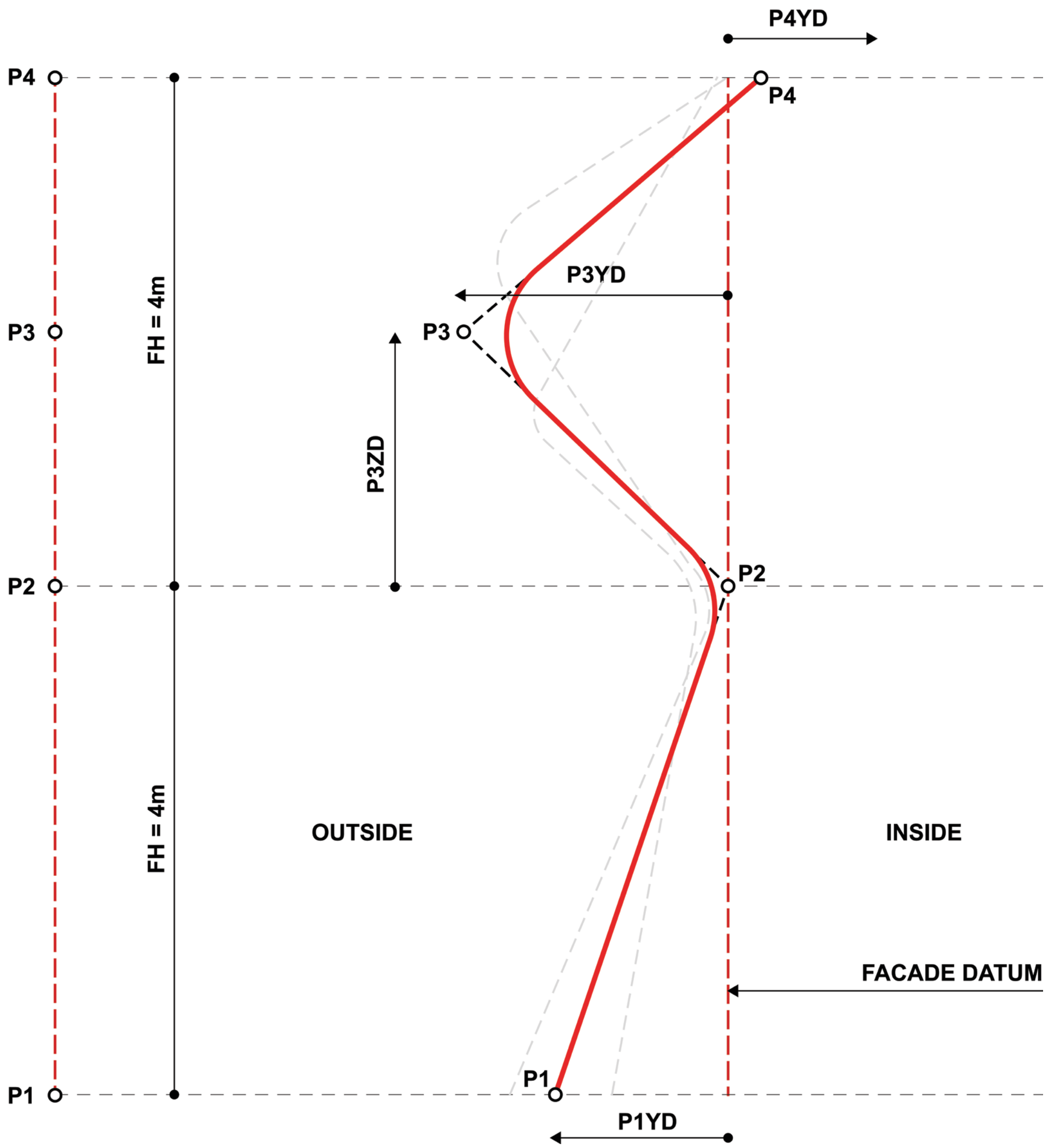

FIG. 7 Key parameters and structure of the façade design.

TABLE 1 Form-finding design parameters with value ranges used to iterate the model.

Parameter	Nomenclature	Value Range (m)	Type
Base-Square-Size	SS	6.0 * 6.0	Fixed
Floor-Height	FH	4.0	Fixed
Point-1_Y-Displacement	P1YD	0.5 - 2.0	Variable
Point-3_Y-Displacement	P3YD	1.5 - 3.0	Variable
Point-3_Z-Displacement	P3ZD	1.2 - 2.8	Variable
Point-4_Y-Displacement	P4YD	0.0 - 1.5	Variable
Point-2_Fillet-Radius	P2FR	0.25 - 1.0	Variable
Point-3_ Fillet-Radius	P3FR	0.25 - 0.5	Variable
Rail_Fillet-Radius	RFR	1.0 - 2.0	Variable
Corner_Displacement	CD	-1.5 - 1.5	Variable

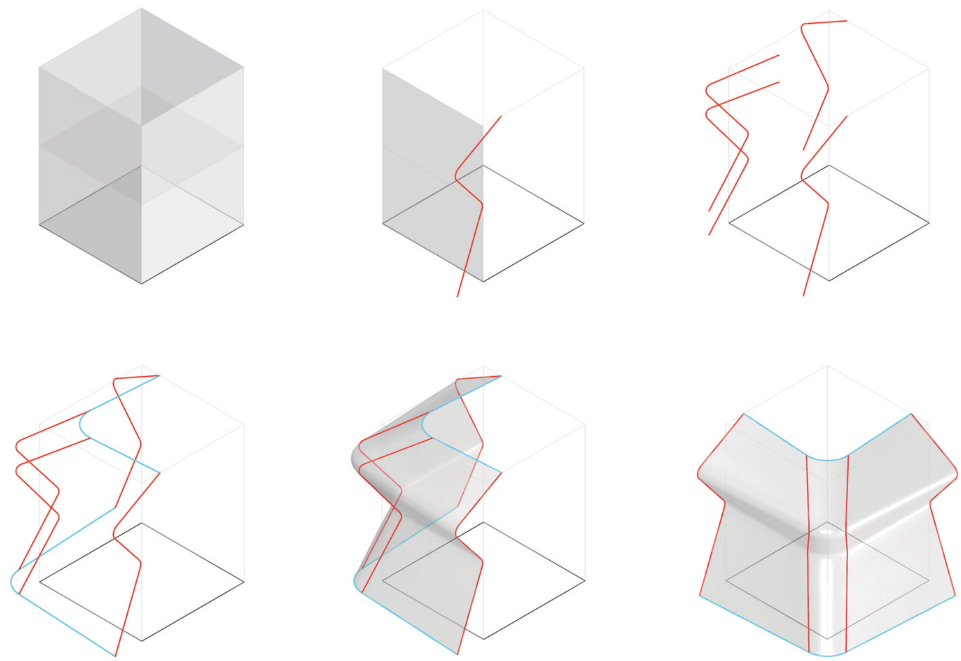

FIG. 8 Parametric generation sequence of the corner façade geometry, showing the transformation from a basic cubic volume to the articulated corner wall surface through the definition, manipulation, and lofting of vertical profiles (red lines).

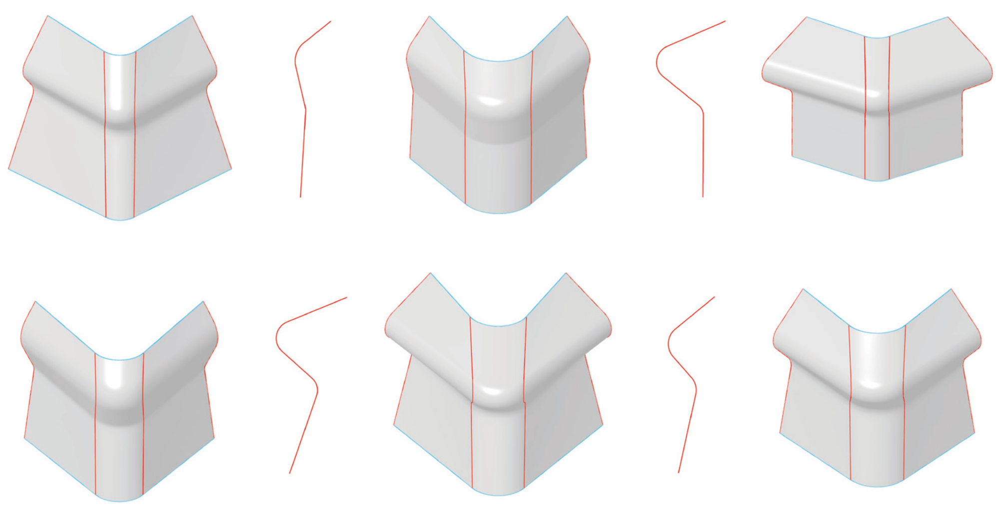

FIG. 9 Six design iterations generated from the parametric form-finding script. Each variation explores changes in key geometric variables that influence façade articulation and self-shading potential.

Environmental Performance

After generating the façade's lofted surface, the design script connects with an additional Ladybug script within Grasshopper to simulate annual solar radiation (FIG 10). This simulation uses the London Heathrow weather file as its climatic input. By applying this data to the façade, the script visualises the distribution of solar radiation across the surface over a typical year, highlighting areas of high and low solar exposure.

The analysis was conducted on the façade with four main orientations: north, east, south, and west. However, this study focuses primarily on the south orientation, which receives the highest solar radiation. To provide seasonal insights, the solar radiation was divided into two key periods: summer (March 21 to September 21) and winter (September 21 to March 21). The main objective is to reduce solar radiation during summer to minimise overheating and cooling energy demand, while maximising solar radiation in winter to enhance passive heating and energy efficiency. These insights are critical for developing optimised shading strategies and improving building performance.

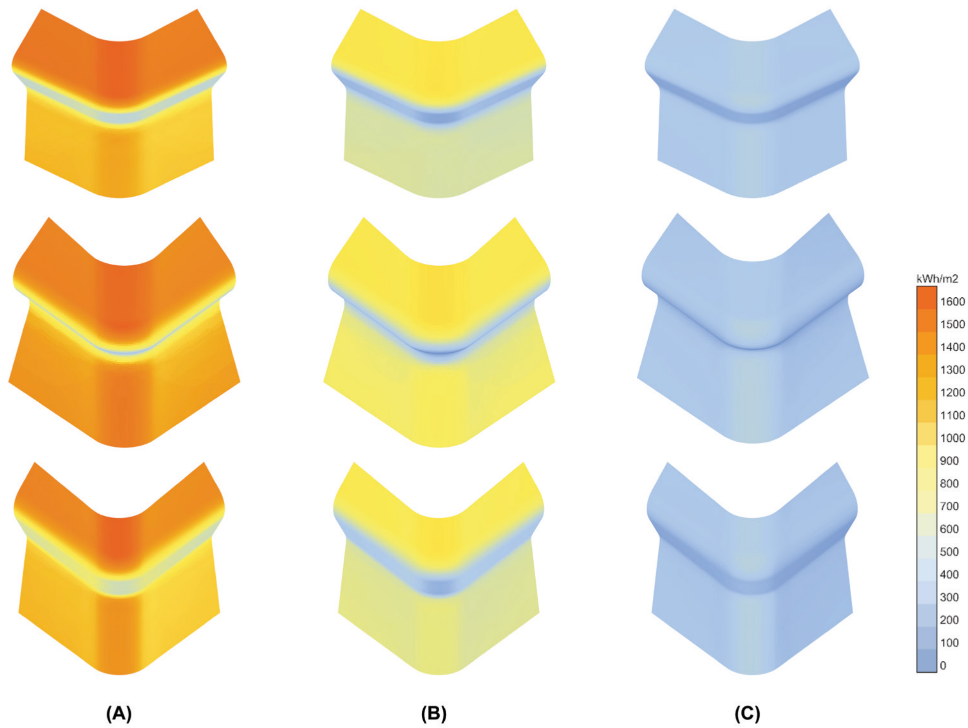

FIG. 10 Incident solar radiation visualisation for three different generated solutions. For each solution, the left column (A) shows the annual total solar radiation, the middle column (B) represents the summer season, and the right column (C) displays the winter season.

Structural Performance

In parallel, a Karamba3D script is integrated into the workflow to evaluate the structural displacement of the lofted surface, illustrated in FIG 11. Material properties are incorporated into the script, with an assumed façade thickness of 10 cm (TABLE 2). PETG's mechanical properties, including elasticity and density, are input into the script to estimate the surface's behaviour under various load conditions. This allows Karamba to calculate and visualise potential displacements or deformations, ensuring the façade's structural integrity.

The analysis assumed the façade structure is fixed only at the base, with gravity and material self-weight as the applied loads, illustrated in FIG 12. While in practice, the structure would be laterally supported by adjacent walls and connected to a roof structure above, analysing it as a self-structural envelope provides a conservative assessment of the façade's inherent load-bearing capacity. This approach isolates the performance of the façade geometry itself, independent of auxiliary support systems, thereby evaluating whether the proposed unified envelope can maintain structural integrity under self-weight, a fundamental prerequisite before considering additional loading scenarios or integration with the broader building structure. This methodology also enables direct comparison across different geometric iterations without confounding variables introduced by varying support conditions.

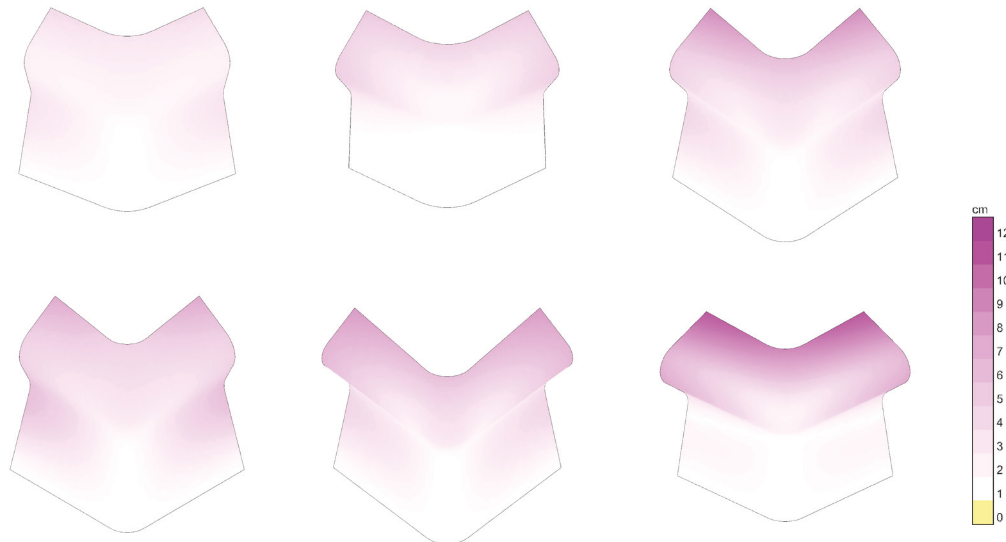

FIG. 11 Displacement of six façade iterations simulated in Karamba (Grasshopper) using PETG material properties. Darker colours indicate higher displacement, measured in centimetres.

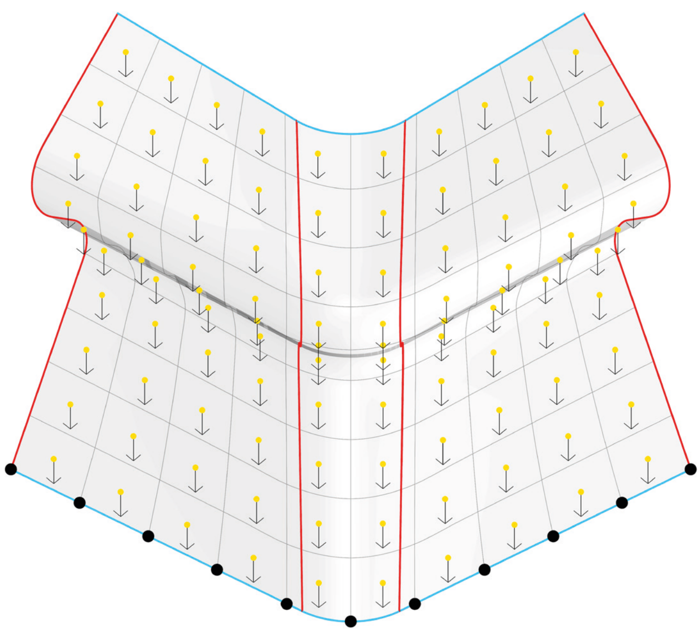

FIG. 12 Structural analysis model in Karamba showing the façade geometry with fixed boundary conditions at the base (black dots) and gravity loads applied to the structure (yellow dots with downward arrows). The red and blue edges delineate the façade profile boundaries.

TABLE 2 PETG material properties.

Material Property	Acronym	Value	Unit
Structure Thickness	T	10	cm
Young's Modulus	E	295	kN/cm^2
In-Plane Shear Modulus	G12	105.43	kN/cm^2
Transverse Shear Modulus	G3	105.43	kN/cm^2
Specific Weight	gamma	12.454	kN/m^3
Coefficient of Thermal Expansion	alphaT	0.000043	1/°C
Tensile Strength	ft	5.868	kN/cm^2
Compressive Strength	fc	5.868	kN/cm^2

3.1.3 Sensitivity Analysis for the Parameters

A sensitivity analysis was conducted to evaluate the relationship between the design parameters and three key objectives: summer and winter solar radiation, and displacement. A simple linear regression was performed for each parameter to assess its R-squared (R^2) value relative to these objectives, measuring the strength of the correlation and the proportion of variance explained.
The method involved varying each parameter individually across its specified range, as outlined in TABLE 1, while keeping all other parameters fixed at their mean values. This approach enabled the isolated examination of each parameter's influence on the objectives. The analysis provided valuable insights into the varying degrees of impact and correlation that each parameter has with the design objectives, aiding understanding of their contributions, as outlined in TABLE 3.

Summer Solar Radiation

The analysis of summer solar radiation across various parameters reveals significant correlations with parameters P1YD, P3YD, P4YD, P2FR, P3DR, and RFR, with R-squared values ranging from 0.848 to 0.996. This indicates that these parameters account for a substantial proportion of the variance in solar radiation, suggesting that they are strong predictors. Parameter P3ZD shows a moderate correlation ($R^2 = 0.781$), whereas CD has the lowest R^2 (0.180), indicating the weakest correlation with summer solar radiation among the parameters. This suggests that CD accounts for only a minimal amount of the variance in summer solar radiation.

Winter Solar Radiation

The analysis of winter solar radiation across various parameters reveals significant correlations for most parameters, with R-squared values ranging from 0.814 to 0.992, indicating that they account for a substantial proportion of the variance in solar radiation and are strong predictors. Parameters P3ZD and P4YD exhibit notably lower R-squared values, 0.559 and 0.768, respectively, suggesting weaker explanatory power for variation in winter solar radiation than other parameters.

Displacement

The linear regression analysis shows strong correlations for parameters P1YD, P3YD, P3ZD, P4YD, P2FR, P3DR, and CD, with R-squared values ranging from 0.856 to 1.00. These parameters demonstrate a reliable linear relationship with the predicted façade displacements. In contrast, RFR exhibits the weakest correlation (R^2 = 0.603), reflecting a weaker linear association.

TABLE 3 Regression results for each parameter across the three objectives: Summer Solar Radiation, Winter Solar Radiation, and Displacement. Reported metrics include R-Squared, Mean Squared Error (MSE), Mean Absolute Error (MAE), Slope, and Intercept.

Objective	Parameter	R-Squared	MSE	MAE	Slope	Intercept
Summer Solar Radiation	P1YD	0.996	0.666	0.650	26.969	571.973
	P3YD	0.991	2.756	1.534	-37.105	689.594
	P3ZD	0.781	2.175	1.318	21.572	594.258
	P4YD	0.996	0.686	0.696	28.517	584.774
	P2FR	0.939	0.218	0.382	7.063	601.829
	P3FR	0.973	0.283	0.369	31.729	593.927
	RFR	0.848	1.057	0.868	-2.717	605.927
	CD	0.180	0.055	0.165	0.347	605.834
Winter Solar Radiation	P1YD	0.814	0.369	0.475	2.758	318.113
	P3YD	0.993	1.198	1.028	-27.471	383.555
	P3ZD	0.559	0.887	0.803	-8.215	325.123
	P4YD	0.768	0.340	0.456	-2.303	323.772
	P2FR	0.869	0.068	0.234	2.593	320.456
	P3DR	0.975	0.138	0.302	23.370	312.931
	RFR	0.992	2.278	1.185	-19.248	323.517
	CD	0.953	0.020	0.112	2.012	319.153
Displacement	P1YD	0.953	0.041	0.175	1.988	6.248
	P3YD	0.989	0.112	0.289	6.772	-6.366
	P3ZD	0.921	0.001	0.020	-0.609	8.826
	P4YD	0.990	0.064	0.216	5.559	4.602
	P2FR	0.856	0.000	0.005	-0.056	8.525
	P3FR	1.000	0.000	0.002	-3.334	9.749
	RFR	0.603	0.084	0.244	0.398	8.197
	CD	0.988	0.001	0.020	-0.699	9.520

3.1.4 Development of a Multiobjective Optimisation Framework

A multiobjective optimisation framework was developed to address the conflicting design goals. The framework utilised the Wallacei plugin within Grasshopper, which implements the NSGA-II to optimise multiple objectives simultaneously. This process was structured as described in the following paragraphs.

Parameter and Objective Definition

The process began by defining the design parameters and objectives. As detailed in TABLE 4, the parameters were carefully selected based on their influence on the design objectives, as determined by the sensitivity analysis. Eight parameters were defined, each representing a critical design variable. The possible values for each parameter were determined in 1 cm increments, resulting in a finely granular range of options.

This granular approach resulted in a vast search space of possible design solutions, calculated as the product of the possible values for all eight parameters. The total number of potential solutions was approximately 8.5 quadrillion. Such an extensive search space highlights the complexity and computational challenge of the optimisation process, as it was impractical to evaluate all possible combinations exhaustively. This further emphasised the need to employ advanced optimisation algorithms, such as NSGA-II, to explore the search space and efficiently identify optimal solutions.

TABLE 4 Design Parameters, Value Ranges, and Search Space for Form Generation.

Parameter	Parameter	Value Range (m)	Number of Values
Base-Square-Size	SS	0.5 – 2.0	151
Floor-Height	FH	1.5 – 3.0	151
Point-1_Y-Displacement	P1YD	1.2 – 2.8	41
Point-3_Y-Displacement	P3YD	0.0 – 1.5	151
Point-3_Z-Displacement	P3ZD	0.25 – 1.0	76
Point-4_Y-Displacement	P4YD	0.25 – 0.5	26
Point-2_Fillet-Radius	P2FR	1.0 – 2.0	301
Point-3_ Fillet-Radius	P3FR	-1.5 – 1.5	101
Rail_Fillet-Radius	RFR	1.0 - 2.0	Variable
Corner_Displacement	CD	-1.5 - 1.5	Variable
	Number of possible solutions [Search Space] 8,479,876,127,884,620		

The sensitivity analysis revealed a critical relationship between the objectives: summer solar radiation and displacement were directly proportional, while winter solar radiation was inversely proportional to both. This interplay introduced additional complexity to the optimisation process, as improving one objective often adversely affected another.

Optimisation Process

The framework was configured with 50 generations and 20 genes per generation, resulting in 1,000 runs. Each design solution, represented as a gene, was evaluated against the three objectives, with the algorithm iteratively refining the solutions through genetic operations, including crossover, mutation, and selection. The result was a Pareto front of non-dominated solutions, where no objective could be improved without worsening at least one other objective. These solutions represented the trade-offs between the conflicting objectives, providing a comprehensive view of the optimisation landscape. To ensure robustness and prevent premature convergence to a local optimum, the optimisation was run multiple times with different initial combinations of design variables.
This approach helped explore the search space more thoroughly and increased the likelihood of identifying global optimum solutions.

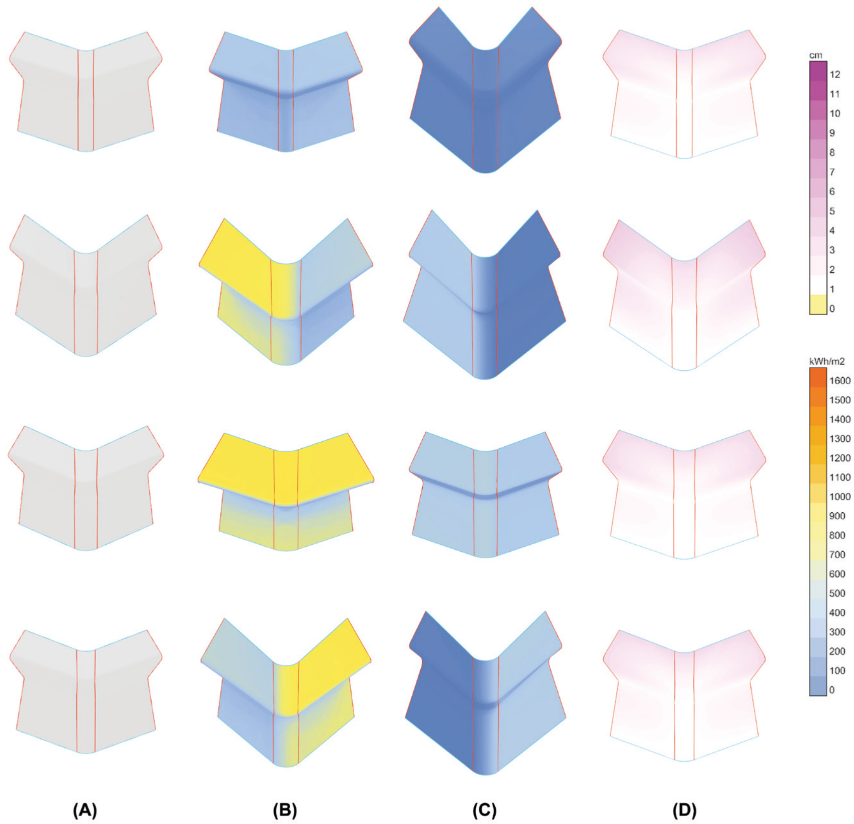

FIG. 13 Visual comparison of the 16 optimal façade solutions categorised by optimisation objective and orientation. Column (a) presents the solutions selected using the TOPSIS method, while columns (b), (c), and (d) show the solutions optimised individually for summer solar radiation, winter solar radiation, and displacement, respectively. Each row corresponds to a specific orientation, from top to bottom: north, east, south, and west, respectively. The colour maps represent solar radiation in kWh/m^2 and displacement in cm.

Optimisation Results

A total of 16 optimal façade solutions were identified through the multiobjective optimisation process, with four optimal configurations generated for each orientation (north, east, south, and west), illustrated in FIG 13. These included the TOPSIS-based optimal solution, along with optimised solutions for summer solar and winter solar radiation, and structural displacement. The results show variation across objectives, with some trade-offs observed between solar performance and displacement. Notably, for both the north and west façades, the displacement-optimal solution coincided with the TOPSIS-optimal one, indicating that in these cases, minimal deformation was aligned with a balanced solar performance. This overlap suggests that specific design configurations can simultaneously meet both structural and environmental criteria, thereby reducing the need for further compromise or adjustment.

The analysis of the optimisation results reveals several key insights into the relationship between solar performance, structural displacement, and surface area. South-facing façades consistently exhibited the highest levels of both summer and winter solar radiation, confirming their critical role in passive solar design. However, these orientations also showed moderate displacement values, indicating a potential trade-off between solar gain and structural flexibility. In contrast, the north façade received the lowest solar radiation but achieved the smallest displacements, making it more structurally stable but less effective for energy capture. The east and west façades demonstrated greater variation in both displacement and solar values, highlighting their performance sensitivity to specific geometric configurations. The surface area was generally larger in solutions optimised for solar gain, suggesting that increased exposure often came at the cost of higher deformation. These findings underscore the importance of orientation-specific design strategies and the value of multiobjective optimisation in achieving balanced façade performance.

To evaluate the performance gains, all solutions were benchmarked against a traditional vertical façade with an identical footprint (6 m x 8 m per façade). The improvement analysis reveals that the optimal summer solar solutions achieved reductions in summer solar radiation ranging from 7.30% (west) to 13.99% (north) compared to the conventional vertical configuration. Simultaneously, the optimal winter solar solutions demonstrated substantial increases in winter solar gain, ranging from 3.61% (west) to 26.80% (north), highlighting the capacity of geometrically articulated façades to enhance passive solar heating during colder months (TABLE 5).

TABLE 5 Comparison of façade solutions based on TOPSIS ranking, summer and winter solar radiation performance, displacement, and surface area across four orientations. The table presents the optimal solution according to the TOPSIS method alongside solutions optimised individually for summer solar gain, winter solar gain, and structural displacement.

	Objective	Traditional Façade	TOPSIS Optimal Solution	Optimal Summer Solar Solution	Optimal Winter Solar Solution	Optimal Displace-ment Solution	Improve-ment	Unit
North	Summer Solar	355	319.33	305.33	466.84	325.74	13.99%	kWh/m^2
	Winter Solar	96	87.40	85.19	121.73	88.01	26.80%	
	Displacement	-	1.71	2.50	7.59	1.66	-	cm
	Surface Area	96	93.86	94.31	153.45	95.29	-	m^2
East	Summer Solar	460	466.61	423.31	500.42	466.61	7.98%	kWh/m^2
	Winter Solar	212	210.17	192.88	226.01	210.17	6.61%	
	Displacement	-	2.56	8.49	6.60	2.56	-	cm
	Surface Area	96	120.10	154.76	149.36	120.10	-	m^2
South	Summer Solar	591	581.38	530.58	616.74	594.22	10.22%	kWh/m^2
	Winter Solar	346	353.57	327.78	379.45	374.74	9.67%	
	Displacement	-	2.33	9.54	2.56	1.78	-	cm
	Surface Area	96	102.41	115.33	97.37	95.46	-	m^2
West	Summer Solar	486	517.80	450.54	504.45	517.80	7.30%	kWh/m^2
	Winter Solar	230	211.80	212.38	238.31	211.80	3.61%	
	Displacement	-	1.81	7.19	4.37	1.81	-	cm
	Surface Area	96	97.12	152.13	146.00	97.12	-	m^2

These quantitative improvements demonstrate the efficacy of the multiobjective optimisation framework in generating façades that outperform conventional planar configurations across multiple environmental criteria.

Analysis of the South-Oriented Façade Pareto Front

To build on the broader optimisation findings, this section provides a deeper analysis of the south-oriented façade, examining how the three objectives interact across its Pareto front.
The south orientation was selected for detailed analysis because of its critical role in passive solar design. Among all façades, it consistently received the highest levels of solar exposure, making

it especially relevant for evaluating both thermal and daylighting performance. Focusing on this orientation enables a clearer understanding of the trade-offs between solar control and structural behaviour. It provides a well-suited basis for selecting a geometry to carry forward into the daylight simulation phase.

The Pareto front analysis of the south-facing façade reveals a clear trade-off landscape between the three primary performance objectives: minimising summer solar gain, maximising winter solar access, and reducing structural displacement. As shown in FIG 14, the 3D scatter and corresponding 2D plots illustrate a well-defined Pareto frontier, where solutions begin to cluster along a curved edge, indicating non-dominated performance trade-offs. Summer and winter solar gains exhibit a positive correlation, while both are inversely related to displacement. This suggests that improving environmental performance often comes at the cost of increased deformation, particularly when surface area is expanded to capture more solar radiation.

TABLE 6 Design parameter values for the four selected south-facing façade solutions: the TOPSIS Optimal Solution, the Optimal Summer Solar Solution, the Optimal Winter Solar Solution, and the Optimal Displacement Solution.

Parameters	TOPSIS Optimal Solution	Optimal Summer Solar Solution	Optimal Winter Solar Solution	Optimal Displacement Solution	Unit
P1YD	0.52	0.51	1.15	0.75	m
P3YD	1.67	2.83	1.53	1.55	
P3ZD	0.59	0.30	0.40	0.60	
P4YD	0.04	0.02	0.20	0.05	
P2FR	0.62	0.35	0.75	0.57	
P3FR	0.35	0.34	0.35	0.33	
RFR	1.28	1.65	1.54	1.34	
CD	-0.78	-1.38	-1.46	-1.39	

From this analysis, four key solutions were extracted and compared in TABLE 6: the TOPSIS-optimal solution, the solutions optimised individually for summer solar gain, winter solar gain, and displacement. These options span the Pareto front, capturing different prioritisation strategies within the solution space. The TOPSIS solution offers a balanced compromise between the three objectives, with moderate solar values and relatively low displacement. In contrast, the summer solar-optimal solution significantly reduces exposure, albeit at a higher displacement and with a larger surface area to provide shade on the lower part of the façade. The winter solar-optimal solution captures the most solar gain in colder months but is also associated with increased surface area and corresponding structural impact. The displacement-optimised solution achieves the lowest deformation while still maintaining moderate solar performance.

This comparative analysis is essential in selecting the candidate for further daylight investigation in Phase 2. The TOPSIS-optimal geometry was ultimately chosen for its well-rounded performance across all objectives. Unlike extremes that prioritise one criterion at the expense of others, this solution offers a balanced design that integrates solar exposure control with structural efficiency. Furthermore, its moderate form of complexity made it suitable for applying transmittance gradients without introducing excessive simulation burden. This decision ensured continuity between performance-based form finding and the subsequent daylight optimisation process.

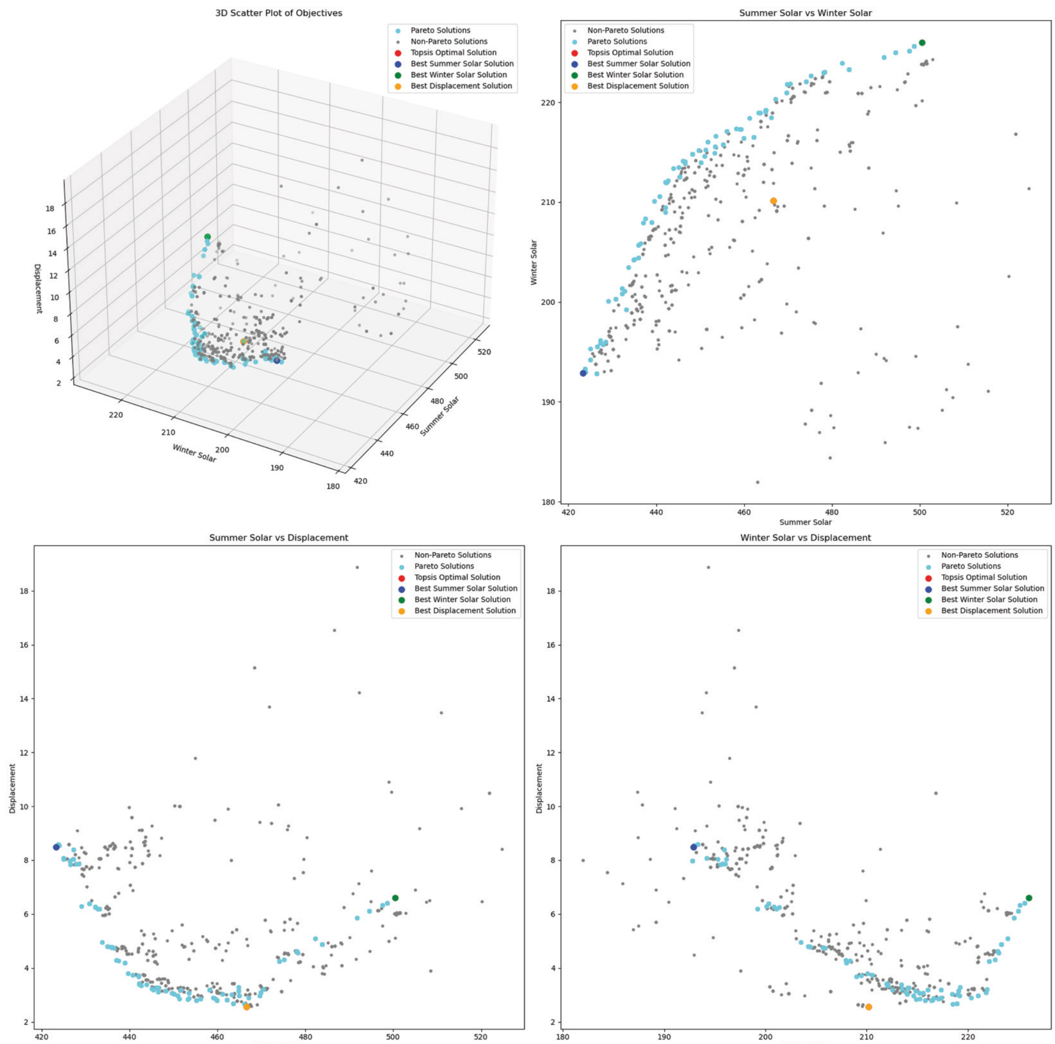

FIG. 14 Optimisation Pareto Front for the south-oriented façade.

3.2 PHASE 2: DAYLIGHT PERFORMANCE ANALYSIS & TRANSMITTANCE GRADIENT GENERATION

The primary objective of this phase was to conduct a daylight performance analysis of the transmittance gradient design, utilising the P1OG, to determine the optimal transmittance values for achieving indoor daylight levels and daylight comfort. This phase consists of two key steps: (1) generating optimised variable transmittance models and (2) conducting daylight performance analysis of the optimised models, summarised in FIG 15.

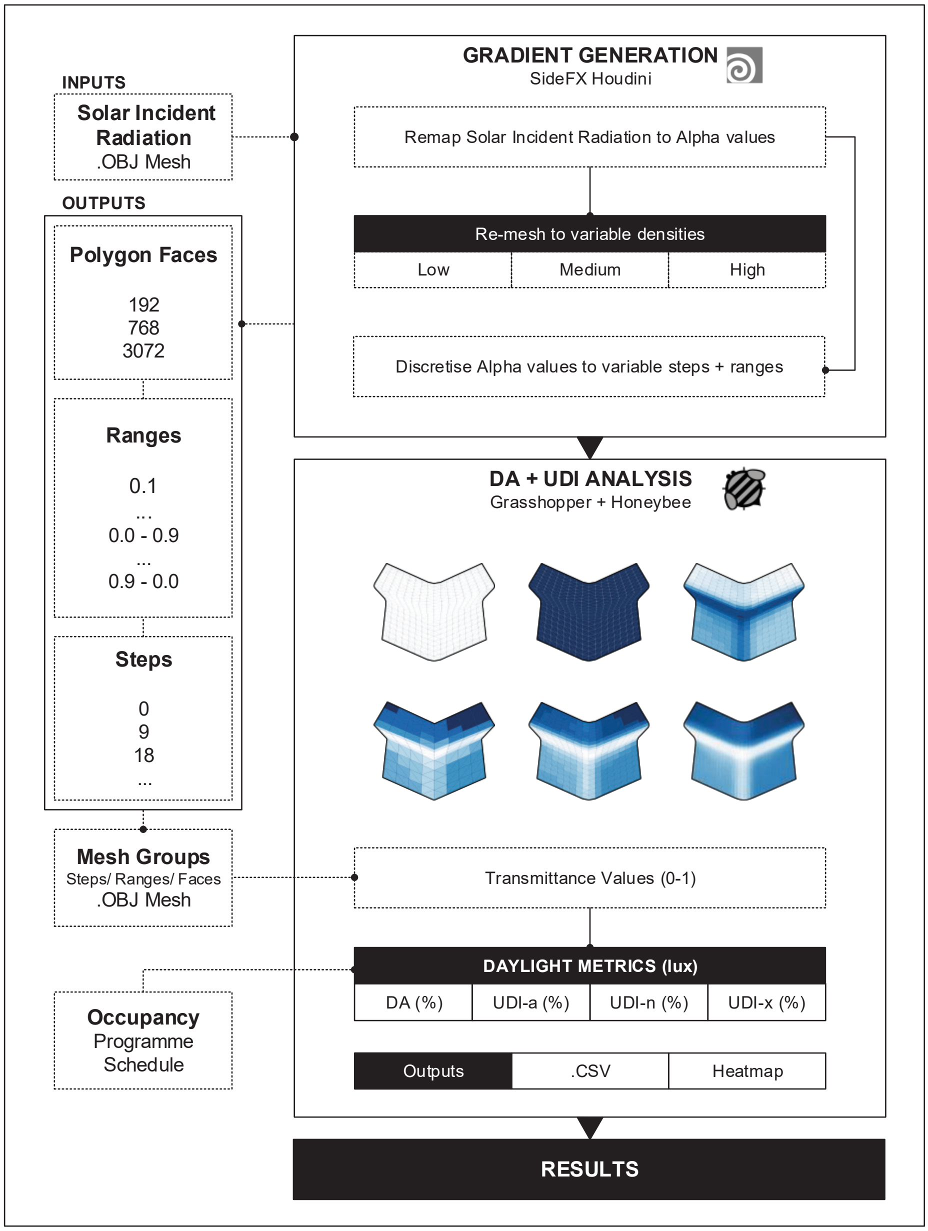

FIG. 15 Diagram summarising the workflow for Phase 2 of the study.

3.2.1 Optimised Gradient Transmittance Models

Various models were generated by reconstructing the P10G at different mesh densities and discretising the gradient into a series of varying step resolutions. It was essential to optimise the model to avoid unnecessarily long simulation times during the daylight performance analysis. This provided an opportunity to compare model complexity, defined by mesh and gradient resolution, against analysis accuracy and simulation runtime to identify the point at which increased model resolution no longer yielded significant benefits. P10G, containing the whole year radiation heatmap, was used in the following steps.

Gradient Generation

The heatmap was converted into a linear grayscale gradient and normalised to the range 0 to 1. Alpha (transparency) values were then assigned to each vertex directly from these remapped values. To enhance the visual distinction of the opaque-to-transparent gradient, a colour was applied to the model gradient. This resulted in a continuous façade geometry exhibiting variable optical properties in both colour and opacity, as illustrated in FIG 16.

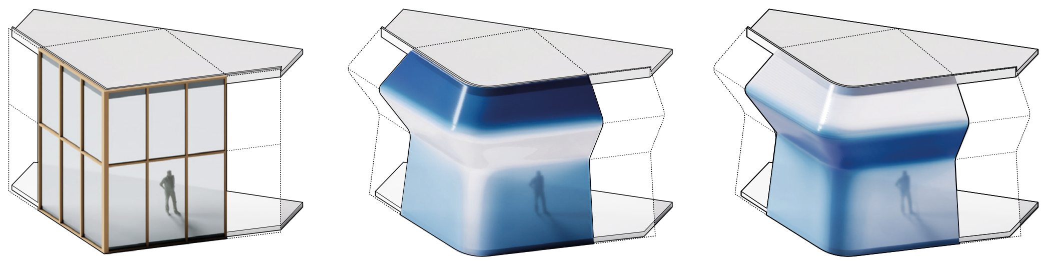

FIG. 16 Diagrams of (a) the standard curtain wall façade, (b) the gradient design on the optimal geometry (blue represents opacity; and white, transparency), (c) the inverted gradient design on the optimal geometry (blue represents opacity; and white, transparency).

Optimised Model Variations

The geometry was reconstructed into a simplified mesh, preserving the displacement parameters of the model profile from the optimal solution, and subdivided into three density versions, Low Poly (LP), Medium Poly (MP), and High Poly (HP), as shown in TABLE 7. An *Attribute Transfer* operation in SideFX Houdini was used to map the solar radiation heatmap, stored as vertex colours, of the original mesh onto the simplified mesh. This function transfers attributes based on spatial proximity (SideFX, n.d.). The colour gradient was discretised into a varying number of steps for each simplified mesh, shown in FIG 17. Colour and Alpha values of each vertex correspond to the transmittance values used in the environmental simulation. Polygons were grouped and sorted by colour attribute and then sent to Grasshopper for environmental analysis.

TABLE 7 Model variations of mesh density and gradient steps.

	Phase 1 Model (P1)	Low Poly Model (LP)	Medium Poly Model (MP)	High Poly Model (HP)
Number of polygons	10396	192	768	3072
Number of gradient steps	202	9	9	9
	-	18	18	18
	-	36	36	36
	-	-	-	180

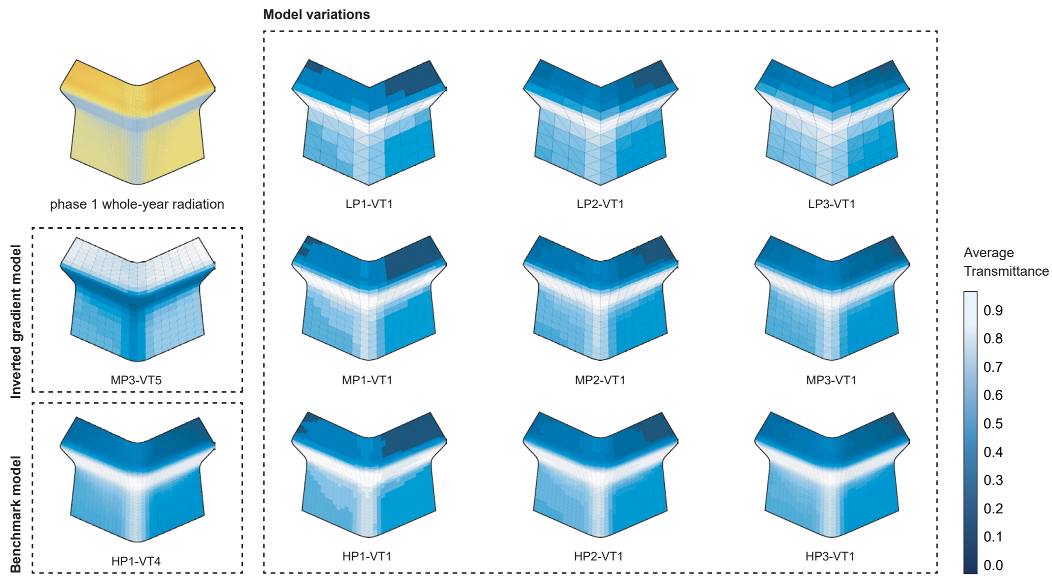

FIG. 17 Phase 1: Optimal façade geometry with whole-year solar radiation heatmap, and Phase 2: Optimised transmittance model variations.

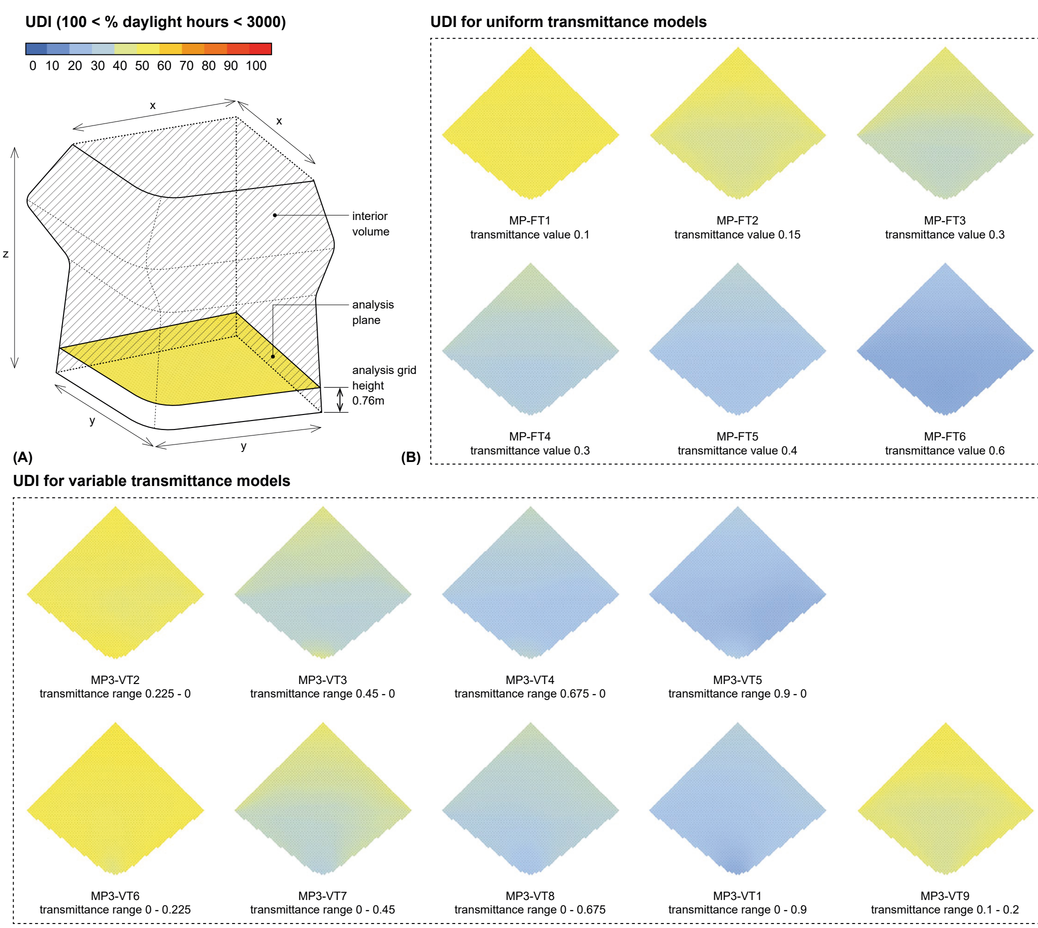

FIG. 18 Diagram of (a) the interior volume, working plane height, and open plan layout alongside UDI analysis heatmaps of (b) uniform and (c) variable transmittance models.

3.2.2 Daylight Performance Analysis

The output mesh groups were mapped to HB transmittance values based on their sorting, within a range of 0 to 0.9, and used to construct an HB model from faces. This simulation uses the London Heathrow weather file as its climatic input. DA was evaluated against a 500-lux threshold, representing a high-performing minimum target illuminance specified in (BS EN 17037:2018, 2021). UDI was assessed within the 100-3000 lux range, capturing a broad spectrum of daylight conditions suitable for office environments. An occupancy programme representing a typical large office was used to define the occupancy schedule, weekdays between 8 AM and 5 PM, specifying the number of occupied hours throughout the year. An open plan floor plan was defined for the occupancy layout. Analysis results were collected for key daylight metrics on a working plane height of 0.76m, including Spatial Daylight Autonomy (sDA), Autonomous Useful Daylight Illuminance (UDI-a), Non-useful Daylight Illuminance (UD-n), and Excessive Daylight Illuminance (UDI-x), each expressed as a percentage of the occupied hours. FIG 18(a) shows the defined interior volume, working plane, and open-plan occupancy layout. UDI-a captures the percentage of occupied hours when illuminance is within the useful range of 100–3000 lux, thereby supporting visual comfort without the need for supplementary lighting. UDI-n captures the percentage of occupied hours when illuminance is below 100 lux, indicating underlit conditions requiring artificial lighting. UDI-x captures the percentage of occupied hours when illuminance exceeds 3000 lux, representing over-lit conditions that may cause glare or visual discomfort (Education Funding Agency, 2014). The aim for each performance metric is shown in TABLE 8.

TABLE 8 Performance criteria aims.

Performance Criteria	Unit	Objective
Autonomous Useful Daylight Illuminance (UDI-a)	%	Max
Non-useful Daylight Illuminance (UD-n)	%	Min
Excessive Daylight Illuminance (UDI-x)	%	Min
Spatial Daylight Autonomy (sDA)	%	Max

TABLE 9 Average DA, UDI-a, UDI-n, UDI-x and simulation run times for different model variations. (Model naming convention: LP: Low polygon count, MP: Medium polygon count, HP: High polygon count, VT: Variable transmittance, FT: Fixed Transmittance)

Model Variations	Faces	Steps	Transmittance Rang	Time (mins)	verage DA 500 (%)	Average UDI-a (%)	Average UDI-n (%)	Average UDI-x (%)
LP1-VT1	192	9	0 - 0.9	4.6	62.28	25.19	32.26	42.55
LP2-VT1	192	18	0 - 0.9	3.6	62.35	24.93	32.23	42.84
LP3-VT1	192	36	0 - 0.9	3.9	63.14	22.35	32.01	45.64
MP1-VT1	768	9	0 - 0.9	5.8	62.32	25.05	32.24	42.70
MP2-VT1	768	18	0 - 0.9	5.4	62.34	24.97	32.24	42.79
MP3-VT1	768	36	0 - 0.9	5.8	62.32	25.07	32.24	42.69
HP1-VT1	3072	9	0 - 0.9	7.1	62.29	25.17	32.26	42.58
HP2-VT1	3072	18	0 - 0.9	6.1	62.31	25.08	32.25	42.68
HP3-VT1	3072	36	0 - 0.9	8.0	62.32	25.08	32.24	42.68
HP4-VT1	3072	180	0 - 0.9	8.9	62.31	25.11	32.24	42.64

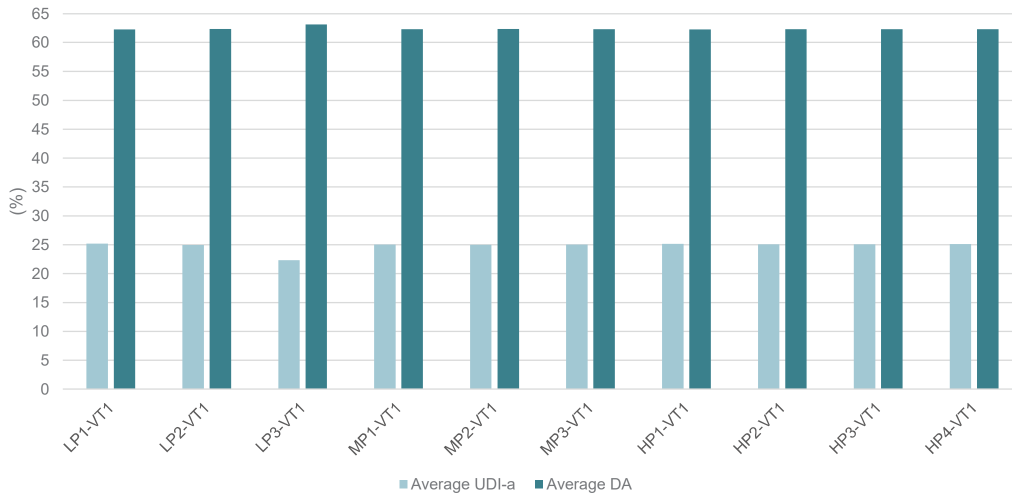

FIG. 19 Bar chart of average UDI-a and DA for the benchmark model and model variations of gradient resolutions.

Evaluating the Impact of Model Resolution on Daylight Analysis Accuracy

Model variations shown in TABLE 9 were first analysed to compare run time and accuracy. The results are compared in FIG 19. In this study, the model variation HP4-VT1 (3072 faces, 180 steps) is used as the benchmark to evaluate the impact of gradient resolution on daylight analysis accuracy across all model iterations, as it has the highest number of steps and mesh resolution, providing the most accurate and closest approximation to a smooth gradient.

To compare the model variations with the benchmark, an Absolute Relative Difference (ARD) was calculated for the mean values of each UDI-a and DA. This is defined as:

$$\text{ARD} = \left| \frac{\bar{x}_{\text{model variation}} - \bar{x}_{\text{benchmark}}}{\bar{x}_{\text{benchmark}}} \right| \times 100$$

The ARD measures the difference between the benchmark mean and each model variation's mean, expressing the magnitude of this difference as a percentage value, as shown in TABLE 10. UDI ARD for LP models differed by an average of 4.02%, MP models by an average of 0.32%, and HP models by an average of 0.17%.

Across all lower-resolution iterations, the DA values remained closely aligned with the benchmark, with a maximum DA ARD of just 1.33%, indicating that gradient and mesh resolution had a minimal impact on the sDA. UDI was more responsive to resolution, with the highest ARD of 11% in model variation *LP3-VT1*, reflecting reduced accuracy in daylight distribution at coarse resolutions. As the resolution increases, particularly in models *MP3-VT1* and *HP3-VT1*, UDI converges toward the benchmark, with differences of less than 0.2%, indicating near-equivalent accuracy.

TABLE 10 The DA ARD and UDI-a ARD for each model variation.

Model Variations	Faces	Steps	DA ARD (%)	UDI-a ARD (%)
LP1-VT1	192	9	0.05	0.32
LP2-VT1	192	18	0.07	0.73
LP3-VT1	192	36	1.33	11.02
MP1-VT1	768	9	0.02	0.24
MP2-VT1	768	18	0.05	0.55
MP3-VT1	768	36	0.02	0.18
HP1-VT1	3072	9	0.03	0.22
HP2-VT1	3072	18	0.00	0.14
HP3-VT1	3072	36	0.01	0.15

This trend indicates that while increased gradient resolution has minimal influence on sDA, it does affect UDI accuracy. The results also demonstrate that simulation time is predominantly influenced by model complexity, with computation time increasing with the number of faces, as shown in FIG 20. In contrast, the number of transmittance steps exhibits a less predictable impact on simulation time. Based on the results, an MP model complexity of 768 faces was selected to determine the optimal transmittance range.

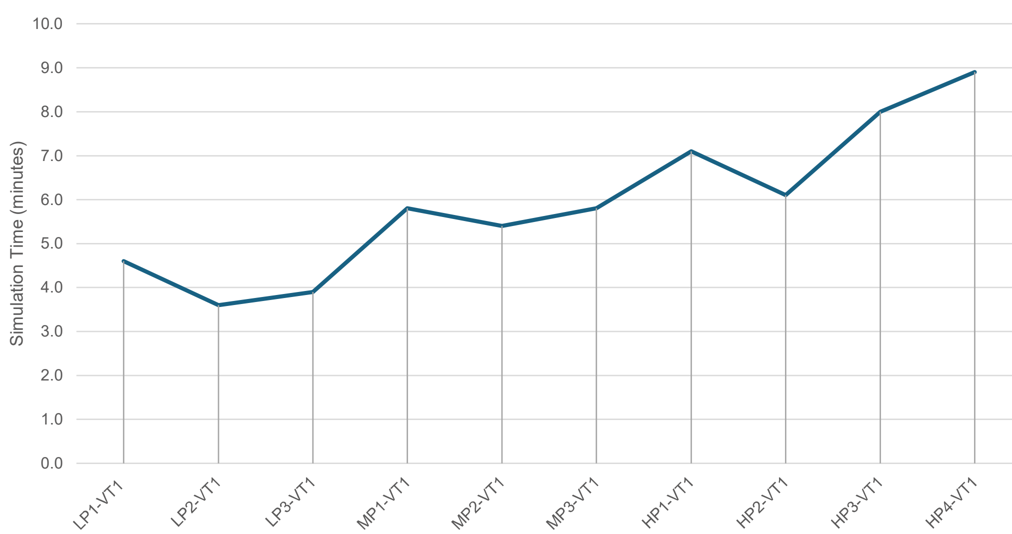

FIG. 20 Line chart of simulation runtimes across model variations.

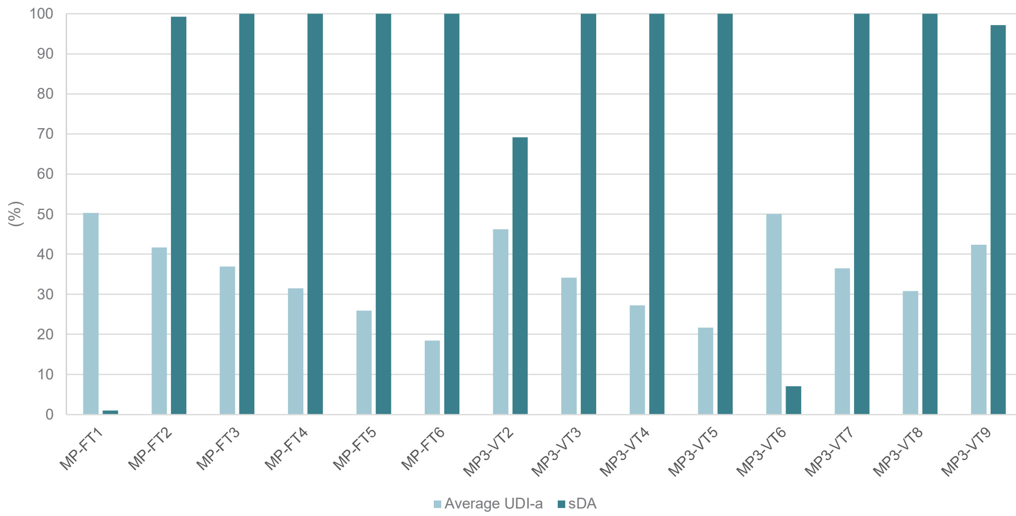

FIG. 21 Bar chart of average UDI-a and sDA for uniform and variable transmittance models.

Determining the Optimal Transmittance Range for Daylight Performance

Additional model variations, shown in TABLE 11 and FIG 21, were analysed to determine the optimal transmittance range for the gradient design.

Based on the Department for Education (DfE) daylight performance criteria (Department for Education, 2022), a scoring methodology was developed to quantitatively compare and rank the performance of each model variation. Models achieving an sDA of 50% or greater were assigned a maximum score of 1. Models below this threshold were scored proportionally, scaled between 0 and 1, defined as:

$$\mathrm{sDA_{score}} = \frac{\mathrm{sDA}}{50}$$

For UDI-a, with a target of 80% within the 100-3000 lux range, the score was based on the absolute difference from this target, normalised between 0 and 1, defined as:

$$\mathrm{UDI_{score}} = 1 - \frac{|\mathrm{UDI} - 80|}{80}$$

A composite score was then calculated, providing a single performance indicator that integrates both daylight sufficiency and distribution quality, as presented in TABLE 12. This was defined as:

$$\text{Composite Score} = \frac{\mathrm{sDA_{score}} + \mathrm{UDI_{score}}}{2}$$

Among the uniform transmittance models, *MP-FT1* (0.1 fixed transmittance) demonstrated the best UDI-a performance with an average of 50.32%; however, the sDA achieved 0%, resulting in the lowest composite score (0.31). *MP-FT2* (0.15 fixed transmittance) achieved the highest composite score (0.76) with an sDA of 99.27% and an average UDI-a of 41.69%.

As transmittance increased, UDI-a declined significantly, indicating a higher risk of daylight discomfort due to excessive illuminance as reflected in higher UDI-x values.

TABLE 11 Simulation run times, average DA, sDA, average UDI, average UDI-n, and average UDI-x for fixed and variable transmittance models.

Model Variations	Faces	Steps	Transmittance Range	Average DA 500 (%)	SDA 500,50% (%)	Average UDI-a (%)	Average UDI-n (%)	Average UDI-x (%)
MP-FT1	768	-	0.1	46.54	0	50.32	37.53	12.15
MP-FT2	768	-	0.15	52.93	99.27	41.69	35.22	23.10
MP-FT3	768	-	0.2	56.83	100	36.93	34.00	29.07
MP-FT4	768	-	0.3	60.40	100	31.48	32.76	35.76
MP-FT5	768	-	0.4	62.16	100	25.93	32.26	41.82
MP-FT6	768	-	0.6	64.53	100	18.50	31.65	49.85
MP3-VT2	768	36	0.225 – 0	50.44	69.21	46.24	36.08	17.68
MP3-VT3	768	36	0.45 – 0	59.11	100	34.16	33.16	32.68
MP3-VT4	768	36	0.675 – 0	61.87	100	27.27	32.35	40.37
MP3-VT5	768	36	0.9 – 0	63.52	100	21.72	31.88	46.41
MP3-VT6	768	36	0 – 0.225	46.51	7.09	50.04	37.57	12.40
MP3-VT7	768	36	0 – 0.45	56.90	100	36.50	34.00	29.50
MP3-VT8	768	36	0 – 0.675	60.44	100	30.83	32.75	36.41
MP3-VT9	768	36	0.1 – 0.2	52.39	97.18	42.38	35.43	22.19

TABLE 12 *Composite score analysis indicated that the sDA score, UDI-a score, and combined score ranked from best to worst performance.*

Optimised Model	sDA Score	UDI Score	Composite Score
MP3-VT2	1	0.58	0.79
MP3-VT9	1	0.53	0.76
MP-FT2	1	0.52	0.76
MP-FT3	1	0.46	0.73
MP3-VT7	1	0.46	0.73
MP3-VT3	1	0.43	0.71
MP-FT4	1	0.39	0.70
MP3-VT8	1	0.39	0.69
MP3-VT4	1	0.34	0.67
MP-FT5	1	0.32	0.66
MP3-VT5	1	0.27	0.64
MP-FT6	1	0.23	0.62
MP3-VT6	0.14	0.63	0.38
MP-FT1	0	0.63	0.31

The variable transmittance model *MP3-VT2* achieved the highest composite score (0.79) among all fixed and variable models, demonstrating a balanced performance across daylight sufficiency (average DA = 50.44%), distribution (sDA = 69.21%), and daylight quality (average UDI-a = 46.24%). Among the variable transmittance models, *MP3-VT6* achieved the highest UDI-a (50.04%); however, again at the cost of sDA (7.09%).

TABLE 13 Results for average DA, sDA, average UDI, average UDI-n, average UDI-x, and Composite Score of a fully glazed curtain wall model, compared with the fixed transmittance model MP-FT6 and the best performing model MP3-VT2.

	Transmittance Range	Average DA 500 (%)	sDA 500,50% (%)	Average UDI-a (%)	Average UDI-n (%)	Average UDI-x (%)	Composite Score
Curtain Wall Model	0.6	63.82	100	20.30	31.80	47.91	0.63
MP-FT6	0.6	64.53	100	18.50	31.65	49.85	0.62
MP3-VT2	0.225 – 0	50.44	69.21	46.24	36.08	17.68	0.79

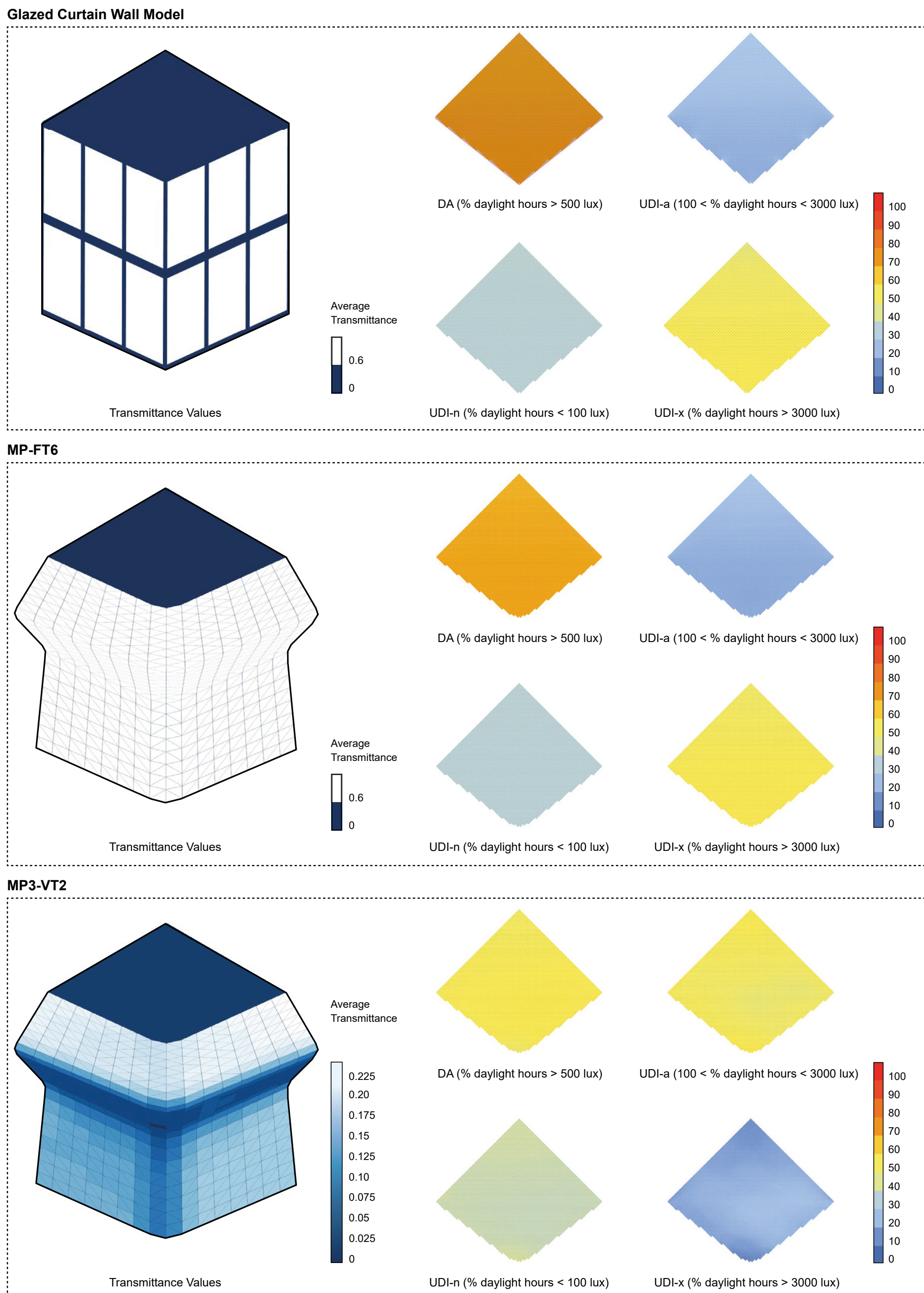

FIG. 22 Diagram of transmittance values and associated DA, UDI, UDI-n, and UDI-x for the Glazed Curtain Wall Model, MP-FT6 and MP3-VT2.

Comparative Analysis

To conclude Phase 2, an analysis of a fully glazed curtain wall façade, with a window-to-wall ratio of 92% on the south-facing walls, in the same position and orientation, was conducted as a further comparison against a fixed transmittance model, *MP-FT6*, and the best-performing variable transmittance model, *MP3-VT2*, shown in TABLE 13 and FIG 22.

MP-FT6 represents the optimal geometry identified in Section 3.1, without any subsequent optimisation of transmittance gradients. In this configuration, a uniform transmittance value of 0.6 is applied, matching that of the glazed curtain wall. As expected, when no transmittance gradients are introduced, the performance of the optimal geometry resembles that of the fully glazed reference façade. The results demonstrate that the variable transmittance model MP3-VT2, which combines optimal geometry with optimised transmittance gradients (shown in FIG 23), significantly outperforms a conventional fully glazed curtain wall system, improving the UDI-a by 25.94%, from 20.30% to 46.24%. Although most model variations exceeded the sDA targets for this study, none achieved a UDI-a target of 80% within the 100-3000 lux range.

Numerous factors may contribute to the target of 80% UDI-a not being achieved. Firstly, the entire room is likely to be underlit during specific periods of the year, particularly in winter mornings and late afternoons when exterior illuminance is naturally low. This is evident from the fully glazed curtain wall, which still yields a UDI-n of 31.80%, indicating that even with maximum daylight exposure for this orientation and configuration, a significant percentage of occupied hours remain underlit. This also suggests that an 80% UDI-a is a highly ambitious year-round target for the occupancy schedule used in this study. Another factor to consider is the specific gradient transmittance pattern applied. In this study, the patterns closely follow the initial solar radiation heatmap on the façade surface. Although the transmittance ranges were adjusted and inverted, the underlying distribution pattern remained essentially unchanged, which is a limitation of the gradient optimisation method. Alternative gradient configurations may therefore yield UDI-a values that exceed those achieved in the current set of models.

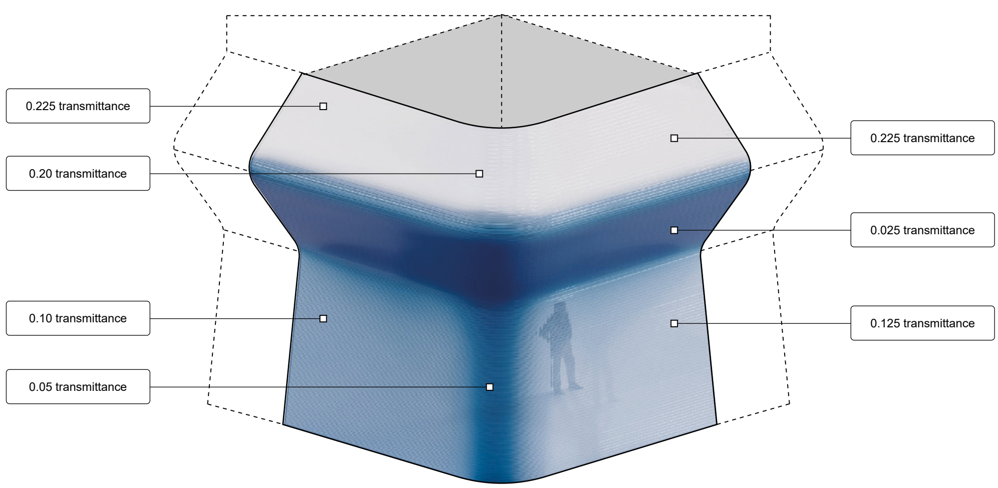

FIG. 23 Diagram of the best-performing variable transmittance model MP3-VT2 demonstrating the gradient applied to the optimal geometry.

4 CONCLUSION

This study investigated the digital design of PETG façades with variable transmittance properties intended for future fabrication via LSR3DP, addressing two fundamental questions: how can multiobjective optimisation be applied to identify façade forms that balance solar performance with structural efficiency, and how can solar-informed transmittance gradients be systematically distributed and discretised to achieve comfortable daylight levels?

The study demonstrates that multiobjective optimisation using NSGA-II can effectively navigate complex design trade-offs, identifying geometrically optimised façades that significantly outperform conventional vertical configurations, achieving reductions in summer solar radiation of up to 13.99% and increases in winter solar gain of up to 26.8% for different orientations whilst maintaining acceptable structural displacement. More significantly, the systematic application of solar-informed transmittance gradients through procedural discretisation workflows proved highly effective for daylight control, with the optimal configuration delivering a 25.94% improvement in Useful Daylight Illuminance compared to a standard curtain wall system. This performance gain was achieved through material-based light modulation rather than mechanical shading devices, validating the premise that transmittance variations can be embedded directly into the façade system to provide spatially responsive daylight control. The results establish that unified, multi-property envelopes enabled by LSR3DP can compete with, and in key metrics exceed, the performance of conventional multilayered façade assemblies.

4.1 SUMMARY OF KEY RESULTS

The proposed two-phase methodology established a unified workflow that responds to both structural and environmental performance criteria.

In Phase 1, a script was developed to generate a diverse range of corner façade geometries, defined by eight geometric parameters. Sensitivity analysis revealed strong correlations between specific parameters and the three target performance objectives, providing insight into which aspects of the geometry most influence environmental and structural outcomes. A multiobjective optimisation process, implemented using the NSGA-II algorithm, was then employed to navigate the extensive design space and identify façade solutions that balanced competing objectives. Sixteen optimal configurations were identified across four main orientations, including solutions individually optimised for solar exposure and structural deformation, as well as aggregated solutions ranked via TOPSIS.

When focusing on the south-oriented façade, additional insights emerged regarding how displacement interacted with the environmental objectives and influenced the resulting geometries. The optimal solution for summer solar reduction exhibited a pronounced overhang, effectively casting self-shade over the lower portions of the façade to reduce incident radiation. This shading strategy resulted in the most geometrically articulated form, with the largest surface area and the highest structural displacement among the four solutions, highlighting a clear trade-off between environmental control and structural stability. In contrast, the displacement-optimal solution, the winter solar-optimal solution, and the TOPSIS-optimal solution shared a similar, more linear profile. These configurations exhibited minimal surface articulation and a more compact geometry, leading to reduced displacement and smaller surface areas. While the winter solar solution introduced a subtle surface extension to enhance solar gain during low-angle winter sun conditions, its overall form remained closely aligned with the structurally efficient displacement-optimal variant. The resemblance among these three solutions suggests a convergence in which structural stability and seasonal solar access can be achieved without excessive formal complexity.

Building on the south-oriented optimal geometry, Phase 2 focused on exploring daylight performance by applying solar-informed transmittance gradients. A procedural workflow was developed to discretise and apply gradient values across the façade surface, replacing the conventional aperture-based daylighting approach. Rather than relying on windows embedded within an opaque envelope, this method modulates light transmission continuously through localised variations in material transparency, offering a more nuanced and spatially resolved form of daylight control.

Simulations conducted in Phase 2 using multiple mesh densities and gradient resolutions confirmed that while spatial daylight autonomy (sDA) remained relatively stable across all model variations, useful daylight illuminance (UDI-a) was more sensitive to resolution and benefited significantly from finer gradient control. A detailed comparative analysis revealed that lower-resolution meshes, particularly those with fewer polygons, led to notable deviations in UDI-a accuracy. In contrast, higher-resolution models provided greater precision but at the cost of significantly longer simulation times. Interestingly, the number of gradient steps had minimal effect on sDA and a less predictable impact on runtime, whereas mesh complexity was the dominant factor influencing computational demand.

Based on the trade-off between accuracy and simulation efficiency, the medium-resolution model with 768 polygons was selected for the final transmittance range analysis. This configuration offered near-equivalent performance to the high-resolution benchmark while substantially reducing computation time, making it the most practical choice for the remaining daylight simulations.
The highest-performing variable transmittance model demonstrated substantial improvements in daylight distribution and quality compared to both uniform transmittance alternatives and a fully glazed curtain wall benchmark. These improvements were achieved without sacrificing structural integrity or geometric expressiveness. The findings demonstrate that by embedding environmental data directly into the form and material logic of the façade, it is possible to produce adaptive, performance-optimised surfaces that integrate structural and daylighting functions holistically.

4.2 STUDY IMPLICATIONS

This integrated approach presents a significant shift from conventional façade strategies, offering new opportunities for environmentally responsive architecture through the interaction of digital fabrication, parametric modelling, and environmental simulation.

The scientific relevance of these findings extends beyond the specific geometry and transmittance values identified. This work establishes quantitative benchmarks for evaluating unified, multi-property building envelopes: the improvement in daylight quality demonstrates that material-based transmittance modulation can achieve performance levels previously requiring mechanical shading systems, whilst the geometric analysis reveals that moderate formal complexity can deliver comparable environmental benefits to highly articulated forms, while maintaining structural efficiency. These outcomes challenge conventional assumptions that high-performing façades necessitate either complex geometries or mechanical systems.

By demonstrating measurable improvements across multiple performance criteria through embedded material properties, this study provides empirical evidence supporting the technical feasibility of LSR3DP-enabled façades as viable alternatives to conventional multilayered assemblies. The discretisation methodology developed in Phase 2 addresses a critical gap in translating continuous performance data into stepped transmittance zones suitable for simulation and eventual fabrication, establishing practical guidance for balancing computational accuracy against simulation efficiency in performance-driven façade design.

4.3 LIMITATIONS AND FUTURE WORK

The simulated transmittance values used in this study relied on proxy material properties and uniform optical behaviour, which can differ significantly from the actual performance of 3D-printed structures. In practice, factors such as print resolution, layer thickness, surface roughness, and internal infill geometry introduce variability in light transmission that daylight simulations often fail to capture. The anisotropic nature of printed layers, combined with material-specific scattering and absorption effects, can substantially alter both the quantity and quality of transmitted light. As a result, empirical testing would be essential to validate and calibrate simulation data, ensuring that predicted daylight performance more closely aligns with physical behaviour. Future research should prioritise physical prototyping and empirical validation of the transmittance gradients, alongside the exploration of fabrication strategies to realise multi-property PETG façades at an architectural scale.

References

BS EN 17037:2018. (2021). BSI. https://knowledge.bsigroup.com/products/daylight-in-buildings-1

Bollinger, K., Grohmann, M., & Tessman, O. (2010). Form follows performance. In *Symposium on Simulation for Architecture and Urban Design*.

Castañeda, E., Lauret, B., Lirola, J. M., & Ovando, G. (2015). Free-form architectural envelopes: Digital processes opportunities of industrial production at a reasonable price. *Journal of Façade Design and Engineering*, *3*(1), 1–13. https://doi.org/10.3233/fde-150031

Cheibas, I., Gamote, R. P., Lloret-Fritschi, E., Arnold, K., Luible, A., Gramazio, F., & Kohler, M. (2024). 3D printing of a multi-performative building envelope: Assessment of air permeability, water tightness, wind loads, and impact resistance. *Journal of Building Engineering*, *98*. https://doi.org/10.1016/j.jobe.2024.111251

Cheibas, I., Piccioni, V., Lloret-Fritschi, E., Leschok, M., Schlüter, A., Dilllenburger, B., Gramazio, F., & Kohler, M. (2023). Light Distribution in 3D-Printed Thermoplastics. *3D Printing and Additive Manufacturing*, *10*(6), 1164–1177. https://doi.org/10.1089/3dp.2023.0050

Department for Education. (2022). *School Output Specification Technical Annex 2E: Daylight and Electric Lighting*. https://assets.publishing.service.gov.uk/media/637e13508fa8f56eb1a0ad14/GDB_Annex_2E_DaylightAndElectricLighting-A-C11.pdf

Education Funding Agency. (2014). *Baseline Design-Daylight Strategy*. https://assets.publishing.service.gov.uk/media/5b3b6a27ed915d33ced545ca/Baseline_designs_daylight_strategy_Dec_2014.pdf

Engelsmann, S., Spalding, V., & Peters, S. (2010). *Plastics*. https://doi.org/10.1515/9783034611947

Fan, Z., Liu, M., & Tang, S. (2022). A multiobjective optimization design method for gymnasium façade shading ratio integrating energy load and daylight comfort. *Building and Environment*, *207*. https://doi.org/10.1016/j.buildenv.2021.108527

Grigoriadis, K., & Lee, G. (2024). *3D printing and material extrusion in architecture: Construction and design manuals*. DOM Publishers.

Grigoriadis, K. (2018). The current state of autography. *International Journal of Rapid Manufacturing, 7* (2/3), 277–294. https://doi.org/10.1504/IJRAPIDM.2018.092902

Grigoriadis, K. (2019). Computational blends: The epistemology of designing with functionally graded materials. *Journal of Architecture*, *24*(2), 160–192. https://doi.org/10.1080/13602365.2019.1578074

Hwang, CL., Yoon, K. (1981). Methods for Multiple Attribute Decision Making. In: Multiple Attribute Decision Making. Lecture Notes in Economics and Mathematical Systems, vol 186. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-48318-9_3

K. Deb, A. Pratap, S. Agarwal and T. Meyarivan, "A fast and elitist multiobjective genetic algorithm: NSGA-II," in IEEE Transactions on Evolutionary Computation, vol. 6, no. 2, pp. 182-197, April 2002, doi: 10.1109/4235.996017.

Kwon, H., Kyttas, T., Eichenhofer, M., & Dillenburger, B. (2019). Digital Composites: Robotic 3D Printing of Continuous Carbon Fiber-Reinforced Plastics for Functionally-Graded Building Components. *Robotic Fabrication in Architecture, Art and Design 2018: Foreword by Sigrid Brell-Çokcan and Johannes Braumann, Association for Robots in Architecture*, 363–376. https://doi.org/10.1007/978-3-319-92294-2_28

Lin, C. H., & Tsay, Y. S. (2024). A practical decision process for building façade performance optimization by integrating machine learning and evolutionary algorithms. *Journal of Asian Architecture and Building Engineering*, *23*(2), 740–753. https://doi.org/10.1080/13467581.2023.2244564

Milano, F., Gamote, R. P., Olivo, N. E., Piccioni, V., Chen, P. Y., Gallagher, C., Schlueter, A., Dillenburger, B., Luible, A., Gramazio, F., & Kohler, M. (2024). Integration of a 3D-Printed Façade Unit in a Curtain Wall System: Prototyping and Assessment. *Journal of Façade Design and Engineering*, *12*(1), 9–28. https://doi.org/10.47982/jfde.2024.325

Mungenast, M. (2017). 3d-Printed Low-tech Future Façades – Development of 3d-printed Functional-Geometries for Building Envelopes. *PowerSkin Conference Proceedings* , 307–317.

Piccioni, V., Turrin, M., & Tenpierik, M. J. (2020). A Performance-Driven Approach for the Design of Cellular Geometries with Low Thermal Conductivity for Application in 3D-Printed Façade Components. *Of the Symposium on Simulation for Architecture and Urban Design SimAUD*.

Preisinger, C. (2013). Linking structure and parametric geometry. *Architectural Design*, *83*(2), 110-113. https://doi.org/10.1002/ad.1564

Robert McNeel & Associates. (n.d.). *Rhinoceros 3D* [Computer software]. Retrieved November 21, 2025, from https://www.rhino3d.com/

Roudsari, M., & Ladybug Tools LLC. (n.d.). *Ladybug Tools* [Software & documentation]. Retrieved November 21, 2025, from https://www.ladybug.tools/

Rutten, D., & Robert McNeel & Associates. (n.d.). *Grasshopper 3D* [Visual programming environment]. Retrieved November 21, 2025, from https://www.grasshopper3d.com/

Quillet, A., & Rogan, D. (2022). *Wonova: the future of façades? - Eckersley O'Callaghan*. https://www.eocengineers.com/wonova-the-future-of-facades/

Sarakinioti, M. V., Turrin, M., Konstantinou, T., Tenpierik, M., & Knaack, U. (2018). Developing an integrated 3D-printed façade with complex geometries for active temperature control. *Materials Today Communications*, *15*, 275–279. https://doi.org/10.1016/j.mtcomm.2018.02.027

Shan, R., & Shi, T. (2016). Multiobjective optimization of building façade design strategies. In *Proceedings of the 3rd Asia Conference of the International Building Performance Simulation Association (ASim 2016)*. IBPSA.

Showkatbakhsh, M., Makki, M., & Song, Y. (n.d.). *Wallacei* [Software plugin]. Retrieved August 1, 2025, from https://www.wallacei.com/

SideFX. (n.d.). (n.d.). *Attribute Transfer*. Retrieved July 27, 2025, from https://www.sidefx.com/docs/houdini/nodes/sop/attribtransfer.html

Taseva, Y., Eftekhar, N., Kwon, H., Leschok, M., & Dillenburger, B. (2020). *LARGE-SCALE 3D PRINTING FOR FUNCTIONALLY-GRADED FAÇADE* (Vol. 1).

Tee, Y. L., Peng, C., Pille, P., Leary, M., & Tran, P. (2020). PolyJet 3D Printing of Composite Materials: Experimental and Modelling Approach. *JOM*, *72*(3), 1105–1117. https://doi.org/10.1007/s11837-020-04014-w

Tenpierik, M., Turrin, M., Wattez, Y., Cosmatu, T., & Tsafou, S. (2018). *View of Double Face 2.0: A lightweight translucent adaptable Trombe wall | SPOOL*. https://spool.ac/index.php/spool/article/view/86/85

Vazquez, E., & Duarte, J. (2022). Exploring the Impact of Geometry and Fibre Arrangements on Daylight Control in Bistable Kinetic Shades. *Journal of Façade Design and Engineering*, *10*(1). https://doi.org/10.47982/jfde.2022.1.03

Wagiri, F., Shih, S. G., Harsono, K., & Wijaya, D. C. (2024). Multiobjective optimization of kinetic façade aperture ratios for daylight and solar radiation control. *Journal of Building Physics*, *47*(4), 355–385. https://doi.org/10.1177/17442591231219793

Yuan, P. F., Beh, H. S., Yang, X., Zhang, L., & Gao, T. (2022). Feasibility study of large-scale mass customization 3D printing framework system with a case study on Nanjing Happy Valley East Gate. *Frontiers of Architectural Research*, *11*(4), 670–680. https://doi.org/10.1016/j.foar.2022.05.005

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