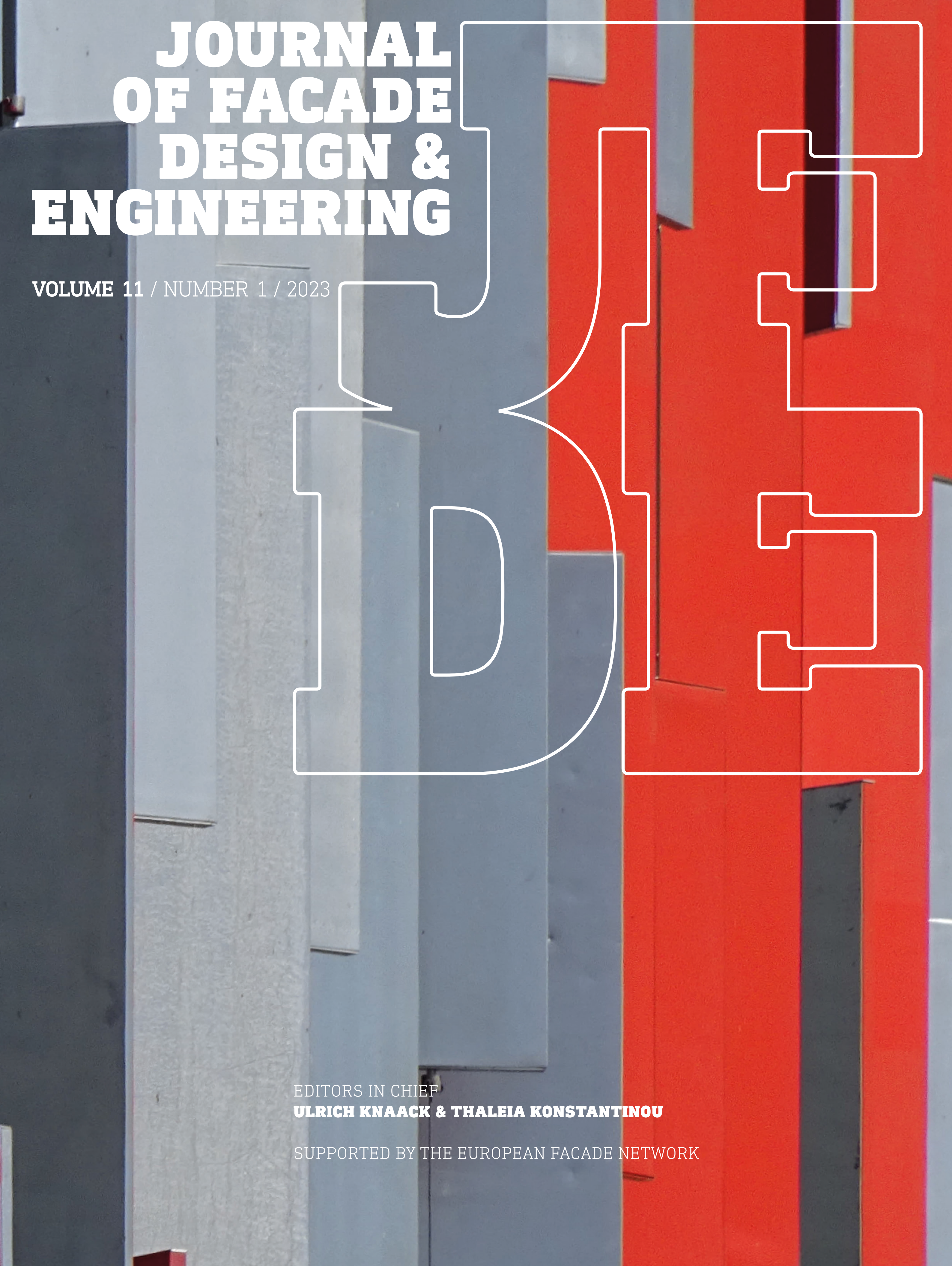

JOURNAL OF FACADE DESIGN & ENGINEERING

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EDITORS IN CHIEF
ULRICH KNAACK & THALEIA KONSTANTINOU

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ENSNARE modular façade system combining RIVENTI's and ONYX's technologies. Image courtesy of Nuria Jorge.

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EDITORIAL

Thaleia Konstantinou[1], Ulrich Knaack[1] (Eds.)

1 Delft University of Technology

The first issue of volume 11 of JFDE elaborates on several topics related to façade design and engineering, focusing on façade systems, their construction, properties, and performance.

The topic of prefabrication in façade construction is one of the themes emerging from this issue. The importance of prefabrication is growing in the building industry as it has the potential to improve productivity by allowing faster, high-quality, and cost-effective construction while reducing risks related to onsite construction. Different articles touch on this topic from varying perspectives. In the context of decarbonization and the large number of buildings to be renovated, prefabrication for energy retrofits is a relevant topic. One notable article presents the development and evaluation of prefabricated timber-based façade modules. The results showed significant energy savings and effective vapor release of the prefabricated façade system. Furthermore, prefabrication and pre-engineering of systems require a paradigm shift in design and engineering practices towards more integrated approaches. A Kit-of-Part (KoP) approach to façade design employed by the authors of a different article enables an architect-led design team to validate design options through digital design tools based on a pre-engineered set of components. Information about the products included in the tool includes performance, cost, and environmental impact.

Focusing further on the properties of façade components, a paper in this issue investigates large-scale applications in building design regarding the aluminum used in façades and underlines the environmental benefits to be gained from reducing the use of raw materials, with particular emphasis on a sustainable approach to façade design. Finally, the issue addresses shading as an essential component of façade function, examining the influence of different shading devices on both performance and aesthetic aspects of the façade.

Overall, the issue provides insights into contemporary trends in façade design, emphasizing the role of pre-engineering and evaluating façade components in contributing to the future of the construction industry.

The Editors-in-Chief,
Thaleia Konstantinou and Ulrich Knaack

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Energy retrofit with prefabricated timber-based façade modules

Pre- and post-comparison between two identical buildings

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Abstract

The introduction of prefabrication into the building façade retrofit market is still difficult due to many financial, economic, and social constraints, as well as technical and performance requirements that differ from those of new construction. The technical feasibility, construction details, and actual comfort and energy-saving benefits provided by the installation of prefabricated façade modules are still being investigated, as is one goal of the specific case study presented here. The Renew-Wall project aims to create a new modular, timber-based, non-intrusive system for retrofitting buildings, developing a series of significant and fully customisable innovations compared to currently available solutions. This paper describes the main properties of the designed prefabricated façade system, with a focus on its energy and thermo-hygrometric performances. Simulation and laboratory tests are compared with an experimental analysis conducted on two identical mock-up buildings (test cells) during a two-year monitoring campaign in which only one of the two test cells was retrofitted. The results show simulated average annual energy savings of 67%, perfectly in line with what was measured on-site. The prefabricated façade system also demonstrates efficient vapour release and a reduced risk of mould and fungus attack.

Keywords

building façade retrofitting, timber-based façade, hygrothermal performance, building renovation, prefabricated construction

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1 INTRODUCTION

In the context of deep energy retrofit of buildings, which is defined as a renovation that captures the full economic energy-efficiency potential of improvement works to existing buildings, leading to a very high-energy performance (Shnapp, Sitjà & Laustsen, 2013), improving the performance of the building façade, even with prefabricated systems, is one of the most successful strategies for reducing overall energy consumption (Martinez & Choil). The number of European-funded projects involving prefabricated façade systems and deep renovation solutions is thus significantly increasing, and the literature (D'oca, Op 't Veld, & Tisov, 2017) demonstrates that significant efforts are being made to advance these solutions both technically and financially.

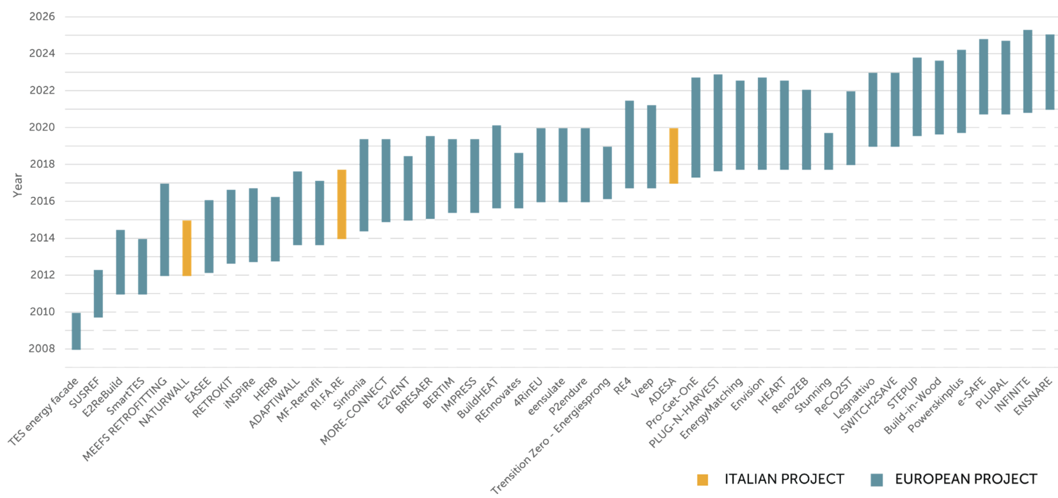

FIG. 1 List of funded European and Italian projects on prefabricated façade modules. The bars represent the duration of the projects.

Currently, prefabrication is widely used in new construction, involving prefabricated concrete staircases, windows, partition walls, and other components (Richard, 2005). Today, building façades can also be completely pre-assembled off-site, with a variety of materials, either timber-based (Callegari, Spinelli, Bianco, Serra & Fantucci, 2015; Capener, Burke, Le Roux & Ott, 2014), metal-based (Dannapfel et al., 2019; Torres et al., 2021) or with reinforced concrete (Pittau, Malighetti, Iannaccone & Masera,2017; Salvalai, Sesana & Iannaccone, 2017). Their benefits are widely discussed in literature, including cost, time, human resources, environmental sustainability (Teng, Li, Pan & Ng, 2018), materials, management and planning, and architectural design: compared to in-situ construction, they ensure less dependence on weather conditions, high quality, and fast assembly (Shahpari, Saradj, Pishvaee & Piri, 2020). Prefabricated façades can also incorporate elements of the HVAC system (Dermentzis, Ochs, Siegele & Feist, 2018) or intelligent control systems (Arnesano et al., 2019), resulting in a multifunctional component (Capeluto, 2019): an additional layer of thermal and acoustic insulation, a structural reinforcement to increase the seismic resistance of the building (Zanni et al., 2021), a component that can improve the hygrometric and air-tightness performance of the wall (Pihelo & Kalamees, 2021), or an element that gives the building a new and improved exterior appearance. The façade module can also include windows, glazing, and shading elements to control solar gain, illuminance, glare, and summer overheating.

Even though these benefits are valid for both new and existing building interventions, introducing prefabrication into the building retrofit market remains problematic. A number of financial, economic, and social barriers (D'Oca et al., 2018), as well as technical and performance requirements, still exist despite interesting innovations in incentives and business models to accelerate the implementation of the integrated product (Azcarate-Aguerre, Heijer & Klein, 2018). Prefabricating is indeed difficult when dealing with constantly changing starting conditions, and designing façade components that can be easily adapted to each experimental use case is still a challenge (Kasperzyk, Kim & Brilakis, 2017), whether in terms of the appropriate materials to be used, the integration of HVAC systems and shading elements or, more generally, the overall relationship to the existing context. This is especially true in Italy, where the built environment displays a wide range of varieties and shapes as a result of its extensive architectural history (Alfano & de Santoli, 2017) and where research on prefabricated façade systems is still limited, not least for this very reason (Fig.1).

The real concern for stakeholders in this field, however, is still to understand the actual energy consumption savings achieved by installing these systems. Many researchers have already contributed to this topic. Silva et al. (Silva, Almeida, Bragança & Mesquita, 2013), using a dynamic simulation model, vary a façade panel's insulation thickness to improve its thermal performance. The panel is then installed and tested on a test cell façade, while the analysis on a real building is conducted using the calibrated simulation model. De Masi et al. (De Masi, Ruggiero & Vanoli, 2021) also work on test cells, conducting thermal analysis of a prefabricated façade at different times of the heating season and with different types of actual outdoor conditions (wind, rain, solar radiation). Paiho et al. (Paiho, Seppä & Jimenez, 2015) describe the advantages of these systems in terms of reducing heating energy consumption in cold climates, not limiting the discussion to the contribution of the insulation layer but including the technological elements that can be included in a prefabricated façade module. Li et al. (Li et al., 2018) work on the construction details, paying particular attention to limiting a façade panel's heat loss, also considering thermal bridges. The panel is then tested in a building whose internal microclimate is monitored for an entire year. The study of thermal bridges is also crucial for Evola et al. (Evola, Costanzo, Urso, Tardo & Margani, 2022), who illustrate significant reductions in mould growth and surface condensation risks due to the higher internal surface temperatures achieved by installing a prefabricated panel on the façade of a pilot building. Bagarić et al. (Bagarić, Banjad Pečur & Milovanović, 2020) monitor the temperature and relative humidity distribution inside a building after the application of a prefabricated ventilated sandwich panel, albeit without a direct comparison with the pre-retrofit condition. Such a comparison can be found in Höfler et al. (Höfler, Knotzer & Venus, 2015), where the retrofit process of a building is described in detail, exploring the pre- and post-construction issues.

However, in all examples presented here and in all those known to the authors, the pre-post retrofit comparison is always made on the same building, before and after the efficiency intervention, and therefore at different times and under different climatic conditions. This methodology risks making the analysis misleading because different boundary conditions can strongly influence the comparison, even when using calibrated simulation models. To close this gap and methodologically enhance the assessment of energy and indoor microclimate improvements made by prefabricated façade systems, this paper compares two identical buildings: one retrofitted with a prefabricated façade and one without any improvement. The retrofit of the first mock-up is carried out with a new, non-invasive timber-based façade module developed specifically for retrofitting existing buildings as part of the "Renew-Wall" project. The system offers customisable modules based on the variety of shapes of existing Italian buildings. It is designed to optimise prefabrication processes to achieve a cost-effective product even compared to conventional energy improvement strategies (ETICS, window replacement, and new CMV systems (Controlled Mechanical Ventilation)). The Renew-Wall system was validated with a two-year environmental monitoring campaign. In the first year, the two mock-ups, without any high-performance thermal design solution, were put under the same starting conditions, to verify their similar behaviour. In the second year, with the prefabricated façade installed on one of the two buildings, the actual energy consumption savings and thermal performance improvement provided by the system were measured and compared with the non-retrofitted case. This paper describes the main properties of the designed prefabricated façade system, focusing on its energy and thermo-hygrometric performance. The definition of these performances was also aimed at obtaining the ETA (European Technical Assessment), a technical assessment of the product's suitability for use, issued by ETA-Danmark, a company accredited as a Danish TAB (Technical Assessment Body).

The paper is organised as follows: Section 2 describes the prefabricated façade module in all its features, underlining the choices behind its design. Section 3 focuses on its thermo-hygrometric performance, illustrating the simulations and laboratory tests conducted on the panel and discussing the results. Section 4 describes and reviews the experimental monitoring campaign of the two identical buildings, with a detailed comparison between the monitored data on real buildings and the simulations conducted on the panel in the previous section. Section 5 lists the innovative aspects of the research work and its future developments.

2 CHARACTERISATION OF PREFABRICATED FAÇADE MODULES

The Renew-Wall prefabricated façade system comprises four different modules, which vary according to the façade portion of the building to be retrofitted (Fig. 2).

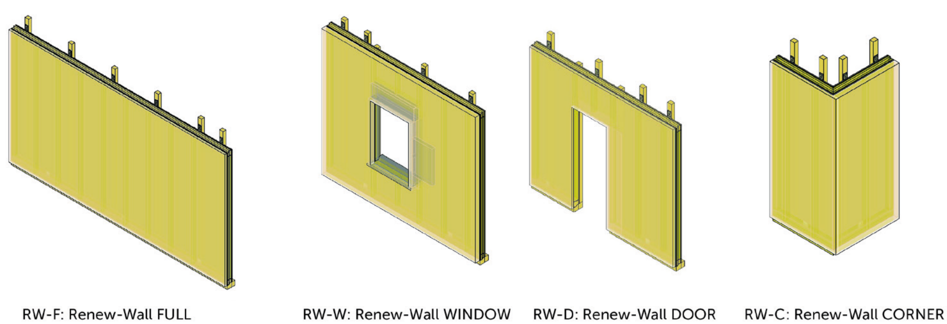

FIG. 2 The four different modules of the Renew-Wall system. Image courtesy of LAMARC Laboratory, University of Trento.

The load-bearing structure consists of a wooden frame with an upper and lower plate and vertical studs arranged at regular intervals, varying in number depending on the length of the panel, and with an insulating layer in between. The frame is reinforced by an OSB (Oriented Strand Board) panel on the inner side and a DWD panel – a vapour-permeable wood-fibre board that can be used as rigid underlays or façade panels – on the outer side to promote vapour transpiration. The next layer on the inner side is a low-density insulating levelling layer of varying thickness depending on the geometric unevenness of the wall to be covered, and the next layer on the external side is an additional insulating layer to achieve the required U-value transmittance. Different types of finishing are available, from plaster with different colour gradations to ventilated façade systems, which are highly customisable in material and texture (Fig. 3).

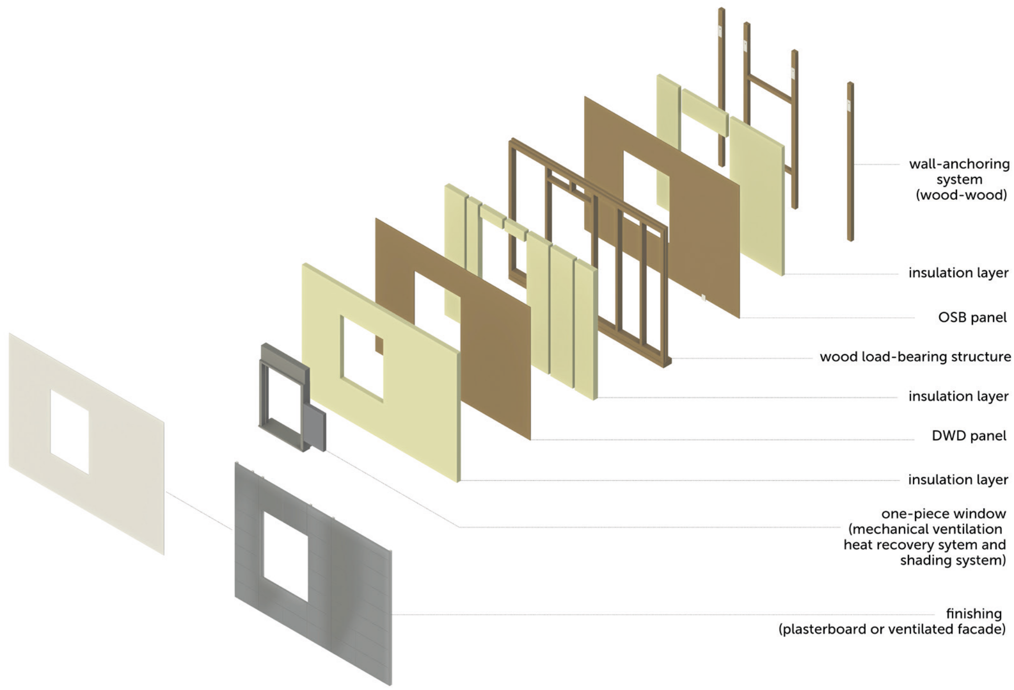

FIG. 3 Exploded isometric view of Renew-Wall Window module components. Image courtesy of LAMARC Laboratory, University of Trento.

Table 1 shows the thermal properties of the Renew-Wall FULL panel (RW-F).

TABLE 1 Thermal properties of the Renew-Wall Full module

Renew-wall RW-F module layers [inside to outside]	Thickness [m]	Thermal conductivity [W/mK]	Specific heat [J/KgK]	Density [Kg/m³]
Mineral wool	0.08	0.038	1030	30
OSB	0.015	0.13	1500	615
Wood structure + mineral wool	0.12	0.05	110	500
DWD	0.016	0.09	2100	615
ETICS (mineral wool)	0.1	0.038	1050	100

Two alternatives (Fig. 4) were designed for the structural connection to the existing wall.

- Wood-wood solution, for load-bearing masonry buildings, realised by anchoring with a plate (240 x 80 x 6 mm) to wood studs that are fixed to the building before the panel is installed.
- Halfen-type solution, for concrete-framed buildings, made with two plates, one C-shape (170 x 86.2 x 6 mm) and one Omega-shape (60 x 170 x6 mm). On the metal plate connected to the Renew-Wall module, there are a series of holes in which to insert the connecting screws, and a horizontal slotted hole, to allow for adjustments, in which to insert the "HZS-type" fixing screw.

An additional stabilisation system with metal plates is provided to facilitate the placement of the panel during installation and to limit out-of-plane movements. The designed anchoring systems and the high flexibility in module sizing allow the application of panels of different heights and widths.

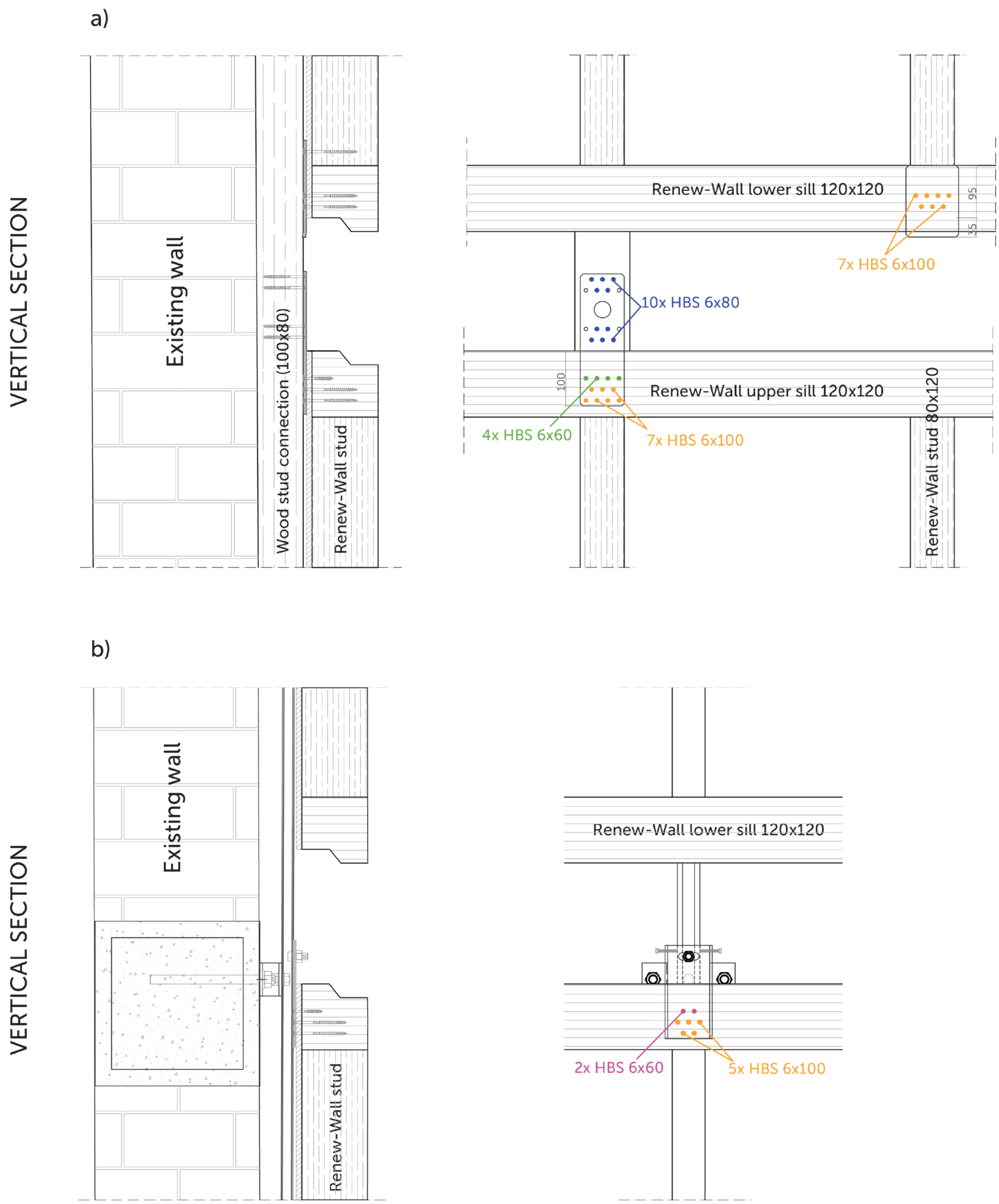

FIG. 4 Renew-Wall structural connection to the existing wall: a) wood-wood solution; b) Halfen-type solution.

With the Renew-Wall panel, the aim was to condense three energy-efficiency solutions for existing buildings into a single intervention: insulation, new CMV systems, and window shading. The following detail elements were designed:

- Window casing
- Embedded Heat Recovery Mechanical Ventilation (HRMV) system
- Shading system
- Wired electrical connections
- Wall gasket system
- Wall joint covers
- Drip Profiles
- Wall baseboards

Although a case-by-case analysis is needed to determine whether the thickness of the newly retrofitted exterior wall can reduce the amount of sunlight entering the building, the one-piece window embedded in the wall panel is perfectly in compliance with Italian and European regulations on thermal behaviour for different climate zones. The HRMV machine – an already marketed product – has a reduced thickness (H x W x T: 830 x 510 x 80 mm) and seamlessly integrates with the external insulation, with minimal impact on the building layout, ensuring the highest levels of indoor comfort. This makes it possible to maintain the size of the existing windows while providing adequate thermal insulation, integrate the HRMV machine while minimising masonry work, and eventually restore existing shading systems. The window casing allows the integration of different solutions for the shading system to filter sunlight according to preferences and needs. Each solution considered can be included in the overall panel thickness, assuming a minimum outer insulation layer of 100 mm or even reducing it if HRMV does not need to be installed. Electrical connections for blinds, HRMV systems, outdoor electric lighting, and alarm systems can also be easily integrated into the panel. To ensure water and wind tightness, Renew-Wall panels include a double gasket system. Along the perimeter of the panel, on the outer side, is a joint metal cover with both an aesthetic and protective function. There is also a drip profile at the bottom of the panel for rainwater drainage.
The Renew-Wall system finishing includes an insulated baseboard at the very base of the building, applied directly to the building before the panels are installed. Its thickness is compatible with the Renew-Wall panel and adapts to a potential unevenness of the existing wall. A preliminary study was also conducted on retrofit methods for balconies and loggias. Figure 5 shows the results of the analysis with prefabricated façade modules indicated by dark grey colour. However, for these parts of a building, traditional techniques are still preferred for simplicity and speed of application.

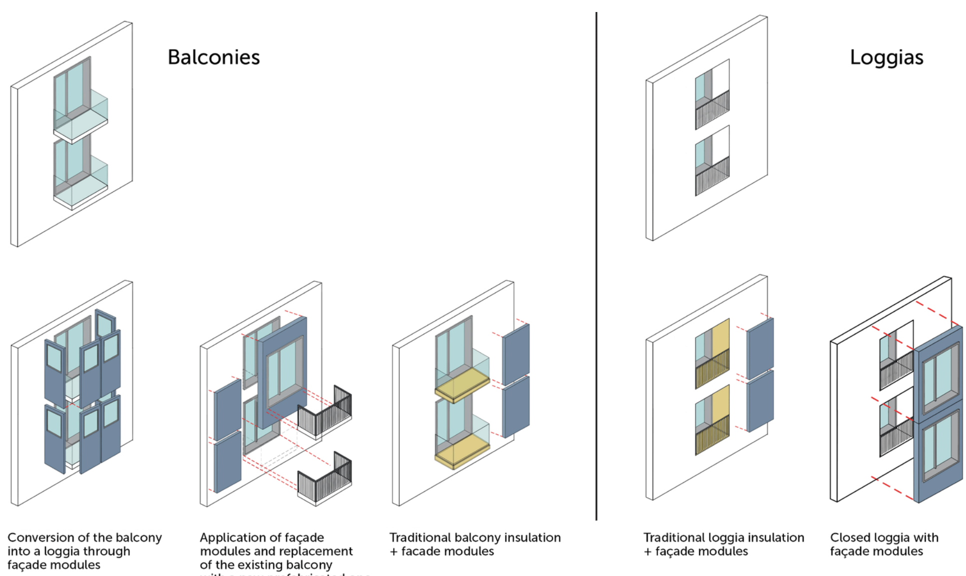

FIG. 5 Potential solutions for retrofitting balconies and loggias with prefabricated façade modules (b).

The installation of prefabricated façade systems also requires another set of procedures and checks to ensure that the work is done correctly. One of the first steps is to accurately survey the building's measurements using tools such as laser scanners or photogrammetry. With this information, a BIM (Building Information Modelling) model of the building can be created, allowing the exact components needed for installation to be designed and manufactured in the factory, which can be virtually pre-assembled on a digital twin for more efficient and accurate installation on site.

The Renew-Wall modules, as shown in Figure 4, are developed to be hung and positioned from top to bottom using a crane and skilled workers, avoiding the need for scaffolding and reducing material waste. The installation is done outside the building, so there is no need for indoor work other than removing existing windows, all the finishing around them and eventually creating a hole for the CMV system. Installation tolerances are largely solved through the digital twin of the building that is made before installation and assembly with an accurate laser scanner survey. However, additional compensation is provided at the depth level (z-axis) thanks to the low-density insulation panel behind the structural layer that absorbs irregularities in the existing wall and at the façade level (x- and y-axes) thanks to the detailed design and flexibility of the previously described structural connections that allow partial roto-translation of the panel itself before fixing.

3 THERMO-HYGROMETRIC PERFORMANCE

3.1 HYGROMETRIC BEHAVIOUR

To achieve efficient vapour release, the values of the air layer thickness equivalent to water vapour diffusion ("sd") were decreased from the inside to the outside of the wall. For this reason, an OSB (Oriented Strand Board) panel is applied as a vapour retarder in the inner part of the wall, while the outer part comprises a DWD panel – an MDF (Medium Density Fiber) vapour-permeable wood-fibre board –, which makes the wall breathable due to its vapour permeability characteristics (water vapour resistance factor "μ" = 11). To corroborate these design choices, some laboratory tests were conducted by the Institute of BioEconomy, IBE-CNR from San Michele All'Adige (TN, Italy), on the façade panels, analysing their water and air tightness, which were found to comply with the requirements of the UNI EN 12865, UNI EN 1026:2016, and UNI EN 12114:2001. Moreover, details of the wall and joints were analysed using WUFI 2D software (Fig. 6). Water tightness between the panels is solved by two different levels of gaskets. Since the connection between the wooden structural part of the two panels is currently under patent application, the detail is darkened in Figure 6, and the horizontal section is not present in Figure 4.

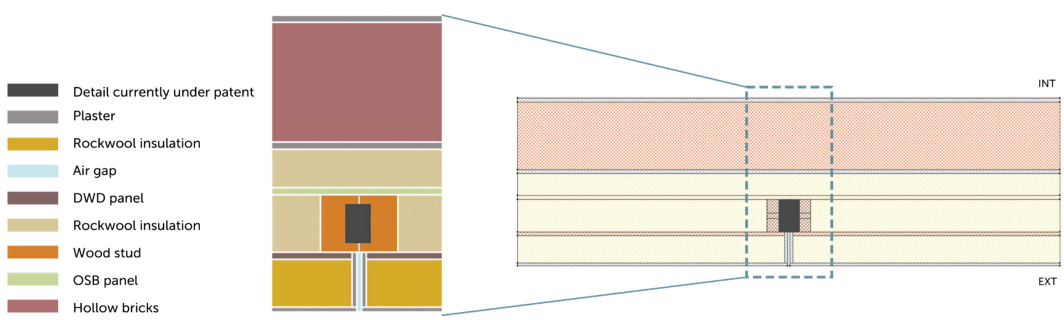

FIG. 6 Detail of the panel-to-panel connection (a) and its modelling in WUFI (b).

Material properties, starting water content and relative humidity conditions for each material, a calculation grid adapted to the geometry of the simulated component, and weather conditions were set by cross-referencing data from data sheets and the software database. The weather file compiled from actual monitored data (see Section 4) was used as the outdoor reference; indoor conditions were set according to UNI EN ISO 15026, internal humidity class 3. The following were assumed: a

north orientation of the wall, which is more damaging given the absence of solar radiation; a building height of less than 10 m; a pitched roof with rain load as prescribed by ASHRAE Standard 160.
The running period of the simulations is 3 years.

The results show that the water content decreases over time, attesting to the ability of the façade panel to dry out during the simulation period (Fig.7).

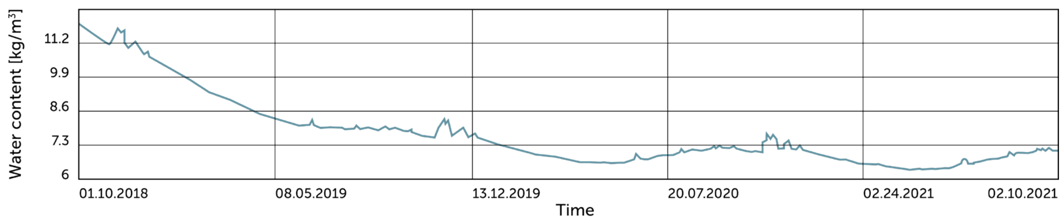

FIG. 7 Water content of the simulated detail (Fig.6) over 3 years of simulation.

The limits prescribed by WTA recommendations (International Association for Science and Technology of Building Maintenance and Monuments Preservation, 2014) regarding moisture content in wood materials are met. Figure 8, for example, shows that by cross-referencing moisture and air temperature values through the WTA conversion table, simulated wood humidity values in the load-bearing panel can be plotted on an XY space (plotted in black). These values always fall within non-risk areas, represented in the graph by a colour scale ranging from green (low risk = wood humidity 0%) to red (high risk = wood humidity 30%).

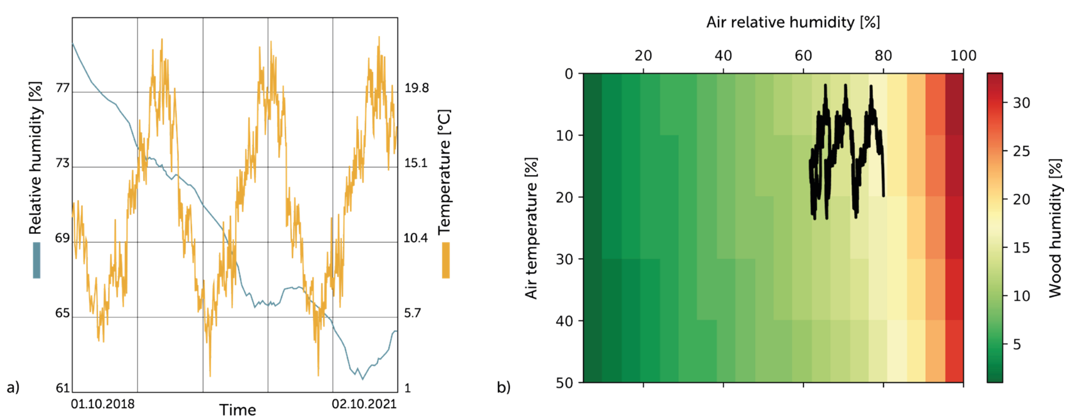

FIG. 8 Simulated (WUFI) air temperature and relative humidity inside the structural wood stud of the Renew-Wall panel (a); correlation between these values and wood humidity according to WTA recommendations (b).

The simulated humidity values for wood components are such that any risk of mould and fungus attack is avoided. The highest values are found in the first year of the simulation, where the initial moisture has to be balanced with the ambient moisture, which, on average, is always lower. These results can be considered valid only when related to the simulation input data, especially the characterisation of the materials and the environmental conditions set. Only small air-filled volumes were modelled, assuming perfect adhesion of the low-density levelling insulation layer to the existing wall. Otherwise, the potential presence of additional air gaps could alter the obtained results. In Section 4, simulated values can be compared with those measured on-site.

3.2 THERMAL PERFORMANCE

The wall stratigraphy described in Table 1 helps meet very low thermal transmittance values as there are a total of three layers of thermal insulation: one between the panel and the existing building, one inside the wooden frame, and one in the outer finishing layer. High standards of energy certification can be accomplished, even for buildings with poor thermal starting performance. Environmentally sustainable and biocompatible materials suitable for obtaining major sustainability certifications were selected. The thermal behaviour assessment was conducted using a finite element simulation software, THERM LBNL (Fig.9). The design thermal transmittance "U" Renew-Wall panel, considered without the existing wall behind, is 0.1281 W/m^{2}K, a value comparable with a high-performance building component.

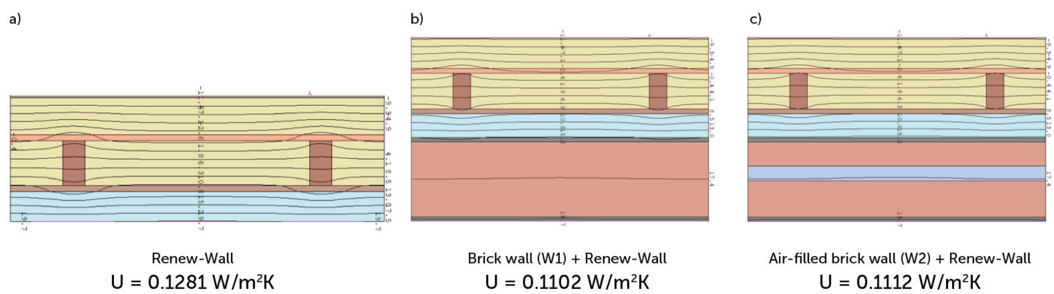

FIG. 9 Finite element simulation of the Renew-Wall panel (a), the panel mounted on the W1 wall (b), and the panel mounted on the W2 wall (c).

Considering the application of the panel on two different existing brick walls (Tab. 2), typical for buildings in Italy from the 1960s-1970s to be retrofitted, the values are confirmed to be excellent (Fig. 9b and Fig. 9c).

4 EXPERIMENTAL ANALYSIS IN TEST CELLS UNDER ACTUAL OUTDOOR CONDITIONS

To test the actual thermo-hygrometric performance of the Renew-wall system under real outdoor conditions and for some experimental tests on the assembly of the façade modules, two small test cells were designed and built in Malosco (TN), Italy, in an area free of shading obstacles (Fig.10).

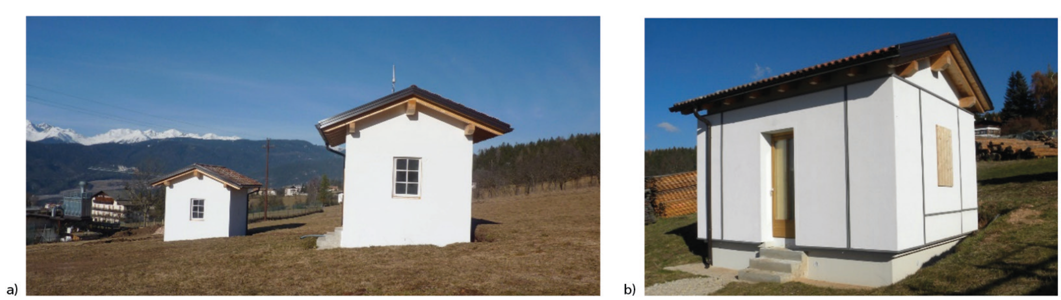

FIG. 10 Test cell A, in the background, and test cell B before retrofit (a); test cell A after retrofit (b).

Test cells are facilities which fill the gap between laboratories and full-scale buildings, allowing to keep all the necessary indoor condition under control, while letting outdoor conditions vary as in the real environment (Cattarin, Causone, Kindinis & Pagliano, 2016). The primary use is for testing building envelope systems, but given the nature and the equipment of the test facility, the interaction between building envelope systems and HVAC terminal units can also be investigated (Goia, Schlemminger & Gustavsen, 2017).

The positioning and the distance between the test cells were optimised in advance using software applications (Ladybug tools) to minimise mutual shading throughout the year. Also, considering the topography of the construction site, a distance of approximately 9 m between one cell and the other avoids any mutual interference. The installation was realised in an open green space, free of any other building. The dimensions of the cell floor plan are approximately 12 m^2 with a volume of 35 m^3 and a height at the roof ridge of 3.6 m (Fig. 11).

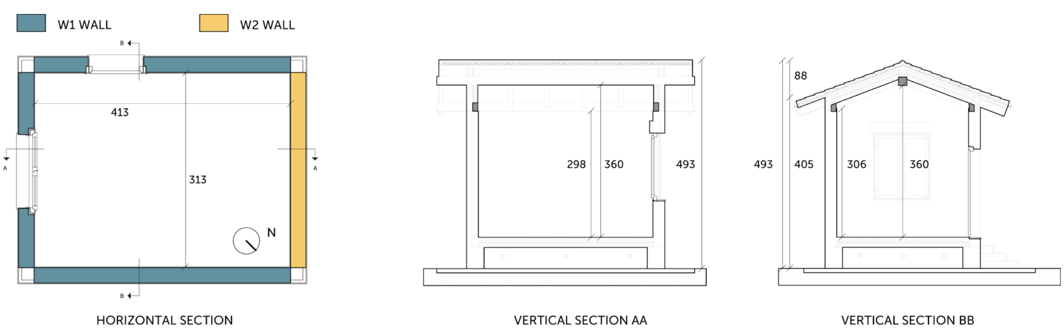

FIG. 11 Horizontal and vertical sections of test cells A and B before retrofit (values in centimeter).

The two mock-up buildings are the same in terms of shape, size, construction materials, exposure, and HVAC system to ensure perfect comparability. Their construction details reflect the typical buildings from the 1960s-1970s that are the main target of retrofit interventions in Italy. Two walls, the one facing northeast and the one facing northwest, were monitored more in-depth. Their thermal properties are shown in Table 2.

TABLE 2 Thermal properties of test cell walls before retrofitting

		Thickness	Thermal conductivity	Thermal resistance	Specific heat	Density
Wall type	Wall layers (inside to outside)	[m]	[W/mK]	[m^2K/W]	[J/KgK]	[Kg/m^3]
Wall W1	Plaster	0.015	0.55	-	850	1530
	Hollow bricks	0.25	0.181	-	840	908
	Plaster	0.015	0.55	-	850	1530
Wall W2	Plaster	0.015	0.55	-	850	1530
	Hollow bricks	0.08	0.212	-	840	942
	Air gap	0.05	-	0.168	-	-
	Hollow bricks	0.12	0.206	-	840	958
	Plaster	0.015	0.55	-	850	1530

To limit upward and downward heat losses and thus focus the performance analysis on the walls, the ground floor and roof are strongly insulated (U = 0.15 W/m^2K). There is only one window, on the southeast wall, which is necessary both to allow ventilation and to test the installation of the RW-W panel solution. The shading system consists of a simple removable external wooden panel. A further opening, on the southwest side, provides access to the building. The heating system consists of an electric fan coil – maximum power 2500W – with adjustable temperature set-points.

The two buildings were monitored for two years. During the first, the identical behaviour of the two cells was demonstrated; in the second year, after the installation of the Renew-wall panel on only one of the buildings, the energy savings and the different thermal performance of the retrofitted test cell were verified. This allowed the comparison of two identical buildings, except for the addition of the Renew-Wall panel on one of the two, under the same indoor and outdoor climatic conditions. Examples like this are extremely rare in the literature because the pre-post retrofit intervention comparison is usually made on the same building in different years and, therefore, with different climatic conditions.

The monitoring system, more extensively described in (Callegaro & Albatici, 2021), includes sensors to monitor the thermal performance of the envelope (Fig 12a):

- Flow meters and temperature sensors, both surface and layer-by-layer, for the northeast and northwest walls;
- Surface temperature sensors for the roof and the ground floor – the indoor environmental conditions;
- T-UR-CO2 sensor – and the external weather data;
- T-UR, wind speed and direction, horizontal radiation.

Table 3 describes the specifications, accuracy, and precision of the sensors. An energy meter measures the consumption of the heating system.

TABLE 3 Technical specifications of installed sensors

		Sensor	Range	Preci-sion	Accuracy
Surface temperature - Wall		PT100	-50 ... +180°c	0,1 °C	±0,3°C
Surface temperature - Roof		NTC 10 kΩ @ 25 °C	-40 ... +105 °C	0,1 °C	0+70°C: ±0,3°C; outside 0+70°C: ±0,4°C
Surface temperature - Floor		0.015	0.55	850	1530
IEQ sensor	Temperature	Thermistor NTC 10 kΩ	0 ... 40°C	0,1 °C	±0,5°C
	Relative humidity	Capacitive	0 ... 95 %	1%	± 3 %UR
	CO2	Non-dispersive infrared (NDIR)	0 ... 2000 ppm		400-1000 ppm: ± 75 ppm or 3% of the reading; 1000-2000 ppm: ± 40 ppm or 5%
Weather station	Temperature	NTC 10 kΩ @ 25 °C	-40 ... +105 °C	0,1 °C	0+70°C: ±0,3°C; outside 0+70°C: ±0,4°C
	Relative humidity	Capacitive	0 ... 100 %UR	0,1 %	± 1,8 %UR (0 ... 85 %UR) / ± 2,5 %UR (85 ... 100 %UR) / ± (2 + 1,5% reading) %@ T=others
	Wind velocity		0-50 m/s	0.1 m/s	
	Wind direction		0-359°	1°	
	Solar radiation	Pyranometer	0-1800 W/m^2	1 W/m^2	

The Renew-wall panel was also equipped with temperature and humidity sensors positioned both on the structural studs (Fig. 12b) and in the central part in each layer, mainly to verify the absence of risk of condensation or fungus attacks, which were previously simulated.

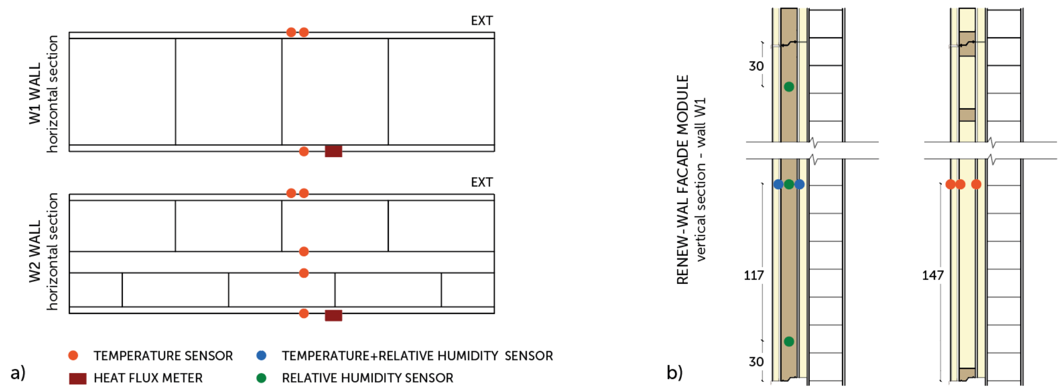

FIG. 12 Sensor's location on the walls (a) and Renew-Wall panel (b)

Figure 13a shows the indoor temperature trend during a summer week without a running HVAC system. Figure 13b shows the heat flux for the northwest wall during a winter week, and Figure 13c the energy consumption in the two cells for the month of February of the first monitoring year, which is considered representative.

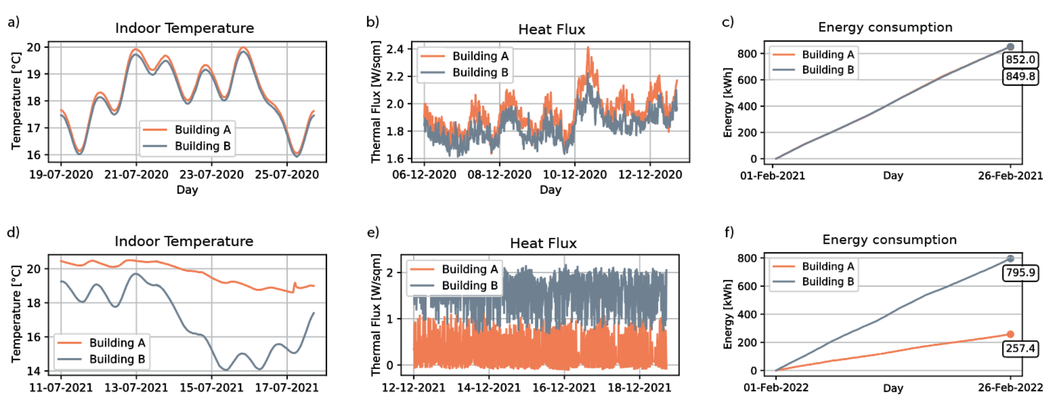

FIG. 13 Comparison between indoor temperature, heat flux for the northwest wall, and energy consumption before (a-b-c) and after (d-e-f) retrofit. The retrofitted building is building A.

These trends are compared with post-retrofit ones (Fig. 13d-e-f) in the same period the following year. The Renew-Wall façade panel is applied to building A. Figure 13a shows the perfect alignment of the thermal behaviour of the two non-retrofitted cells. Figure 13e shows the reduction in terms of measured heat flux for one of the monitored walls, while 13f reveals the enhancement brought by the installation of the Renew-Wall panel in terms of energy consumption. Focusing on this aspect, Table 4 shows that the average monthly saving is about 65%. The analysis also covered all other monitoring months and all other monitored variables not shown here.

TABLE 4 Difference in energy consumption between the two test cells after retrofit of cell A (second year of monitoring)

	Test cell B	Test cell A	
Months	**Energy consumption [kWh]**	**Energy consumption [kWh]**	**Energy savings [%]**
October	501.7	168.7	66.37
November	843.3	231.0	72.61
December	865.5	323.3	62.65
January	735.0	335.4	54.37
February	795.9	257.4	67.66

To check whether the pre- and post-retrofit energy consumption could already be predicted by simulation, two energy models were realised, one in semi-steady state and one in dynamic state conditions, using TERMUS and EnergyPlus software. In the latter case, the model was calibrated using monitored data. An *epw* weather file was created with data collected from the weather station installed on the roof of one of the two test cells while the building was modelled, taking into consideration the data sheets for the building materials and for the electric fan coil unit. The heating system schedule was set up based on the monitored heating fan coil performance data. Since no one lived in the test cells, internal loads were not modelled. The values obtained from the on-site blower-door test were included to simulate infiltration. Model calibration was performed after a series of sensitivity analyses on the variables with the largest discrepancies by comparing the indoor ambient temperature data and the energy consumption of the heating system, respecting the limits of Normalised Mean Bias Error (NMBE) and Root Mean Square Error (RMSE) coefficient of variation defined by the standard (ASHRAE Guideline 14, 2014). The results show an energy saving of 35% in the case of the semi-stationary simulation, which is known to be less accurate, and an average annual saving of 67% through dynamic simulation, perfectly in line with what was measured on-site. These results may not be representative of other buildings as well since the test cells are not inhabited, and the thermal loads are not comparable to actual buildings, but they still represent a valuable benchmark for future work.

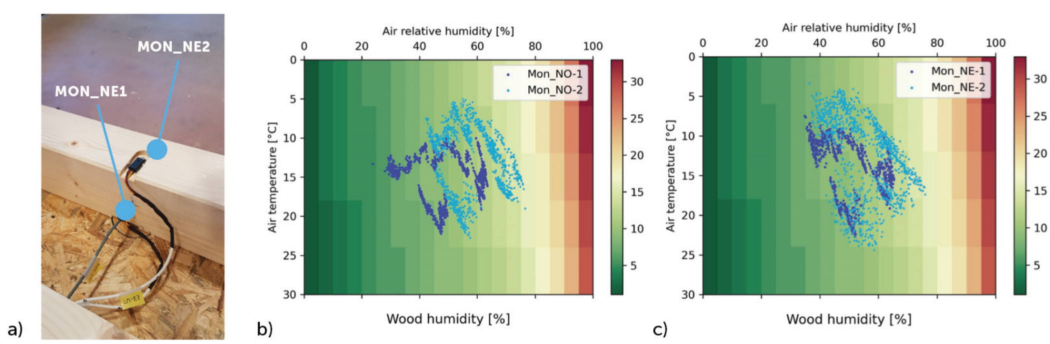

FIG. 14 Temperature and relative humidity sensors on the wood structural stud of the northeast Renew-Wall panel (a); Measured values of air temperature and relative humidity correlated with wood humidity (according to WTA recommendation) for the wood stud of the northeast (b) and northwest (c) Renew-Wall panel.

The monitoring of the hygrometric performance of the façade panel also confirmed what was simulated during the design phase. The graphs in Figures 14a and 14b, realised following what was done for Figure 8, show the air temperature and relative humidity data monitored in two structural wood studs (northwest wall: MON_NO; north-east wall: MON_NE) over a period of one year. The sensors were placed during the construction of the panel before the on-site installation

(Fig. 14a). The measured values, plotted in blue and light blue in Figures 14b and 14c, are even less worrying than the simulations (Fig. 8b), which represents the worst-case scenario.

Through heat-flux meters mounted on the two northeast and northwest walls, the actual thermal transmittance was measured to compare it with the simulated one. The analysis lasted 7 days, from Dec. 27, 2020 for the non-retrofitted cell and from Oct. 24, 2021 for the cell with Renew-Wall panel. Table 5 summarises the comparisons for both designed and actual thermal transmittance.

TABLE 5 Designed and measured thermal transmittance of the two walls of test cell A before and after retrofit

Designed thermal transmittance [W/m²K]	PRE-RETROFIT		POST-RETROFIT		Percentage reduction	
	Wall W1	Wall W2	Wall W1	Wall W2	Wall W1	Wall W2
	0.62	0.735	0.111	0.114	82.1 [%]	84.5 [%]
Measured thermal transmittance [W/m²K]	**PRE-RETROFIT 7 days of analysis from December 27, 2020**		**POST-RETROFIT 7 days of analysis from October 24, 2021**		**Percentage reduction**	
	Wall W1	Wall W2	Wall W1	Wall W2	Wall W1	Wall W2
	0.6317	0.9361	0.1551	0.3606	75.5 [%]	61.5 [%]

There is a negligible discrepancy for the W1 wall, while in the air-filled brick wall (W2), the air gap has probably led to convective air movements that have affected the measurement: the on-site thermal transmittance is higher than the designed for both the building without and the building with the Renew-wall panel. The percentage reduction is highlighted in the rightmost column of Table 5.

These differences, in terms of heat flux, between before and after renovation, are also clearly highlighted by thermographic images taken during the winter season of the second year of monitoring (Fig. 15). The images were captured with the NEC Avio Handy Thermo TVS-200EX, with an outdoor temperature between 2 and 3°C and an indoor temperature of about 21.5°C. The emissivity of the envelope surface was set at 0.95. In Building B, heat losses are evident at masonry mortar joints and at major thermal bridges. In the retrofitted building, the only small surface temperature variations occurring are visible at the joints of façade modules.

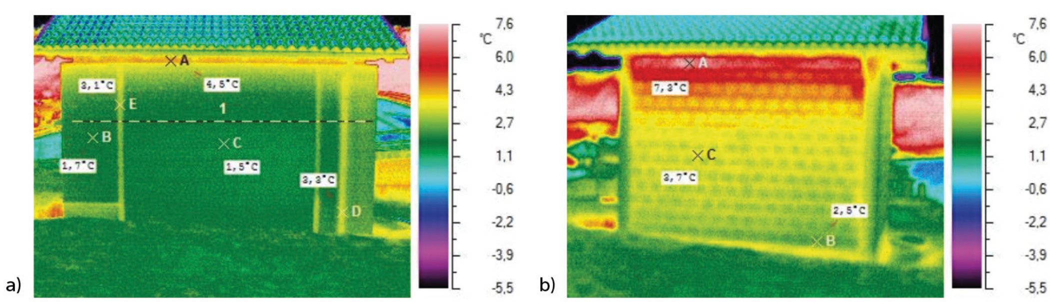

FIG. 15 A comparison between thermographic images: retrofitted test cell A (a) and test cell B (b).

5 CONCLUSION

The research carried out and described in the previous sections involved the design and testing of a prefabricated timber-based façade panel for building retrofitting purposes, developed within the Renew-Wall project. The project addressed different aspects of the design of a prefabricated module, from its prototyping to its site installation and characterisation in terms of thermal, acoustic, structural and fire resistance, air-water tightness performance and life cycle assessment. This paper, specifically, describes the energy and indoor microclimatic simulation and monitoring analysis of the Renew-Wall system, both in laboratory tests and in two experimental test cells. The comparison between two identical buildings, of which only one was later retrofitted with Renew-Wall panels, allowed the researchers to understand the strengths and weaknesses of the system, with particular regard to thermal, hygrometric, and energy performance. In literature, the assessment of the benefits of energy efficiency retrofit solutions is usually carried out by monitoring a single building before the retrofit intervention, e.g., for one year, and then, the following year, by monitoring the same building, renovated. In this way, however, the boundary conditions are different: for example, outdoor weather conditions can vary from one year to the next, or the occupancy and internal gains schedules, which certainly change between two monitoring campaigns, affect the building's thermal performance differently. Instead, in this specific case study, two identical buildings were compared, verifying for one year their performance was the same and then retrofitting only one of the two, thus making the comparison as objective as possible. The test cells were extensively monitored, and two years of data were collected on indoor and outdoor microclimatic conditions and heating consumption. The results show that the Renew-Wall panel has an excellent thermo-hygrometric performance, reducing the monitored building's energy consumption by 67%. The absence of mould and fungus attacks was also verified. Although it was likely easy to predict that the retrofit would lead to a decrease in energy consumption, the acquired data can be considered extremely reliable because it is based on an objective comparison, as explained before. The information gathered represents a first step in the validation process of the Renew-Wall façade panel, as it comes from non-inhabited buildings used as a test. Future developments will involve the installation of the system in actual buildings to evaluate its response to real internal thermal loads – people, lights, equipment – and its summer energy performance, even in the presence of a cooling system. The computational and simulation models, calibrated on the monitoring data, will be used to assess the installation of the Renew-Wall panel in other locations and under other environmental conditions as well. Thanks to these models and the data collected, it will be possible to compare such innovative retrofit systems with standard renovation approaches. The ultimate goal is to improve the system created so far to highlight the benefits and accelerate the adoption of these solutions in the energy retrofit market.

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Numerical Analysis of Aluminium Façade Components: Material Properties, Elastic-Plastic Response and Sustainable Impact

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Abstract

This paper commences with a scientific literature review of current research that underlines the environmental benefits to be gained from using smaller quantities of raw materials in the construction industry, with particular emphasis on a sustainable approach to façade design. Life cycle assessment modelling is advocated to validate the sustainability of building structures to achieve optimal solutions. A real-life application of the design of an aluminium façade bracket is presented, demonstrating that a weight reduction of up to 35-45% is attainable by exploiting the post-elastic properties of a material. The work described ranges from a discussion of the current conventional numerical techniques adopted by the industry to the most recent and advanced computational methods permitted by the introduction of Eurocode 9. This code facilitates a substantial enhancement in structural performance by incorporating an evaluation of the material's elastic-hardening behaviour and allows for a noteworthy reduction in component size and increased geometric design flexibility.

Keywords

façades and cladding components, material optimisation, elastic-plastic, elastic-hardening analysis

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1 INTRODUCTION

In recent years, several areas of research have explored new perspectives regarding ecological or even sustainable building design. Sustainability in building construction is meant to promote efficiency, reduce costs, and ensure a positive environmental impact (Akadiri, Chinyio & Olomolaiye, 2012). Undoubtedly, the construction industry has a significant impact on the natural environment through its use of building materials. According to the global footprint network, approximately 70% of raw material consumption exceeds what the planet can naturally regenerate. Moreover, the type of structural systems employed plays a pivotal role in the development of sustainable design, as building strategies and sustainable design principles are closely tied to it. Indeed, the structure and form of a building determine land use, material usage, energy consumption, greenhouse gas emissions, maintenance costs, risk management, and recycling. Therefore, achieving sustainability in the future requires that all major industrial sectors worldwide focus on understanding and significantly reducing their environmental footprints (Maxineasa, Isopescu, Baciu & Lupu, 2021). Life cycle assessment (LCA) is a methodology which investigates and sets the system boundaries concerning all industrial processes, from raw material supply, transportation, installation, usage and maintenance, repair or replacement, through to the end-of-life stage of dismantling or demolition, waste transportation, disposal, reuse, and recovery recycling.

Webster (2004) divides the life cycle impact into four categories for LCA and evaluation of the environmental impact of building systems over their lifetimes: (a) initial effects, which include the construction and manufacture of raw materials; (b) energy use during the life cycle of the building system; (c) the consequences of refurbishment; (d) the end-of-life effects, or the environmental repercussions following the life cycle. LCA must consider a number of crucial issues, including energy consumption, resource use, and green gas and pollution production. The initial impacts are mainly influenced by the building and construction type. Renovations, maintenance, and refurbishment depend more on the structural materials and less on the structural form. The disposal of structural materials has an end-of-life impact on the life cycle assessment (Wang & Adeli, 2014).

The European Technical Committee CEN/TC 350 'Sustainability of construction works' carries out and represents some of the efforts of the industry and academic and research institutions, providing guidelines and standard recommendations for the optimal use of processes and building materials. It also introduced the Environmental Product Declaration (EPD) to assure material conformity and the full consistency of the industrial process to obtain it in accordance with the European Standard EN 15804. The standard exclusively covers material supply, transportation, and manufacturing, whereas subsequent stages such as use in buildings, maintenance, repair, waste processing, and disposal are currently regulated by EN 15978 'Sustainability of construction works - Assessment of environmental performance of buildings - Calculation Methods. In particular, EN 15978 indicates that façades and architectural cladding are part of the superstructure, Level 1 Group.

Therefore, EN15804 and 15978, as well as the entire set of relevant guidelines, now represent a mandatory approach to the correct assessment of ecological and sustainable material usage. However, when referring to façades and cladding components made of aluminium, which also need to be designed for safety and protection purposes as indicated in CPR305/2017, a lack of information appears in terms of structural design methodology. For these elements, it is rather common to refer to Eurocode 9 EN 1999-1-1 (CEN 2007), which encompasses an exhaustive set of technical recommendations ranging from the design material properties to the section classification, resistance, and stability requirements. It is precisely this 2007 standard that allows engineers the possibility to thoroughly and exhaustively use different criteria for modelling the stress-strain response of structures. An interesting review in this regard can be found in Georgantzia, Gkantou & Kamaris (2021) and Gardner, Yun & Walport (2023).

2 SUSTAINABLE APPROACH FOR FAÇADE DESIGN

2.1 THE CONCEPT OF SUSTAINABILITY

The concept of sustainability focuses on the condition of the biophysical environment of the earth, particularly regarding the use and depletion of natural resources. It is more a matter of finding a sort of permanent state to support the people on Earth or a part of it without endangering the health of human beings, animals, and plants (Sadollah, Nasir & Geem, 2020). Sustainability can be defined as a way to design a product using natural renewable resources in a manner that does not eliminate or degrade them (Zabihi, Habib & Mirsaeedie, 2012). It is a multi-disciplinary concept (FIG 1). A sound and thorough analysis of every factor and element contributing directly or indirectly to this concept leads to an objective understanding and method of evaluation of sustainability (Abu-Rayash & Dincer, 2019). The Intergovernmental Panel on Climate Change (IPCC) stated that one of the available pathways to limit global warming to 1.5°C above pre-industrial levels is that global carbon emissions need to fall to 45% from 2010 levels by 2030 and continue a steep decline to zero net emissions by 2050. One sector that addresses this reduction process is building construction and operations, which accounted for 36% of global final energy use and 39% of energy-related carbon dioxide (CO_2) emissions in 2017 (Wallace, Marvuglia, Benetto & Tiruta-Barna, 2014).

Due to the significant economic, environmental, and social impacts of the construction industry on society, various sectors have put a lot of effort into improving the primary environmental performance of buildings. While most of the existing literature reports on the sustainability assessment of buildings as a whole, research on the sustainability performance of individual building components (e.g., beams, columns, walls, façades) is insufficient. Building façades and their related structures can significantly influence the sustainability performance of the entire building as they are some of its most important components.

Several strategies have been presented in literature concerning sustainable building design from the perspective of structural engineering. In this regard, we can refer to the following examples. Maxineasa et al. (2021) developed an overall concept of environmental performance by investigating the effect of various structural steel parts on the Earth's ecosystem regarding sustainability issues and the effects of an over-the-floor reinforced concrete slab. The paper also offers up-to-date information on the environmental performance of the analysed structure, providing reassuring conclusions for those in the construction industry regarding the use of steel as a material, which can contribute to the current global effort to reduce the environmental burden that the construction industry places on the environment.

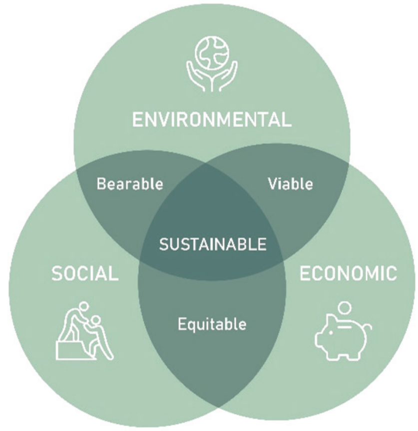

FIG. 1 Concept of sustainability and the three-phase interpretation.

The strategies presented by Anderson and Silman (2009) for structural engineering design that reduces greenhouse emissions include material selection, structure reuse, material efficiency optimisation, thermal mass effects, and future adaptation. Radlbeck et al. (2006) point out that aluminium has exceptional qualities for sustainable design, such as low weight and low maintenance requirements, strong corrosion resistance, and the capacity to be recycled. The authors assert that aluminium structures, if designed and executed properly, may ultimately outperform steel in the long run, both economically and ecologically.

By considering and prioritising materials with lower environmental footprints, it becomes possible to reduce a project's overall environmental impact. In addition to improving energy efficiency standards in the construction sector, we also need to improve the types and amounts of materials used. It is possible to reduce the negative effects of massive materials used in the design of buildings by finding different solutions and/or using different materials. For instance, by considering structural systems that can be disassembled, by design optimisation of construction profiles, or by using various highly recyclable structural materials (Maxineasa et al., 2021). Sustainability can be achieved through building design, but its performance must be quantitatively assessed. This must be done in the context of optimising the environmental impact and/or life cycle assessment (LCA) of buildings (Sarma & Adeli, 2002).

2.2 MATERIAL OPTIMISATION OF FAÇADE COMPONENTS

Optimisation is widely recognised as one of the key tools for achieving sustainability. It involves a systematic search process tailored to a specific problem, considering its unique conditions and constraints. The primary objective of optimisation is to identify the most feasible solution that best addresses the problem at hand. By leveraging optimisation techniques, complex scientific and engineering challenges can be effectively tackled, enabling the discovery of innovative and sustainable solutions (Sadollah et al., 2020).

The impact of the construction industry on the environment is significantly influenced by the production of building materials. According to the most recent report from the Global Environment

Facility (GEF), humans consume raw materials at a rate more than two-thirds higher than the Earth's natural regenerative capacity. The selection of a structural system holds paramount importance in creating sustainable designs as it is intricately linked to building strategies and sustainable design principles. Moreover, the structure and form of a building determine the amount of land used, the use of materials, the amount of energy consumed, the number of greenhouse gases released, the cost of maintenance, risk management, and even recycling. Therefore, all global industrial sectors must focus on understanding and achieving sustainability in the future, with the goal of drastically reducing their environmental footprints (Maxineasa et al., 2021). Optimisation can be defined as a process meant to achieve the best use of available materials for their sustainability. To obtain the best-optimised results, various criteria are considered in the procedure. They must include the following items:

- Availability of the material being evaluated
- Production costs
- Local climatic conditions
- Environmental impact
- Durability
- Predicted service life based on LCA models
- Material transportation (whether local or imported)
- The related environmental impact

The building industry is the largest consumer of raw materials in the world today. Therefore, a significant reduction in raw material consumption should be a fundamental guiding principle for the future. Another important consideration is the waste of resources during production, the construction process, and throughout the lifetime of the completed building. The reuse of materials after demolition should be considered. Models for the recycling process should be defined and promoted at all levels (Makenya & Nguluma, 2007).

The material selection during the engineering design phase has a significant influence on the amount of energy used and the amount of greenhouse gases (GHG) released over the whole product life cycle. Improper material choices will increase energy use and environmental pollution, ultimately leading to the product's failure on the market. It will also be detrimental to a company's reputation and interests (Bi, Zuo, Tao, Liao, & Liu, 2017). It is highly impractical to select materials during the design stage based solely on the usage phase. For example, focusing merely on reducing greenhouse gas (GHG) emissions in one phase may lead to an increase in GHG emissions in other phases. This underscores the importance of adopting a comprehensive strategy, such as LCA (Geyer, 2007).

3 STRUCTURAL ANALYSIS OF ALUMINIUM FOR CURTAIN WALL FAÇADES

3.1 OVERVIEW: STANDARDS AND DESIGN APPROACH

In section 2.2, the subject of material optimisation has been introduced, considering factors such as material availability, production cost, climatic conditions, durability, service life, transportation, and associated environmental impact. In the case of the building envelope or façade, the vast combination of architectural trends, technological solutions, materials used (such as glass, metal panels, stone), and the shape compatibility of components creates a complex scenario. In this sense, aluminium components used as connecting brackets play a fundamental role. Different solutions facilitate the interconnection of the exterior architectural cladding to the interior living space of a building, simultaneously ensuring lightweight components, ease of installation, and effective transmission of design loads from the exterior to the interior (FIG 2). Nowadays, aluminium is the key solution for fabricating the mechanical chain, particularly in bracket industrialisation, to ensure static stability and resistance. Over the years, the material has gained importance due to its easy availability, durability, affordable production cost and industrial machinability, which permits the creation of complex shapes.

Alongside its machinability, aluminium is structurally characterised by a recognised elastic-hardening progressive response. In FIG 3, four common alloys are shown by their stress-strain relationship under tensile load for a conventional strain range $\varepsilon = 0.00$ to 0.08. Eurocode 9 (CEN, 2007), Annex E, now offers an accurate description of the tensile response of aluminium, encompassing the elastic phase through the post-elastic phase and extending up to the ultimate strain (ε_u). This comprehensive characterisation allows structural engineers to assess the behaviour of aluminium more accurately and allows them to leverage its plastic-hardening properties effectively.

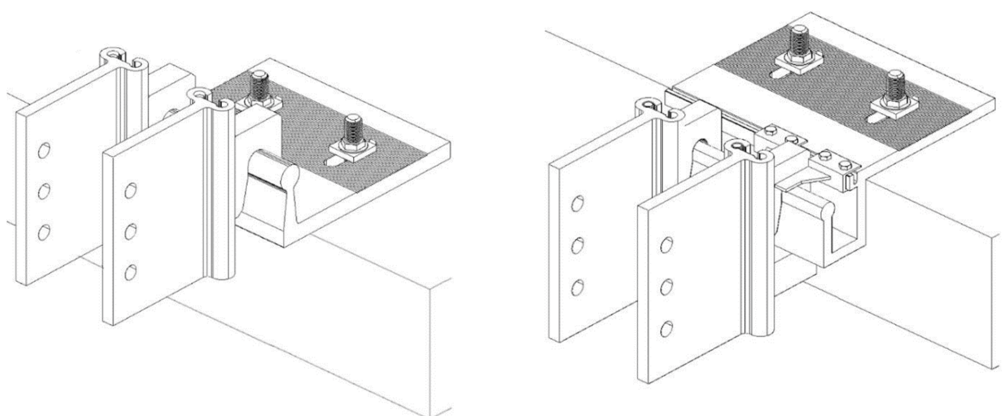

FIG. 2 Two different bracket configurations for the mullion-to-floor slab interconnection.

However, before delving into the elastic-plastic or elastic-hardening design applicability of the EC9 standardised alloys, it is crucial to address the current national and European design regulations in a comprehensive discussion. Curtain walling systems comply with Construction Product Regulation (CPR305/2011, 2011), which is a European Union (EU) regulation that sets out the rules for the harmonised performance of construction products within the EU, and with standard EN 13830 (2015). EN 13830 specifies the requirements for curtain walling systems designed to serve as building envelopes, offering weather resistance, safety, energy efficiency, and heat retention. The standard also provides test methods, assessments, and calculation criteria to evaluate the performance of these systems and ensure compliance with the specified requirements. The standard defines curtain walling as a component of the building envelope comprising a framework typically composed of horizontal and vertical profiles interconnected and anchored to the building's supporting structure. It incorporates fixed and/or openable infills and fulfils the necessary functions of an internal or external wall or its part without contributing to the load-bearing or structural stability of the building. Curtain walling is a self-supporting construction that transfers dead loads, imposed loads, environmental loads (wind, snow, etc.), and seismic loads to the main building structure. It can also be replaced independently of the main building structure (CPR305/2011, 2011).

The entire building must adhere to the Basic Requirements for Construction Works (BRCWs) outlined in the general scope of the (CPR305/2011, 2011), specifically:

1. Mechanical resistance and stability
2. Safety in case of fire
3. Hygiene, health, and the environment
4. Safety and accessibility in use
5. Protection against noise
6. Energy economy and heat retention
7. Sustainable use of natural resources

Curtain walling systems, along with other building products, play a crucial role in enabling entire buildings to meet the aforementioned basic requirements. According to mandate M/108 issued by the Commission to CEN/CENELEC (1994), for curtain walling systems, the first basic requirement, i.e., Mechanical resistance and stability, pertains solely to the main structure of the building. Therefore, curtain walling is considered a non-structural product related to the fourth requirement, i.e., Safety and accessibility in use. In general, curtain walling sytems are composed of three main elements: the fixings (including fixings and brackets, etc), the frame, and the infill panel.

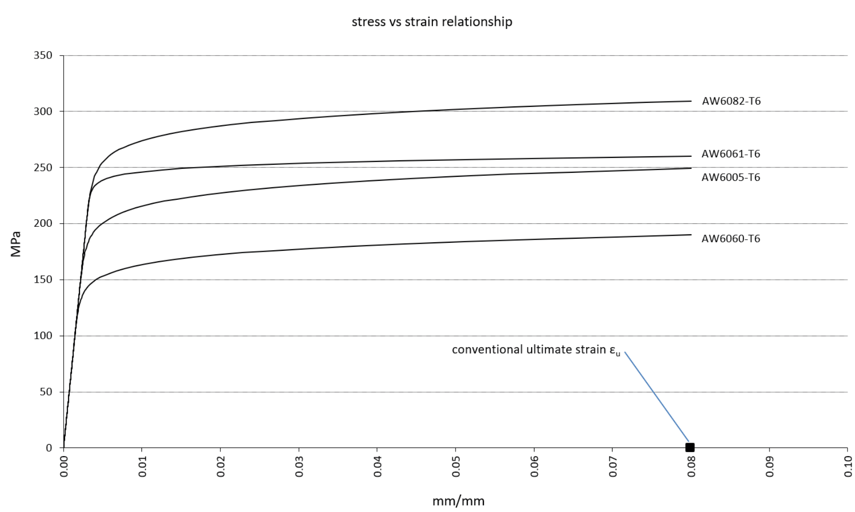

FIG. 3 Typical elastic-hardening progressive response for four characteristic aluminium alloys (up to ε= 0.08).

The bearing capacity of these components must be verified under defined conditions to meet the essential requirement for “Safety in use”. In this sense, the classes of consequences play a fundamental role in the façade risk-assessment classification (European Committee for Standardization, 2002; CNR-DT 210/2013, 2013), allowing for the fact that the failure of the curtain walling framework of the infill panels does not typically have the same economic and/or human consequence as the failure of the building structure. An interesting discussion can be found in (Bedon, Amadio & Noé, 2019).

Modern structural design codes are established to provide a simple, safe, and economically efficient basis for the design of structures under normal loading and environmental conditions. The primary principle of limit-state design for structural components is to define an acceptable level of risk and ensure it is never exceeded. This is achieved through the appropriate choice of design situations, design equations, and representative values. The design values used in the design equations are selected to ensure an adequate and sufficient level of reliability for all relevant failure modes of the considered structures. This practice allows for straightforward reliability verification of a given design through a simple comparison of resistances and load effects. Since resistances and loads are subject to uncertainties, partial reduction factors for the strength and partial amplifying factors for the actions are defined. These factors guarantee the required performance level in terms of the probability of failure.

As mentioned above, European Standard EN13830 (2015) defines the technical characteristics of curtain walling systems and encompasses a comprehensive set of requirements and offers test methods, assessments, calculation methods, and compliance criteria for related performances. However, it does not include specific codes for non-structural elements. Therefore, existing codes for building structures, such as Eurocodes and National Laws, should be utilised in the design and evaluation of non-structural elements, including curtain walling systems.

The practice code, whether based on National, European (EN), American (USA), Australian (AU), or other updated guidelines and codes, does not specifically regulate the connecting elements (brackets) in an application-specific manner. In the European market, the curtain wall aluminium (alloy) frame is commonly designed following Eurocodes (EC9), and the calculation and verification process for these elements adhere to a standardised procedure which relies on common standardised structural elements. This process involves following specific codes such as EC3 (2005) and AISC360 (2016) or AS4100 (2016) for steel structural elements, etc. In this sense, the AISC Specification provides the generally applicable requirements for the design and construction of structural steel buildings and other structures. This standard has been approved by ANSI as an American National Standard. On the other hand, the AS is the Australian Standard for Steel Structures, approved on behalf of the Council of Standards Australia.

It should be highlighted that all these standards are conceptually based on the semi-probabilistic method, which means that the uncertainty of the basic variables, such as the strength of the materials and the loads acting on the structure, are taken into account by using characteristic values and partial safety factors. This approach employs the characteristic values derived from the available statistical data as the calculation values within the design procedure. The characteristic value for an action represents the value with a defined probability of either being exceeded or not being reached during the relevant reference period. The partial factors are then used to account for the remaining uncertainties in the design process (European Committee for Standardization, 2002). Moreover, the most recent codes allow for post-elastic behaviour in the semi-probabilistic approach, ensuring a certain degree of plastic behaviour throughout the loading event. This means that the plastic deformation capacity of metal alloys can be harnessed in structural design, resulting in supplementary strength that can be incorporated into the design procedure. However, this is only possible if local buckling in sections does not compromise the overall equilibrium stability of the load-bearing system. Therefore, the well-known concept of “section classification” is often adopted by designers and engineers to ensure that structures are designed to be both safe and efficient. This is a method of classifying structural sections according to their buckling resistance, which allows for selecting sections that are suitable for the loads and conditions that they will be subjected to. However, given its computationally heavy workload, designers may resort to verification methods based on fully elastic requirements. It is important to note that the local stability requirements for structural sections should not be blindly applied to façade elements such as aluminium brackets. This is because these components have a remarkable inherent stability capacity that can be easily demonstrated. This characteristic enables pronounced post-elastic behaviour, which provides a significantly higher resistance capacity than is possible using linear assumptions. This results in advantages such as reduced bracket volumes, lightweight components, and cost-effective production.

3.2 MECHANICAL RESPONSE: THE ELASTIC-HARDENING APPROACH ACCORDING TO EUROCODE 9

The mechanical properties of the aluminium alloy AW6005A-T6, which the hook bracket to be investigated is made of, can be obtained from Eurocode 9 (CEN, 2007). For this case, these properties are determined by the fundamental ductility parameter $\xi=\xi(\varepsilon_u)$ and the temper parameter T=T6. The standard allows the continuous elastic-hardening distribution to be represented by the Ramberg-Osgood formulation, described by equations (1) and (2).

$$\varepsilon = \frac{\sigma}{E_0} + \varepsilon_{0.el} * \left(\frac{\sigma}{f_{0.el}}\right)^n$$ equation 1

$$n = (ln\frac{\varepsilon_{0.el}}{\varepsilon_{0.x}}) * (ln\frac{f_{0.el}}{f_x})^{-1}$$ equation 2

In this formulation, σ represents the independent variable of the distribution. The initial elastic modulus, denoted as E_0, is 70 GPa. The conventional residual deformation at yielding is $\varepsilon_{0.el}$ = 0.002 (0.2%), while the conventional deformation at the ultimate load is ε_u = 0.08 (8%). Additionally, $f_{0.el}$ = 200 MPa represents the conventional yielding stress at 0.002 of the residual deformation ($\varepsilon_{0.el}$). To obtain the hardening parameter n, two characteristic points are considered: $\varepsilon_{0.x}$ = 0.076 (7.6%) and f_x = 250 MPa. Note that these reference points can be selected anywhere in the residual strain range, from $\varepsilon_{0.x}$ = 0.001 (0.1%, linear regression for elastic applications) to $\varepsilon_{0.x} = \varepsilon_{0.max}$, where $\varepsilon_{0.max}$ is the linear regression obtained from the maximum stress experienced by the sample for plastic applications, with $f_x = f_{max}$, as indicated by EC9, §E.2.2.2 (4).

For the specific case at hand, the n-parameter is determined, according to the plastic range under investigation, by setting $f_x \equiv f_u$ with reference to the EN AW 6005-T6 alloy mechanical properties. The graphical representation of the Ramberg-Osgood relationship can be observed in FIG 4.

The Ramberg-Osgood distribution is then logarithmically transformed to generate the true stress-strain curve, commonly known as the Cauchy curve, to take the geometric necking of the material into account during the high-strain deformation process. The mathematical transformations are described by equations 3 and 4.

$$\varepsilon_{true} = ln(1 + \varepsilon)$$ equation 3

$$\sigma_{true} = (1 + \varepsilon) * \sigma$$ equation 4

It is worth mentioning that the conventional ultimate strain $\varepsilon_u = 0.08$ is commonly used to facilitate the technical discussion across all types of aluminium. However, Eurocode allows for customising the ultimate plastic strain for each specific alloy type, providing flexibility in its application.

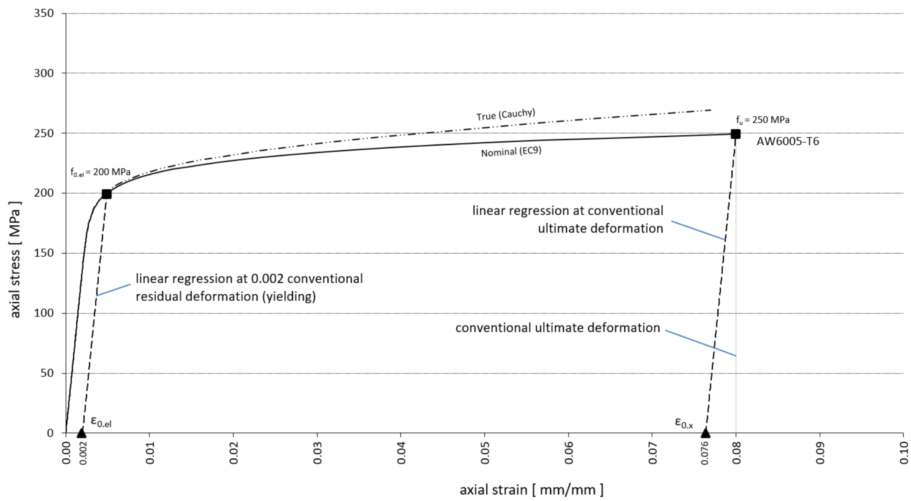

FIG. 4 Ramberg-Osgood stress-strain relationship for the aluminium alloy EN AW6005-T6.

4 ANALYSIS METHODOLOGY AND COMPUTATIONAL MODELLING

4.1 CASE STUDY: DESCRIPTION

The CMA-CGM complex in Marseille (FIG 5), designed by Zaha Hadid Architects, exemplifies an intriguing application of the elastic-hardening approach for verifying the aluminium façade brackets. The headquarters tower, standing at a height of 143 metres, features a concrete core, whilst two steel-glass architectural systems complement the remarkable form of this structure. The structure is enveloped by around 42,500 m^2 of single and double-skin façades, with the distinctive design featuring 3,569 glass-aluminium unitised panels, each with unique geometrical characteristics.

The connection between the façade system and the floor slab is achieved through a sophisticated assembly of brackets, enabling the structural and kinematic requirements of the façade-building interaction. The bracket geometry is meticulously designed to accommodate the varying inclination of the façades and effectively transmit external wind pressure to the concrete floor slabs (FIG 6). Considering the unique wind exposure of the building, which is situated on the seafront, and the substantial size of the unitised systems, reaching approximately 6 m^2, the brackets must be designed to minimise the transfer of ultimate limit tensile forces (ULS) of up to 18 kN.

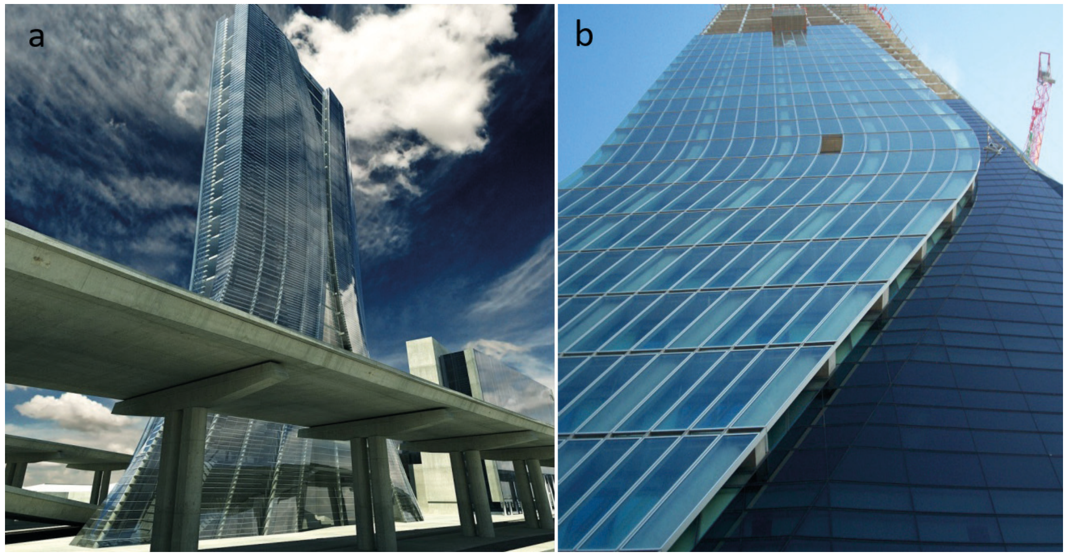

FIG. 5 The new CMA-CGM Headquarters in Marseille by Zaha Hadid Architects. a) render, b) installation phase.

This accounts for the characteristic values of pressure and suction, which can reach up to 3.80 kPa. Notably, the aluminium systems utilised in the CMA-CGM façades are designed to effectively accommodate the post-elastic behaviour of the material. In particular, the design incorporates continuous elastic-hardening criteria.

To illustrate this, a detailed study is presented focusing on one of the three bracket types, commonly known as the "hook" due to its distinctive shape (FIG 6, component 2). This dedicated analysis provides a comprehensive understanding of the bracket's behaviour and performance.

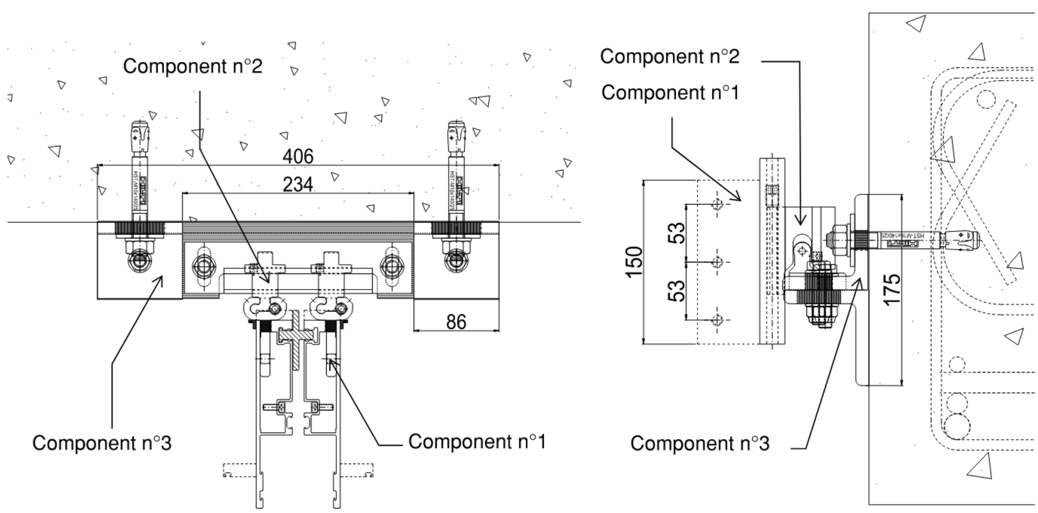

FIG. 6 The aluminium brackets system used for the façade-building interaction (dimensions in mm).

The geometric model is created using the Catia software by Dassault Systems, whilst the FE computational setup is implemented through Abaqus, also by Dassault Systems.

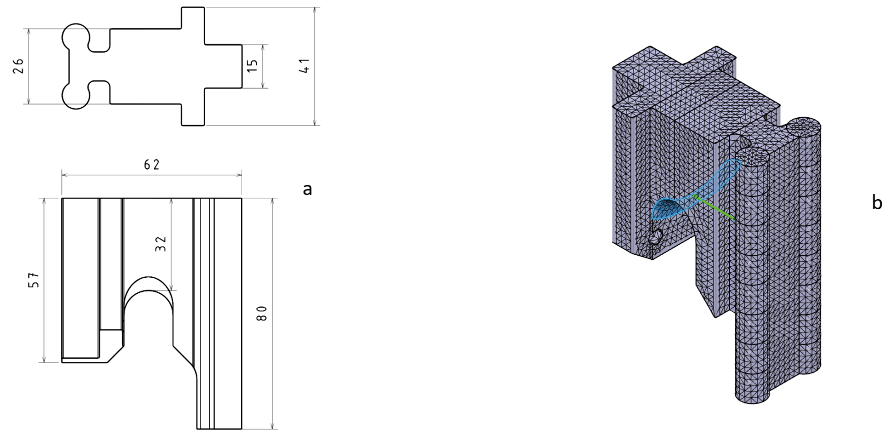

FIG. 7 The bracket case study: the hook. a) the geometry in mm, and b) the computational model.

A 3D mesh is generated using second-order tetrahedral elements, resulting in a continuous distribution of 62,105 finite elements and 35,385 nodes. The component is constrained along its *dog-bone* insertion edge (the right part of the component in the right-hand picture of FIG 7) with a non-linear elastic support that allows compression-only behaviour. Additionally, a parametric suction load is applied to the contact area of the throat (the left part of the component in the right-hand picture of FIG 7).

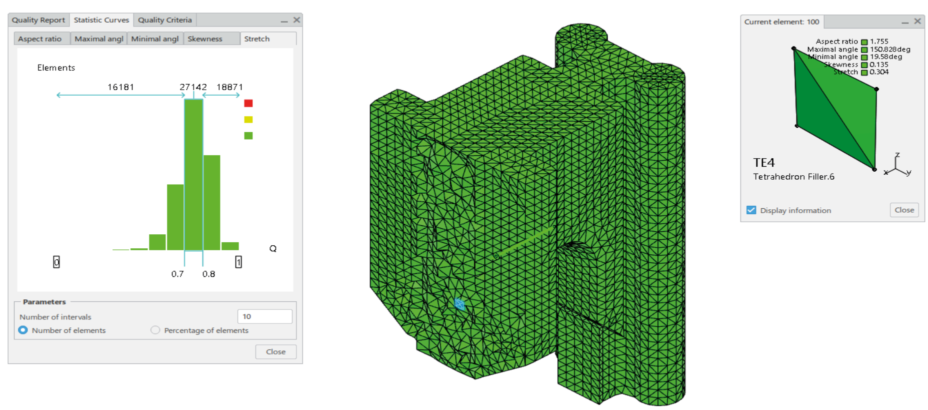

FIG. 8 The computational model (statistic quality mesh check, by Simulia/Abaqus).

The use of this type of restraining-load assumption is suggested during the mechanical verification phase as it accurately replicates the realistic kinematic and mechanical behaviour of the component in terms of internal deformation, providing reliable results. Consequently, the distribution of internal stress and strain within the component can be considered to be a fundamental parameter for assessing its structural suitability. The mesh refinement was achieved using a skin-to-core algorithm (i.e., external-to-internal), ensuring an average element length of 2.00-2.50 mm for each finite element of the skin (source mesh) and maintaining invariancy of the sequential generation of elements throughout its volume. This leads to a uniform distribution of the finite elements across the component, as depicted in FIG 8.

4.2 NUMERICAL OUTPUT AND DISCUSSION

Incremental analysis is performed, considering both material non-linearity (NLM) and geometric non-linearity (NLG). Focusing on the mechanical response in terms of stress and strain, two distinct load levels are identified: the ultimate elastic load UL_{00} (corresponding to an equivalent plastic strain PEEQ of 0.00) and the ultimate plastic load UL_{08} (corresponding to a PEEQ of 0.08, conventionally regarded as the limit point according to Eurocode 9). FIG 9 and FIG10 illustrate displacement and stress contours for UL_{00} and $UL_{08,}$ respectively.

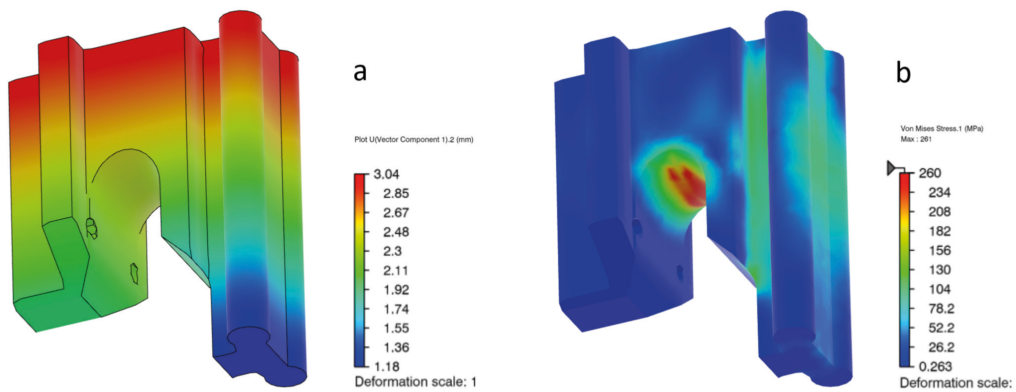

FIG. 9 a) displacement (in mm) and b) Von Mises stress (in MPa), at ultimate elastic load UL_{00}

As anticipated and in line with the numerical findings, the throat section of the component proves to be the most critical part, primarily due to its reduced height. Under the suction load of the façade or cladding panel, the cross-section mentioned is usually subjected to a tensile force and a resulting bending moment. This bending moment is generated due to the misalignment between the point of external force application and the restrained surface (FIG 7, right). More precisely, the numerical results illustrate that the maximum stress and strain concentrations occur in the lower region of the throat section, where the highest tensile stress is experienced.

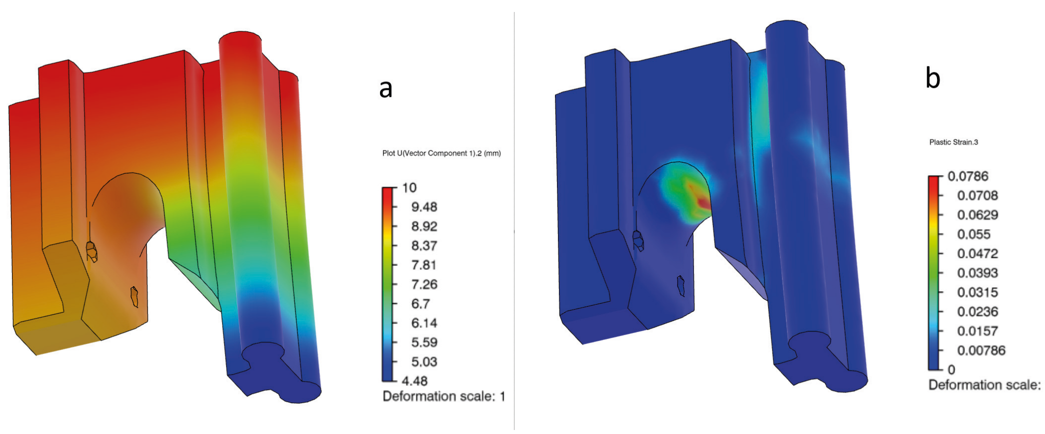

FIG. 10 a) displacement (in mm) and b) equivalent plastic strain PEEQ, at ultimate plastic load UL_{08}

Furthermore, it is possible to deduce from FIG 11 that the ultimate elastic load is UL_{00} = 20 kN whilst the ultimate plastic load is UL_{08} = 84 kN. The final design situation, therefore, shows 18 kN as the ultimate design load, 20 kN as the ultimate elastic strength and 84 kN as the ultimate plastic strength. This results in an efficiency plastic ratio $\chi_{epr} = UL_{08}/UL_{00}$ = 4.20. This ratio represents the extra-load capacity that the component can provide, allowing its material to "move" from the elastic limit (i.e. the post-elastic onset) to the plastic limit. Significant levels of over-strength in the component (χ_{epr} >1.00) can be reached even with modest values of ε_u, such as 0.02 or 0.03.
It should be noted that for the specific case of the Zaha Hadid Tower in Marseille, a reduced plastic limit UL_{02} (corresponding to a PEEQ of 0.02) was set, despite Eurocode 9 actually allowing for a full capacity exploitation of 8%.

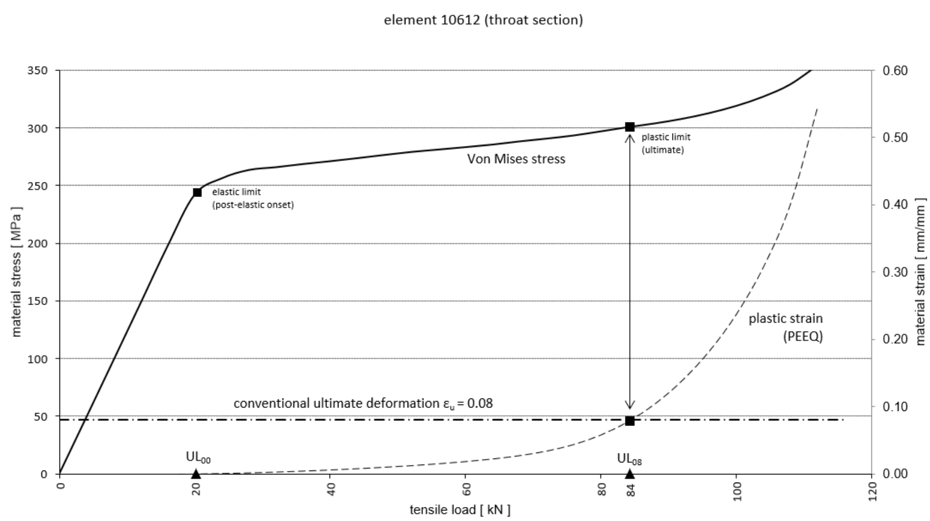

FIG. 11 Stress-strain response of the material in the critical throat section (FE10612).

However, it is important to note that the façade designer must always ensure that the kinematic stability of the component is maintained throughout the incremental load analysis. It is worth noting that aluminium components used in façades and cladding systems are typically characterised by a high level of compactness, which renders them well-suited to elastic-plastic or elastic-hardening analysis, particularly under tensile loading conditions. It should be noted that the non-linear finite element analysis described for the "hook" bracket sample mentioned above can be readily extended to other aluminium components. This allows for similar conclusions regarding the exceptional capabilities of aluminium in terms of exploiting post-elastic properties for a wide range of brackets commonly employed in façade engineering applications. A comparative analysis was conducted for several brackets of the Zaha Hadid Tower in Marseille using a fully linear hypothesis (i.e. using UL_{00} as the design limit point). This showed a weight increase in the range of +35 to +45% of the included components compared to the plastic analysis utilised, which assumed UL_{02} (corresponding to an equivalent plastic strain PEEQ of 0.02).

5 CONCLUSIONS AND FUTURE PERSPECTIVES

The efforts and the investments being applied in current industrial research, such as *ecological design*, *sustainable design* and life cycle assessment, have been described. The building industry is the world's largest consumer of raw materials, which is why a significant reduction in raw material consumption should be a fundamental objective for the future.

A real-life application of material reduction has been described in one of the first large-scale applications in building design regarding the aluminium used in façades. It's been demonstrated that the mechanical post-elastic properties of aluminium alloys offer remarkable design advantages. The analysed case study demonstrated that by employing the Ramberg-Osgood formulation, as outlined in Eurocode 9, Annex E, it can significantly enhance the ultimate load strength of aluminium brackets and, more generally, other common components used in the field of façade and building engineering. In fact, the current standard analysis method widely used in the industry for such components does not fully incorporate one of the fundamental aspects of the ultimate limit state philosophy, which is the utilisation of post-elastic resources. It has been observed that by conventionally setting the ultimate strain ε_u in the range of 0.02 to 0.08, as allowed by Eurocode 9, the following benefits can be achieved:

A Significant improvement in the ultimate design load capacity of the components
B Optimisation of the component's volume and weight, leading to implications related to sustainability and life cycle assessment (LCA) factors.

It is recommended that post-elastic numerical analysis is utilised during the design and validation of aluminium façade components to achieve weight savings, ensuring that they meet the assembly's displacement and stability requirements. Moreover, ongoing research is expected to advance towards a broader application of the Ramberg-Osgood elastic-hardening progressive response to other brackets and components. It will be necessary to conduct specific laboratory tests to precisely validate and calibrate the obtained results. Lastly, it is worth mentioning that in parallel with the application of advanced non-linear numerical analysis techniques to achieve component weight loss, appropriate studies should be carried out to interrelate these savings to the LCA measurement factors.

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An Evaluation Study of Shading Devices and Their Impact on the Aesthetic Perception vs. Their Energy Efficiency

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Abstract

Sunlight control tools, such as shading devices, are used to improve buildings' thermal and visual conditions. One of the concerns about using shading devices is their potential to harm the visual appearance of buildings. This study aims to study the aesthetic perception of different shading devices while concurrently evaluating their energy performance. Augmented reality was used to place virtual shading devices onto a building's façade at Jordan University of Science and Technology (JUST). One hundred two students from JUST evaluated eight shading devices on a seven-step semantic differential scale. Participants comprised 49 students from Architecture and Design College and 53 students from other colleges. The energy efficiency of shading devices was tested using DesignBuilder. The results revealed that certain types of shading devices were perceived as more aesthetically pleasing than others. Architecture students and non-architecture students showed significant differences in their affective responses. Regarding shading devices, shape-morphing and horizontal-louvres devices are the most preferred by participants, while egg-crate devices are the least recommended. Regarding energy efficiency, results showed that the tested shading devices improved buildings' energy efficiency by 7% (vertical fins) to 17% (egg crate) compared to the base case and did not negatively impact their visual appearance.

Keywords

shading device, experimental aesthetics, perception, augmented reality, semantic differential scale, energy efficiency

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1 INTRODUCTION

Research on shading devices has a long tradition. Since their invention, shading devices have become vital tools in improving energy efficiency and thermal comfort in buildings with glazed façades. The Building Energy Conservation Design Standard defines shading devices as devices installed to reduce solar heat entering a room (Kim, Shin, Kim, & Cho, 2017). They are primarily used to prevent overheating and reduce peak cooling loads in hot seasons, thus enhancing thermal comfort therefore saving energy (Nadiar & Nusantara, 2021; Rana, Hasan, & Sobuz, 2022). Additionally, shading devices should allow maximum solar energy penetration during cold seasons to minimize heating loads (Kim et al., 2017). Furthermore, by carefully controlling the distribution of luminance and illuminance, shading devices can address glare and visual discomfort issues, contributing to a more comfortable visual environment (Freewan, 2014; Esquivias, Munoz, Acosta, Moreno, & Navarro, 2016).

Research on shading devices is ample and mainly focused on their thermal and visual performance (Alzoubi and Al-Zoubi, 2010; David, Donn, Garde, & Lenoir, 2011; Choi, Lee, Ahn, & Piao, 2014; Freewan, 2014; Nadiar & Nusantara 2021; Rana et al., 2022). Recently, researchers have shown a growing interest in exploring the combination of photovoltaic cells and shading devices (Zhang, Lau, Lau, & Zhao, 2018; Custódio, Quevedo, Melo & Rüther, 2022). Additionally, researchers have been investigating the impact of shading devices on energy usage and carbon dioxide emissions, as shown in the study conducted by Razazi, Mozaffari Ghadikolaei & Rostami (2022).

For architects and designers, shading devices hold significance beyond their functional role as façade design elements. However, if not designed properly, these devices can negatively influence the aesthetics of a building's façade (Freewan, 2014). In research, the aesthetic aspect of shading devices and their influence on the visual appearance of buildings have not received extensive attention. As far as the authors know, only a few researchers and designers have attempted to explore the aesthetic qualities of shading devices. For instance, the Adaptive Building Initiative (ABI), an institution dedicated to developing environmental building performance, created Tessellate, a shading device that combines aesthetic appeal with energy and mechanical efficiency (Drozdowski, 2011). Furthermore, Al-Masrani, Al-Obaidi, Zalin, & Isma (2018) studied the aesthetic appeal of shading devices that utilize parametric designs.

Based on the short preview above, there is a lack of research on how shading devices impact the aesthetic perception of building façades or spaces. To fill this gap, this study aims to explore the aesthetic preferences of users when shading devices are integrated into building façades. The main hypothesis is that different types of shading devices can impact the aesthetic preference and evaluation of building façades. Additionally, based on previous research, the study suggests that the user's experience and knowledge impact the aesthetic perception and evaluation process. As such, architects and non-architects may have different perceptions of these shading devices. Equally important, the study will assess the compatibility between users' preferences for shading devices and their energy efficiency.

1.1 TYPES OF SHADING DEVICES

Shading devices can be categorized using various classification systems, most commonly orientation-based. This system categorizes shading devices into vertical, horizontal, and egg-crate types. Vertical shading devices are widely used on western and eastern elevations but are deemed the least effective (Choi et al., 2014; Esquivias et al., 2016). Horizontal shading devices are most effective on southern and northern elevations (Choi et al., 2014; Esquivias et al., 2016). Lastly, egg-crate devices combine both vertical and horizontal elements (Nadiar & Nusantara, 2021) and are considered more energy-efficient compared to vertical and horizontal fins (Esquivias et al., 2016; Al-Masrani et al., 2018).

Another categorization system is based on energy requirements (Al Dakheel & Tabet Aoul, 2017; Al-Masrani et al., 2018). This system classifies shading devices into passive, active, and hybrid groups. Passive shading devices operate without energy and can be either fixed or movable. Fixed shading devices eliminate the issue of user performance but block the view permanently (Esquivias et al., 2016; Al Dakheel & Tabet Aoul, 2017; Zulkarnain, Salleh, & Aziz, 2021). Movable shading devices offer user control and privacy, but their performance depends on user behaviour (Esquivias et al., 2016; Al-Masrani et al., 2018; Vercesi, Speroni, Mainini, & Poli, 2020). Passive shading devices are cost-effective and easy to install but lack year-long adaptability and struggle to control daylight under different sky conditions (Al-Masrani et al., 2018).

On the other hand, active shading devices require energy to operate and are mechanically movable systems that can rotate, fold, or slide. They can be automatically or manually controlled, with the automatically controlled ones responding to external environmental conditions (Al Dakheel & Tabet Aoul, 2017; Al-Masrani et al., 2018). Automatically controlled shading devices are considered more efficient than passive devices as they do not depend on user behaviour (Al-Masrani et al., 2018). However, active shading devices are more complex and have higher costs and risks of failure (Al Dakheel & Tabet Aoul, 2017; Al-Masrani et al., 2018).

The third category, hybrid shading systems, incorporates smart materials and biomimetic designs. Shape-morphing façades use smart materials that respond to environmental stimuli, such as heat or light, by changing their shape (Al-Masrani et al., 2018; Fiorito et al., 2016). However, the usability of these systems may be limited due to the inability of manual intervention (Barozzi, Lienhard, Zanelli, & Monticelli, 2016). Hybrid shading devices are still in the early stages of development, with solar shading devices made entirely of smart materials being limited by cost and the experimental stage of shape-memory materials (Al Dakheel & Tabet Aoul, 2017; Premier, 2019). The efficiency and effectiveness of hybrid shading devices in improving energy efficiency are still under investigation and are the subject of several research projects (Sheikh & Asghar, 2019; Yoon & Bae, 2020; Vercesi et al., 2020).

Figure 1 presents a combination of the mentioned categorization systems, showcasing various types of shading devices that will be analysed from an aesthetic standpoint. Table 1 summarises the different categorizations, advantages, and challenges of shading devices.

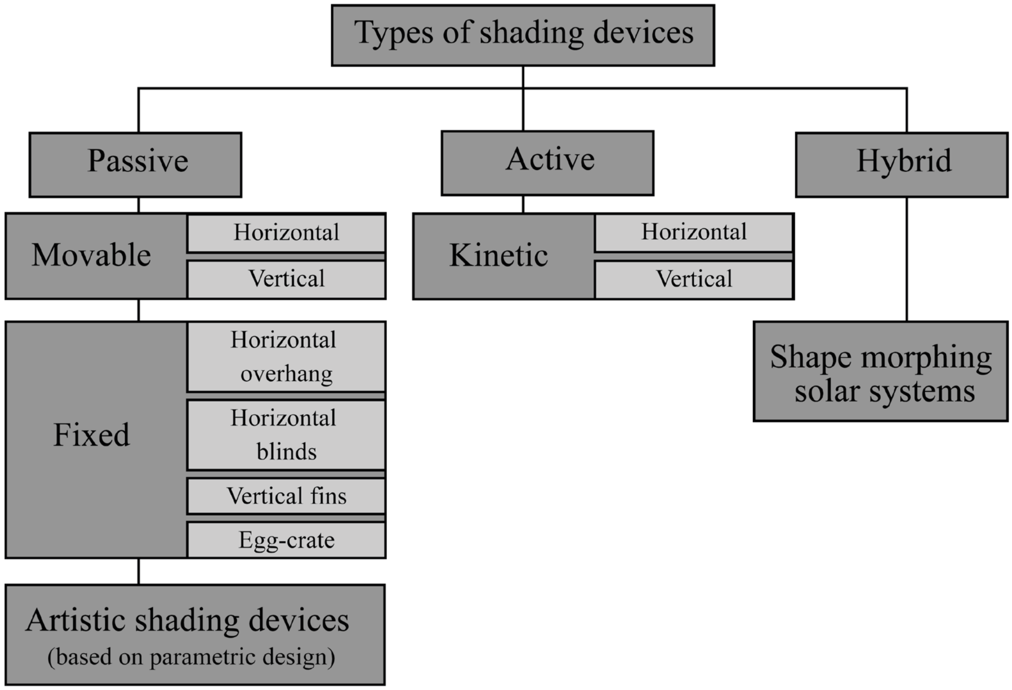

FIG. 1 Types of shading devices.

TABLE 1 Comparison between different shading devices in terms of advantages and challenges of every technology

Shading Device Category	Advantages	Challenges
Vertical Shading Devices	- Suitable for western and eastern elevations	- Least effective shading type - May not be suitable for all orientations
Horizontal Shading Devices	- Most effective in southern and northern elevations	- May not be suitable for all orientations
Egg-Crate Shading Devices	- Combines advantages of both vertical and horizontal shading	- More complex design
Passive shading devices	- No energy requirements - Simple, low-cost, and easy to install	- Limited adaptability to changing environmental conditions - Ineffective in controlling daylight in different sky conditions
Passive Shading Devices (movable)	Allow users to control their environment and offer privacy when required	- Depends highly on the user's preference and behaviour
Passive Shading Devices (Fixed)	- Does not depend on users' performance	- Permanently block the outside view
Active Shading Devices	- Automatically respond to environmental conditions	- Higher complexity and costs
Hybrid Shading Systems/ Shape-Morphing Shading Devices	- Improved energy efficiency	- Limited efficiency due to exposure to external conditions - Limited by material cost and testing stage

1.2 EXPERIMENTAL AESTHETICS

It is important to illustrate the fundamentals of human affective responses, including aesthetical judgements, to understand the logic behind how people perceive shading devices. Experimental aesthetics, a branch of psychology, was founded in 1876 by Gustav Fechner, who suggested that aesthetics can be measured objectively (Brachmann & Redies, 2017). Aesthetic experience includes three main domains: perception, or the initial gathering of information about an environment (Lang, 1987); cognition, or the processing of the information to develop an understanding (Veitch & Arkkelin, 1995); and affect, or the initial response to the environment (Brachmann & Redies, 2017). These three domains and their relation to the observer are illustrated in FIG. 2.

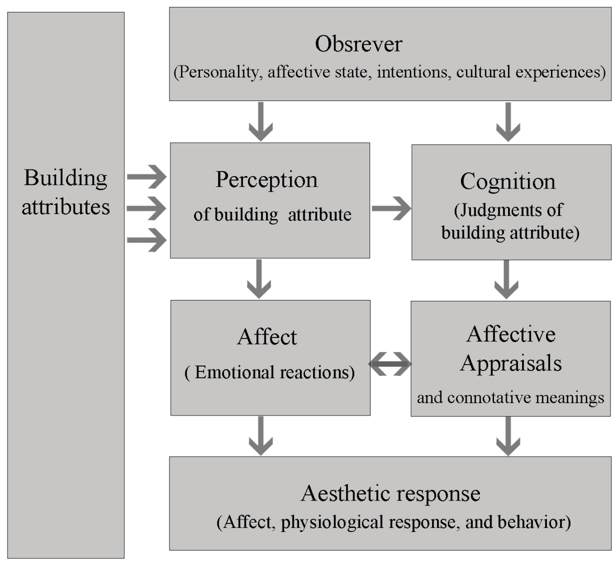

FIG. 2 Aesthetic response model (After Nasar, 1994).

Numerous studies in the field of architecture have concentrated on assessing the aesthetic worth of architectural elements and surroundings and comprehending the mechanisms that govern the evaluation process. (Ibrahim, Abu-Obeid, & Al-Simadi, 2002; Abu Obeid, Hassan, & Ali, 2008; Yazdanfar, Heidari, & Aghajari, 2015; Shemesh, Talmon, Karp, Amir, Bar & Grobman, 2017; Moscoso & Matusiak, 2018).

Researchers in the field of experimental aesthetics agree on three polar components of feelings relevant to aesthetic judgements: pleasure, arousal, and dominance. Pleasure and dominance have positive and negative extensions, whereas arousal begins at zero and can only increase (Stamps, 2013; Veitch & Arkkelin, 1995). These dimensions were first defined and developed in the studies of Osgood (1957) and Berlyne (1971) and were further studied later. Biaggio & Supplee (1983) described the three dimensions mentioned above as hedonic tone, arousal, and uncertainty, standing for the dimensions defined by Osgood as evaluating, activity, and potency.

In their early research, Nasar (1994) suggested two dimensions that affect aesthetic judgments: formal variables, which are features that concern the physical form of objects, and symbolic variables, which are the human responses to the content of objects. Moreover, other researchers have tried to identify these dimensions. Shemesh et al. (2017) defined the dimensions affecting aesthetic judgments as physical and cultural dimensions. Yazdanfar et al. (2015) added a personal dimension to the previous dimensions. Personal dimension was the focus of a study by Ibrahim et al. (2002), who studied personal traits mediating perception and aesthetic judgments. Education was also considered a variable by several researchers (Nasar ,1994; Abu Obeid et al., 2008; Akalin et al. 2009; Marković & Alfirević, 2015; Yazdanfar et al., 2015). The studies conducted by these researchers have provided evidence to support the notion that the aesthetic evaluation of an architect is distinct from that of a non-architect. Consequently, the current research acknowledges education as a variable that has the potential to influence aesthetic evaluation.

2 METHODOLOGY

The current study's assumptions were examined by an experimental approach and by administering a survey that measured participants' opinions as the dependent variables and considered the physical structure of shading devices as the independent variables. The study employed Augmented Reality (AR) as a visualization tool. Furthermore, an assessment of the energy efficiency of each shading device was conducted. A flowchart detailing the procedure is depicted in Figure 3.

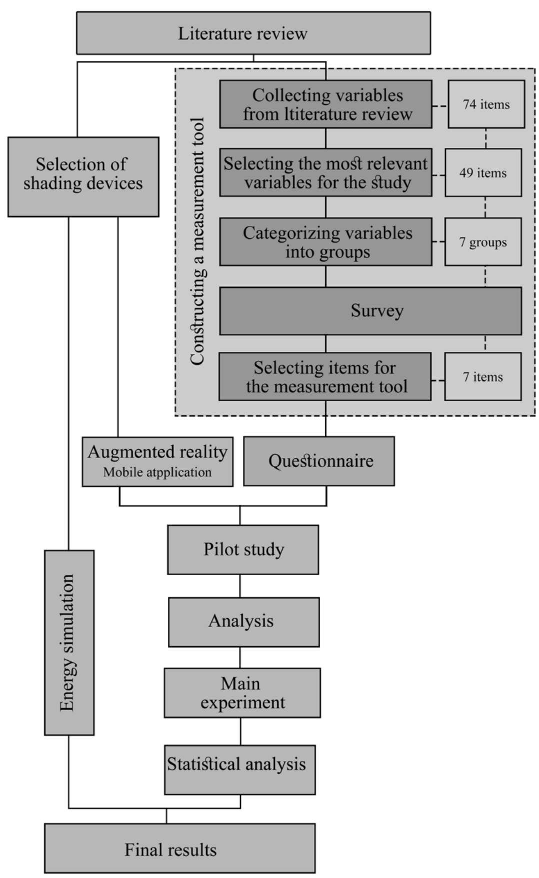

FIG. 3 Data collection procedure.

2.1 MEASUREMENT TOOL – SEMANTIC DIFFERENTIAL SCALE

The Semantic Differential Scale, SDS, was used as a measurement tool. The SDS uses words to determine feelings based on the notion that language is a means of communication. The tool relies on contrasting adjectives or expressions denoting object properties (Seyedkolaei, Alishah, Rasouli & Siami, 2015; Zeisel, 2006). To develop the scale for this study, 49 pairs of aesthetic semantics were collected from previous studies of experimental aesthetics. These semantics were categorized into seven groups based on their qualitative characteristics and meanings. To minimize the number of semantics, a ranking question survey was conducted by a group of qualified academic architects from Jordan University of Science and Technology (JUST). Survey respondents were tasked with ranking items within each group of attributes in terms of relative importance. Multiple correspondence analysis was conducted to analyse the pattern of relationships within each of the seven groups. The attribute with the highest loading was then chosen from each group (Table 2).

TABLE 2 Highest loading for items within groups (multiple correspondence analysis)

Group #	Item	Loading value	Range of loadings for group
1	Bright – Dull	.753	.453 – .753
2	Unique – Common	.721	.406 – .721
3	Depressing – Cheerful	.701	.453 – .701
4	Impressive– Unimpressive	.753	.507 – .753
5	Protected – Exposed	.778	.285 – .778
6	Rugged – Delicate	.670	.389 – .670
7	Loose – Tight	.708	.409 – .708

The attributes were further categorized into groups similar to Osgood's categorization to understand the results obtained from the final data analysis. This categorization was based on the studies of Hershberger & Cass (1974), Nasar (1994), and Marković & Alfirević (2015) as follows:

1. Affective variables, similar to Hedonic tone or Evaluative factor: Bright – Dull, Impressive – Unimpressive, and Cheerful – Depressing.
2. Formal variables, similar to Arousal or Activity factor: Unique – Common and Tight –Loose
3. Organizational variables, similar to Potency or Uncertainty factor: Protected – Exposed and Delicate – Rugged.

For the affective variables, bright, impressive, and cheerful are the positive adjectives. In other words, if a respondent perceives an object as bright, impressive, or cheerful, that object positively impacts the respondent's perception. Therefore, based on the survey responses, the eight tested shading devices were ranked from 1 (most favourable shading device) to 8 (least favourable shading device) `based on their impact on the affective variables.

The concept of positivity and negativity for other formal and organizational variables is subjective. The designation of positive or negative may depend on the gender of the perceiver, the context, and other situational factors, or some attributes may not have negative and positive polarity (Al-Hindawe, 1996). According to Veitch & Arkkelin (1995), there is an inverted U-shape relation between uniqueness and aesthetic value. It must be remembered that people perceive objects with moderate levels of uniqueness to be more pleasant than extremely common or extremely unique objects.

2.2 PARTICIPANTS

A random sample of 102 students from JUST participated in this study. Respondents were categorized into the expert group, which included 49 architecture students (14 males and 35 females), and the non-expert group, which included 53 students from other majors (13 males and 40 females). Participants in the expert group were selected from sophomore and above levels, while in the non-expert group, participants were from different academic levels and were aged between 18 and 23 years.

2.3 STIMULUS MATERIAL

Based on the classification of Choi et al. (2014), Esquivias et al. (2016), Al Dakheel & Tabet Aoul (2017), and Al-Masrani et al. (2018) (FIG. 1), eight shading devices that covered both passive and active movable shading devices were selected:

1. Horizontal overhang;
2. Fixed horizontal fins;
3. Fixed vertical fins;
4. Egg crate;
5. Parametric-designed shading device, taken from Al-Masrani et al. (2018);
6. Movable horizontal louvres;
7. Movable vertical louvres and
8. Shape-morphing shading device, taken from Al-Masrani et al. (2018).

Movable vertical and horizontal louvres were not specified as manually or automatically controlled.

2.4 AR APPLICATION

Augmented Reality (AR) was implemented in this study to present shading devices to participants through a mobile application specially developed for this research. AR is an interactive, real-time tool that adds virtual objects into real environments (Tecchia, 2016). This technology combines the flexibility of computer-generated environments with the comfort and familiarity of real environments (Wang, 2009).

An ample number of studies have used Virtual Reality (VR) to understand users' perceptions of architecture (Orzechowski, de Vries, & Timmermans, 2003; Shemesh et al., 2017; Moscoso, Chamilothori, Wienold, Andersen, & Matusiak, 2021; Banaei, Ahmadi, Gramann, & Hatami, 2020). According to Milovanovic, Moreau, Siret, & Miguet (2017), VR applications are used more frequently than AR in sense and cognition research due to the immersive experience offered by VR visualization. However, Tan, Yang, Leopold, Robeller, & Weber (2019) claimed that AR is easier to use and less time-consuming than VR. Compared to the AR technique, VR devices need more preparation before the virtual experience, including installation and instruction. AR applications provide a simpler alternative to VR. Projecting virtual objects onto real-world scenes enhances the sense of scale. Shadow projections enhance realism in AR applications by making a solid connection between virtual and real objects (Ghadirian & Bishop, 2002). The increased realism in AR applications increases the validity of the augmented experience. With these features in mind, AR technology was demonstrated to be an efficient method of representation in architecture by Tan et al. (2019) and Lee, Seo, Abbas, & Choi (2020). This study used a marker-based AR application.

A professional specialist programmer created a mobile application specifically for the present study. Autodesk Maya and Unity 3D software created an interactive AR mobile application that places virtual shading devices onto a building surface from the outside and the inside. Researchers, with the help of an expert, worked on transforming shading devices into virtual objects. Cirulis & Brigmanis (2013) recommended that the application recognize surfaces based on a QR code programmed for this experiment.

The application's home screen asks users if they are standing inside or outside the building. Based on the answer, the application uses the device's camera to display shading devices on the screen. The virtual shading devices were designed to fit the façade so the participant could move the camera around the building to see the shading devices from different angles. When a participant views the shading devices from inside the building, the application casts a virtual shadow that mimics the shadow of the real shading device.

2.5 SETTING

The study was conducted on the halls complex of JUST. The complex consists of two longitudinal buildings. Each building includes seminar halls on the three floors: basement, ground, and first. It is a long, curved, and linear building running from the southeast to the south with a single-loaded corridor plan. The northern building of the halls complex, specifically the ground floor of the south-oriented façade, was selected for the experiment. This particular study location is due to the building's south-facing continuous glazed façade. This feature allows participants to concentrate solely on the shading device without any distractions from the design or appearance of the façade itself (see FIG. 4). Furthermore, feedback from users of this specific building indicates that a control strategy is required to manage excessive solar exposure, making it a suitable and relevant location for experimenting.

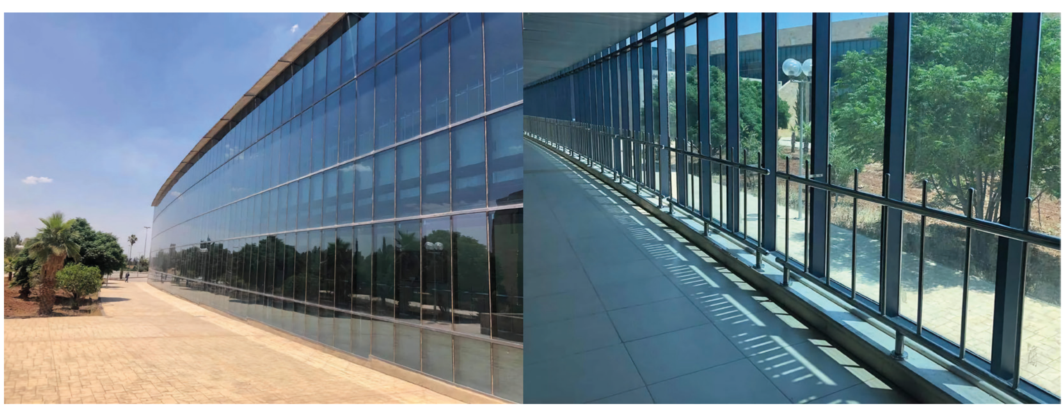

FIG. 4 Outdoor and indoor shots from the ground floor of the northern building of the halls complex.

2.6 THE QUESTIONNAIRE

The questionnaire included a cover page with initial directions, followed by the body of the questionnaire, and a closing page with a thank you note. The body of the questionnaire was divided into two parts. The first part included a total of 18 questions about the physical attributes of the shading devices, categorized into indoor and outdoor questions. Each participant evaluated different scenes using a seven-step SDS without numerical values to avoid bias related to positivity and negativity.

The first part of the questionnaire included scenes of the façade under various conditions: without any shading device (base case) and with eight different shading devices (Shading Device 1 to Shading Device 8). Participants evaluated each scene from both outdoor and indoor perspectives.

In the second part of the questionnaire, participants were asked demographic questions to ensure the sample's representativeness and gain insights into potential response variations based on the participants' backgrounds. The demographic questions included age, gender, and field of expertise (architect or non-architect).

2.7 EXPERIMENT

The experiment occurred between October and November 2020, specifically between 9:00 am and 12:00 pm. It spanned 23 days. Throughout the duration, the weather remained consistently sunny with clear skies. A QR code was printed and affixed to the glass surface of the building's façade to facilitate the experiment. Another code was attached to the inner surface of the same façade. Each participant was provided a 10-inch tablet with the required application installed and ready for use. The respondents were instructed to view the building using the tablet's camera with virtual shading devices. In total, eight shading devices were individually presented to the participants for evaluation (see FIG. 5).

The dimensions of the chosen shading devices are as follows:

1. Horizontal overhang: 1 m depth and 0.02 m thickness.
2. Fixed horizontal fins: 0.02 m depth with a spacing of 0.25 m between slats.
3. Fixed vertical fins: 0.1 m depth with a spacing of 0.1 m between fins.
4. Egg crate: 0.15 m depth with 0.15 spacing between vertical slats and 0.15 spacing between horizontal slats.
5. Artistic shading device – parametrically designed (adapted from Al-Masrani et al., 2018).
6. Movable horizontal louvres: 0.15 m depth with 0.15 m spacing between slats. The control type, encompassing passive and active horizontal movable shading devices, was not specified.
7. Movable vertical louvers: 0.15 m depth with 0.15 m spacing between louvers. The control type, encompassing passive and active vertical movable shading devices, was not specified.
8. Shape-morphing shading device (adapted from Al-Masrani et al., 2018).

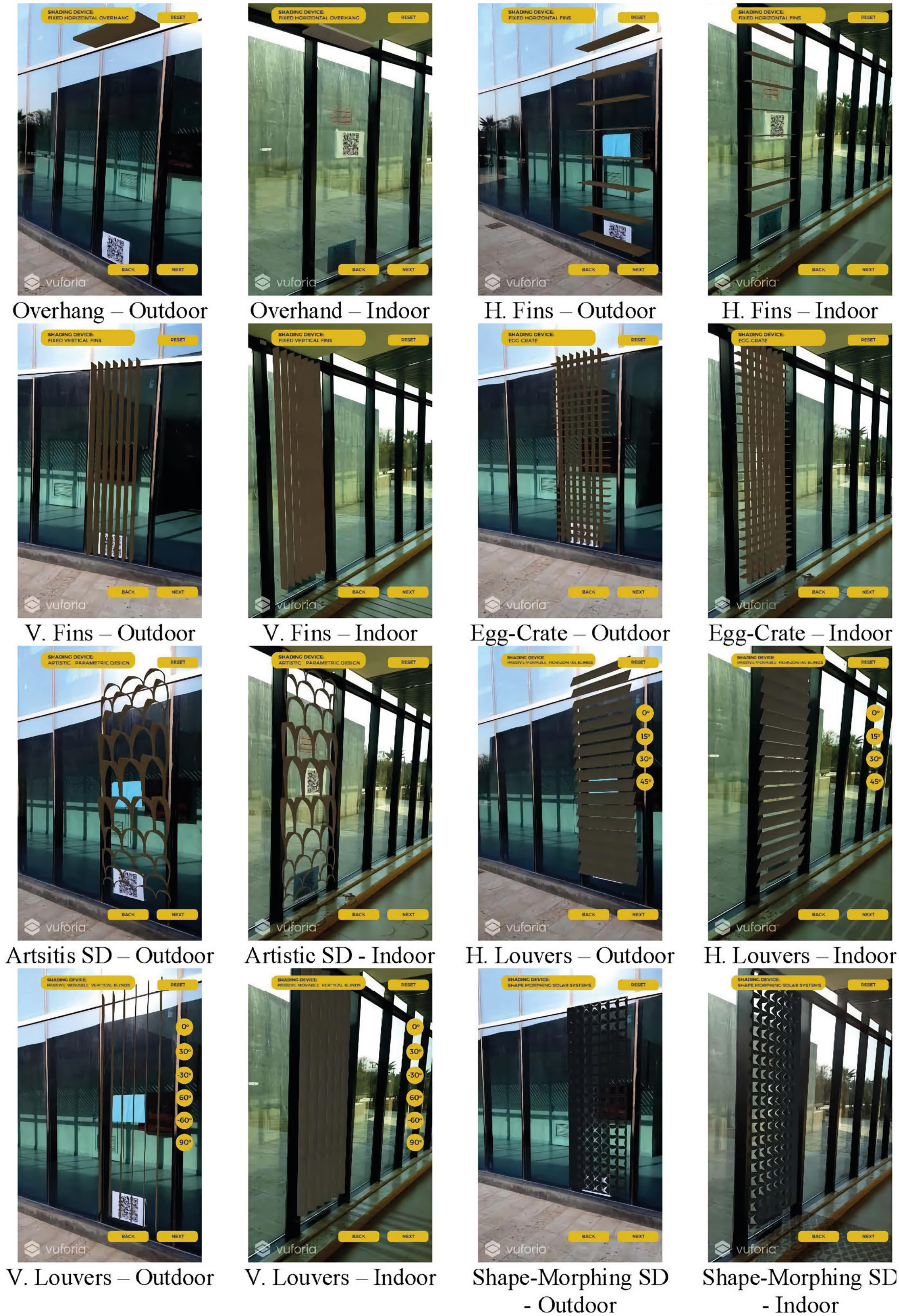

FIG. 5 The eight shading devices as they were screened using AR, outdoor/indoor.

2.8 ENERGY SIMULATION

A simulation was run using the DesignBuilder software to examine the thermal efficiency of the shading devices. The simulation focused on a prototype seminar room (FIG. 6) located in the halls complex of JUST, situated in Irbid, Jordan, at a longitude of 35.9° East and a latitude of 31.90° West. The seminar room is a prototype seminar room with a capacity of 100 people and covers an area of 136 m^2. The south elevation of the building is 100% glazed, while the north elevation has a continuous strip window with a 30% window area.

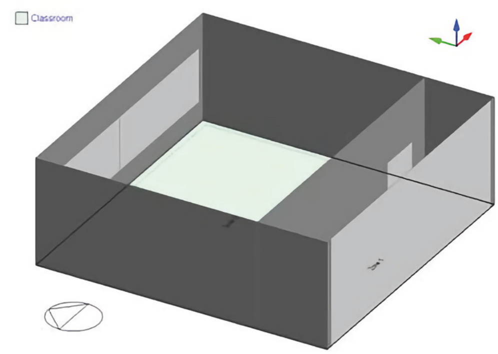

FIG. 6 Classroom model.

The energy simulation was conducted for one year, considering the region's specific cooling and heating demands. The cooling period was set from April 1 to October 31, while the heating period covered November 1 to March 31. The building operates as classrooms with a schedule of five days a week, from Sunday to Thursday, operating from 8:00 am to 5:00 pm.

To define the thermal properties of the building elements, the following U-values were considered: walls (0.42), roof (0.22), floor (0.25), and glazing (1.6). These values conform to the local Jordanian codes. The heating load set-point was set to 19°C with a set-back temperature of 14°C, while the cooling load set-point was set to 25°C with a set-back temperature of 30°C.

For comparison purposes, the simulation included a base case and four shading devices: a 1-m depth overhang, horizontal fins, vertical fins, and an egg crate.

2.9 DATA MANAGEMENT AND ANALYSIS

The study employed t-tests and one-way ANOVA with post hoc analysis to analyse the collected data. The t-tests assessed differences in perceptions between architect and non-architect groups, while ANOVA explored aesthetic attributes of shading devices. Augmented Reality (AR) was used for visualization, with physical attributes of shading devices as independent variables and participant opinions as dependent variables. The study thoroughly examined aesthetic values such as brightness, uniqueness, cheerfulness, impressiveness, protectiveness, delicateness, and tightness.

Additionally, simulation results were presented to illustrate the energy performance of shading devices. This holistic approach, combining statistical methods, AR technology, and simulation, provided a thorough understanding of the aesthetic perceptions and potential differences between user groups.

3 RESULTS

Two types of statistical analysis were used to analyse the collected data: *t*-test and one-way analysis of variance (ANOVA) with post hoc analysis. T-test is used to determine if there is a significant difference between two groups of variables, using the mean for each group as a basis. The difference between the means of the two groups is *t*, represented in standard error units. It is assumed that the two means are equal, and the rejection of this null hypothesis indicates a significant difference between the two groups—the greater the magnitude of *t*, the greater the evidence against the null hypothesis. The present study used a t-test to assess the differences between the architect and non-architect groups.

Additionally, this study used an ANOVA F-test to analyse the results concerning the devices' aesthetics. The ANOVA F-test is used to determine if there is a significant difference between three or more groups of variables, once again using the mean for each group. ANOVA uses F-tests to test the equality of the means statistically. If F-test results show significant differences between the means, then post hoc analysis is used to compare individual differences between each pair of variables. The F-test and post hoc pairwise comparisons were used in the present study to determine the differences between the eight types of shading devices.

3.1 AESTHETIC VALUE OF SHADING DEVICES

3.1.1 Bright – Dull

The results of the F-test show that there was a significant difference in the perception of different types of shading devices in terms of brightness: F (1,101) = 1418.410, p = .00. Based on the ANOVA results, movable vertical louvres are the brightest, and the egg crate is the dullest (Table 3 and FIG. 7).

TABLE 3 Pairwise comparisons (Bright – Dull)

	Overhang		Horizontal fins		Vertical fins		Egg-Crate		Artistic SD		Horizontal louvers		Vertical louvers		Shape-Morphing SD	
	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.
Overhang			-.108	.469	-.466(*)	.009	.745(*)	.000	-.490(*)	.012	-.191	.358	-1.000(*)	.000	-.745(*)	.001
Horizontal fins	.108	.469			-.358(*)	.029	.853(*)	.000	-.382(*)	.045	-.083	.634	-.892(*)	.000	-.637(*)	.004
Vertical fins	.466(*)	.009	.358(*)	.029			1.211(*)	.000	-.025	.897	.275	.117	-.534(*)	.000	-.279	.189
Egg-Crate	-.745(*)	.000	-.853(*)	.000	-1.211(*)	.000			-1.235(*)	.000	-.936(*)	.000	-1.745(*)	.000	-1.490(*)	.000
Artistic SD	.490(*)	.012	.382(*)	.045	.025	.897	1.235(*)	.000			.299	.194	-.510(*)	.003	-.255	.255
Horizontal louvers	.191	.358	.083	.634	-.275	.117	.936(*)	.000	-.299	.194			-.809(*)	.000	-.554(*)	.007
Vertical louvers	1.000(*)	.000	.892(*)	.000	.534(*)	.000	1.745(*)	.000	.510(*)	.003	.809(*)	.000			.255	.238
Shape-Morphing SD	.745(*)	.001	.637(*)	.004	.279	.189	1.490(*)	.000	.255	.255	.554(*)	.007	-.255	.238		

3.1.2 Unique – Common

The results of the F-test show that there was a significant difference in the perception of different types of shading devices in terms of uniqueness: $F(1,101) = 988.374$, $p = .00$. Based on the ANOVA results, the shape-morphing shading device is the most unique, and the horizontal overhang is the most common (Table 4 and FIG. 7).

TABLE 4 Pairwise comparisons (Unique – Common)

	Overhang		Horizontal fins		Vertical fins		Egg-Crate		Artistic SD		Horizontal louvers		Vertical louvers		Shape-Morphing SD	
	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.
Overhang			.574(*)	.000	-.480(*)	.011	-.775(*)	.001	-1.495(*)	.000	-.485(*)	.008	-.873(*)	.000	-2.064(*)	.000
Horizontal fins	.574(*)	.000			.093	.530	-.201	.337	-.922(*)	.000	.088	.583	-.299	.069	-1.490(*)	.000
Vertical fins	.480(*)	.011	-.093	.530			-.294	.125	-1.015(*)	.000	-.005	.979	-.392(*)	.002	-1.583(*)	.000
Egg-Crate	.775(*)	.001	.201	.337	.294	.125			-.721(*)	.000	.289	.219	-.098	.618	-1.289(*)	.000
Artistic SD	1.495(*)	.000	.922(*)	.000	1.015(*)	.000	.721(*)	.000			1.010(*)	.000	.623(*)	.001	-.569(*)	.000
Horizontal louvers	.485(*)	.008	-.088	.583	.005	.979	-.289	.219	-1.010(*)	.000			-.387(*)	.033	-1.578(*)	.000
Vertical louvers	.873(*)	.000	.299	.069	.392(*)	.002	.098	.618	-.623(*)	.001	.387(*)	.033			-1.191(*)	.000
Shape-Morphing SD	2.064(*)	.000	1.490(*)	.000	1.583(*)	.000	1.289(*)	.000	.569(*)	.000	1.578(*)	.000	1.191(*)	.000		

3.1.3 Cheerful – Depressing

The results of the F-test show that there was a significant difference in the perception of different types of shading devices in terms of cheerfulness: $F(1,101) = 1298.185$, $p = .00$. Based on the ANOVA results, the shape-morphing shading device is the most cheerful, and the egg crate is the most depressing (Table 5 and FIG. 7).

TABLE 5 Pairwise comparisons (Cheerful – Depressing)

	Overhang		Horizontal fins		Vertical fins		Egg-Crate		Artistic SD		Horizontal louvers		Vertical louvers		Shape-Morphing SD	
	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.
Overhang			-.255	.088	-.294	.147	.426(*)	.040	-.422(*)	.045	-.436(*)	.041	-.775(*)	.000	-1.397(*)	.000
Horizontal fins	.255	.088			-.039	.807	.681(*)	.000	-.167	.400	-.181	.276	-.520(*)	.002	-1.142(*)	.000
Vertical fins	.294	.147	.039	.807			.721(*)	.000	-.127	.519	-.142	.432	-.480(*)	.000	-1.103(*)	.000
Egg-Crate	-.426(*)	.040	-.681(*)	.000	-.721(*)	.000			-.848(*)	.000	-.863(*)	.000	-1.201(*)	.000	-1.824(*)	.000
Artistic SD	.422(*)	.045	.167	.400	.127	.519	.848(*)	.000			-.015	.953	-.353	.076	-.975(*)	.000
Horizontal louvers	.436(*)	.041	.181	.276	.142	.432	.863(*)	.000	.015	.953			-.338(*)	.048	-.961(*)	.000
Vertical louvers	.775(*)	.000	.520(*)	.002	.480(*)	.000	1.201(*)	.000	.353	.076	.338(*)	.048			-.623(*)	.003
Shape-Morphing SD	1.397(*)	.000	1.142(*)	.000	1.103(*)	.000	1.824(*)	.000	.975(*)	.000	.961(*)	.000	.623(*)	.003		

3.1.4 Impressive – Unimpressive

The results of the F-test show that there was a significant difference in the perception of different types of shading devices in terms of impressiveness: $F(1,101) = 1052.386$, $p = .00$. Based on these ANOVA results, the shape-morphing shading device is the most impressive, and the egg crate is the most unimpressive (Table 6 and FIG. 7).

TABLE 6 Pairwise comparisons (Impressive – Unimpressive)

	Overhang		Horizontal fins		Vertical fins		Egg-Crate		Artistic SD		Horizontal louvers		Vertical louvers		Shape-Morphing SD	
	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.
Overhang			-.328(*)	.032	-.407(*)	.037	.132	.501	-.260	.211	-.578(*)	.002	-.711(*)	.000	-1.642(*)	.000
Horizontal fins	.328(*)	.032			-.078	.630	.461(*)	.021	.069	.748	-.250	.094	-.382(*)	.027	-1.314(*)	.000
Vertical fins	.407(*)	.037	.078	.630			.539(*)	.009	.147	.522	-.172	.351	-.304(*)	.026	-1.235(*)	.000
Egg-Crate	-.132	.501	-.461(*)	.021	-.539(*)	.009			-.392	.057	-.711(*)	.002	-.843(*)	.000	-1.775(*)	.000
Artistic SD	.260	.211	-.069	.748	-.147	.522	.392	.057			-.319	.223	-.451(*)	.039	-1.382(*)	.000
Horizontal louvers	.578(*)	.002	.250	.094	.172	.351	.711(*)	.002	.319	.223			-.132	.460	-1.064(*)	.000
Vertical louvers	.711(*)	.000	.382(*)	.027	.304(*)	.026	.843(*)	.000	.451(*)	.039	.132	.460			-.931(*)	.000
Shape-Morphing SD	1.642(*)	.000	1.314(*)	.000	1.235(*)	.000	1.775(*)	.000	1.382(*)	.000	1.064(*)	.000	.931(*)	.000		

3.1.5 Protected – Exposed

The results of the F-test show that there was a significant difference in the perception of shading devices in terms of protectiveness: $F(1,101) = 1043.372$, $p = .00$. Based on the ANOVA results, the shape-morphing shading device renders the interior the most protected, and the artistic shading device leaves it the most exposed (Table 7 and FIG. 7).

TABLE 7 Pairwise comparisons (Protected – Exposed)

	Overhang		Horizontal fins		Vertical fins		Egg-Crate		Artistic SD		Horizontal louvers		Vertical louvers		Shape-Morphing SD	
	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.
Overhang			-.701(*)	.000	-.289	.102	-1.216(*)	.000	.466(*)	.029	-1.088(*)	.000	-.623(*)	.001	-1.495(*)	.000
Horizontal fins	.701(*)	.000			.412(*)	.007	-.515(*)	.000	1.167(*)	.000	-.387(*)	.007	.078	.598	-.794(*)	.000
Vertical fins	.289	.102	-.412(*)	.007			-.926(*)	.000	.755(*)	.000	-.799(*)	.000	-.333(*)	.008	-1.206(*)	.000
Egg-Crate	1.216(*)	.000	.515(*)	.000	.926(*)	.000			1.681(*)	.000	.127	.462	.593(*)	.000	-.279	.063
Artistic SD	-.466(*)	.029	-1.167(*)	.000	-.755(*)	.000	-1.681(*)	.000			-1.554(*)	.000	-1.088(*)	.000	-1.961(*)	.000
Horizontal louvers	1.088(*)	.000	.387(*)	.007	.799(*)	.000	-.127	.462	1.554(*)	.000			.466(*)	.000	-.407(*)	.008
Vertical louvers	.623(*)	.001	-.078	.598	.333(*)	.008	-.593(*)	.000	1.088(*)	.000	-.466(*)	.000			-.873(*)	.000
Shape-Morphing SD	1.495(*)	.000	.794(*)	.000	1.206(*)	.000	.279	.063	1.961(*)	.000	.407(*)	.008	.873(*)	.000		

3.1.6 Delicate – Rugged

The results of the F-test show that there was a significant difference in the perception of different types of shading devices in terms of delicateness: $F(1,101) = 1779.868$, $p = .00$. Based on the ANOVA results, the artistic shading device is the most delicate, and the egg crate is the most rugged (Table 8 and FIG. 7).

TABLE 8 Pairwise comparisons (Delicate – Rugged)

	Overhang		Horizontal fins		Vertical fins		Egg-Crate		Artistic SD		Horizontal louvers		Vertical louvers		Shape-Morphing SD	
	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.
Overhang			.245	.096	.039	.811	1.044(*)	.000	-.270	.143	.260	.148	-.221	.230	-.093	.659
Horizontal fins	-.245	.096			-.206	.179	.799(*)	.000	-.515(*)	.002	.015	.925	-.466(*)	.006	-.338	.107
Vertical fins	-.039	.811	.206	.179			1.005(*)	.000	-.309	.119	.221	.179	-.260(*)	.041	-.132	.530
Egg-Crate	-1.044(*)	.000	-.799(*)	.000	-1.005(*)	.000			-1.314(*)	.000	-.784(*)	.000	-1.265(*)	.000	-1.137(*)	.000
Artistic SD	.270	.143	.515(*)	.002	.309	.119	1.314(*)	.000			.529(*)	.017	.049	.800	.176	.438
Horizontal louvers	-.260	.148	-.015	.925	-.221	.179	.784(*)	.000	-.529(*)	.017			-.480(*)	.003	-.353	.068
Vertical louvers	.221	.230	.466(*)	.006	.260(*)	.041	1.265(*)	.000	-.049	.800	.480(*)	.003			.127	.563
Shape-Morphing SD	.093	.659	.338	.107	.132	.530	1.137(*)	.000	-.176	.438	.353	.068	-.127	.563		

3.1.7 Tight – Loose

The results of the F-test show that there was a significant difference in the perception of different types of shading devices in terms of tightness: $F(1,101) = 1716.687$, $p = .00$. Based on the ANOVA results, the egg crate is the tightest, and the artistic shading device is the loosest (Table 9 and FIG. 7).

TABLE 9 Pairwise comparisons (Tight – Loose)

	Overhang		Horizontal fins		Vertical fins		Egg-Crate		Artistic SD		Horizontal louvers		Vertical louvers		Shape-Morphing SD	
	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.	Mean Dif.	Sig.
Overhang			-.314(*)	.028	-.147	.330	-1.039(*)	.000	.402(*)	.041	-.588(*)	.000	.083	.651	-.461(*)	.024
Horizontal fins	.314(*)	.028			.167	.210	-.725(*)	.000	.716(*)	.000	-.275	.063	.397(*)	.017	-.147	.414
Vertical fins	.147	.330	-.167	.210			-.892(*)	.000	.549(*)	.005	-.441(*)	.003	.230	.114	-.314	.068
Egg-Crate	1.039(*)	.000	.725(*)	.000	.892(*)	.000			1.441(*)	.000	.451(*)	.010	1.123(*)	.000	.578(*)	.004
Artistic SD	-.402(*)	.041	-.716(*)	.000	-.549(*)	.005	-1.441(*)	.000			-.990(*)	.000	-.319	.103	-.863(*)	.000
Horizontal louvers	.588(*)	.000	.275	.063	.441(*)	.003	-.451(*)	.010	.990(*)	.000			.672(*)	.000	.127	.467
Vertical louvers	-.083	.651	-.397(*)	.017	-.230	.114	-1.123(*)	.000	.319	.103	-.672(*)	.000			-.544(*)	.003
Shape-Morphing SD	.461(*)	.024	.147	.414	.314	.068	-.578(*)	.004	.863(*)	.000	-.127	.467	.544(*)	.003		

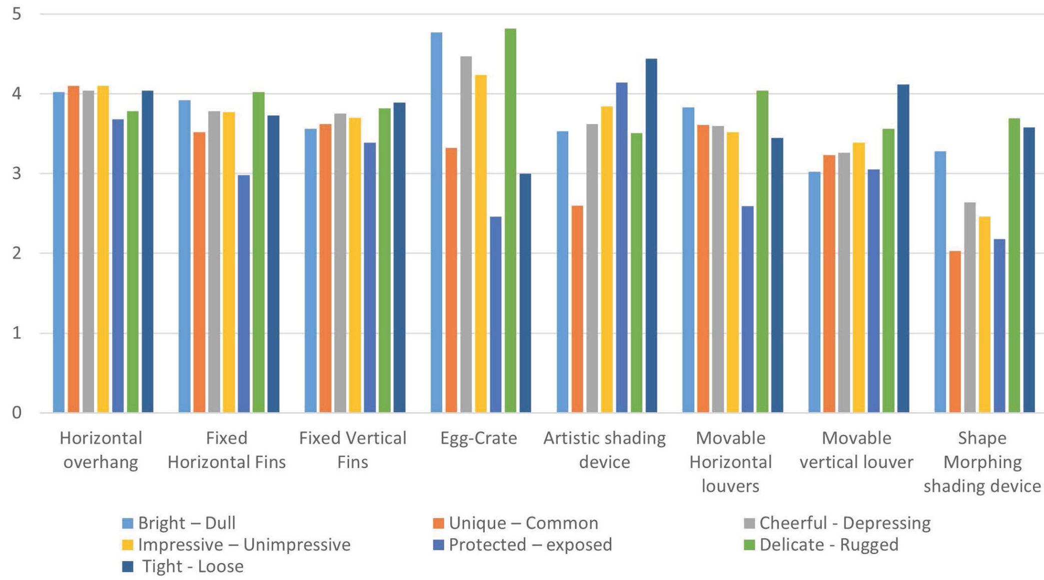

FIG. 7 The order of shading devices based on the results of the F-test.

3.2 ARCHITECTS VS. NON-ARCHITECTS

T-tests were conducted separately for each variable to determine the differences in perception between architect and non-architect groups. The results indicated significant differences between the two groups in their perception of shading devices.

The findings indicated that the variations between architects and non-architects were most pronounced when it came to their assessments of impressiveness, followed by the attributes of brightness and cheerfulness. The results suggest that non-architects viewed shading devices as impressive, whereas architects perceived them as more neutral or unimpressive. Similarly, non-architects perceived shading devices as brighter and more cheerful than architects (Table 10).

3.3 SIMULATION RESULTS

The results of the energy performance simulation for each shading device are presented in Table 11, depicting the heating and cooling loads resulting from the DesignBuilder simulation. Specifically, the energy consumption of a 1-meter overhang, horizontal fins, vertical fins, and egg crate is compared against the base case, representing the building's energy consumption without the use of any shading devices. As indicated in the table, the 1-meter overhang consumes 90% of the energy, horizontal fins consume 84%, vertical fins consume 93%, and egg crate consumes 83%, all compared to the base case's energy consumption.

TABLE 10 Significant results of T-test based on academic major (architects and non-architects)

Variables		College	N	Mean	Std. Deviation	*t*	Sig. (2-tailed)
Fixed Vertical Fins – Outdoor	**Impressive – Unimpressive**	Arch.	49	4.10	1.558	2.729	.008
		Non-arch.	53	3.15	1.925		
Egg-Crate – Outdoor	**Bright – Dull**	Arch.	49	5.39	1.835	2.114	.037
		Non-arch.	53	4.60	1.905		
	Cheerful – Depressing	Arch.	49	5.24	1.762	2.595	.011
		Non-arch.	53	4.28	1.965		
	Impressive – Unimpressive	Arch.	49	5.02	2.046	2.945	.004
		Non-arch.	53	3.81	2.094		
Artistic Shading Device – Outdoor	**Protected – Exposed**	Arch.	49	3.73	1.955	-2.254	.026
		Non-arch.	53	4.58	1.855		
Movable Horizontal Louvers – Outdoor	**Bright – Dull**	Arch.	49	4.78	1.817	3.539	.001
		Non-arch.	53	3.45	1.947		
	Cheerful – Depressing	Arch.	49	4.35	1.774	3.137	.002
		Non-arch.	53	3.21	1.885		
	Impressive – Unimpressive	Arch.	49	4.27	1.857	3.405	.001
		Non-arch.	53	3.00	1.891		
Movable Vertical Louver – Outdoor	**Impressive – Unimpressive**	Arch.	49	3.80	1.779	1.996	.049
		Non-arch.	53	3.09	1.768		
Egg-Crate – Indoor	**Bright – Dull**	Arch.	49	5.02	1.702	2.517	.013
		Non-arch.	53	4.13	1.851		
	Cheerful – Depressing	Arch.	49	4.67	1.842	2.490	.014
		Non-arch.	53	3.74	1.953		
	Impressive – Unimpressive	Arch.	49	4.67	1.908	2.882	.005
		Non-arch.	53	3.53	2.090		
	Protected – exposed	Arch.	49	2.22	1.403	-2.088	.039
		Non-arch.	53	2.91	1.842		
	Tight – Loose	Arch.	49	2.76	1.690	-2.684	.009
		Non-arch.	53	3.70	1.846		
Movable Horizontal Louvers – Indoor	**Bright – Dull**	Arch.	49	4.10	1.723	2.874	.005
		Non-arch.	53	3.09	1.811		
	Cheerful – Depressing	Arch.	49	4.12	1.752	3.864	.000
		Non-arch.	53	2.83	1.626		
	Impressive – Unimpressive	Arch.	49	4.02	1.750	3.208	.002
			53	2.91	1.757		

TABLE 11 Heating and cooling loads resulting from DesignBuilder simulation

	Cooling loads (Kwh)	Heating loads (Kwh)	Total	Saving
Base case	27,745.93	1,469.69	29,215.6	
Overhang	24,451.63	1,724.59	26,176.2	3,039.4
Horizontal Fins	21,609.24	2,838.35	24,447.6	4,768.03
Vertical Fins	25,363.25	1,794.29	27,157.5	2,058.08
Egg-Crate	20,604.99	3,623.45	24,228.4	4,987.18

4 DISCUSSION

The primary goal of this research was to investigate the ways shading devices influence the visual perception and assessment of a building. The study also aimed to determine the degree of consistency between the functionality of the shading device and its aesthetic preference. The study's findings demonstrated that shading devices significantly influenced the aesthetic perception and assessment of the building's façade. The impact varied depending on the type of shading device being tested, with some devices being perceived as pleasing while others were found to have a negative effect on the judgment and evaluation of the building's façade. These results strongly support the main hypothesis of the research, highlighting the influence of shading devices on the overall aesthetic appeal of a building.

Two shading devices, namely Shape Morphing and Egg Crate, clearly stood out in terms of respondent preferences. Shape Morphing shading device was rated as the most unique among the tested shading devices and was positively perceived and evaluated. This positive perception can be attributed to their dynamic shape, which can enhance the visual appeal of the building façade. In contrast, the Egg Crate shading device was negatively perceived, with high ratings for dullness, unimpressiveness, and a sense of depression. The grid-like pattern of the Egg Crate devices might be found unappealing for the participants.

Vertical Movable Louvers were rated as the brightest and the second most cheerful and impressive option. Other shading devices showed relatively similar evaluation results, including Horizontal Overhang, Fixed Horizontal Fins, and Fixed Vertical Fins. However, Horizontal Overhang was evaluated as the most common shading device and was perceived as dull and unimpressive. This finding is consistent with Berlyne's proposition of an inverted U-shaped relationship between uniqueness and aesthetic value (Veitch & Arkkelin, 1995). According to this theory, individuals tend to find objects with moderate levels of uniqueness more enjoyable than objects that are extremely common or excessively unique.

4.1 ARCHITECTS VS. NON-ARCHITECTS

The study results revealed significant differences in the assessments of shading devices between architects and non-architects. These findings align with previous research (e.g., Ibrahim et al. (2002)) and are particularly evident in the affective aspects of impressiveness, brightness, and cheerfulness. While the non-architect group evaluated the shading devices as impressive, bright, and cheerful, the architect group tended to have more neutral or unimpressed perceptions.

The outcome of non-architects perceiving shading devices as impressive supports the notion that individuals without architectural training or expertise may greatly appreciate these devices' visual impact and functionality. Factors such as novelty or aesthetic appeal could influence their perception of impressiveness. Conversely, more rational architects may judge aesthetics more strictly than non-architects, as Yazdanfar et al. (2015) explained. Furthermore, these results emphasize the previous studies conducted by Hershberger & Cass (1974), Nasar (1994), Abu-Obeid et al. (2008), and Akalin et al. (2009), which provided evidence that experts and non-experts perceive architectural objects differently. These researchers attributed this difference to the influence of experience and continuous exposure to architecture throughout an architect's career's learning and practice stages.

Furthermore, this difference in perception could also stem from varied perspectives on lighting preferences or the effectiveness of shading devices in creating a visually pleasant and uplifting environment. Non-architects may prioritize a brighter and cheer ambience, while architects may consider more nuanced factors related to lighting design and specific project requirements.

In contrast to the significant differences concerning affective variables, the outcomes relating to organizational variables revealed only slight disparities between architects and non-architects, while the formal variables demonstrated almost negligible distinctions. This finding can be better interpreted by referring to a study conducted by Šafárová, Pírko, Juřík, Pavlica, & Németh (2019), which concluded that architecture students, who are not yet considered experts due to their limited practical experience, perceive the physical characteristics of buildings in a relatively similar manner to non-architects. This suggests that during the early stages of their architectural education, students may exhibit more similarities with non-architects in their perceptions, indicating that they are still developing their expertise.

4.2 SHADING DEVICES AND ENERGY EFFICIENCY

As anticipated, the simulation results confirmed that shading devices are effective in terms of their energy performance and ability to reduce energy consumption to various degrees. This finding aligns with previous studies conducted by Freewan (2014), Esquivias et al. (2016), and Al-Masrani et al. (2018). However, a discrepancy was observed between the aesthetic preferences for shading devices and their efficiency and performance.

Contrary to the aesthetic preferences, the most efficient shading device in terms of energy performance was the egg crate, followed by horizontal fins, overhang, and vertical fins, with vertical fins demonstrating the least efficient performance. This discrepancy can be explained by inefficient vertical shading devices used on south-oriented façades. While Choi et al. (2014) suggested using vertical shading devices on western and eastern elevations, Esquivias et al. (2016) claimed that this type of shading device is the least effective, especially in preventing solar exposure from the east due to the lower intensity of morning solar radiation. This claim is consistent with the results of the present study.

It is important to note that other types of shading devices were not simulated due to limitations in the modelling tools of the simulation software. However, other research has provided findings on these devices. Al-Masrani et al. (2018) tested a parametrically designed shading device and found that it improves daylight quality inside buildings and reduces lighting demands. Regarding shape-morphing systems, previous research has highlighted the need for more studies to assess the performance of these devices over extended periods and under real conditions (Al-Masrani et al., 2018; Premier, 2019). Additionally, Sheikh & Asghar (2019) attempted to calculate the energy efficiency of a biomimetic façade but did not compare it to other types of shading devices.

5 CONCLUSIONS

This study aimed to investigate the impact of shading devices on the visual perception of buildings while also comparing their energy efficiency. The findings indicate that incorporating shading devices into buildings enhances their energy efficiency without necessarily compromising their visual appearance. These results hold true despite the varying degrees of favorability that users associate with different types of shading devices and the differences observed in the energy performance of various shading devices. Acknowledging the distinctions between architects and non-architects in this evaluation process is important. Understanding these assessment patterns can assist architects and designers in making informed decisions about selecting and designing shading devices. This involves considering not only functional requirements but also the aesthetic preferences and perceptions of the building's occupants and users. Based on this study and the integration of the results regarding aesthetic value and energy performance, the following conclusions can be drawn:

- Horizontal louvres are the most recommended shading device for southern and northern façades. They ranked third in terms of aesthetic value and second in energy performance.
- Fixed horizontal fins and artistic shading devices are the second recommended types. Fixed horizontal fins showed high effectiveness in reducing energy demands despite being among the three least favourably rated in terms of aesthetics. The artistic shading device, although not simulated, is assumed to provide solar control similar to an egg crate and horizontal fins, indicating its potential for effective energy demand reduction. Aesthetically, the artistic shading device and horizontal fins were rated as moderate in terms of affective variables, suggesting that parametric design can play a role in creating aesthetically pleasing shading devices.
- Overhangs, while not highly ranked in terms of aesthetics, proved effective in energy performance and are therefore recommended, albeit after other horizontal shading devices.
- Vertical louvres and vertical fins were favourably rated in terms of affective variables but demonstrated the least efficiency in terms of energy. Hence, they are not recommended.
- Egg-crate shading devices had the best energy performance but had a negative impact on the visual appearance of buildings. Therefore, designers are not recommended to use egg-crate shading devices.
- Shape-morphing shading devices had the most positive effect on the visual appearance of buildings among the tested shading devices. Further research is needed to understand how their energy efficiency compares to other types of shading devices.

There is much room for further progress in determining the effect of shading devices on the perception of buildings:

- Further research is needed to establish a recommendation for shape-morphing shading devices.
- Future studies should evaluate a more comprehensive range of shading devices.
- Future studies should consider the experience stage of architects and the differences between academic architects and architects from the practical fields.
- Shading devices may be studied in contexts other than educational buildings to enhance the generalizability of the present results.

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Prefab Façades – From Prototype to Product?

The Kit-of-Parts approach to a façade design

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Abstract

Building envelopes are not only the prime element of the exterior aesthetic quality of buildings; they have also become a major driver both for building construction cost and operational performance. The importance of prefabrication is growing in the building industry as it allows faster, high-quality, and cost-effective construction while reducing risks associated with onsite labour. Although prefabrication for structural components is a relatively recent development, it has been widely used in the manufacturing of building envelopes for many years, particularly in the case of unitized curtain wall systems. However, whether using prefabricated components or not, façade design development remains a challenge due to the need for façade engineers to rapidly develop technically viable and financially feasible solutions that achieve the desired architectural design intent. Particularly at the early stages of the design process, the turnaround for multiple iterations is often fast-paced, and abortive work is, therefore, not uncommon.
This paper outlines an approach to addressing this challenge, attempting to bridge the gap between façade design, fabrication, and installation. A new design approach and tools are presented that allow designers to iteratively validate concepts based on a pre-engineered system that is optimized for performance and take fabrication, transport, installation costs, maintenance, and circularity into account. As a result, the tool/design workflow will ensure consistent quality, meeting budgets and timelines while enhancing material efficiency and fostering energy-conscious and circular envelope design approaches.

Keywords

façade design; design for manufacture & assembly; Engineer-to-Order; Kit-of-Parts; product configuration, customization, circularity, sustainability

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1 INTRODUCTION

In the last two decades, increasingly strict energy regulations and building standards have led to continuous demand for better-performing buildings that are delivered in increasingly shorter timeframes with reduced budgets (Antunes & Gonzalez, 2015; Otter & Prins, 2001). At the same time, more than any other technology-driven industry, the construction sector has shown a significant lag in productivity and quality assurances due to large amounts of onsite work performed (McKinsey & Company, 2017; Blismas, Pasquire, Gibb, 2006). Designs tend to become multistage design processes involving a variety of design teams, conventionally interacting on a linear design approach basis with iteration loops (Lawson, 1997; Kagioglou et al., 2000). Efficiency and quality outcomes are, therefore, highly susceptible to the degree of organization and engagement of the teams involved. Poor organization often results in inadequate communication and inefficient performance and risk management. On a day-to-day level, it may lead to missed connections and links between the various businesses involved, often coupled with limited talent management, such as deferring to familiar contractors rather than challenging the market supply (Goulding et al., 2015). These factors not only slow down the on-site construction process significantly but also leave room for a subjective interpretation of deliverable quality (The Economist, 2017). This is supported by an intensive literature survey presented by Kassem and Mitchell (2015), who compare studies evaluating factors contributing to poor project performance; the most common denominators causing delays and compromises in quality were found to be communication and planning. The most common results for large-scale projects are time and budget overruns, without ensuring a consistent quality of the deliverables (Assaf, Al-Hejji, 2006).

Learning from other industries and the potential of their production lines, the construction industry grew an increased desire for prefabrication, delivering higher performance components facilitated by increased quality control and reduced risk on site (McKinsey & Company, 2019). While prefabrication allows the designer to achieve better-performing buildings, it requires decision making at early stages with little flexibility in modifying components once they are produced and delivered on-site. The shift towards prefabrication is generally trending in the construction sector (Rocha et al., 2022), but particularly for building envelopes, where prefabrication and system quality play a significant role as performance targets become more stringent.

The performance of the building envelope is fundamental to the overall efficiency and durability of the building. It provides the weather and thermal barrier, solar and glare protection while allowing daylight in and views out of the building (Klein, 2013; Knaack et al., 2007). The building skin has a significant effect not only on the operational energy required and embodied energy/carbon but also fundamentally affects occupant comfort (Pottgiesser, Strauss, 2013; Gasparri, Aitchison, 2019; Zani et al., 2018). In addition to its impact on the performance of the building, the façade also plays a significant role in its appearance and design language, helping to provide architectural identity and uniqueness. This has led to an increasing complexity of the building skin that typically requires inputs from various stakeholders to address multiple competing parameters with conflicting performance and design requirements (Kassem, Mitchell, 2015; Cucuzza et al., 2022; Montali et al., 2019).

Curtain walls are a common approach, particularly to commercial building envelopes. Despite their potential to be fully systemised, in most cases, customized building components are required; the product delivery process is re-initiated from the ground up for each project in the early design stage and at best, existing parts are adapted to the specific design of the building where possible (Montali et al., 2017). This approach to developing a custom system adds time, costs, and risk to the overall delivery process of the façade. A reduced level of customization, for example through the definition of standard and optimized system types, may decrease the design effort and the delivery process but must guarantee a broad range of variability in order to fulfil architectural freedom and design intent. This paper identifies the main design parameters that can be optimized by using a bespoke toolset, and it presents a façade Kit-of-Parts (KoP) developed within the scope of this research initiative.

2 BASIS OF RESEARCH

Typically, the design of a building and its envelope is an iterative process in which, starting from an architectural idea, various technical consultants such as façade, structural, mechanical, environmental, daylight, acoustic and fire engineers provide input that leads to the generation of further design iterations. Through this process, a technically feasible solution that adopts and incorporates established performance requirements is developed – ideally without significant impact on the design intent. In a secondary assessment, which typically occurs at a later design stage, a specialist contractor would be added to an additional iterative process in which the technical feasibility is assessed from a fabrication, installation, and maintenance perspective as well as in relation to cost (Figure 1A). This linear approach does not connect the expertise of the different teams at a level that can facilitate a feedback loop to allow technical comments to influence the design early in the process. Instead, it primarily allows for the integration of feedback once the design stage is complete (Boswell, 2013), resulting in compromises in design, performance, and cost. Integrating continuous feedback in design concept stages would allow the design team to make informed decisions and balance parameters from an early stage, requiring less costly re-work and iteration. The proposed design approach (Figure 1B) is more interactive, involving all teams with their different expertise from the beginning, permitting an informed decision-making process during the design stage rather than the conventional iterative review approach.

A - Conventional design approach

B – Integrated circular design approach

FIG. 1 Façade design workflow. A) Typical linear design workflow currently implemented. B) Proposed continuous design workflow.

As an example, in the early stages of the design, a construction expert is prone to pinpointing choices that can prevent additional expenses at a later stage, while a procurement manager is better equipped to understand how to cut material expenses (The Economist, 2019), which means both provide valuable input from different perspectives. Implementing this information at very early design stages can help to identify key performance parameters, technical and fabrication limitations, and cost drivers to reduce pivotal design iterations. When implemented across various projects, this could reduce the budget needed for design iteration, shifting it towards quality delivery of the product itself (*i.e.*, the façade).

There are multiple ways of ensuring early-stage implementation of cross-functional information. The main objective is to provide enough information to the architect prior to the completion of the conceptual design, which can be achieved by direct involvement of the engineering team and façade contractor. However, this would suggest that all teams involved have to be established and available from the earliest stages of design. A more efficient and independent method to support the architectural design team is to establish tools that assist and inform during the design process, using continuously updated information provided by the engineering team and façade contractor. These tools offer benefits to the design process by enabling not just engineering-driven, cost-effective decision-making in the project's initial phases but also by efficiently optimizing collaboration among diverse engineering teams and specialist contractors. This is expected to improve the quality of design and reduce material use and cost, as well as fabrication and construction time.

3 METHODOLOGY AND RESEARCH

The goal of this paper is to investigate the conventional approach used in façade design and present an integrated approach addressing the problems inherent to this iterative, linear process. The research focuses on developing an interactive toolset that facilitates the implementation of innovative façade workflows and technology.

3.1 INNOVATIVE FAÇADE TECHNOLOGY: KIT-OF-PARTS

The concept of kit-of-parts design has already been partially introduced to façade engineering. In Europe, the curtain wall market is dominated by system providers with specific profiles and various typical details that enable architects to design conventional envelopes that are sized based on load tables, i.e., approximate profile sizes can be dimensioned at an early stage in the design without relying on a specialist engineering input (Kassem, Mitchell, 2015). This allows designers to resolve typical details; however, most projects still require customization. In North America, contractors commonly use their in-house bespoke systems that typically rely on custom dies for every project. Although fabrication occurs off-site, the design of every project is highly customized and could benefit more from the potential offered by prefabrication.

Typically, throughout the design process of a building, various options are explored and engineered by the design team to validate ideas. For the development of curtain walls, this typically means iterations of grid sizes, geometries, material combinations, and additional components that might add loads to the curtain wall structure (e.g., solar shading) (Boswell, 2013). Although essential for an iterative design approach, this process of performance validation is time-consuming, inefficient and requires significant resources for simple iterative tasks. Furthermore, it is typically done in an isolated manner for every project without considering learnings from previous projects and designs.

3.2 APPROACH

The Kit-of-Part (KoP) approach employed by the authors enables an architect-led design team to validate design options through digital design tools based on a pre-engineered set of components. The set of engineering tools incorporated in the web-based user interface allows the architectural team to explore several façade options during the early stages of the design (i.e., concept and schematic phase). Set details, samples, and pre-tested components help the designer speed up the selection and testing process. In addition, it allows the design team to achieve the desired performance and ensure consistent quality throughout a broad portfolio of projects. From an owner's perspective, the KoP reduces risk and helps maintain quality while providing increased cost certainty throughout design, fabrication, shipping, and installation. Specific constraints on panel sizes, geometry, and use of material guide the design process towards a solution that is optimized for performance but aims to find sweet spots in the supply chain to achieve economically effective solutions.

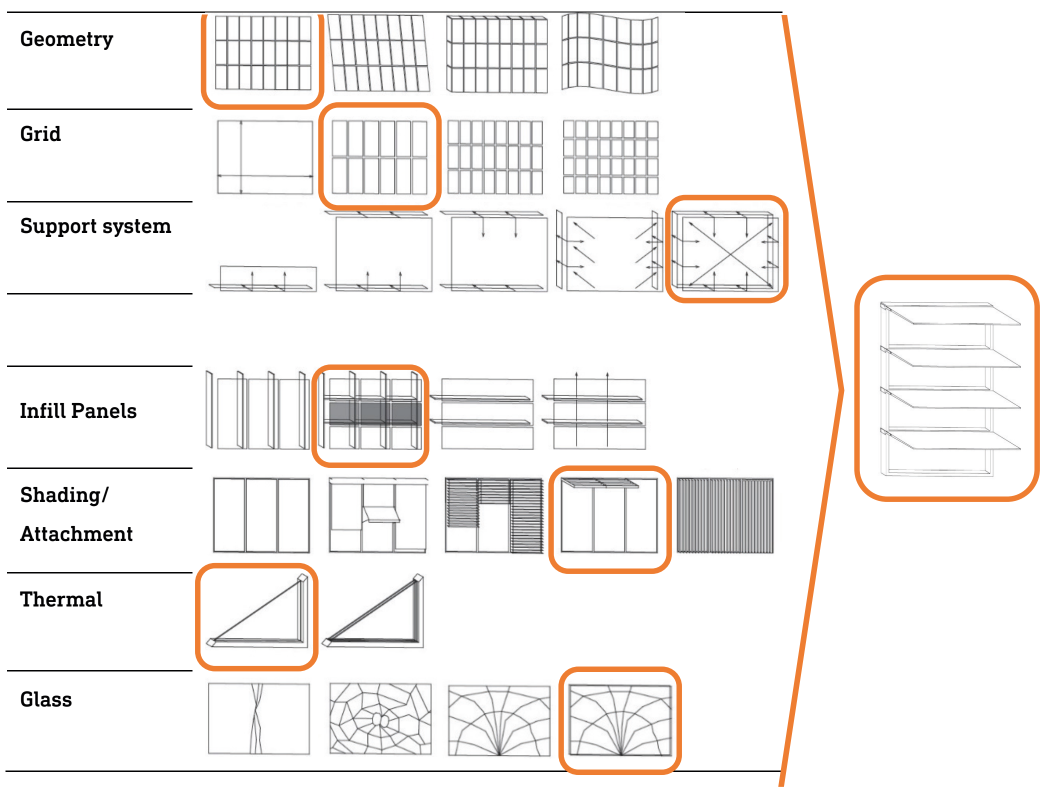

FIG. 2 Technical categories for KoP approach with exemplary decision-making process: Flat geometry, large-scale grid, four sides supported, horizontal infill profile, glass infill panel, horizontal shading attachment, double glazing, heat strengthened -laminated glass.

This integrated circular design approach is based on the idea of breaking down a façade into its fundamental elements, where a multitude of options are provided for each element. The categories start with broader topics like geometry and grid, and narrow down to details like frame sizes, materials, and additional components like solar shading elements (Figure 2). The design team can use the various categories and options to create proposals and concepts. The tools developed are based on the same process, guiding designers through each step in a logical workflow, allowing them to select the option that best matches their design intent within each category while receiving performance and cost feedback on the implications of each selection.

4 RESULTS

4.1 TOOLS

The authors have developed a digital toolkit that allows a design team to pre-engineer the unitized curtain wall based on a variety of factors. The KoP design workflow consists of five engineering tools that are interconnected and integrated into one user interface. The calculation methods and overall workflow presented in this section are currently under beta testing, and the web-based interface is under development. The engineering tools are based on US codes and industry standards such as ASCE 7-16 for load combinations, ASTM E1300 for glass design, AAMA TIR-A11-15, and Aluminium Design Manual for mullion design, as well as NFRC 100-200 for thermal calculations. Overall system performance (e.g., air and water leakage, accommodation of movements, fire resistance) is based on industry guidelines and technical notes such as AAMA (American Architectural Manufacturer Association), ASTM and CWCT (Centre for Window and Cladding Technology).

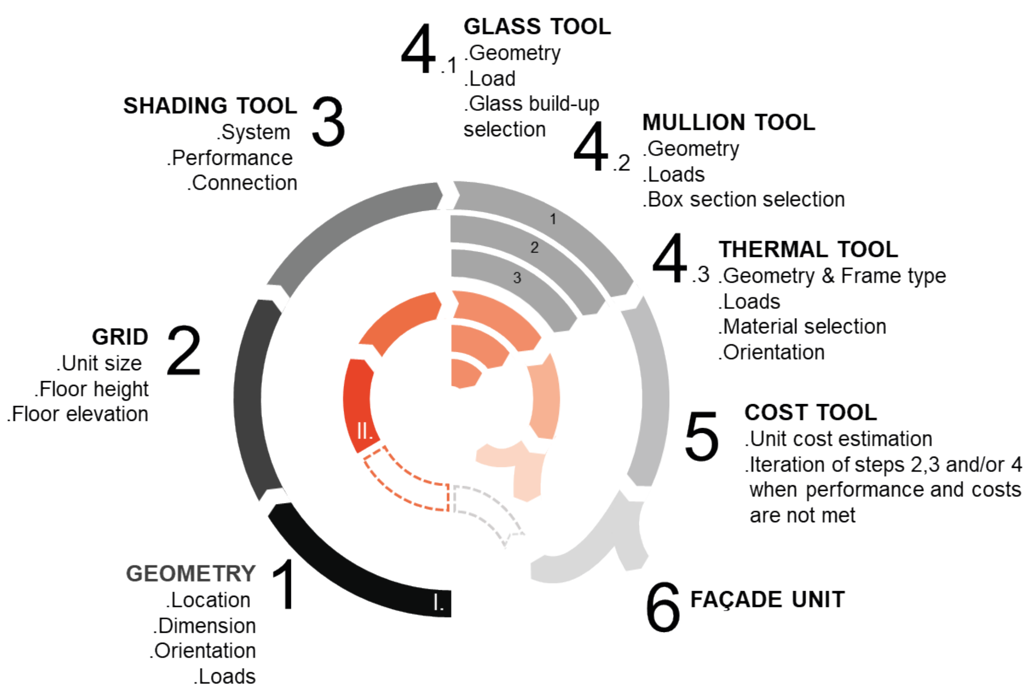

FIG. 3 Tool functionality map. Streamlined design process allows for design iterations (orange) when cost estimates exceed budget without disturbing the overall workflow.

Figure 3 shows a schematic of the workflow for the component-based approach that has been applied for the development of the KoP.

The designer is guided step-by-step through translating the design intent into KoP façade elements and engineering tools, consisting of a structural calculator for framing elements and glazing, a thermal calculator and shading performance evaluation (developed by Loisos + Ubbelohde). For each design iteration, the cost tool runs in the background and provides real-time feedback to the designer on whether the proposed solution remains within the specified project budget.

The tool workflow begins with a series of project-related questions, such as location, building use and orientation, building and façade dimensions, number of wall types, project complexity, and façade budget, to define a baseline façade and cost. The tool will be able to assess and generate a vertical planar façade with a regular rectangular grid. Once the general information is entered in the tool, the designer can generate a façade unit through the unit configurator by defining the unit width, height, number of intermediate framing elements, and infill materials (e.g., glass, shadowbox, aluminium panel, GFRC). As shown in Figure 4, the user can set up a single unit with multiple infill materials (e.g., glass IGU and metal panel). Alternatively, a fully transparent or a full spandrel unit can be chosen, as well as a multitude of other material configurations. If the project comprises multiple unit configurations, the users can create and save these different units and apply a percentage of coverage for each unit across each façade orientation of the building.

In parallel, the designer can generate and evaluate the effectiveness of various solar shading systems such as horizontal/vertical louvres, external blinds or perforated meshes for different façade orientations. Based on design intent and performance goals (e.g., daylight, view, glare), the user is then able to select the most appropriate shading strategy in combination with specific glass treatment (e.g., solar/low-e coatings, frit). Geometry and material information are automatically transferred to the pre-engineering tools for the façade performance assessment, which are provided as the final output.

Typically, mullion depth is driven by loads and span, while mullion width is primarily driven by shading attachment requirements. As soon as span or loading criteria (either wind load or shading attachment load) exceed the deflection or stress limit for one mullion size, the next larger size will be used. However, an optimization tool allows to reinforce aluminium mullions with steel to choose a smaller mullion size. Percentage-based cost feedback is provided for these options so that sizing decisions can be made conscientiously if a more slender appearance is desired. The mullion cost is influenced by the amount of aluminium used, the thickness of the flanges and steel reinforcements if required. This might mean that the minimum structurally sufficient design may not necessarily be the most economical option.

A similar approach is used for sizing the glass build-up. Based on wind loads, code, and performance requirements, i.e., safety, acoustic and thermal performance, as well as the design intent, the tool generates the most feasible and cost-effective glass build-up. Overall glass build-up (thickness and assembly) and size (width and height) can significantly impact overall façade cost, so the cost tool is based on a pre-verified supply chain.

Outputs from the previous tools feed into a thermal calculator tool that provides the U-value calculation for the typical units across the façade. Typical details (e.g., mullions, stack joints) and centre of panel (CoP) U-value for each material and combination included in the KoP were simulated using (NFRC-compliant software) Bisco and imported into a database. The tool extracts frame and CoP thermal performance values and calculates the system U-value using an area-weighted average method according to NFRC and EN standards. With the thermal tool calculator, the user receives live feedback on how the façade unit performs thermally. This information is provided based on modification of opacity ratio, frame size, material choice, and level of insulation. In addition, by inserting the percentage of coverage for each unit, the user can evaluate the overall thermal performance of the façade and compare it with specified, code-based targets to meet overall building performance requirements.

In order to assist the design team in developing a façade within budget, the KoP design tool incorporates a cost tool into the workflow. The cost tool provides a cost range per square foot of façade considering general façade configuration items such as direct costs, e.g., material, crating, and transportation costs, but also more project-specific elements such as fabrication, engineering, installation, and project management costs.

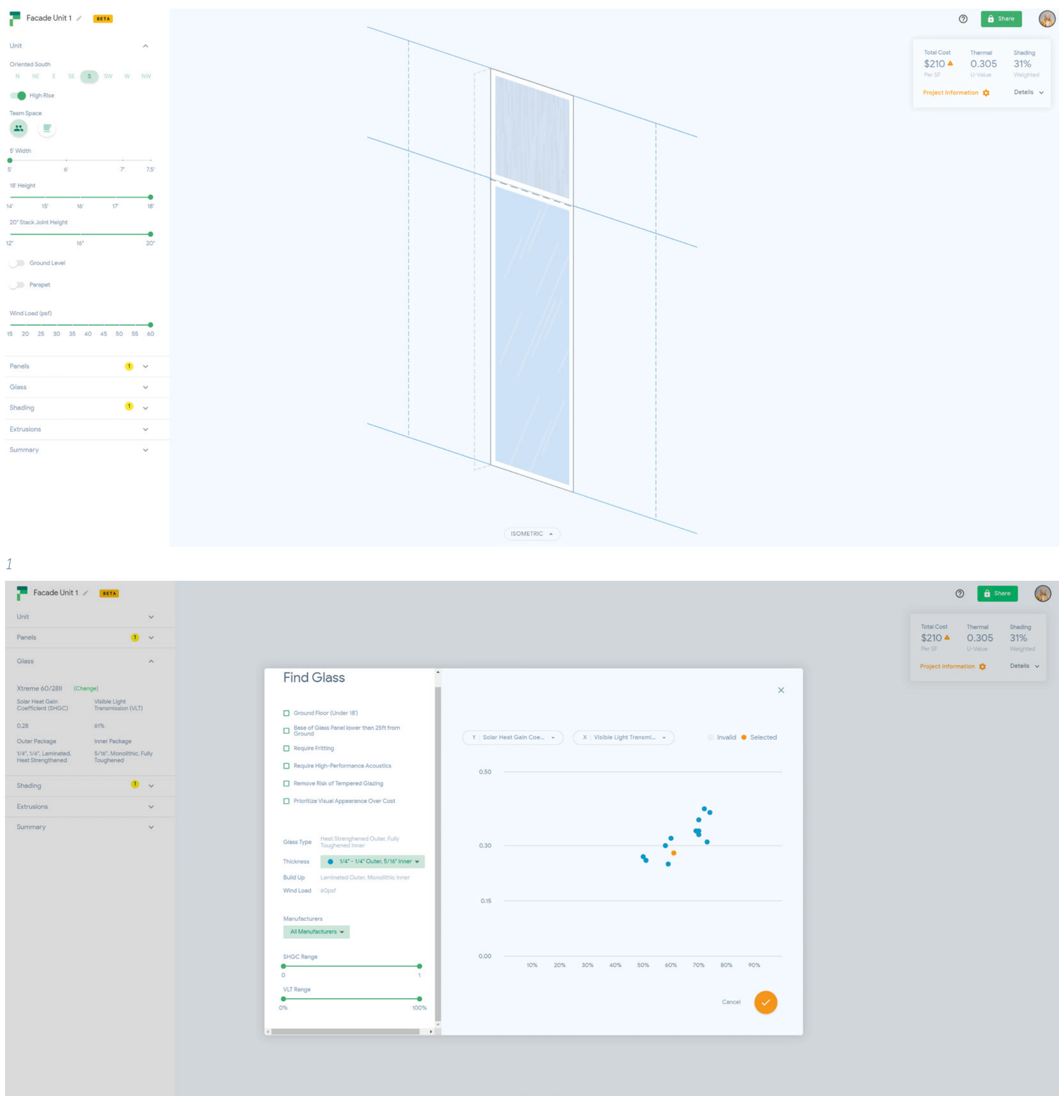

FIG. 4 Façade configurator interface allowing for an eased design process due to linked informative tools. 1. Upper – Unit configurator, 2. Bottom – Glass calculator.

All materials, as well as the profile and shipping cost information, are currently being implemented into a database specific to the KoP supply chain. Project-specific costs are calculated based on economic analysis of historical project data as a percentage of the material and shipping costs based on the main characteristics of the project that is being developed, such as project size, geometric complexity, number of wall types, and project timeline. The cost tool operates in the background and can provide live feedback to the designer for any change generated in the unit configurator or shading tool. As a result, the designer can understand and validate the cost impact of a design decision and be conscious of cost drivers.

Based on the output of the various tools discussed, an optimized solution integrating performance and cost while providing a simple and fast approach to exploring alternates and their implications is generated. All tools are combined into a façade configurator application with a visual interface, as illustrated in Figure 4. All developed tools, such as geometry, glass, shading, mullion, and thermal, are integrated and linked to one interface, allowing an easy and fast way of exploring different design solutions and combinations while keeping the original design intent.

In addition to the performance and cost outputs, the tool produces a set of typical reference details, including typical mullion sections, stack joints, and bracket attachments (Fig.5). The graphic outputs generated by the web-based application can be downloaded and help the design team with the production of project specific façade drawings.

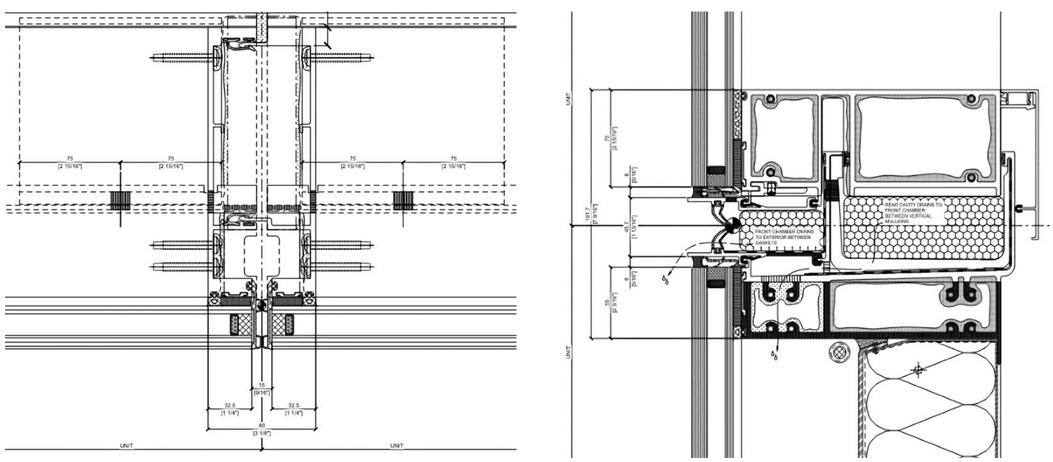

FIG. 5 Typical KoP façade details. Left – Typical mullion, Right – Typical Stack Joint.

4.1.1 Environmental Performance

In addition to performance and cost, sustainability is another emerging design directive which has been implemented into the KoP approach. Environmental impact in the building sector has traditionally only focused on reducing operational energy. More recently, alongside the traditional focus on building energy consumption, there has been increased attention on the influence of embodied carbon in construction materials across various life cycle stages (Bach, Mohtashami, Hildebrand, 2018). Within the KoP approach, materials have been assessed in terms of Global Warming Potential (GWP) and the total non-renewable primary energy (PENRT) through the production life cycle stages (A1-A3). The assessment results can be translated to the KoP tools by highlighting materials with lower embodied carbon results, for example, wood-based infill products.

Circularity is also a core principle of the KoP to emphasize long-lasting materials that can circulate through different future reuse options. For instance, recycled aluminium profiles show significantly lower embodied carbon values than original material, and they can be recycled without being downcycled. Additionally, circular design is not only considered on a material level, but also on a system level. The system's construction considers dry connections, mechanical fasteners, and, overall, joints that are easily disassembled. Throughout different case studies (Deniz and Dogan, 2014; Mule, 2012; Durmisevic, 2006), it was proven that ease of disassembly translates to ease of reuse and recycling, therefore allowing for different options that bring the components back into the loop. As part of the development of the tool, it was further found that using standard-sized products, connections, and modular design eases the path to re-life instead of recycling. An aluminium profile has a typical service life expectancy of approximately 75 years, while the glazing unit in the system tends to have a service life of 25-30 years. Using details with standardized profiles that allow for glass replacement to avoid premature recycling of aluminium units increases the overall service life of the façade and significantly lowers embodied carbon.

FIG. 6 Façade component library. Visualisation of implemented design solutions to support virtual decision-making tool.

4.2 FAÇADE COMPONENT LIBRARY

To support project team engagement with the KoP approach, a physical sample library was created in addition to the digital content and database implemented into the tool. This library contains small-scale samples of the typical materials that are part of the KoP, as well as physical representations of profile shapes and sizes. Full-scale 3D printed extrusion elements that can be disassembled help designers understand configuration ranges and allow them to assess profile sizes based on loading, spans and joint sizes depending on the loads, and type of chosen shading. Joint sizes are affected by loads as well as material choices, with heavier and larger shading elements requiring larger brackets, which in turn lead to increased joint widths. Like the KoP itself, the library is based on flexible modules that can be re-arranged to accommodate the needs and focus of each project team (Figure 6). Design teams can use the space as per their needs and combine materials and finishes in physical form to represent the configurations that are assessed in the configurator. This can occur in parallel, which again helps to increase efficiency within the process as the design team is not reliant on lead times for materials to be provided; instead, immediate access to the library from the beginning of the project allows the team to compare products, materials, and finishes with every iteration of the design.

Prior to final engineering and system design, a visual mock-up is typically used to assess profile and unit dimensions, dimensional relationships of the geometry as well as material combinations and finishes. When a bespoke system is designed, the visual mock-up is often a physical representation of the profile sizes but made from a more rapidly constructible, readily available material (e.g., timber) to evaluate visual aesthetic and detailing but not structural integrity or performance. Depending on the project size, various forms of visual validation are possible within the KoP approach; starting from a digital mock-up that allows the team to walk through in virtual reality while validating material finishes in the material library to container mock-ups with full-size panels and complete visual mock-ups with full representation of a portion of the building envelope. Depending on the complexity of the project, as well as budget and timeline constraints, the appropriate form of visual validation can be chosen. Pre-validation of the materials reduces the need for multiple visual mock-ups, resulting in time and cost savings.

Even for the larger scale mock-ups, the advantage of a KoP approach over a bespoke façade system approach is that typical profiles will be available, and the mock-up can be built with actual profiles faster than through a traditional approach.

FIG. 7 Visual mock-ups for visual material review: Glass viewing.

FIG. 8 Performance mock-up: Dynamic air and water infiltration is tested by using a wind turbine to generate dynamic wind loads.

4.3 PERFORMANCE TESTING

Physical testing of the building envelope, in addition to analytic validation, is typically required due to the complexity of façade performance criteria. For this reason, a performance mock-up using project-specific profiles, infill materials, and interfaces is typically assembled to replicate the worst-case scenario and tested for air and water tightness as well as structural and seismic performance. In traditional building projects, this performance test is a major factor both in terms of design and timeline of a project as well as cost. In contrast, because the KoP always uses the same set of base components, teams can avoid project-specific testing because the system is pre-tested for a worst-case scenario under a defined range of conditions. Currently, the tool kit is applicable to projects within a specific geographic location (San Francisco Bay Area) and building type (Commercial building, risk category II and III). Performance testing is carried out for the most complex conditions to allow results to be scaled and applied to any project that is designed using the KoP approach and within the geographical boundaries and defined limits of the tool kit.

While performance testing is outlined in national and international standards, validation of visual quality is more complex to assess in a consistent manner, as it is partly subjective. To make sure that a consistent quality can be achieved through a broad portfolio of projects and across multiple suppliers, a review procedure has been developed to pre-assess and validate manufacturers through the entire supply chain for the KoP. Only pre-vetted vendors can supply materials for the KoP, which increases the level of quality achieved in the façade components. Visual quality is pre-assessed and evaluated in terms of replicable parameters. These adhere to proven industry guidelines where available, e.g., Hadamar guidelines for visual assessment of glass. For other materials and components, visual assessment guidelines are developed based on similar parameters, ensuring that materials can always be viewed under consistent conditions and according to parameters that maintain an objective review. With this approach, the KoP process employs more resources upfront while risk impact is lower and allows for a streamlined process per project with significantly reduced risk by benchmarking quality at an early stage.

5 CONCLUSION

The KoP approach outlined in this paper translates the integrated continuous design process typically used in other industries for the development of commercial products and efficiencies related to it, to the design of building envelopes. Façades are usually designed and produced on a 'prototype' basis where each design is specific to the building and the performance requirements associated with it. The digital tool-based design approach allows project teams to work in an integrated process without having to wait for input from each specialist discipline, as would be the case in a traditional linear process. Façade performance is pre-engineered through the developed tools, which, combined with the validation of the supply chain, results in consistent quality, reduced cost, and improved circularity throughout a broad portfolio of designs and projects.

Given that the tool is still in its beta state, with the web-based application under development, the implementation of the application to a typical project design workflow remains to be verified. The main challenge will be to guarantee sufficient variability and flexibility to meet the design intent envisioned within the boundaries of the KoP. Another challenge is related to future proofing the day-to-day operation, particularly maintaining calculation methods in line with code modifications, updating the material component library, and keeping cost and supply chain information up to date.

As a result, however, the façade as a component or a product — rather than a prototype that requires testing for every application — has the potential to be delivered in consistent quality, within an understood budget and timeline, and with significantly higher efficiency of material use, leading to a more energy conscious and circular approach to envelope design.

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