Journal of Cleaner Production 356 (2022) 131900

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Experimental characterization of comfort performance parameters and multi-criteria sustainability assessment of recycled textile-reinforced cement facade cladding

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ARTICLE INFO

Handling Editor: Prof. Jiri Jaromir Klemeš

Keywords:
Fiber cement sheets
Fire behavior
MIVES
Multi-criteria decision making
Sustainable criteria
Textile waste fiber
Thermal and acoustic behavior

ABSTRACT

Within the building construction sector, fiber cement boards have attracted interest as facade cladding materials in the last ten years, especially those that incorporate –for reinforcing purposes– natural and/or recycled synthetic fibers (i.e, from the textile industry). So far, the design-governing parameters of facade cladding panels have been mechanical strength, durability, constructability, aesthetics, insulation capacity, and fire resistance. From the sustainability perspective, the impact of the facade on the economic and energy efficiency performance is most often the parameter that leads the decision-making process. Within this context, the quantification of the sustainability performance of the facade –accounting for economic, environmental, and social indicators– is unfrequently carried out in design and project phases, this being attributed to the lack of methodologies that allow considering and quantifying some relevant indicators representative of the facade sustainability performance. As consequence, decisions made based on solely economic and on some of the environmental indicators might lead to solutions with lower sustainability performance than that required (or expected). Recycled textile waste fabric-reinforced cement board as a facade-cladding material for building envelopes is the focus of this research. In order to characterize the fire resistance, and thermal and acoustic insulation –as relevant serviceability parameters– of this material, an experimental program was carried out. Likewise, the sustainability performance of this facade-cladding is assessed through a method based on the *Integrated Value Model for Sustainability Assessment* (MIVES). This multi-criteria decision making (MCDM) model relies on the value function concept and the multi-disciplinary participation of experts to identify and quantify the relevant indicators of the facade sustainability performance and the relative importance of indicators and requirements. The MIVES-based model generated for this research can be straightforwardly used for assessing the sustainability performance of facade-cladding techniques made of any material and for any type of building (and location). The application of the MIVES model led to the sustainability index of this new material for facade-cladding ranging from 0.68 to 0.71 (/1.00) for different weighting scenarios.

1. Introduction

The construction sector adversely affects the environment during phases that comprise material manufacture, site building, usage phase, and demounting/demolition (Pons and Wadel, 2011). According to statistics, the construction industry accounts for approximately 35% of CO_2 emissions, 40% of total energy consumption, and 45% of generated waste in the EU (High energy performing buildings - Publications Office of the EU; Gálvez-Martos et al., 2018; Lazar and Chithra, 2020). Thus, although significant efforts are being carried out, research and

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https://doi.org/10.1016/j.jclepro.2022.131900
Received 21 November 2021; Received in revised form 27 March 2022; Accepted 20 April 2022
Available online 25 April 2022
0959-6526/

innovations are still required to improve the sustainability performance of buildings in all phases. In this sense, there is a wide array of development strategies and materials that can be utilized in different elements of buildings.

Facades, as one of the main parts of buildings, play a key role in improving energy efficiency through protecting the interior space against adverse environmental effects, such as climate change, noise, or pollution (Gilani et al., 2019; Hartkopf et al., 2012). In this regard, a construction solution known as double-skin facade systems is increasingly being used in both new and renovated buildings (Densley Tingley et al., 2015). In this facade system, the exterior lightweight cladding panel and the outdoor side of the external wall are divided by an air cavity or insulation layer, typically constructed by perforated steel studs. The presence of an external discontinuous protective enclosure permits air ventilation while preventing direct sunlight heating, thereby providing energy-saving benefits in terms of heating and cooling loads (Claramunt et al., 2016).

The external cladding material should fulfill both the engineering and architectural requirements such as strength-to-weight ratio, durability, serviceability, and aesthetics while guaranteeing an acceptable level of sustainability performance. Conventional materials for facade cladding include natural stones and ceramics, as well as aluminum and wood composites. Although these materials are predominantly used for facade construction due to their competitive costs and availability, there are some drawbacks. On the one hand, the formers are known to present limited flexibility against imposed deformations (i.e., due to variation of temperature and movements of the building) and elevated weights that lead to costly connections and mounting operations. On the other hand, the latter group suffers from durability aspects and less competitive costs when compared with the formers (Claramunt et al., 2016). Furthermore, regarding sustainability, marble and aluminum panels are recognized for being scarcely environment-friendly materials due to the high environmental burden involved with the extraction and processing of the raw materials (Kvočka et al., 2020). As a result, a new generation of composite panels for facade cladding known as fiber-reinforced cement (FRC) sheets, which were believed to be more eco-friendly than aluminum or steel (Nguyen et al., 2020), stated to be researched and promoted.

Over the previous decade, steel, glass, and polymers have been considered as predominant materials for fibers oriented to reinforcing cement-based matrices (Brandt, 2008; Gong et al., 2020; Jia et al., 2017; Lei et al., 2021; Wang et al., 1987). However, there are some shortcomings associated with the use of these fibers, these being high cost, and specifically, substantial environmental footprint (Ardanuy et al., 2015). Therefore, natural (i.e., cellulose) fibers (Batista dos Santos et al., 2021; Claramunt et al., 2017a; Rakhsh Mahpour et al., 2022), as well as recycled fibers (Brazão Farinha et al., 2021; Halvaei, 2021; Rahman et al., 2022; Yina et al., 2016), have gained significant attention in recent years as sustainable reinforcements in cement composites for construction applications.

Sustainability assessment in the construction industry plays a pivotal role in moving toward buildings that have less negative economic, environmental, and social impacts (Balali and Valipour, 2020; Pons et al., 2016). The construction industry and the built environment are involved in several targets and objectives of the Sustainable Development Goals (SDGs) assigned by the United Nations, namely in the 9th and 11th SDGs (Cities - United Nations Sustainable Development Action, 2015). In building and civil engineering fields, there are a variety of databases, tools, and methods to evaluate sustainability performance, namely Green Star, BREEAM, LEED, and LCA, among others (Cabeza et al., 2014; Colangelo et al., 2021; Sørensen and Wenzel, 2014). However, most of the existing assessment approaches merely consider environmental performance, thus, leading to a non-comprehensive evaluation (Akadiri et al., 2013; Ding, 2008). Tools and methods that include other sustainability requirements, such as economic, social, technical, and functional have been recently developed (Ali and Al Nsairat, 2009; Salzer et al., 2016).

In addition, sustainability assessment of building elements such as slabs, columns, pavements, and facades should be investigated further since this kind of assessment could contribute significantly to the selection of sustainable materials in the early design stages of construction projects (John et al., 2005; Mohammadi et al., 2022). Based on the literature review, a few studies have evaluated the environmental sustainability of facade-cladding panels through life cycle assessment (LCA), such as geopolymers or ceramic facade panels (Han et al., 2015; Kvočka et al., 2020), concrete panels (Hay and Ostertag, 2018), green facades (Ottelé et al., 2011), and curtain walls (Kim, 2011).

This study aims to develop a novel model for evaluating the sustainability index (SI) of facade-cladding panels by analyzing multiple requirements based on MIVES. This multi-criteria decision making (MCDM) method, enables an objective assessment and quantification of indicators governing the sustainability performance (economic, environmental, social, and even technical) through the value function concept (Alarcon et al., 2010; Gilani et al., 2017). MIVES has already been successfully used in other fields, such as post-disaster housing management (Hosseini et al., 2021, 2018; S M Amin Hosseini et al., 2016; S. M. Amin Hosseini et al., 2016); active architectural learning (Pons et al., 2019); school edifices (Pons and Aguado, 2012); Spanish code of concrete structures (Del Caño et al., 2012), and infrastructure (De La Fuente et al., 2016). Moreover, the initial and conceptual of this model for facade panels was reported by the authors in the recent contribution (Sadrolodabaee et al., 2021e).

To this end, the MIVES-based model for facade-cladding sustainability performance assessment was applied to the textile waste fiber reinforced-cement (TWFRC) panel as a potential alternative in residential buildings in Barcelona, Spain. The remainder of this paper is laid out as follows: Section 2 presents a review of TWFRC boards, including their mechanical characteristics. Section 3 presents the details of the experimental programs carried out within the context of this research to characterize the thermal, acoustic, and fire-resistant properties of this material. In Section 4 the MIVES-based model developed for the sustainability assessment of facade claddings is thoroughly explained. Section 5 is devoted to covering the results and discussion. This is finally, followed by a summary of conclusions.

2. TWFRC board

Proper waste materials management can be beneficial to the recycling and building industries, especially in terms of lower environmental impacts (Perugini et al., 2005). However, recycling and reusing rates are quite low since there is still skepticism about the quality of recycled materials. Thus, new research should be conducted using recycled materials to overcome these uncertainties (Li et al., 2022). The textile leftover, including pre-consumer and post-consumer waste, is one of the predominant waste resources worldwide, (Giesekam et al., 2014; Nautiyal et al., 2015).

In our previous studies, cement composites reinforced with recycled textile waste (TW) fibers from discarded fashion clothes, in both short random fibers and fabric form, were developed (Sadrolodabaee et al., 2021a, 2021b; 2021c). Those studies proved that a composite made of Portland cement paste as a matrix, reinforced with six layers of TW nonwoven fabric (TW6L, hereinafter), had the most efficient mechanical characteristics to be used as a thin and lightweight cement board. This cement board was successful in improving the flexural strength, energy absorption, durability, and crack resistance by exhibiting multiple cracking behaviors with deflection hardening.

Fig. 1a shows a TW nonwoven fabric reinforcement and Fig. 1b shows an uncoated TW cement board without any pigments. This prefabricated panel had a square-size of 300 mm and a surface mass of approximately 16 kg/m^2 which is often lighter than comparable products constructed of concrete or natural stone. Mechanical properties of this type of cement composite obtained from our previous study

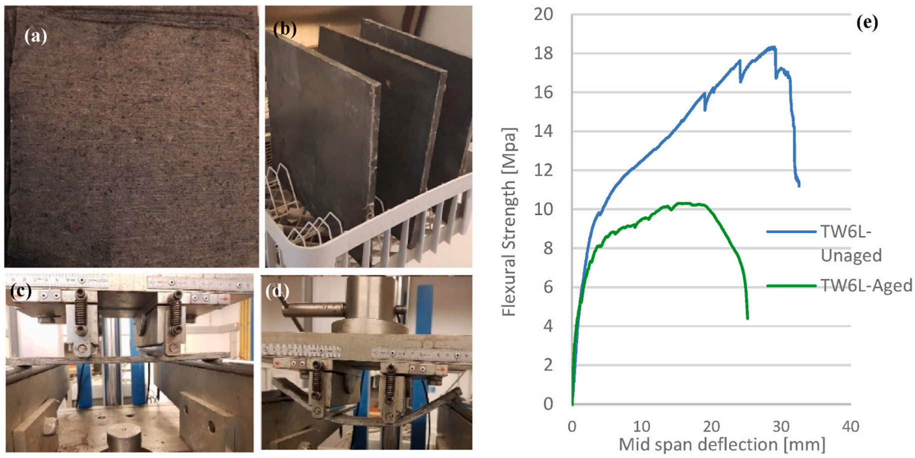

Fig. 1. TW cement composites: a) TW fabric; b) TW cement boards; c) initial of the flexural test on the machined specimen; d) end of the flexural test; e) representative flexural stress – deflection relationships; According to Sadrolodabaee et al. (2021d)..

(Sadrolodabaee et al., 2021d) are summarized in Table 1. The configuration of the flexural test was shown in Fig. 1c and d, while Fig. 1e demonstrates the experimental flexural stress–deflection relationships obtained from a four-point flexural test in both unaged and aged conditions. Unaged samples were tested after the 28 curing days whilst the aged ones were tested after 28 curing days plus 25 wet/dry accelerating aging cycles as durability test.

To comprehensively assess the SI of this cement board based on the defined model design (section 4), more experimental properties were needed; thus, new tests were carried out on TW6L to assess the thermal, acoustic, and fire behaviors.

3. New experimental procedures

3.1. Materials and sample preparation

The cement paste was made with Portland cement Type I 52.5R, UNE-EN 197–1:2011, provided by Cementos Molins Industrial, S.A. (Spain). TW nonwoven fabric as an internal reinforcement is made up of roughly 80% vegetable fibers (45% cotton and 35% Flax) together with 20% polyester fiber produced through card clothing and needle-punching process as explained in detail in (Sadrolodabaee et al., 2021d). This fabric, roughly 1 mm thick and weighed 155 g/m2, had a tensile rupture force of 2.0 N/g.

The composite production technique, including vacuuming and compression treatments, was described in detail in previous studies by the authors (Sadrolodabaee et al., 2021c, 2021d, 2021c). Briefly, TW6L was made with 6 layers of nonwoven TW fabrics saturated in matrix paste and stacked as a laminate in a vacuum-treated drilled-bed mold. The sample was then pressed at 3.3 MPa and cured for 28 days at >90% RH and 20 ± 1 °C, resulting in a laminate plate with a thickness of roughly 10 mm. The control sample (CTR) without any fiber was produced with dewatering treatment as well. From each plate, specimens with different sizes were machined to carryout out the thermal, acoustic, and fire tests. Table 2 shows the mix proportions and the properties of the two samples.

Table 1
Mechanical characteristics of TW6L cement board composite obtained from four-point flexural test.; According to Sadrolodabaee et al. (2021d).

Parameters	Unaged sample	Aged sample
Modulus of rupture [MPa]	15.5	10
Toughness index [kJ/m^2]	9.7	6.8
Flexural stiffness of the pre-cracked zone [GPa]	11.3	12
Flexural stiffness of the post-cracking zone [GPa]	0.41	0.16

Table 2
Mix proportions of the samples.

Sample	$(w/c)_{initial}$	$(w/c)_{final}$	Cement (gr)	Water (gr)	Fiber weight fraction	Density [kg/m^3]
TW6L	1	0.45	1500	1500	5.4	1600
CTR	1	0.50	2000	2000	0	1900

3.2. Thermal test

The thermal conductivity coefficient (λ) was determined by using a Quickline-30 Electronic Thermal Properties Analyser, based on ASTM D5930 standard, with a surface probe (Fig. 2a). Such equipment is based on the analysis of the transient temperature response of the material to heat flow variations induced by electrical heating using a resistor heater having direct thermal contact with the surface of the sample. The same method has been already used in some other studies to calculate λ (Gonzalez-Lopez et al., 2021). Two opposite surfaces of each sample, TW6L and CTR plates (300 mm × 300 mm × 10 mm) were tested, each surface two times. When the samples were in thermal equilibrium with the surrounding environment, the heat flow has been generated by applying heat impulse.

3.3. Acoustic test

Cylindrical specimens of diameter and height of 50 and 10 mm, respectively, were used to assess the acoustic characteristics of the samples, namely the sound absorption coefficient (α), as shown in Fig. 2b. Measurements were carried out in an impedance tube in accordance with EN ISO 10534–2, as described in detail in (Novais et al., 2020). Briefly, the approach is based on measurements of the transfer function between two microphones. The sample was inserted at one end of the tube whilst the sound source was attached to the other end. Two microphones monitored the acoustic pressures of the tube near the sample. The source created a random signal from which the complex acoustic transfer function for frequencies between 500 and 3150 Hz was calculated. Three samples of TW6L with six runs and one sample of CTR with two runs were tested.

3.4. Fire tests

3.4.1. Epiradiator test

The samples were subjected to a fire reaction test using an epiradiator, according to standard UNE 23725–90, to assess the effect of the

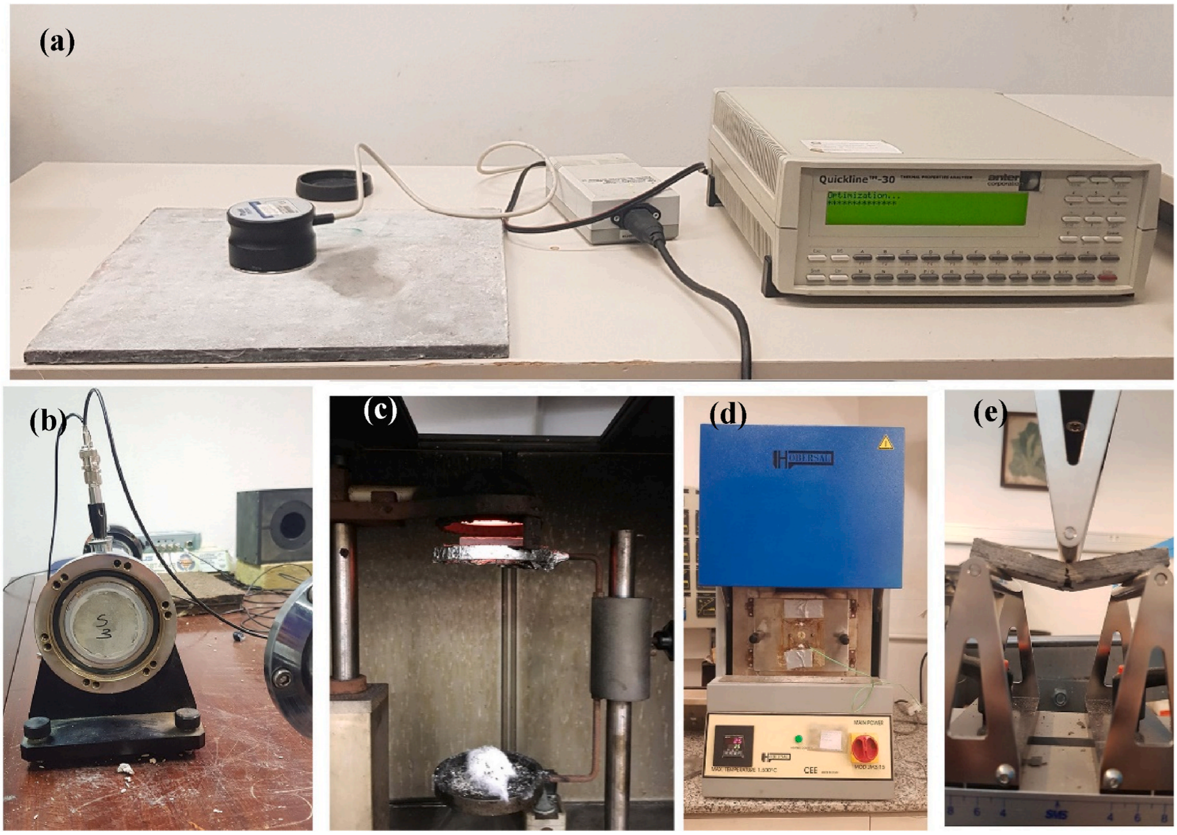

Fig. 2. Experimental setup*: a) thermal test; b) acoustic test; c) epiradiator test; d) oven for small-scale fire resistance test; e) three-point flexural tests setup.*

inclusion of TW fibers on the composites' fire resistance (Fig. 2c). Specimens of 70 × 70 mm^2 were put on a metallic grid 3 cm below a 500 W heating source, implying a heat flux of 3 W/cm^2 for 5 min. Time of the first ignition, flame persistence time, and sample weight loss were determined. Two specimens of TW6L and two specimens of the CTR were tested.

3.4.2. Small-scale fire resistance test

The impact of high temperatures (up to 950 °C) on the characteristics of the plaques was studied by Hobersal JM3-15 oven, as shown in Fig. 2d. Samples of 100 × 100 mm^2 were placed on the oven door with one of the faces exposed to an ISO 834–1:1999 temperature-time curve. Attaching k-type thermocouples to the sample's external face allowed the temperatures to be measured during the test.

3.4.3. Post-fire mechanical behavior

The mechanical behavior of the samples after exposure to the small-scale fire test (exposure up to 950 °C) was evaluated using a three-point flexural test with a cross-head speed of 6 mm/min, as illustrated in Fig. 2e. The dimensions of the tested specimens were 100 × 50 mm^2, and the distance between the supports was fixed at 70 mm.

The following mechanical parameters were obtained through the same procedure as described in the literature (Claramunt et al., 2017b): the limit of proportionality (LOP) as the breaking flexural stress of the matrix (first crack strength), the modulus of rupture (MOR) as the maximum flexural stress of the composite, toughness index (I_G) as specific fracture energy through the area under the force-displacement curve, and elastic flexural stiffness of the pre-cracked zone (E) between 60% and 80% of the LOP.

4. Model design

The general methodology of the MIVES was described in detail in previous studies (Hosseini et al., 2021, 2018; S M Amin Hosseini et al., 2016; S. M. Amin Hosseini et al., 2016). Briefly, the MIVES method includes a particular holistic discriminatory tree of requirements, assigning of weights for each index, value function concept to attain specific and global satisfaction, and expert seminars using the analytic hierarchy process (AHP) to define the previous components. In the following, the aforementioned steps of MIVES are designed and oriented for facade-cladding panels in order to analyze the SI for the TWFRC board as a real case.

4.1. Requirements tree

The requirements tree, a unique hierarchical diagram showing the main properties of the products, is organized at three levels: indicators, criteria, and requirements. This requirements tree is fixed *a priori* and filtered according to the preferences of the stakeholders, as identified through seminars with experts and an extensive literature review.

The preliminary requirement tree for facade-cladding panels was reported by the authors in (Sadrolodabaee et al., 2021e). However, the final filtered one for this case study is shown in Fig. 3. As can be seen, the requirements (R) were considered on three main aspects: economic, environmental, and social. These requirements were further divided into seven criteria (C) and ten indicators (I). The functional unit in analyzing the indicators considered a 1-m^2 area of the facade cladding panel, where applicable. In the following, each index and the boundaries considered in the estimation of each indicator's value are discussed. Generally, the values of indicators were estimated based on the various methods, including experimental test results; various databases mainly the BEDEC from the Technological Institute of Catalonia (ITeC) (BEDEC, 2020), as well as Inventory of Carbon and Energy (ICE) (Hammond and Jones, 2011); Environmental Product Declaration (EPD) of materials; and seminars with experts. Table 3 shows the data source used in the calculation of each indicator.

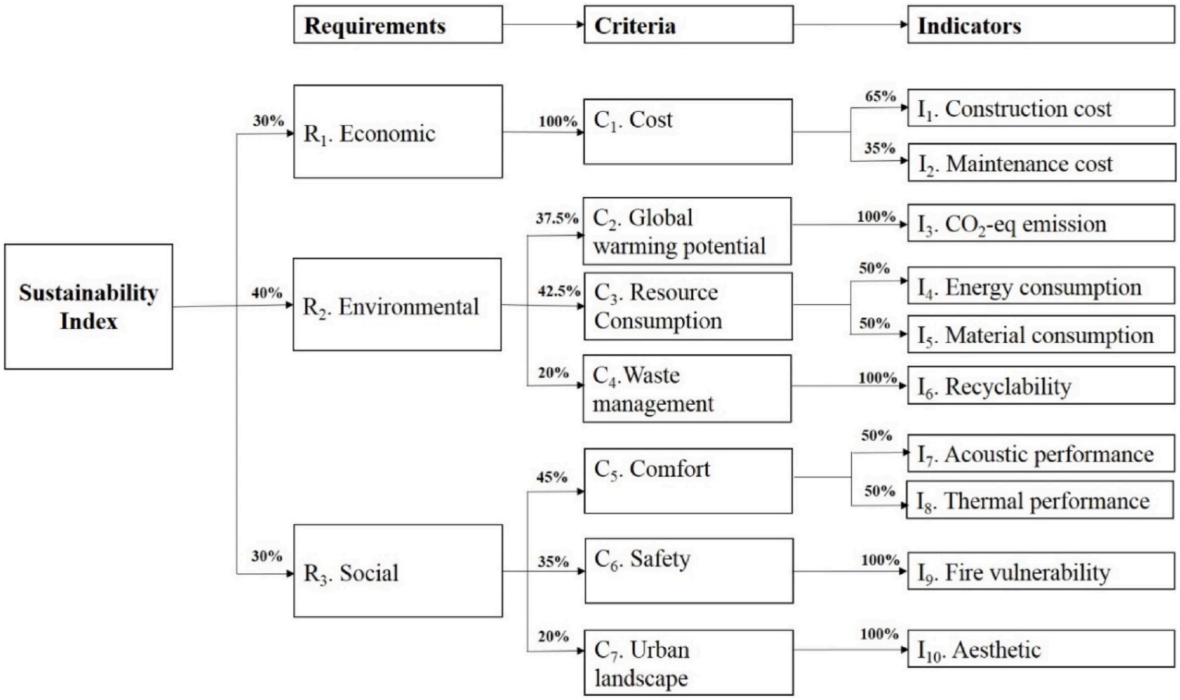

Fig. 3. Requirements tree for facade cladding panels.

Table 3
Summary of data sources used.

Indicators	Sources
I_1	BEDEC database (BEDEC, 2020)
I_2	BEDEC database (BEDEC, 2020); Scientific publications: (Brunsdon, 2018)
I_3	BEDEC (BEDEC, 2020) and ICE (Hammond and Jones, 2011) databases; Scientific publications: (Claramunt et al., 2016; Malabi Eberhardt et al., 2021; Ricciardi et al., 2014)
I_4	BEDEC (BEDEC, 2020) and ICE databases (Hammond and Jones, 2011); Scientific publications: (Ricciardi et al., 2014)
I_5	BEDEC database (BEDEC, 2020); EPD of materials; Experimental test
I_6	Seminars with experts; Scientific publications: (Addis, 2012; Alarcon et al., 2010; Li et al., 2022; Souza et al., 2021)
I_7	Experimental test results; Scientific publications: (António, 2011; Novais et al., 2021; Quintaliani et al., 2022; Ricciardi et al., 2014; Rubino et al., 2018.; Tie et al., 2020)
I_8	Experimental test results; Scientific publications: (Asadi et al., 2018; Bagheri Moghaddam et al., 2021; Borri et al., 2016; Buratti et al., 2016; Gonzalez-Lopez et al., 2021; Quintaliani et al., 2022; Rubino et al., 2018)
I_9	Experimental test results; Scientific publications: (British Standards Institution., 2018; Gonzalez-Lopez et al., 2021; Kolaitis et al., 2016; Nguyen et al., 2020)
I_{10}	Seminars with experts

Economic requirement (R_1) represents the whole expenditure required to implement the facade cladding for the estimated life cycle, with *Cost* (C_1) serving as the only criterion. *Environmental requirement* (R_2) considers the overall environmental impact of the life cycles of the panels through *Global warming potential* (C_2), *Resource consumption* (C_3), *and Waste management* (C_4) criteria. Finally, *Social sustainability requirement* (R_3), with the aim of improving the quality of human life and health of the users (Shen et al., 2010) embraces three criteria: *Comfort* (C_5), *Safety* (C_6), and *Urban landscape* (C_7).

C_1 encompassed two indicators: *Construction cost* (I_1) and *Maintenance cost* (I_2) of the external cladding panel. The former, assessed by considering roughly 40 composites and cladding panels of various materials, comprises material manufacture, shipping, installation, and labor costs. However, only the most relevant and homogenous data were collected, for instance, copper and bronze claddings were not considered, as their values would be much higher than those of the other conventional claddings. The online BEDEC database was implemented for this purpose. The latter predicts the cost of cleaning, repairing, and replacing the panel over its expected service life of 50 years. I_2 was estimated as approximately 10% of I_1 yearly (Brunsdon, 2018).

Carbon dioxide equivalent (kg CO_2-eq) is a common unit of measurement for *Global warming potential* (Yina et al., 2016). Thus, C_2 was represented by the indicator of *CO_2-eq emissions* (I_3) quantifying the amount of CO_2-eq emissions (carbon footprint) for each cladding panel during the production and construction phases. The reference databases used for measuring C_2 were the BEDEC and the ICE. According to Kvočka et al. (2020), the manufacturing and construction stages contribute the most to the environmental footprint of prefabricated panels, thus just these two stages were considered in the estimation of environmental indicators.

C_3 was designed to measure the consumption of natural resources by means of two indicators: *Energy consumption* (I_4) and *Material consumption* (I_5). The former quantified the amount of energy used during the production and construction stages (embodied carbon) by employing BEDEC and ICE databases. Energy consumption during the demolition phase was reported to be negligible, less than 3% (Pons and Aguado, 2012), with respect to the previous phases, thus, it was ignored. The other indicator considered the amount of raw materials and water consumed in the manufacturing stage through BEDEC, EPD of materials, and the experimental reports available in the literature.

C_4 was evaluated by the indicator of *Recyclability* (I_6) to estimate the amount of waste and recycled materials consumed during the fabrication process or the amount that could be recycled after demolition or end-of-life. I_6 was rated qualitatively on a measurable scale of 0–20 through seminars with multidisciplinary experts as well as literature reviews. Fifteen experts (6 civil engineers, 6 architects, and 3 building engineers), mainly from UPC, gave their opinions on the mentioned scale and the final value was the average of those proposed values.

C_5 comprised two indicators: *Acoustic* (I_7) and *Thermal performances* (I_8). I_7 considered the rate of α of the material by calculating the noise reduction coefficient (NRC) while I_8 was used to assess the thermal conductivity of cladding panels. The thermal performance of facade systems could significantly reduce the annual energy demand (Monge-Barrio and Sánchez-Ostiz, 2015).

C_6 was used to evaluate the safety and security levels of the occupants and included the indicator *Fire vulnerability* (I_9), which assessed the post-fire residual resistance in MPa through a flexural strength test.

C_7 included *the aesthetic* indicator (I_{10}) and qualitatively assessed the appearance and visual quality of the facade cladding. I_{10} was rated on a measurable scale of 0–10 through seminars with fifteen multidisciplinary engineers/architects, mainly from UPC.

It should be emphasized that the indicators were identified and determined based on an extensive literature review (see Table 3). Furthermore, although the indicator categorizations were mentioned above, these indicators could have been allocated to other requirement groups simultaneously concerning their impact. In other words, there could be many interactions among the indicators; however, according to the concept of the MIVES method (Gilani et al., 2017), each indicator is normally considered according to its main impacts in order to prevent the double-counting effect in the assessment. That is the reason why technical sustainability (to construct a durable and reliable structure) was not considered separately, as its indicators, such as strength-to-weight ratio or durability, could be covered and overlapped by the economic indicators.

Moreover, the ultimate identification and filtration of the indicators are influenced by the function and location of the building. The above-mentioned indicators were fixed and filtered for residential buildings in Barcelona. Nonetheless, for a similar building in another region or a building with different functionalities, the final indicators could be different. For instance, earthquake vulnerability could be considered as a final indicator for earthquake-prone countries, however, due to the region's low seismicity, this indicator could be ignored in Barcelona.

4.2. Assigning of weights to parameters

To identify the relative importance of each parameter in addition to prioritizing the indices, weights should be assigned to each branch of the requirements. The weights of the tree were assigned qualitatively based on the knowledge of fifteen professors/experts, mainly from architecture and civil engineering faculties of the UPC, via their involvement in a seminar on the AHP method (Cartelle Barros et al., 2015; Saaty, 1990). The final filtered proposed weight of each index is the average of those proposed by the experts after eliminating the outliers.

4.3. Establishing value functions for each parameter

After estimating the value of each indicator based on its specific unit (see X_i in Table 6), the value function concept needs to be implemented to the indicators' values to normalize the indicators' units and transform the results to non-dimensional values. This dimensionless value (ranging from 0.0 to 1.0, the minimum and maximum degrees of sustainability satisfaction) intends to indirectly measure the satisfaction grade of the stakeholders and users leading to minimizing subjectivity in assessments (Aguado et al., 2012).

Allocating value function to the indicators was explained in-depth in (Aguado et al., 2012; Alarcon et al., 2010; Gilani et al., 2019; Hosseini et al., 2020). Briefly, the function's tendency (increasing or decreasing) should be specified initially. An increasing (In) function indicates that an increase in the measurement unit caused an increase in satisfaction whilst a decreasing (D) one was used when an increase in the measurement variable decreased the decision maker's satisfaction. Secondly, the points (X_{min} and X_{max}) that produced the lowest and highest level of satisfaction for each indicator should be defined according to existing rules and regulations, experience gained from previous projects, and values obtained by various alternatives (see Table 3). These points would be the *x*-axis boundaries with satisfaction values of 0.0 (X_{min}) and 1.0 (X_{max}) that were connected by one of the suggested shapes for value function's type: concave, convex, linear, and S-shaped. A concave-shaped (C_v) function was used if satisfaction increased swiftly or decreased marginally whilst a convex (C_x) one was more appropriate on the contrary case to the former. If the satisfaction increased/decreased continuously, a linear (L) function was employed while an S-shaped (S) one was more suitable when the satisfaction tendency contained a combination of C_v and C_x (see Fig. 4).

Finally, the mathematical expression of the value function was applied through Equation (1) to obtain each indicator value satisfaction, V_i. Equation (2) was applied to achieve factor B for Equation (1), which would allow homogenization of the indicators' values ($V_i(x_i)$) between 0.0 and 1.0.

$$V_i = A + B\cdot\left[1 - e^{-k_i\cdot\left(\frac{|X_i - X_{min}|}{c_i}\right)^{p_i}}\right] \tag{1}$$

$$B = \left[1 - \ e^{k_i\cdot\left(\frac{|X_{max} - X_{min}|}{c_i}\right)^{p_i}}\right]^{-1} \tag{2}$$

where.

V_i: the indicator's satisfaction value;
A: response value of X_{min} (usually $A = 0$);
B: factor that keep the function in the range (0.0, 1.0);
X_i: an indicator that generates the value V_i;
X_{min}: point with the lowest satisfaction;
X_{max}: point with the highest satisfaction;
P_i: shape factor
($P < 1$ means the curve is concave; $P > 1$ means it is convex or S-shaped; $P = 1$ means it is linear);
C_i: factor that is used for the inflection point in curves with $P_i > 1$.
K_i: factor that describes the response value to C_i;

4.4. Assessing sustainability index (SI)

Equation (3) was applied to each level of the requirement tree to calculate the SI of each alternative. In addition to determining the total SI, this method enabled the calculation of economic, social, and environmental satisfaction indices separately.

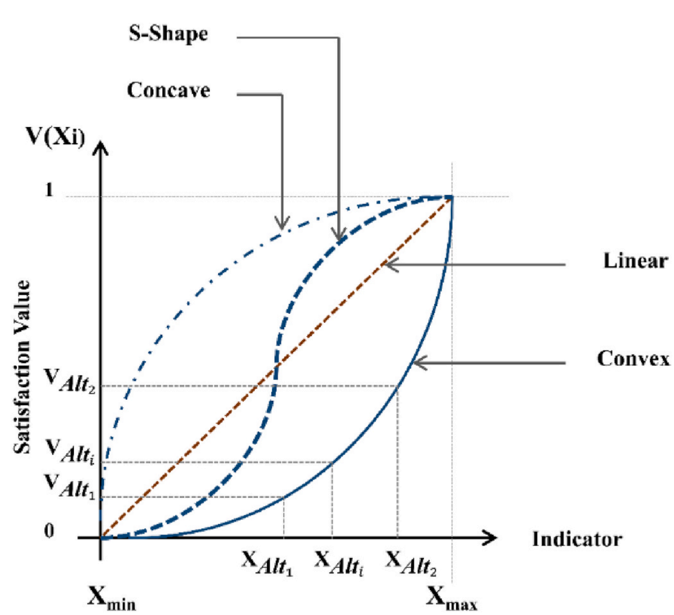

Fig. 4. Value function shapes based on the MIVES method.

$$SI = \sum \lambda i \cdot V_i(x_i) \quad (3)$$

Where $V_i(x_i)$ and λ_i are the value function of each index and the associated weight, respectively.

5. Results and discussion

5.1. Thermal test

As shown in Table 4, the control sample, without any fiber, had 40% higher thermal conductivity than the TW6L plate, proving that the incorporation of TW fibers improved the thermal behavior of the material. Thus, the indicator I_8 for the TW cement plate and control plate were chosen, 0.83 W/mK and 1.17 W/mK, respectively.

This result was in line with the study of (Gonzalez-Lopez et al., 2021), in which the thermal conductivity of two-overlapped cement plates, composed of calcium aluminate cement (CAC) and different percentages of metakaolin reinforced with flax fiber, was evaluated with the same method. Based on that study, the thermal conductivity of the cement composite varied between 0.650 and 0.840. Further, other studies (Khedari et al., 2001; Lertwattanaruk and Suntijitto, 2015) similarly proved that the addition of vegetal and natural fibers to the cement-based materials could enhance the thermal performance with respect to the control sample by 40–80%, depending on the fiber type and volume. Increasing the fiber quantity in the material, generally, leads to higher porosity which, in turn, may decrease the thermal conductivity, thereby better thermal insulation (Quintaliani et al., 2022).

5.2. Acoustic test

The sound absorption coefficient (α) of the TW6L and CTR specimens across the frequency range of 500–3150 Hz is shown in Fig. 5. The maximum α for the CTR sample was 0.17 at a frequency of approximately 2270 Hz, whereas for the composite, which incorporated the TW fiber, this increased to 0.26 at 1530 Hz. Thus, the fiber improved the acoustic behavior by up to 50%. This result was consistent with the study of Quintaliani et al. (2022), in which the addition of various waste vegetal fibers by 10% weight, could increase the absorption coefficient by 42–60% in cementitious materials.

For the indicator I_7, the NRC, which was the average value of α at specific frequencies (500, 1000, and 2000 Hz) was calculated. The values of this parameter for the TW6L and CTR specimens were approximately 0.2 and 0.12, respectively. The values of α and NRC theoretically ranged from 0 to 1; however, for most of the relevant cladding panels, the NRC ranged from 0 to 0.5 (Tie et al., 2020).

However, the acoustic performance of TW6L was relatively low, and one solution to increase this parameter was to increase the thickness of the layer, which could increase α, as reported in (Novais et al., 2021). Furthermore, the sound absorption of cement-based materials can be increased by adding porous structures into the materials by various means, such as integrating lightweight aggregates or generating voids with the use of foam in cellular concrete (Tie et al., 2020). In general, the creation of pore structures in cementitious materials decreases the density, which, in turn, improves α and NRC. Nonetheless, TW fibers in the present study could only marginally increase the porosity and reduce the density of the cement plate, as the production of this type of plate is accompanied by vacuuming and compressing, which reduce the voids and porosity.

Table 4
Values of thermal conductivity of the analyzed samples.

Sample	Thermal Conductivity [W/(m·°K)]
TW6L	0.83
CTR	1.17

5.3. Fire test

5.3.1. Epiradiator test

The TW6L specimens did not display any ignition, flames, or smoke during the epiradiator test after attaining a temperature of 420 °C for 5 min. This suggests that the fibers did not contribute to the appearance of flames. Fig. 6a and b shows images of the faces unexposed and exposed to the radiation, respectively, for TW6L. As can be seen, the studied sample had some surface cracks but no major material detachment. TW6L lost approximately 15.6% of its weight due to the dehydration and the transformation of various hydrated cement components into oxides, with a corresponding volume reduction. The lack of chipped pieces on the surface of the samples indicates a remaining bridging effect of the fiber reinforcement. As reported in (Gonzalez-Lopez et al., 2021), the vegetable fibers were discovered to retain their reinforcing capacity up to 450 °C, beyond which disintegration increased. Thus, the capability of this material to preserve its integrity could be attributed to the fiber reinforcement's bridging effect, which caused no material loss by spalling.

On the other hand, the control cement plate after 5 min of exposure to 420 °C showed no flame or smoke. However, owing to the loss of fiber and brittleness, it broke after the appearance of the cracks (Fig. 6c).

5.3.2. Small-scale fire resistance test

As can be seen in Fig. 7a and b, the TW6L sample developed superficial, fine, and uniformly distributed cracks, which were more prevalent on the heat source-facing face; this face may have reached up to 950 °C, compared to the face exposed to room temperature, which hardly reached 850 °C (Fig. 8). The cracks were caused by water loss as a result of sample drying; however, the integrity of the composite was maintained even when subjected to temperatures more than 800 °C for approximately 100 min. The CTR sample showed a cracking pattern with more separated, thicker, and deeper cracks, which ended in chipped pieces and spalling owing to a lack of fibers (Fig. 7c). Thus, as reported by Nguyen et al. (2020); Zhang et al. (2018), the addition of fibers could mitigate the explosive spalling of the inorganic binder matrix at elevated temperature by releasing gradually the accumulated vapour pressure.

As can be seen in Fig. 8, as the CTR plate had a higher heat transfer coefficient, the non-exposed face of this plate has a higher temperature than TW6L. For instance, when the exposed faces had a temperature of approximately 800 °C at 40 min, the unexposed faces of TW6L and CTR samples had temperatures of approximately 400 and 600 °C, respectively. In other words, the incorporation of TW induced a thermal delay of roughly 20 min because the unexposed face of the CTR specimen reached 600 °C after approximately 40 min, while the unexposed face of the TW board reached this temperature at approximately 60 min.

5.3.3. Post-fire mechanical behavior

Fig. 9 depicts the representative flexural stress-displacement curves of the tested samples, and Table 5 summarizes the mechanical parameters. For the composite not exposed to high temperatures (TW6L), the reinforcing effect of the fibers allowed a relatively high deformation capacity, which led to an increase in toughness and post-cracking flexural strength (MORm/LOPm >1.0). Nonetheless, after exposing the composite to 950 °C (TW6L-Fire), the bending behavior changed with respect to the former sample. In this case, the fibers mostly lost their effectiveness and the material became relatively brittle, that is, the effect of the reinforcement was negligible (MORm ≈ LOPm). Therefore, the toughness decreased considerably as it depended mainly on the fiber pull-out mechanism. The cement matrix degraded as well owing to the high temperature; the LOP_m and E_m decreased dramatically from 11.4 to 0.85 MPa and from 1.50 to 0.28 GPa, respectively.

As for the non-exposed cement plate sample, i.e., CTR, the fracture type was brittle, as there was no fiber for bridging the cracks. After the exposure to fire (CTR-Fire), the sample still exhibited brittle behavior

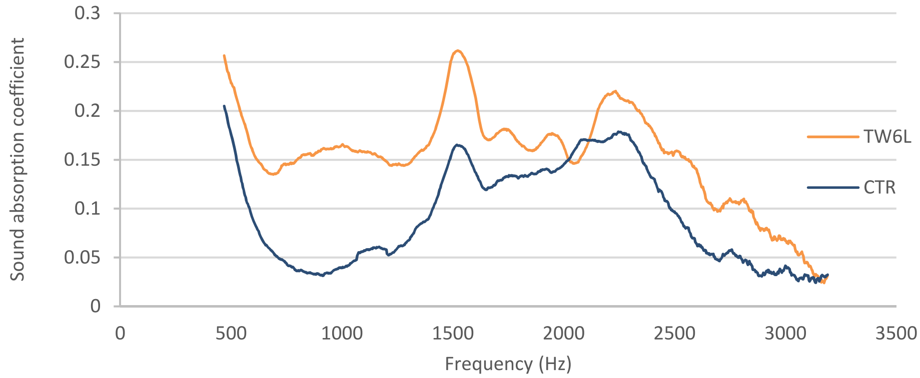

Fig. 5. *Sound absorption coefficient spectra of the measured samples.*

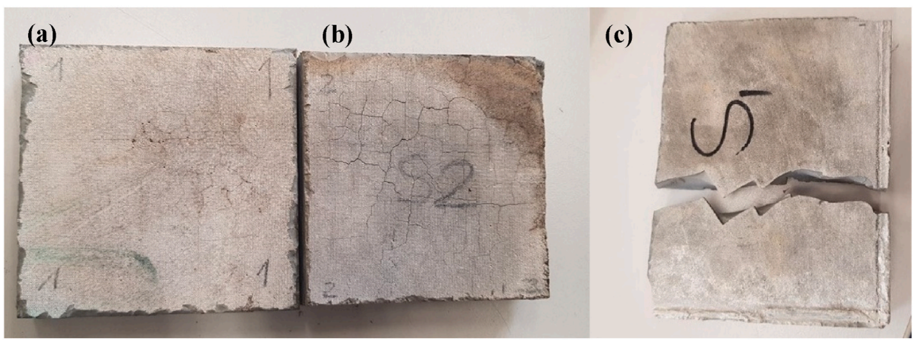

Fig. 6. Epiradiator test: a) TW surface not exposed to the heat source; b) TW surface exposed to the heat source after 5 min; c) CTR after exposure.

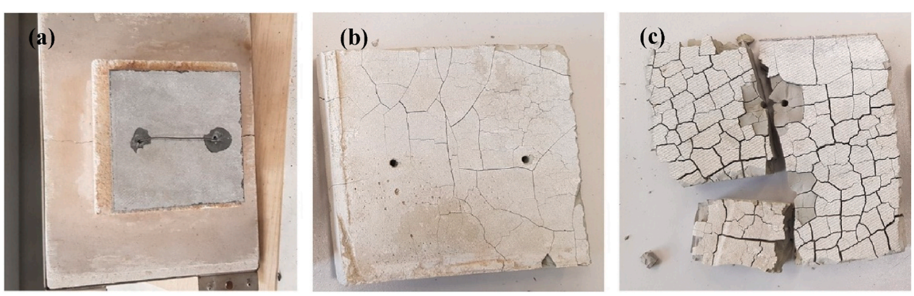

Fig. 7. Small-scale fire resistance tests: a) specimen before the test; b) heat-exposed face of TW specimen after the test; c) heat-exposed face of CTR plate after the test.

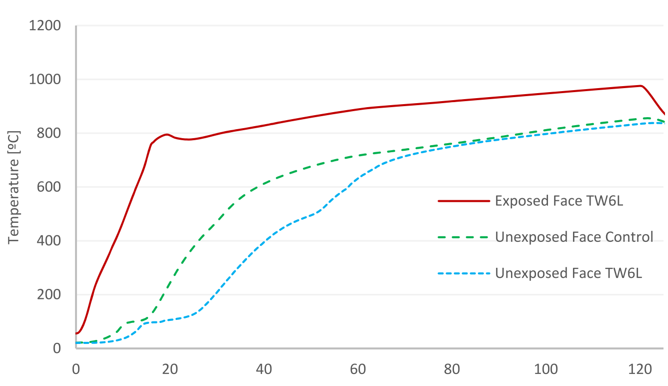

Fig. 8. Temperature evolution of the surfaces in the small-scale fire resistance test based on ISO 834.

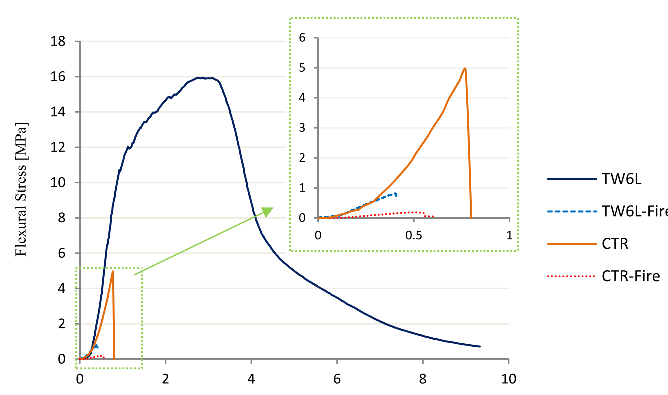

Fig. 9. Representative flexural stress: deflection relationships obtained from the three-point flexural test.

Table 5
Mechanical properties obtained from the three-point flexural test (CoV in %).

Code	LOP_m [N/mm^2]	MOR_m [N/mm^2]	I_{Gm} [kJ/m^2]	E_m [GPa]	$(W/c)_{final}$	No. of Specimens
TW6L	11.40 (7)	16.20 (10)	4.70 (16)	1.50 (17)	0.45	6
TW6L-Fire	0.85(24)	0.90 (22)	0.04 (19)	0.28 (14)	0.45	6
CTR	5.60 (24)	5.60 (17)	0.20 (30)	0.40 (19)	0.55	6
CTR-Fire	0.15 (19)	0.15 (29)	0.02 (10)	0.03 (20)	0.55	6

but with less flexural resistance.

However, among the samples exposed to fire, the plate reinforced with the fibers showed better mechanical properties than those without the reinforcement. As shown in Table 5, TW6L-Fire had a higher MOR (almost six times) and I_G (almost 2 times) compared to CTR-Fire. The MOR of TW6L-Fire, 0.9 MPa, was chosen as the value of indicator I_9. This result was in line with (Gonzalez-Lopez et al., 2021), in which the flexural strength after exposure to fire test was measured for the cement plates consisting of CAC and different percentages of metakaolin reinforced with flax fibers. Based on that study, the MOR varied between 0.0 and 1.7.

5.4. Sustainability analysis

Table 6 gathers all the indicators and the associated constitutive parameters for TW cement boards in order to reach the satisfaction value for each indicator (V_I). As can be seen, there were five indicators with decreasing convex shapes (I_1–I_5: DC_X), three ones with increasing concaved shapes (I_6, I_7, I_9: InC_V), only one with decreasing S-shaped (I_8:DS), and another one with an increasing linear function (I_{10}:InL). Moreover, as already explained, X_{min} and X_{max} were assigned based on the literature review (Table 3), and X_i values were calculated specifically for the case study of this research, TW cement board. $X_{7\text{-}9}$ were measured according to the new experiments carried out in this study.

Fig. 10 shows the function shape of I_1, as an example, and the estimation of its satisfaction value (V_1) from the cost value of the TW cement board (X_1). As the satisfaction value of I_1 decreased rapidly with increasing cost, a convex shape was chosen.

The final proposed weights (percentage) of the indices was shown in Fig. 3. As can be seen, experts believed that *Environmental requirement,* with a weight of 40%, was more important than *Economic* and *Social requirements,* each with a weight of 30%, when selecting sustainable facade materials. This ranking is in line with the study of Mohammadi et al. (2022) in which environmental sustainability gained more points than the other aspects. Regarding the criteria, C_1 had 100% as it is the only criterion of R_1. C_3 gained the highest point among the environmental criteria, 42.5%, as it is composed of two important indicators. C_2 and C_4, each embracing only one indicator, had 37.5% and 20% respectively. Among the social criteria, C_5 was the most important one, 45% weight, followed by C_6 and C_7, 35% and 20% respectively. Four indicators (I_3, I_6, I_9, I_{10}) were assigned 100% weight since there is only one indicator for each associated criterion. The indicators' weights of the *Cost* criterion were 65% and 35% for I_1 and I_2, respectively, showing the greater importance of the former. I_4 and I_5, as well as I_7 and I_8, weighted 50% as it was believed to have the same importance for C_3 and C_5, respectively.

The satisfaction values of each indicator, criterion, and requirement for the TW plate are shown in Fig. 11. As can be seen, all the parameters yielded satisfaction values above 50%, which was promising for this type of cladding panel. However, two of the indicators and one of the criteria had values higher than 75% (the target value) and showed very high sustainability levels. The indicator I_8 had the highest value of satisfaction (85%), while the indicators I_{10} and I_7 had the lowest value (55%). The SI of this material based on the proposed weight (Fig. 3) was calculated as 70%, which was only 5% less than the target value. All the three requirements demonstrated an acceptable satisfaction value (>65%), which showed that this cladding panel could satisfy all aspects of sustainability.

In terms of R_1, both indicators of construction and maintenance costs (I_1 and I_2) showed the same satisfaction value, near 75%, which was an acceptable range for the stakeholders.

R_2 attained almost the same value as R_1, i.e., 71%. Among these criteria, C_2 and C_4 had values higher than 70%. As to I_3, CO_2 emission of this material was considerably lower than that of other materials typically used for this application, such as aluminum composites, ceramics or stone, as was reported in (Claramunt et al., 2016). However, this value could be improved by partial substitution of the Portland cement matrix with pozzolanic industrial by-products such as silica fume, metakaolin, or fly ash because the production of the cement involved an emission of 5%–8% of all the CO_2 generated worldwide (Schneider et al., 2011; Villar-Cociña et al., 2020). I_6 had a high value as the fibers in the production of the TW board were mainly from recycled materials. Moreover, the cement board after demolition can be recycled as an aggregate in concrete or pavements. However, criterion C_3 with related indicators, I_4 and I_5 showed an average sustainability level with a satisfaction value of 64%. Using a more environmentally friendly source of energy, such as generating electricity by solar panels, could improve I_4 (Kvočka et al., 2020).

R_3 reached the lowest satisfaction value among all the requirements (65%). C_5 almost reached the target level as previously reported TW fibers and fabrics proved to be proper acoustic and thermal insulation materials (Briga-Sá et al., 2013; Lee and Joo, 2003; Zhou et al., 2010). However, there are some strategies to improve the acoustic performance of this material, as discussed in Section 5.2. In addition, it is even possible to improve further the thermal performance of the panels by adding phase change materials (PCMs). With regard to I_9, the resistance to fire was acceptable, as already reported for this type of fabric (Lee and Joo, 2003). The counterpart lightweight prefabricated composite panel made up of fiber-reinforced polymer (FRP) was reported to have unsatisfactory fire performance by causing several critical issues in the event of fire such as rapid spreading or releasing smoke and toxic gases

Table 6
Parameters and coefficients for each indicator value function for TW panel.

Indicators	Function Shape	Units	X_{min}	X_{max}	C	P	K	X_i
I_1	DC_X	€/m^2	20.5	183.0	200.0	1.8	0.3	51.4
I_2	DC_x	€/m^2	125.0	915.0	2000.0	1.8	0.3	257.0
I_3	DC_X	Kg/m^2	6.1	60.0	22.0	1.5	0.4	19.0
I_4	DC_X	MJ/m^2	92.6	350.8	250.0	1.5	0.4	171.0
I_5	DC_X	Kg/m^2	11.0	80.0	50.0	1.5	0.4	33.0
I_6	InC_V	points	0.0	20.0	30.0	0.9	1.0	15.0
I_7	InC_V	points	0.0	0.5	0.3	1.1	0.9	0.2
I_8	DS	W/m K	0.1	6.0	4.0	0.35	4.5	0.83
I_9	InC_V	MPa	0.0	2.0	2.0	0.8	0.8	0.90
I_{10}	InL	points	0.0	10.0	10.0	1.0	45.0	5.5

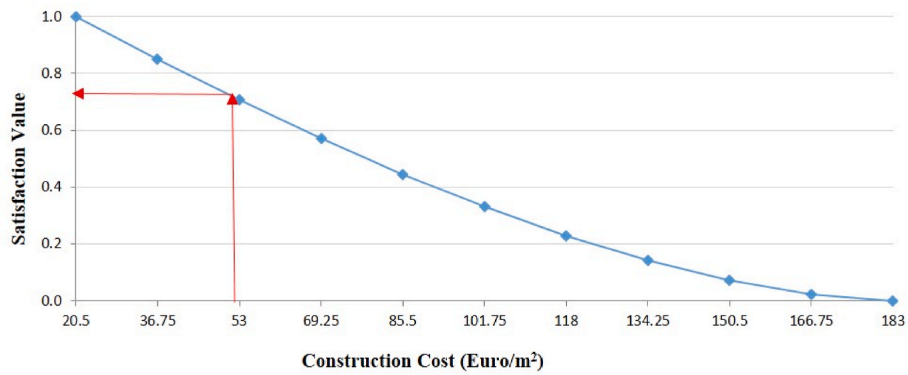

Fig. 10. Value function shape of indicator I_1 for TW panel.

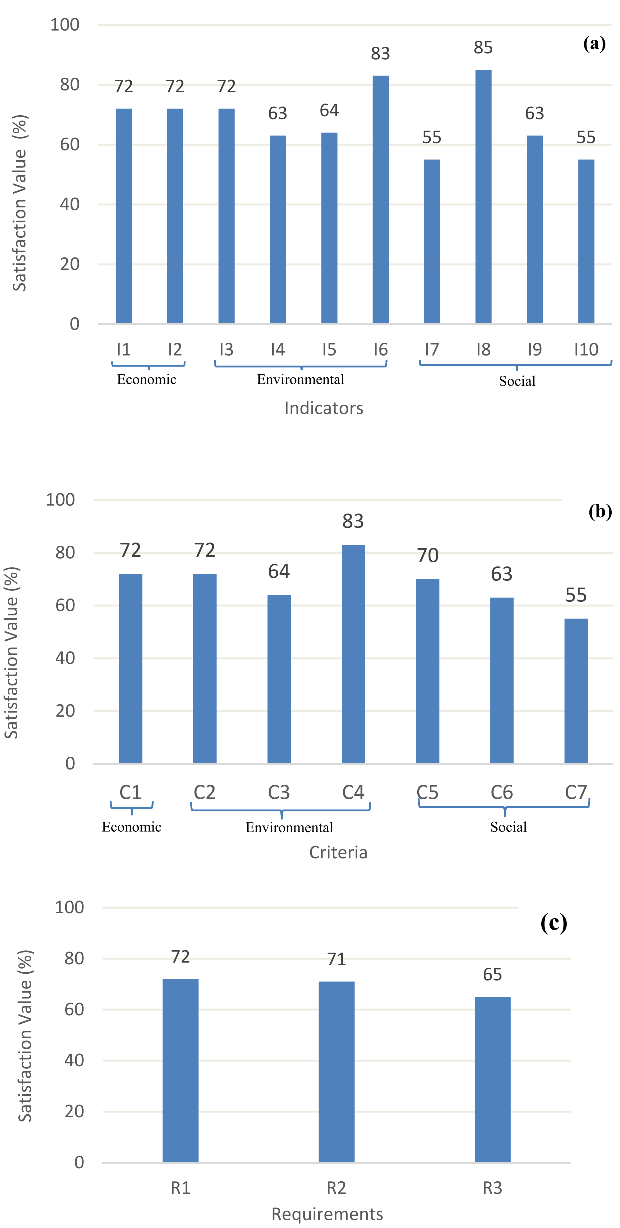

Fig. 11. Satisfaction values of TW cement board: a) indicators; b) criteria; c) requirements.

(Nguyen et al., 2020). As for I_{10}, it should be improved by taking some measures, including production panels with a larger size, and coloring or coating the panels.

The satisfaction values of indices for the CTR plate were gathered in Table 7 as the comparison with the TW6L cement board. The SI of this material based on the proposed weight (Fig. 3) was calculated as 46%, 24% less than TW6L. R_1 dropped to 52% as the construction cost (I_1) of CTR was higher due to the more cement amount used. Moreover, I_2 decreased as this panel was brittle, thus, repairing and replacing were more frequent during the service life. In terms of $R_{2,}$ C_2 and C_3 decreased as more amount of cement lead to more amount of CO_2 emission and more energy consumption in the production of the material. In addition, C_4 dropped to 47% as no waste materials were used in the manufacturing phase. R_3 reached the lowest satisfaction value among all the requirements (40%) for CTR. C_5 and C_6 decreased 19% and 46%, respectively, as was already explained in previous sections based on the experimental results. C_7 was the only parameter that remained constant since the appearance of the plate was not changed by omitting the fibers. Thus, incorporating textile waste fabric into the cement board not only improved the mechanical characteristics, but also developed the sustainability aspects including economic, environmental, and social.

Besides the final filtered weights allocated to the requirements for estimating the SIs of panels (30%, 40%, and 30% for *Economic*, *Environmental*, and *Social*, respectively), other possible weighting scenarios, according to the proposals by experts or those considered as outliers,

Table 7
Satisfaction values of all indices for the CTR and TW cement plates based on the proposed weights.

Indices	Satisfaction Value of CTR	Satisfaction Value of TW
I_1	0.55	0.72
I_2	0.47	0.72
I_3	0.46	0.72
I_4	0.50	0.63
I_5	0.45	0.64
I_6	0.47	0.83
I_7	0.35	0.55
I_8	0.67	0.85
I_9	0.17	0.63
I_{10}	0.55	0.55
C_1	0.52	0.72
C_2	0.46	0.72
C_3	0.48	0.64
C_4	0.47	0.83
C_5	0.51	0.70
C_6	0.17	0.63
C_7	0.55	0.55
R_1	0.52	0.72
R_2	0.47	0.71
R_3	0.40	0.65
SI	0.46	0.70

were analyzed to recognize the requirements that governed the sustainability performance. This type of sensitivity analysis, a reliable validation tool in decision-making problems (Balali and Valipour, 2020), was carried out by considering 15 scenarios. As can be seen in Fig. 12, the SIs did not change dramatically for the TW panel (<5% in the range of 0.68–0.71) by changing the weights of the requirements since three requirements had satisfaction values in the same range; social requirements had a lower value of only 5%. Thus, when the weight of the social requirements reached a maximum value (70%), the SI had the lowest value (0.68). However, the economic and environmental requirements had the same importance and effect, that is, the SI value of the TW panel for the final suitable weight, the highlighted point (30Ec/40En/30S), was equal to 40Ec/30En/30S. This shows that for various stakeholders (private or public clients) and industry representatives with different viewpoints on sustainability, thereby different weighting scenarios according to the requirements, this material could maintain its acceptable SI.

Regarding the sensitivity analysis of the CTR panel, the SIs followed the same trend as the TW panel, i.e, no significant change was observed (about 7% in the range of 0.43–0.50). The lowest SI was obtained when the social requirements reached the highest point (70%) as this requirement had the lowest satisfaction value, 0.4. On the other hand, the highest SI obtained for the weight scenario included the highest economic and lowest social weights (70% and 10%, respectively).

6. Conclusions and perspectives

Sustainability performance assessment is complex and unfree of uncertainties related to the quantification and treatment of the indicators. This research presented a MIVES-based multi-objective approach for assessing the sustainability index (including economic., environmental. and social aspects) of facade panels. The approach was applied to new textile waste (TW) cement boards. Furthermore, an experimental program oriented to the characterization of the thermal, acoustic, and fire resistance of this material was performed within the context of this research, and the results were included in the sustainability assessment model.

To this end, the sustainability sensitive indicators were identified through extensive literature review and multi-disciplinary seminars. The relative importance (weights) of the indicators were established by means of the analytic hierarchy process with the experts' seminars. After estimating the indicators' performances for each material, and taking into account the value (satisfaction) functions defined and the weights' set, sustainability index (ranging from 0.0 to 1.0) for each material alternative was computed.

Based on the analysis of the obtained results, the following conclusions can be drawn:

- The fire, thermal, and acoustic performance characterization revealed that the new material is compatible with external facade panels. Fire resistance was evaluated through epiradiator and small-scale fire testing. The TW samples proved not to be inflammable and maintained integrity above 950 °C. The post-fire flexural residual resistance of the TW cement board was almost six times higher than that of the control plate without any fiber. Moreover, the incorporation of TW fiber could improve the thermal and acoustic performance of the plate by 40% with respect to the benchmark.
- All the three requirements of sustainability (economic, environmental and social) resulted to perform equivalently (ranging from 0.65 to 0.72) for the TW cement board.
- The sustainability index of the prefabricated TWFRC facade-cladding panels for different weighting scenarios was in an acceptable range of 0.68–0.71, particularly for the optimum proposed weights was 0.7 (24% higher than the control plate).
- Although the general result was promising, for these new panels to achieve higher sustainability performance, some measures should be implemented: (1) to improve the aesthetic and external appearance by coating or coloring the panels and (2) to optimize the cement consumption through partial substitution by pozzolanic by-products or organic PCM paraffin waxes. However, any modification could affect other indicators, especially those related to economic performance.

Thus, based on this proposed model, designers and decision-makers may compare the sustainability index of various building materials to achieve the optimal facade cladding panels. MIVES, unlike other methods that overemphasize the environmental impacts, makes it feasible to analyze and prioritize material and construction alternatives while taking into account the three key pillars of sustainability and reducing the sources of subjectivity in the decision-making process.

It should be noted that in the present research study, this sustainability assessment was implemented on only two types of cement boards in a specific location, Barcelona. The weights proposed by the experts involved in the seminars could be adapted to reflect the perceptions and local preferences. Other study cases should be performed with the MIVES-based approach proposed in order to confirm whether the conclusions and outcomes exposed herein could be generalized and extrapolated.

CRediT authorship contribution statement

Payam Sadrolodabaee: Investigation, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **S.M. Amin Hosseini:** Investigation, Data curation, Formal analysis, Methodology, Validation, Writing – review & editing. **Josep**

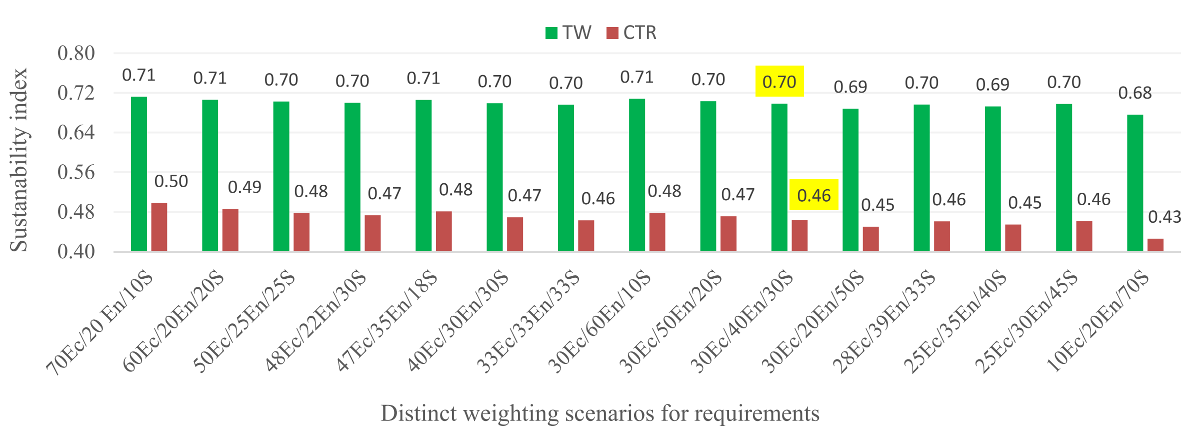

Fig. 12. SIs generated by the model for TW and CTR panels based on several weighting scenarios. (Note: Ec, En and S refers to Economic, Environmental and Socail requirements, respectively).

Claramunt: Supervision, Conceptualization, Validation, Resources, Writing – review & editing. **Mònica Ardanuy:** Supervision, Validation, Funding acquisition, Resources, Writing – review & editing. **Laia Haurie:** Investigation, Methodology, Data curation, Writing – review & editing. **Ana M. Lacasta:** Investigation, Methodology, Data curation, Writing – review & editing. **Albert de la Fuente:** Supervision, Conceptualization, Methodology, Validation, Funding acquisition, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors express their gratitude to the Spanish Ministry of Economy, Industry, and Competitiveness for the financial support received under the scope of the projects CREEF (PID2019-108978RB-C32) and RECYBUILDMAT (PID2019-108067RB-I00).

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