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Sustainability-Oriented Approach to Assist Decision-Makers in Building Facade Management

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Abstract. The building sector has a major economic, environmental and social impact on society; hence, it is crucial to promote sustainable construction practice. The facade is one of the largest main components of a building, which could strongly contribute to the sustainability performance for the whole building. Previous studies started defining tools to assess facade sustainability, although relevant indicators were dismissed or, if considered, they were rather subjectively quantified. Likewise, most existing tools omit stakeholder satisfaction in the assessment process for optimal facade systems. In this regard, this paper presents a new systematic approach based on MIVES (The Integrated Value Model for Sustainable Assessment) for holistic sustainability assessment of building facade systems by integrating stakeholders' satisfaction in the decision-making process. To this end, for the first time to the authors' best knowledge, the most representative and discriminative indicators for quantifying facade sustainability were identified to define a new approach to minimise subjectivity in the decision-making process and, consequently, to ease the task of decision-makers when choosing and designing facade alternatives for new buildings and rehabilitation. This approach is validated and initially applied to assess the six most common residential facade systems in Barcelona. Results indicate that these building elements have low to medium sustainability performance.

Highlights:

- Sustainability assessment tools lack relevant indicators and stakeholder satisfaction
- New systematic, holistic, multi-participant sustainability assessment tool for facades
- Most representative indicators included based on an extensive literature review
- Assessment of the sustainability index of the common facade systems found in the city of Barcelona

Keywords: *Sustainable Facades, Residential buildings, MIVES, MCDM, AHP*

Word Count: 7192 (excluding abstract)

Abbreviations

S_{min}: Minimum satisfaction
S_{max}: Maximum satisfaction
AHP: Analytical Hierarchy Process
SI: Sustainability index
FS: Facade system
AAC: Autoclaved Aerated concrete blocks
EPS: Expanded polystyrene
XPS: Extruded polystyrene
α_i: Requirement weight
β_i: Criteria weight
γ_i: Indicator weight
R-value: Thermal resistance
DS: Decrease S-shape
DL: Decrease lineally
DC_{VX}: Decrease convexly
IC_{CV}: Increase concavely
DC_{CV}: Decrease concavely
IC_{CV}: Increase concavely
IS: Increase S-shape
MCDM: multi-criteria decision making
LCA: Life cycle assessment
VR_k: Requirement value
VC_k: Criteria value
VI_k: Indicator value

1. Introduction

According to Eurostat databases (Eurostat, 2018), the EU building industry is responsible for up to 40% of final total energy consumption (27% residential, 13% non-residential) and 35% of associated carbon dioxide (CO_2) emissions (20% residential, 15% non-residential). It is also responsible for a major share of the world's economy, up to 45% (Rhodes, 2015). Such significant economic and environmental impacts have led to a considerable effort in different areas of the building industry to improve building sustainability. In this respect, many studies have focused on sustainability issues within the construction sector (Pitney, 1993; Spence and Mulligan, 1995; Segnestam *et al.*, 2003; Dasgupta, 2007; Myers & Reed, 2008; Abidin, 2010). Furthermore, various building performance assessment tools have been developed to assess architecture sustainability such as the rating tools BREEAM, GBC, CASBEE, Green Globe, LEED, Green Star, HQE.

While most of the existing literature reports on the sustainability assessment of buildings as a whole, there is lack of research into the sustainability performance of independent building components (e.g., beams, columns, walls, facades) accounting for the three pillars of sustainability - economic, environmental and social (Brundtland, 1987; ICLEI, 1994).

The facade is one of the main and largest components of a building, which could strongly contribute to the sustainability performance for the whole building. Previous studies confirmed the predominant role of facades in minimising environmental effects and decreasing building costs as well as providing comfort for inhabitants (Rivard, 1995; Allen, 1997; Emmanuel, 2004; Taborianski and Prado, 2012; Aksamija, 2013; Harirchian, 2013; Azari and Palomera, 2015; Schuetze *et al.*, 2015; Martabid and Mourgues, 2015; Garmston, 2017; Hartman *et al.*, 2019). According to Zavadskas *et al.* (2008), much of the building envelope heat loss takes place via the facade, 60%, while only 15% is lost through the floor and 25% through the roof. The facade provides linkage between the inside of building and the external environment to protect the interior space against adverse environmental effects such as pollution, wind, rain, humidity, HVAC load and lighting load among others (Horner *et al.*, 2007). Apart from its protective, environmental and regulatory functions, the facade may control the indoor air quality, fire, and acoustic effects on buildings and provide comfort for inhabitants (Manioğlu &Yilmaz, 2006; Yeang, 2007).

On the other hand, around 25% of the total construction cost is related to building facades (Kragh, 2011; Layzell & Ledbetter, 1998), sometimes even up to 40% (Wigginton & Harris, 2013). Furthermore, previous studies (Brolin, 1980; Groat, 1988; Moughtin *et al.*, 1999; Utaberta *et al.*, 2012; Ghomeshi *et al.*, 2012) indicate that the facade plays an important role in the urban landscape and city image since it is always in the public eye and determines the character of buildings, towns and cities, all of which can positively influence social attitudes.

In this respect, as explained above, selection of the suitable facade system can govern the sustainability performance of the whole building (Markelj *et al.*, 2014). This selection is becoming increasingly complex, even challenging, due to the increasing number of commercial alternatives and construction methods available for facades, each with different environmental, economic and technical performance. This includes uncertainties to be considered due to the numerous stakeholders involved, indirect costs and other technical requirements that may vary according to the project (Jin & Overend, 2010).

In order to establish an effective decision-making process and select the most sustainable facade system, it is essential to consider the rational estimation of climatic, economic, social conditions and traditions as well as the satisfaction of the stakeholders involved in decision making procedure to
ensure project success (Horner *et al.*, 2006; Ginevičius *et al.*, 2008; Zavadskas *et al.*, 2013; Nadoushani *et al.*, 2017)

According to previous studies (Pohekar & Ramachandran, 2004; Frenette *et al.*, 2010; Kaklauskas *et al.*, 2006; Zavadskas *et al.*, 2008; Simanaviciene and Ustinovicius, 2012; Hopfe *et al.*, 2013; Ginevičius *et al.*, 2008; Moghtadernejad *et al.*, 2018), most of the tools used previously to assess facade sustainability have not fulfilled all the aforementioned requirements. Some involve indicators that are difficult to quantify and assess and, in some, cases might even be misinterpreted. In addition, almost none of them integrate stakeholder satisfaction in the assessment and selection process for facade systems. Meanwhile, most of them focused on the opaque part of the facade (wall systems), disregarding the transparent areas. However, glazed elements have always been considered a critical component (Lori *et al*. 2019).

On the other hand, the existing literature has been focused mainly on environmental and economic aspects, disregarding the third pillar of sustainability, which is the social aspect. In fact, through a holistic overview of around 100 studies on the sustainability performance of facade systems (more detail can be found in Gilani, 2020, pp. 21-23), it can be stated that 60% of the studies have focused on environmental criteria, while only 10% of the available literature included the economic, environmental and social impacts of facades.

Numerous studies have been conducted to evaluate the life cycle environmental impact of different facade systems (Kahhat 2009; Kim, 2011; Monteiro & Freire, 2012; Azari & Palomera, 2015; Azari, 2014; Han *et al*. 2015; Ingaro *et al*. 2016). In addition, several research projects (30%) have attempted to consider both economic and environmental impacts of different facade systems, aiming to provide a more extensive sustainability assessment (Zavadskas *et al*. 2008; Bolattürk, 2008; Chou, 2010; Cetiner & Edis, 2014). Gu *et al*., (2008) in their study assessed the environmental and economic performance of various facade design by combining LCA and LCC (life cycle costing) and indicated that the result is different when both parameters are considered in decision-making process.

Therefore, based on the above, the main objective of this research project is to develop a comprehensive approach for sustainability assessment of the whole facade system, including both opaque and transparent parts. The approach integrates the most representative economic, environmental and social indicators while considering the stakeholders' needs and satisfaction. This project also addresses the following issues: (1) identify indicators with a significant impact on building facade sustainability; (2) apply the proposed approach to the six most used residential facade systems in Barcelona to quantify the sustainability index of each system and, based on the results, detect enhancement aspects.

Related to these objectives, this project main contribution is the design and validation of this new approach, which will be a decisive support tool for decision-making in the field of facade management. This approach is extendable to different countries and locations by including for the first time exclusively the most appropriate holistic discriminative indicators and adjusting the weights to each particular context including the involved stakeholders' preferences.

It must be emphasised that the model was meant to be used by public authorities in Barcelona as a decision-making tool to quantify and design polices and measured with the intention of increasing the sustainability of the city’s existing and new facades.

2. Methodology

To overcome the identified drawbacks and bridge the gaps, this paper proposes a new approach for assessing and rating the sustainability of facade systems using MIVES (Integrated Value Model for Sustainable Assessment) (Alarcon *et al.*, 2010; Viñolas, 2011; Aguado et al, 2012). This method makes it possible to make decisions regarding the most suitable facade systems by considering the indicators belonging to the three pillars of sustainability as well as stakeholder satisfaction.

MIVES is a multi-criteria decision-making (MCDM) model that enables decision-makers to objectively assess the sustainability of processes and production based on the use of value functions and an analytic hierarchy process (AHP). Among the wide variety of existing multi-criteria decision making models, MIVES was selected as the most appropriate one for this study due to the 3 main reasons. First, it makes it possible to add and use both qualitative and quantitative indicators and, therefore, with different units and scales. For this purpose, the indicators are normalised by applying value functions (Alarcon *et al.*, 2010; Viñolas, 2011). In fact, one of the main characteristics of MIVES, that makes it unique among other MCDM methods, is its use of value functions to measure the degree of satisfaction for various stakeholders involved in the decision-making process. Secondly, uncertainty analyses can easily be integrated into the evaluations. Finally, it can be adapted to different locations with diverse characteristics without this being limited by the present conjuncture. In addition, this model is capable of engaging local specialist and authorities from diverse fields in decision-making processes.

MIVES has already been satisfactorily applied within the framework of a range of real architecture and civil engineering projects (Aguado *et al*., 2012; Pons & Aguado, 2012; Caño *et al*., 2012; Pons & de la Fuente, 2013; Casanovas *et al*, 2014; Pardo & Aguado, 2015; de la Fuente at al., 2016; Pons *et al*., 2016; Hosseini *et al*., 2016; Pujadas *et al*., 2017; de la Fuente *et al*., 2019).

2.1. MIVES-based approach for sustainability assessment of facades

The MIVES-based approach proposed herein for assessing facade sustainability consists of 3 phases as indicated in Fig. 1, these being:

- Phase 1, to determine the element, process or technology to be assessed. In this paper, this refers to residential facades in Barcelona, Spain. Subsequently, according to MIVES, a decision-making tree is built based on a theoretical framework to identify the most representative indicators. This tree is a hierarchical diagram that organises the most representative indicators of the specific product, system or processes to be evaluated, in an organized manner normally at three levels: requirements, criteria, and indicators. The tree must have a minimum number of indicators, which are independent from each other, to ensure that it offers a reliable assessment scenario. Section 4.1 presents a detailed explanation regarding the defined decision-making tree for the case study of the first application of this new approach.
- In Phase 2, after determining the quantification procedure for each indicator and the databases to be considered, value functions should be calibrated to normalise the indicator magnitudes. This normalised magnitude is intended to indirectly measure the stakeholders' degree of satisfaction. For this purpose, a scale from 0 to 1 is considered, where 0 indicates minimum satisfaction (S_{min}) and 1 indicates maximum satisfaction (S_{max}). More details on the characteristics of value functions can be found at section 2.2. The final step of this phase consists of establishing the weights for different components of the multi-criteria decision tree. In MIVES, the weights of the indicators are evaluated by a group of multidisciplinary experts by means of using the Analytical Hierarchy Process (AHP) (Saaty, 1990), although other methods (e.g., DELPHI) can be used as an alternative (Casanovas-Rubio & Armengou,

2018). The AHP method uses pairwise comparisons to assess decision maker's preferences regarding indicators importance. In this respect, in order to facilitate decision makers task, a questionnaire was defined for assigning weights to the parameter of the tree through pairwise comparison, which is fully presented in Appendix B. This questionnaire would be applicable for any location.

- In phase 3, the sustainability index (SI) of each alternative to be assessed is calculated using a formula that is presented in Eq. (3). A sensitivity analysis might eventually be carried out to identify the elements (weights and indicators) that govern the sustainability performance so that specific measures can be taken to enhance this performance. The SI value (or range) of each alternative might eventually be used to prioritise and assist the stakeholders in making the decision.

The SI formula, the value function equations and their factors explained in section 2.2, as well as the value analysis schema, is common to all models designed based on the MIVES method. More information can be found in earlier papers (Lombera & Aprea 2010; Alarcon *et al,* 2011; Pons & Aguado, 2012).

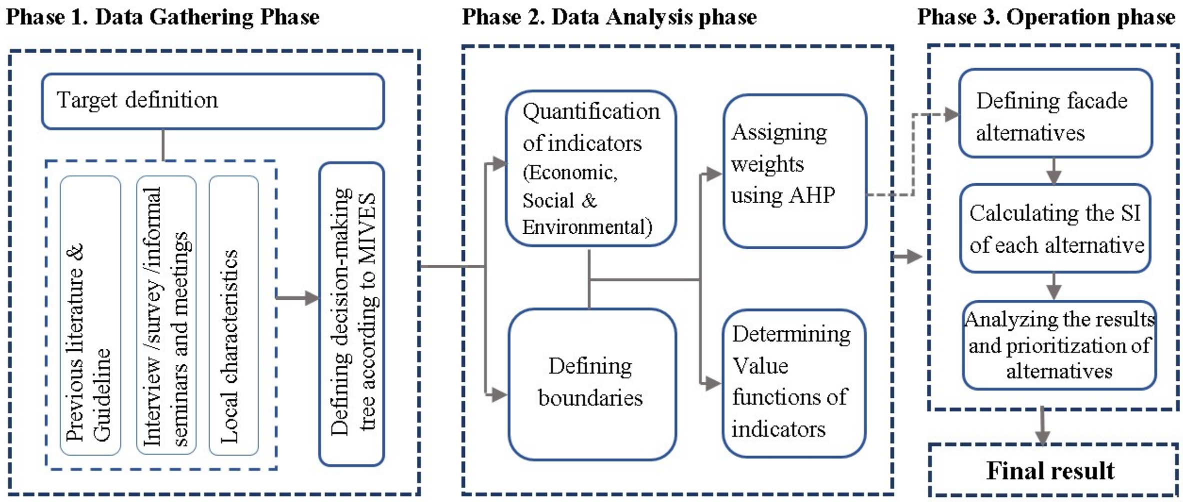

Fig.1. Proposed MIVES-based approach for sustainability assessment of facade systems

2.2. Value functions

The main objective of value functions is to homogenize the indicators units and facilitate the satisfaction (value) assessment of the indicators. These values represent minimum and maximum degree of satisfaction in terms of sustainability, which vary from 0 to 1, respectively.

The value functions (satisfaction values) are defined through a procedure consisting of the following four stages (Alarcón *et al.* 2011):

Stage 1. Defining the tendency (increase or decrease) of the value function (Fig. 2).

Stage 2. Defining the points corresponding to minimum (S_{min}) and maximum (S_{max}) satisfaction.

Stage 3. Defining the shape of the value functions (linear, concave, convex, S-shaped) (Fig. 2).

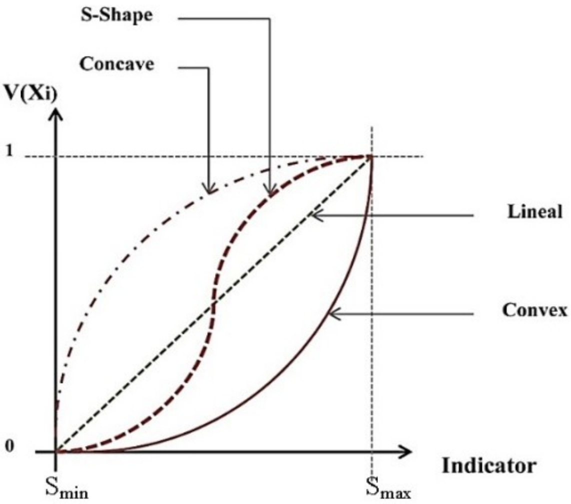

Fig.2. Different value function shapes (Hosseini *et al.*, 2016)

Stage 4. Obtaining each indicator value using equations (1) and (2) (Alarcon *et al*, 2011).

Equation (2) is applied to achieve factor *B* for equation (1). Equation (1) allows the indicators' values $V_i\ (x_i)$ to be normalised between a range from zero to one.

$$V_i = A + B.\left[1 - e^{-k_i \cdot \left(\frac{|S_{ind} - S_{min}|}{C_i}\right)^{P_i}}\right]$$

(1)

A : The response value *Smin* (indicator abscissa value), generally *A* = 0

Sind : The indicator abscissa value that generates value *Vi*

Smin & Smax : Maximum and minimum points in the scale of the indicator under consideration.

Pi : A shape factor that determines whether the curve is concave or convex, linear or S-shaped

Ci : The factor that establishes the value of the abscissa for the inflection point in curves with Pi > 1.

Ki : The factor that defines the response value to *Ci*

B : The factor preventing the function from leaving the range (0.00, 1.00); obtained with equation (2).

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

3. Case studies: facade systems on residential buildings in Barcelona

The first facades assessed using this new approach for the first time are located on residential buildings since the housing sector has proven to be the most representative from a sustainability point of view; nonetheless, the applicability of the proposed approach can also be extended to office buildings among other uses. In this paper, the term facade includes both opaque and transparent parts of the exterior enclosure, the opaque part accounting for the wall system from exterior layer to interior while the transparent part includes the openings. The new MIVES-based approach has been applied to six facade systems which were identified as the most commonly used facade systems (FS, hereinafter) for residential uses in Barcelona (Häkkinen, 2012; Pérez-Bellaa, 2015; Pombo, *et al.* 2016); they are listed below:

- FS-A, Fig. 3a: single-leaf wall of solid brick masonry with double glazed Aluminium windows
- FS-B, Fig. 3b: brick cavity wall without insulation with double glazed Aluminium windows
- FS-C, Fig. 3c: brick cavity wall with insulation with double glazed Aluminium windows
- FS-D, Fig. 3d: concrete block cavity wall with insulation and double-glazed Aluminium window
- FS-E, Fig. 3e: precast concrete panel with double glazed Aluminium windows
- FS-F, Fig. 3f: in this facade, the opaque part is the same as FS-A and the only difference lies in the transparent part, which is a single-glazed Aluminium window.

The composition of the opaque parts of the aforementioned facade systems is explained in detail in Fig.3 and appendix A.

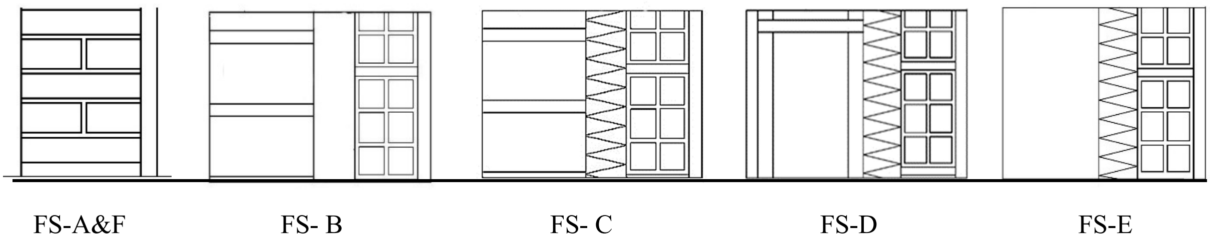

Fig.3. (a) Layers of the opaque part from outside to inside; (facade system A) 30cm solid brick wall, 1.5cm gypsum plaster; (b) 11.5cm perforated facing brick, 4cm air cavity without insulation, 7cm hollow clay brick, 1.5cm gypsum plaster; (c) 11.5cm perforated facing brick, 6cm expanded polystyrene (EPS), 7cm hollow clay brick, 1.5cm gypsum plaster; (d) 1.5cm cement plaster, 12cm AAC block, 6cm polyurethane (PUR), 7cm hollow clay brick, 1.5cm gypsum plaster; (e) 12cm prefabricated concrete panel, 6cm extruded polystyrene (XPS), 7cm hollow clay brick, 1.5cm gypsum plaster; (f) the same as facade system A.

FS-A and FS-B were mainly constructed before 1980, when there was no thermal protection for buildings (Gaspar *et al*., 2014). In fact, 56% of the Spanish residential building stock was built before 1980 (Instituto Nacional de Estadística, 2013), 75% of this was represented by the FS-A and FS-B (Häkkinen, 2012), and must be adapted to meet current standards. FS-C, -D and -E were installed mainly after 2008, when buildings were erected under the Technical Building Code (CTE, 2013; Gangolells *et al*., 2016).

Table 1 depicts the properties of the materials used into the analysed FSs and Table 2 shows their main features.

Table.1. Main materials and their properties

Features material	**Density (kg/m^3)**	**Thermal conductivity (W/mk)**	**Embodied energy (MJ/m^2)**	**Embodied CO_2 ($kgCO_2/m^2$)**	**References**
Gypsum plaster	1120	0.2	26.93	4.65	CTE, 2013; BEDEC , 2019
Cement mortar (1:6)	1650	0.44	19.45	3.61	
AAC block	500	0.12	370.80	35.52	Hammond & Jones, 2011; BEDEC,2019
Perforated brick	1550	0.6	36.12	23.22	
Hollow clay brick	1120	0.32	223.62	16.96	

Prefabricated concrete panel	2100	0.44	759.42	71.51	CTE, 2013; BEDEC, 2019
Polyurethane (PUR)	24	0.03	352.8	52.07	
EPS	23	0.04	147.42	21.76	
XPS	35	0.03	221	32.64	
Double glazed AL window (4/12/6)	-	0.042	4559	504	
Single glazed AL window 6mm	-	1.1	3995	484	

Table.2. Important features of the facade systems

Facade systems	**Heat transfer coefficient (W/m^{2}k)**		**Average maintenance cost (€/m^2)**	**Average construction cost (€/m^2)**	**Solid waste (kg/m^2)**	**References**
	opaque	openings				
FS-A	2.7	1.92	235	175	43	CTE, 2013; BEDEC, 2019
FS-B	1.8	1.92	219.3	139	16.83	CTE, 2013; BEDEC, 2019
FS-C	0.49	1.92	219.3	148	16.97	BEDEC, 2019; CTE, 2013
FS-D	0.39	1.92	303	168	12.82	CTE, 2013; BEDEC, 2019
FS-E	0.52	1.92	225.5	161.5	7.37	
FS-F	2.7	5.7	235	164	43	

4. Results

4.1 Phase 1 results

In this phase, the first step is to define the aim clearly in order to have an accurate assessment. In this paper, this refers to sustainability assessment of the six most common residential facade systems in Barcelona, Spain.

4.1.1. Definition of the decision-making tree

As the second step, the following decision-making tree was developed that includes the most representative indicators for sustainability assessment of residential facades (Table. 3). This diagram consists of three levels: requirements, criteria, and indicators. The first level includes parameters that are rather general and qualitative, whereas the last level accounts for the specific aspects by means of defining indicators.

Table. 3. Decision-making tree for sustainability assessment of residential facades

Requirement (α_i)	Criteria (β_i)	Indicators (γ_i)
R_1. Economic (0.34)	C_1. Cost (1)	I_1. Construction cost (0.61) I_2. Maintenance cost (0.39)
R_2. Environmental (0.33)	C_2. Consumption (0.39)	I_3. Energy consumption (1)
	C_3. Emission (0.32)	I_4. CO_2 emission (1)
	C_4.Waste (0.29)	I_5. Total solid waste (1)
R_3. Social (0.33)	C_5. Safety (0.29)	I_6. Extra fire performance (1)
	C_6. Constructability (0.18)	I_7. Skilled labour requirement (1)
	C_7. User added Comfort (0.32)	I_8. Extra thermal performance (0.38) I_9. Extra acoustic performance (0.28) I_{10}. Daylight comfort (0.34)
	C_8. Aesthetics (0.21)	I_{11}. Contextual compatibility (0.55) I_{12}. Visual quality (0.45)

According to the location and/or stakeholders' preferences, some indicators were found to be determining or negligible. This research project considered the common involved stakeholders during facades life cycle in order to develop this new sustainability assessment approach and the stakeholders from Barcelona specific residential facades context to calibrate and validate the approach for the specific case study in the first application of this novel approach (Gilani, 2020). For instance, the natural disaster risk should be considered as an important indicator for earthquake prone countries while, in Barcelona, this indicator can be discarded since the seismicity in Spain is low, with a few exceptions. On other hand, based on MIVES model the final number of criteria and indicators in each tree branch shall be the minimum and the most representative so that overlapping among indicators is avoided. Likewise, this approach makes it possible to discard indicators with low relative weight (namely <5%) with a low impact on the final SI although this might be a difficult and time-consuming process (sometimes highly uncertain).

The resulting decision-making tree shown in Table 3 can be applied in different stages of design, construction and renovation of residential buildings' facades. However, its application can be recommended at early stages since the results may lead to improved comfort, energy efficiency, health and safety in buildings (Saparauskas *et al*. 2010).

The criteria and indicators presented in Table 3, as the principal indicators for residential building facades in Barcelona, were defined in 2 phases:

First, the initial set of most recurrent indictors was identified through the extensive review of previous studies about the sustainability performance of facades (Fig. 4) (more information can be found in Gilani, 2020, pp. 21-23).

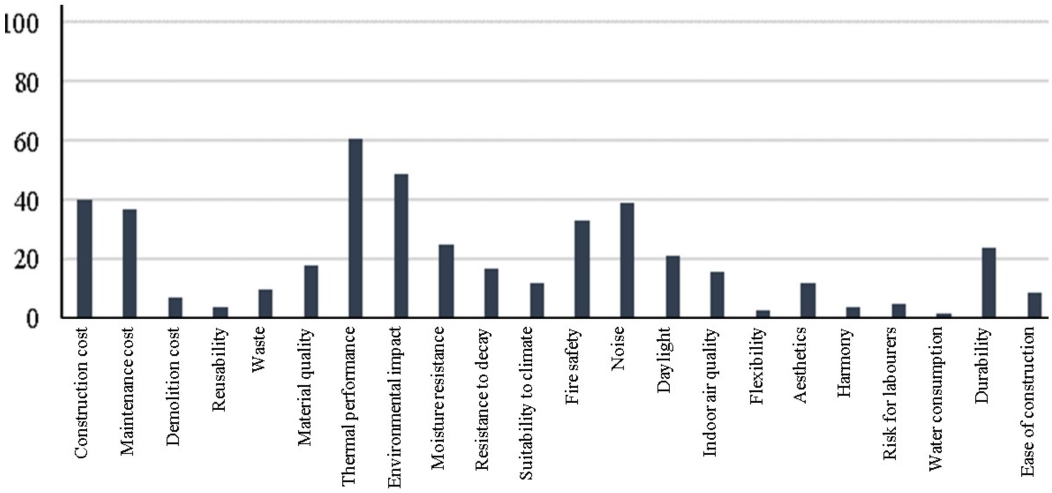

Fig.4. Use frequency of each criterion in previous literature

Then, the 22 initial indicators were further refined through attending 2 conferences on sustainability, seminars where multidisciplinary local practitioners (civil engineers, architects, contractors, project managers, and building inspectors) and researchers actively participated, plus reference to standards.

Finally, as indicated in Table 3, 12 indicators were selected to be most representative for sustainability assessment of residential building facades in Barcelona and independent from each other. To the authors best knowledge there is not any previous facades study that incorporates all these essential indicators. The life-span period considered in this research was set at 50 years, embracing all stages from the extraction of the facade’s constituent materials up to recycling.

The *economic requirement* (*R1*) considers the economic impacts of the facade over the whole life cycle. The *environmental requirement* (*R2*) assesses the environmental impact of facade systems based on the four LCA phases. The *social requirement* (*R3*) assesses the impact of facades on users’ health and comfort as well as considering the stakeholders.

Two economic indicators were considered for economic requirement (R1): I_1 assesses the *construction costs*, both direct and indirect. This evaluation was based on the Spanish cost database BEDEC to be able to derive accurate results for Barcelona (BEDEC, 2019). Had this assessment been carried out in another location, its relevant local costs database should have been used. The indirect costs can also be included in this indicator. I_2 covers the *maintenance cost* expected during the life cycle of facade systems. The life-cycle of facades is considered to be 50 years so maintenance cost will be calculated considering this interval. These costs can be estimated through previous experiences and following criteria proposed in guidelines and recommendations; for this research, the Spanish building maintenance book (Manteniment de l'edifici, 1991; Flores-Colen, and De Brito, 2010; Pons & Aguado, 2012) was considered.

Demolition cost should get a special mention. This was discarded since the life expectancy of facades is often over 50 years (British Standards Institution, 2003; Dias, 2013; Udawattha and Halwatura, 2017). In fact, facades are mostly renovated by repairing or replacing some of the cladding components during the lifespan or afterwards. Should this indicator be determining, it could be included as an additional indicator within criterion C_1.

Three criteria, with each respective indicator, were considered for the environmental performance. This LCA is a simplified version of the methods described in (ISO, 2006; Lecouls, 1999). This approach is meant to optimise time-efforts and cost of the assessment without compromising the rigour by using free access local databases (BEDEC, 2019) and energy simulation software (LIDER, 2010).

In this regard, indicator I_3 *energy consumption* accounts for the energy according to LCA covering two phases: manufacturing (material production, transportation) and construction (construction and assembly including the machinery used for the building processes). This indicator does not include energy consumption during the operation phase since this is considered in the thermal performance indicator (I_8) and so avoids overlapping criteria. Energy consumption during the demolition phase is reported to be negligible by Pons & Wadel *et al.* (2011) when compared to previous phases (< 3%). Indicator I_4 *CO_2 emissions* stands for the CO_2 emissions produced during the same two phases considered for I_3. Indicator I_5 *waste* assesses the total amount of waste material remaining from the construction (assembly) and demolition (disassembly) phases. Water consumption associated with the production and construction of the facade is minor (< 0.01%) when compared with the use phase of the building (Pons & Aguado, 2012; Crawford & Pullen, 2011); thus, this indicator was excluded from the decision-making tree.

The social requirement consists of four criteria and seven indicators. The *safety criterion* aims to assess the robustness of facades against natural and man-made disasters. Since Barcelona has extremely low probability of natural disaster occurrence, this indicator is excluded. However, the *extra fire performance* (I_6) indicator is considered because it represents one of the most important man-made disasters. Indicator I_6 is meant to add value and promote facade alternatives with higher fire resistance than determined by the standards. The Spanish Building Code (CTE, 2013) is used in this research for this purpose. Indicator I_7 *skilled labour requirement* assesses the need for on-site skilled labour for assembling the facade system. This indicator is intended to evaluate the construction time-effort and ease-of-assembly of the facade system. The latter is related to advanced technology and automation of the construction process. Therefore, a system that requires a minimum number of on-site skilled workers is the most satisfactory (Wallbaum *et al.*, 2012). The I_8 *extra thermal performance* indicator measures the added value associated with facade systems with higher thermal insulation capacity than required by the project specifications (CTE, 2013). As previously said, this 8th indicator assesses the energy consumption of the facade during its operation phase, because this insulation capacity highly contributes to this energy consumption phase (Iribarren et al., 2016; Monge-Barrio & Sánchez-Ostiz, 2015). The I_9 *extra acoustic performance* indicator considers the added value for noise facade damping capacity by comparing the air-borne soundproofing with what is required in the reference standard (CTE, 2013), which therefore has a similar approach to I_6 and I_8. I_{10} *daylight comfort* measures whether there is sufficient daylight for occupants to carry out normal activities during the day. The Average Daylight Factor (ADF) proposed by Crisp and Littlefair (1984) is used to quantify the daylight quality in indoor spaces. I_{11} *contextual compatibility* considers the aesthetic performance of the facade as an element to be integrated and accepted within the context of a city, with an identity and cultural background. According to Utaberta *et al* (2012), in addition to the protective role of facade, this also plays an important role in the urban landscape and image of the city. In this respect, this indicator evaluates the rate of harmony between facades and their neighbourhood by considering physical and objective parameters that can affect facade-neighbourhood visual compatibility. The I_{12} *visual quality* indicator assesses perceptual properties that have a positive effect on observers' and users' aesthetic preferences. Through literature review, four aesthetic parameters, that could greatly influence the observers' aesthetic judgments, were identified; these being uniqueness, medium complexity, quality of details and proportionality (Gifford, 2000; Imamoglo, 2000; Ghomeshi *et al*. 2012; Nasar, 1994; Berlyne, 1963; Zinas and Jusan, 2012; Moussavi Nadoushani, *et al*. 2017). Originality was identified as positive innovation and change of an established trend, style, ornament, among others. Medium complexity was defined as neither very simple nor very complex facade systems that could lead to chaos. Quality of details stands for the quality of installation/assembling of materials in facade systems. The proportionality parameter prioritises solutions that provide a sense of proportion for observers between different parts of a facade. A measurable scale of 1- 4 was used to rate different facade systems based on these parameters.

4.2. Results from phase 2

This phase, first quantifies each indicator related to each facade system. Table 4 presents the results of this phase for the case study. There is a detailed explanation of each indicator, from the economic to the social, in Gilani, 2020, pp. 43-53.

Table. 4. Quantification of each indicator related to each facade system

Indicators		**FS-A**	**FS-B**	**FS-C**	**FS-D**	**FS-E**	**FS-F**	**References**
I_1 (€/m^2)		175	139	148	168	161.5	164	BEDE, 2019
I_2 (€/m^2)		235	219.3	219.3	303	225	235	BEDEC, 2019; informal seminars with maintenance service of Campus Nord, UPC
I_3 (MJ/m^2)	Opaque	1160	832	875	1027	1072	1160	BEDEC, 2019. Hammond & Jones, 2011
	Opening	4379	4379	4379	4379	4379	3200	
I_4 (kgCO$_2$/m^2)	Opaque	93	68	81	101	89	93	
	Opening	482	482	482	482	482	389	
I_5 (kg/m^2)	Opaque	43	16.83	16.97	12.82	7.37	43	BEDEC, 2019
	Opening	0.09	0.09	0.09	0.09	0.09	0.01	
I_6 (min)		–	–	0.0	0.0	0.0	-	CTE, 2013; Based on the proposed strategy in Gilani, 2020; p. 45
I_7 (points)		6.2	7.3	7.8	6.5	2.6	6.2	Based on proposed questionnaire in Gilani, 2020; p. 47

I_8 (%)	Opaque	–	–	18%	33%	11%	-	CTE, 2013; Based on the proposed strategy in Gilani, 2020; p. 48
	Opening	38%	38%	38%	38%	38%	-	
I_9 (dB)		2.0	2.0	2.0	2.0	2.0	-	CTE, 2013; Based on the proposed strategy in Gilani, 2020; p. 48
I_{10} (%)		6.8%	6.8%	6.8%	6.8%	6.8%	6.8%	Yarham & Wilson,1999; Based on the proposed strategy in Gilani, 2020; p. 49
I_{11} (points)		2.8	4.0	4.0	2.9	2.7	2.8	Based on the proposed questionnaire in Gilani, 2020; p. 51
I_{12} (points)		1.0	1.6	1.6	1.3	2.3	1.0	Based on the proposed questionnaire in Gilani, 2020; p. 53

4.2.1 Value functions

Then, the value function for each indicator (Table 5) was determined based on guidelines, scientific literature, and the background of experts, including professors and multidisciplinary engineers and practitioners from the construction sector.

For example, the indicator I_1 value function was established as: S_{min} =50€/m^2 and S_{max} =400€/m^2 as the minimum and maximum costs, respectively, of a set of 620 facade systems gathered in the BEDEC database (BEDEC, 2019). Likewise, since satisfaction decreases rapidly as the building cost increases, a decreasing S-shape tendency was assigned to I_1 (Fig. 5). The curvature of the function was established according to the existing construction market in Barcelona, which is very competitive with costs over 110€/m^2, leading to sharp drops in stakeholder satisfaction.

Table.5. Basic data for each indicator value function

Indicators		**unit**	**S_{max}**	**S_{min}**	***C***	**K**	**P**	**shape**	**References**
I_1. Construction cost		€/m^2	400	50	150	0.1	5.5	DS	BEDEC, 2019
I_2. Maintenance cost		€/m^2	1400	100	400	0.05	1.1	DL	Pons & Aguado, 2012; Madureira, *et al*, 2017
I_3. Energy consumption	opaque	MJ/m^2	2700	300	1500	0.9	3.3	DS	Hammond & Jones, 2011; BEDE C, 2019
	openings		6400	450	3000	0.8	3.2	DS	
I_4. CO_2 emission	opaque	KgCO2/m^2	290	40	130	0.3	5.1	DS	Hammond & Jones, 2011; BEDEC, 2019
	openings		740	30	445	1.2	3.8	DS	
I_5. Total solid waste	opaque	Kg/m^2	24	4	14.3	2.5	7	DS	BEDEC, 2019
	openings	Gr/m^2	240	30	200	0.05	2.7	DC_{VX}	
I_6. Extra fire performance		Min	30	-3	1.2	2.9	0.7	IC_{CV}	CTE, 2013; proposed strategy in Gilani, 2020; p. 45
I_7. Skilled labour requirement		Points	10	0	8.5	2.5	3.9	DS	Isaac, 2016; questionnaire proposed in Gilani, 2020; p. 47
I_8. Extra thermal performance	opaque	%	100	-11	0.5	3	0.9	DC_{CV}	CTE, 2013; proposed strategy in Gilani, 2020; p. 48
	openings		100	-11	2.1	3.8	0.9	DC_{CV}	
I_9. Extra acoustic performance		dB	5	-1	1	2.7	0.75	IC_{CV}	CTE, 2013; proposed strategy in Gilani, 2020; p. 48
I_{10}. Daylight comfort		%	5	2	1.9	1.3	3	Is	Naeem and Wilson, 2007; proposed strategy in Gilani, 2020; p. 49
I_{11}. Contextual compatibility		Points	5	0	2.9	1.2	3.6	Is	proposed questionnaire in Gilani, 2020; p. 51
I_{12}. Visual quality		Points	4	0	2	0.6	3	IS	proposed questionnaire in Gilani, 2020; p. 53

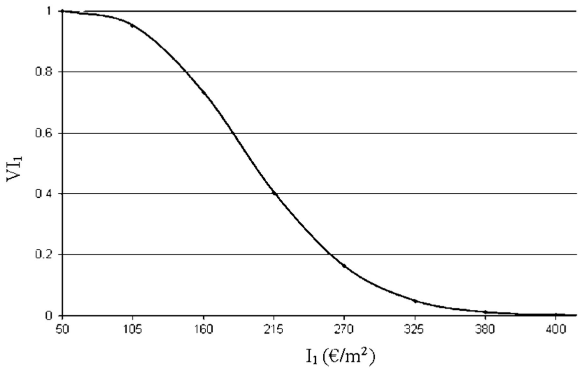

Fig.5. Value function of construction cost indicator (I_1)

4.2.2. Weights assignment

After determining the value function for each indicator, weights were assigned to each requirement (α_i), criteria (β_i) and indicator (γ_i) using the analytic hierarchy process (AHP) (Saaty, 1990) (Table 3) based on a questionnaire survey with 20 respondents (Appendix B). The respondents were 14 architects, 3 facade consultants who work in the Spanish construction industry plus 6 experts from the university. Then, the Grubb's test was used to identify the outliers (Grubbs, 1950). The results obtained from the questionnaire survey can be found in Appendix C.

4.3. Results from phase 3

In this phase, the six case studies indicated in Fig.3 were analysed with the new MIVES-based approach to determine the sustainability performance of each alternative. An LCA through the 50-year life span together with the local standards and requirements of Barcelona were assumed. The functional unit fixed for evaluation is 1.0 m^2 facade.

The Sustainability Index (SI) of each alternative is computed by using Eq. (3) (more details can be found in Aguado *et al.*, 2012)

$$SI = \sum_{i=1}^{i=N} \alpha_i \cdot \beta_i \cdot \gamma_i \cdot V_i(S_{i.x})$$

Where:

α_i, β_i and γ_i : The weights of each requirement, criterion and indicator, respectively.

V_i $(S_{i,x})$: The value of the alternative x with respect to a given indicator i

N : The total number of indicators.

Apart from the SI value of each alternative, the values of each requirement (V_{Rk}), criterion (V_{Ck}), and indicator (V_{Ik}) for each facade system are obtained (Table 6). These magnitudes are the elements used in the decision-making process. In this regard, after a sensitivity analysis, the most sustainable alternative can be identified as the one that demonstrates a balanced and robust performance in each of the requirements, with a high SI value (not necessarily the highest).

Table.6. Values of SI, V_{Rk}, V_{Ck} and V_{Ik} for each of the six facade systems

Alternatives	**SI**	V_{R1}	V_{R2}	V_{R3}	V_{C1}	V_{C2}	V_{C3}	V_{C4}	V_{C5}	V_{C6}	V_{C7}	V_{C8}
Facade A	0.46	0.74	0.33	0.30	0.74	0.37	0.52	0.08	0.00	0.12	0.67	0.31
Facade B	0.56	0.86	0.52	0.33	0.86	0.69	0.68	0.12	0.00	0.02	0.67	0.55
Facade C	0.65	0.84	0.51	0.58	0.84	0.67	0.67	0.11	0.50	0.01	0.88	0.75
Facade D	0.59	0.74	0.49	0.55	0.74	0.57	0.50	0.36	0.50	0.07	0.90	0.51
Facade E	0.65	0.79	0.49	0.66	0.79	0.41	0.40	0.70	0.50	0.37	0.88	0.8
Facade F	0.48	0.80	0.42	0.19	0.80	0.41	0.58	0.27	0.00	0.12	0.34	0.31

	V_{I1}	V_{I2}	V_{I3}	V_{I4}	V_{I5}	V_{I6}	V_{I7}	V_{I8}	V_{I9}	V_{I10}	V_{I11}	V_{I12}
Facade A	0.64	0.89	0.37	0.52	0.08	0.00	0.12	0.32	0.75	1.00	0.50	0.07
Facade B	0.88	0.83	0.69	0.68	0.12	0.00	0.02	0.32	0.75	1.00	0.75	0.30

Facade C	0.80	0.91	0.67	0.67	0.11	0.50	0.01	0.86	0.75	1.00	0.99	0.45
Facade D	0.68	0.84	0.57	0.50	0.36	0.50	0.07	0.91	0.75	1.00	0.74	0.22
Facade E	0.72	0.9	0.41	0.40	0.70	0.50	0.37	0.86	0.75	1.00	0.74	0.87
Facade F	0.74	0.89	0.41	0.58	0.27	0.00	0.12	0.00	0.00	1.00	0.50	0.07

5. Discussion

After measuring the SI of each FS with the proposed MIVES-based approach, this section analyses the results. For this purpose, the sustainability and requirements performance for each alternative are presented in Fig. 6.

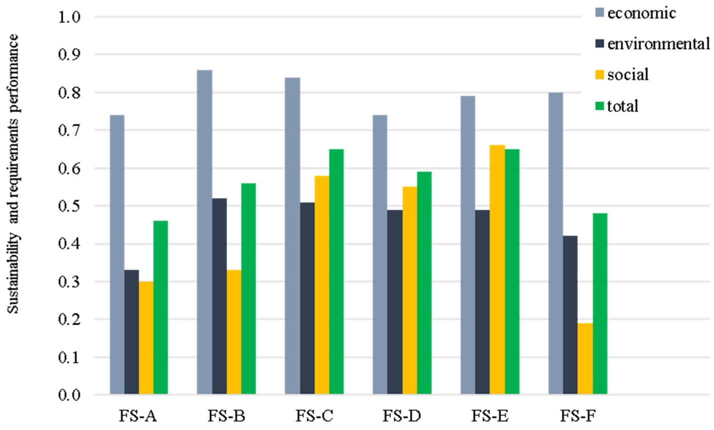

Fig.6. Total sustainability index and requirement values for the six facade systems

From both Fig. 6 and Table 6, it can be remarked that the SI of the alternatives ranged from 0.46 (FS-A) to 0.65 (FS-C) when considering a set of balanced requirements weights ($\alpha_i = 0.33$, $i = 1$ to 3), stating that: (1) there is still plenty of room to improve sustainability of the commonly used facade systems in Barcelona and, (2) that, as expected, FS-A and FS-F perform with the lowest SIs (0.46 and 0.48) since both were mainly designed and constructed before 1980. At that time, building standards and regulations were, besides being more conservative in terms of structural design, less sensitive towards environmental and social aspects. Likewise, the sustainability concept was still not sufficiently consolidated.

From a general perspective, the SIs of facade systems B, D and E fell within the obtained range, although their performance was still below the minimum target value (namely SI ≥ 0.75) according to current standards and demands. This confirms that most environmental and social indicators included in the proposed model were not directly considered in the design phase but were considered implicitly and most probably from a subjective point of view (e.g., aesthetics).

This result was, however, to be expected since this new façade-oriented MIVES-based approach is the first, in the authors' knowledge, that embraces all these governing indicators for the sustainability assessment.

It is worth mentioning that the facade systems analysed had an attractive economic requirement (R_1) performance ($V_{R1} \geq 0.74$), as it is also a symptom that economic aspects drove the decision-making process. This is confirmed by the low social performance values that were detected for the FS-A (0.30) and, particularly, for the FS-E (0.19). The same pattern can be observed for environmental performances.

In terms of the environmental requirement (R_2), the FS-B, -C, -D and -E performed equivalently ($0.49 \leq V_{R2} \leq 0.52$) and FS-A obtained $V_{R2} = 0.33$, see Fig. 7. These results also highlight the need to make improvements intended to enhance the environmental performance, particularly energy consumption (I_3) for FS-A, -B and -C. It is important to notice that, although there is still plenty of room for progress, the CO_2-eq emission indicator (I_4) computed values $V_{I4} > 0.50$ (except for FS-E, with $V_{I4} = 0.40$) which confirm that there might already have been some awareness of environmental aspects when these facade systems were designed; however, its quantification was probably unclear, mostly due to lack of guidelines and an agreed roadmap.

As for the social requirement (R_3), FS-F obtained the lowest social performance ($V_{R3} = 0.16$) due its insufficient thermal resistance (0.37 m^2k/w for opaque and 0.17 m^2k/w for transparent part) according to current Spanish regulations (CTE, 2013) (Minimum R-value for opaque part: 1.33 m^2k/w, Min R-value for transparent part: 0.32m^2k/w). On the contrary, FS-C, -D and -E presented both the maximum fire ($V_{I6} = 0.50$) and thermal ($0.86 \leq V_{I8} \leq 0.91$) performances. Regarding the aesthetics criterion (C_8), FS-C obtained the maximum contextual compatibility ($V_{I11} \approx 1.00$) with rather low visual quality ($V_{I12} = 0.45$) whilst FS-E showed less duality between V_{I11} and V_{I12} indicators with values of 0.74 and 0.87, respectively. Finally, it should be highlighted that the skilled-labour requirement (I_7) values for the analysed facade technologies were high, even for FS-E, which consists of prefabricated panels for cladding, since these require an on-site skilled workforce to construct other layers of these facades. Consequently, the performance of this indicator is low $V_{I7} \leq 0.37$. This indicator performance can be enhanced by using similar technologies to those often installed in pre- and post-disaster housing (Hosseini *et al*., 2016); however, using them might compromise the performance of other indicators.

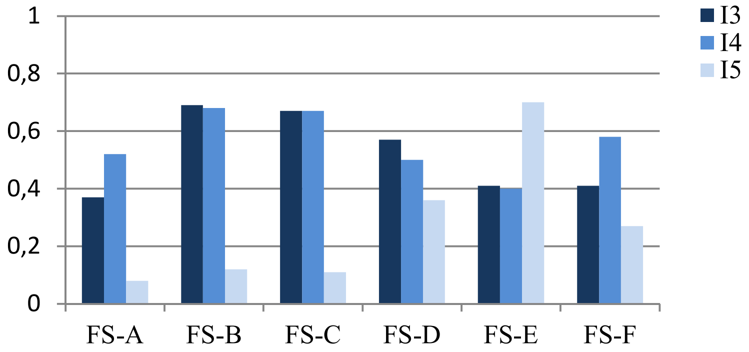

Fig.7. Performance of the environmental indicators for each facade system

Finally, both FS-C and -E performed with the higher SI (both 0.65). In this sense, FS-E achieved the highest social requirement value (V_{R3} = 0.66) whilst FS-B obtained the better economic (V_{R1} = 0.86) and environmental (V_{R1} = 0.52) performances. As no insulation is installed in FS-B, construction cost, energy consumption and CO_2 emission decreased and consequently, environmental and economic requirements performances are higher. However, social performance decreased instead due to the low thermal and acoustic performance of this facade, see Table 6. By adding insulation to FS-B, resulting in FS-C, the social requirement value increased significantly (58%) and, consequently, this led to an alternative with a higher SI. Regarding the latter, should a decision have to be made, this would not be possible by directly comparing the SI obtained since the differences are negligible and non-decisive in this case (due to the weights established and alternatives analysed). Nonetheless, the results are valid and helpful to: (1) quantify, as objectively as possible, the sustainability of each facade system analysed, and (2), identify strengths and weaknesses that would allow improvement measures to be implemented.

A sensitivity analysis of the results (see Fig. 8) was carried out by considering different scenarios simulated by adapting the requirements' weights (α_i; i = 1 to 3). In this regard, high values of α_1 (max. 0.80) would represent scenarios in which economic aspects are determining, e.g., global depression and/or economic crisis period, and/or excessive importance in the decision-making process of stakeholders solely driven by the economic factor. On the other hand, scenarios in which the stakeholders are aligned and committed to balancing the importance of sustainability requirements or even prioritising the environmental and social pillars, are represented by α_2 and α_3 values greater than assigned to α_1. It should be mentioned that other stochastic-based approaches, such as proposed by Caño *et al.* (2012), could have been applied; however, these do not fall within either the scope or the objective of this research.

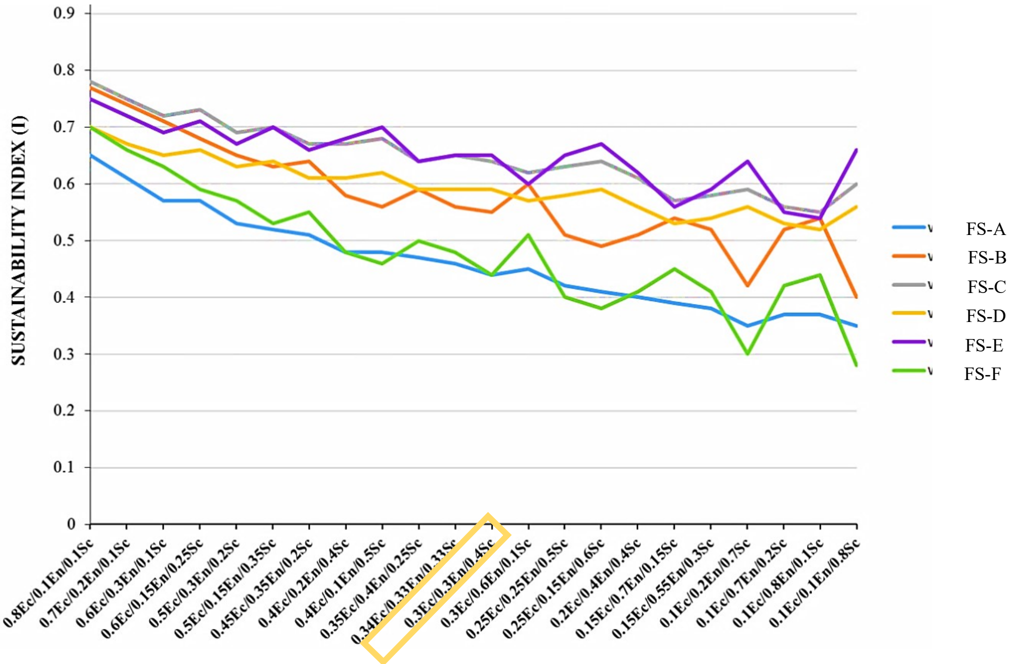

Fig.8. Sustainability indexes for the six alternatives considering different sets of requirement weights sets: economic (Ec), environmental (En) and social (Sc)

The results depicted in Fig. 8 allow confirming that:

- Economy was the governing design condition of facade systems since a range of $0.60 < \text{SIs} < 0.80$, for $\alpha_1 = 0.80$, was derived from scenarios with high values of α_1. On the contrary, for greater values of $\alpha_2 + \alpha_3$, SI tends to decrease.
- FS-C, and –E obtained a higher SI value in most of the scenarios (SI>0.60). Thus, this alternative, compared to others, turned out to be the most suitable from the sustainability perspective.

These results can also be explained in the technical literature. In this sense, the energy performance of building envelopes has improved considerably in Spain since 1980, especially since 2008 due to compulsory use of the Technical Building Code (CTE, 2006). Improvements are revealed when comparing FS-A and FS-C. The former was mainly installed prior to 1980, and no thermal protection for buildings or building units was mandatory, whilst FS-C was built after 2008, when the Technical Building Code (CTE, 2006) already regulated the building construction sector.

In addition, 56% of the Spanish residential building stock was built before 1980 (Instituto Nacional de Estadística, 2013), 75% represented by the FS-A and –B (Häkkinen, 2012). Thus, the results obtained emphasise the urgent need for renovation/improvement of these facades to meet not only minimum standards but also go beyond existing buildings codes and meet more advanced and strict sustainable development goals.

6. Conclusions

An innovative MIVES-based approach to assist decision-makers in the design efforts and facade system selection stage was proposed in this research paper. This approach enables assessment of facade sustainability by considering and quantifying representative indicators from economic, environmental and social pillars and taking into consideration stakeholder satisfaction.

After a thorough review of both technical and scientific literature on facade sustainability, twenty-two (22) indicators were identified. For this study, however, a set of twelve (12) indicators was considered representative and significant according to the results derived from seminars involving multidisciplinary experts. The weights and other components from the approach were agreed during these seminars.

As a case of application, the sustainability index of the six most representative facade systems in Barcelona (Spain) for residential buildings was assessed using this approach. In this regard, based on analysis of the results, the following conclusions can be drawn:

- The approach proved to be sensitive to the performance of the indicators considered and to be applicable to both opaque and opening parts of the facade since specific parts (i.e., cladding layer, window glasses, frames, and others) can be included in the analysis. This feature of the model is an advance compared to most other approaches.
- The range of the sustainability indexes obtained varied from 0.46 to 0.65, with lower scores for the oldest facades (constructed before 1980). In this regard, the vast majority (namely

75%) of the installed facade systems in Barcelona present this sustainability performance range.

- The performance of each indicator and requirement can be used to identify measures that would make it possible to increase the sustainability of the facade system being evaluated.

It must be mentioned that the approach developed might be extended in future works to apply to other building facade types (i.e., offices, shopping centres) and other boundary conditions (i.e., country, standards and recommendations) by including suitable indicators and calibrating weights by involving the representative stakeholders and relying on a robust and transparent methodology. Also a parametric study about different groups of stakeholders preferences, among other analysis in the way to move forward more sustainable facades to achieve more resilient cities in the future.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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