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MCDM approach for assessing the sustainability of buildings' facades

Golshid Gilani

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MCDM Approach for Assessing the Sustainability of Buildings' Facades

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ABSTRACT

Construction industry is known to cause major social, economic and environmental impacts on the society so that promoting sustainable construction practice affects positively and allows generating a balance among these pillars. Besides, to achieve sustainability goals in a building project, the stakeholders' needs and expectations have to be met and taken into consideration.

One of the main and largest components of a building, which could highly contribute to the sustainability performance of the whole building is the facade. Previous studies confirmed the predominant role of facades in minimizing environmental effects and decreasing buildings' costs as well as providing comfort for inhabitants.

Despite the impact of facades on sustainability, indicators that govern the performance of the pillars are often dismissed or, if considered, these are rather subjectively measured - especially those associated with the social requirement. On the other hand, the vast majority of the existing tools fail at considering stakeholders' satisfaction in the assessment and selection process of optimal facade systems.

Within this context, a new comprehensive approach to quantify the sustainability index of facade systems including the most representative economic, environmental and social indicators and integrating the stakeholders' satisfaction was developed.

The approach is based on MIVES (Integrated Value Model for Sustainable Assessment), a Multi Criteria Decision Making (MCDM) model, which allows minimizing the subjectivity in the decision-making process and relies on the value function concept.

This new approach was particularly optimized for residential building facades and successfully validated by analyzing five residential facade systems commonly used in Barcelona. The model is applicable for other countries and cities as well. Furthermore, through assessing the sustainability of two real buildings and validating the goodness of the results, the applicability of this approach was demonstrated.

The results proved several capabilities and potentials of the model, these being: (1) quantify, objectively, the sustainability of facade systems from the economic, environmental and social perspectives involving the stakeholders' preferences and (2), identify strengths and weaknesses of facades that would allow implementing improving measures.

The proposed approach was designed to be a decisive support for decision-making in the field of facade management. Findings confirm that the approach is valuable and suitable for use in practice by public and private stakeholders. Future works could be to develop a digital application for building and architectural offices so that these could consider sustainability in the design, assessment and selection processes of facades to make the best decision. Next research steps could also adapt this approach to other types of buildings in order to move towards more sustainable architecture and construction.

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LIST OF ABBREVIATIONS

FS	: Facade system
S_{min}	: Minimum satisfaction
S_{max}	: Maximum satisfaction Sustainability index
SI	: Sustainability index
I_k	: Indicator k
R_k	: Requirement k
C_k	: Criterion k
α_i	: Requirements weight
β_i	: Criteria weight
γ_i	: Indicators weight
AAC	: autoclaved aerated concrete blocks
EPS	: Expanded polystyrene foam
XPS	: Extruded polystyrene foam
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
V	: Value
V_{Rk}	: Requirement value
V_{Ck}	: Criterion value
V_{Ik}	: Indicator value
R-value	: thermal resistance
BREEAM	: Building Research Establishment Environmental Assessment Method
LEED	: Leadership in Energy and Environmental Design
BEPAC	: Building Environmental Performance Assessment Criteria
CASBEE	: Comprehensive Assessment System for Built Environment Efficiency

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Chapter 1

Introduction

1.1. Introduction

Sustainability is a broad and complex concept, which has grown to be one of the major issues in the construction industry. Over the last three decades, this concept has emerged as a new paradigm in building and construction industries for achieving the sustainable development goal. Whilst, there exists a vast amount of literature on sustainability of buildings, major drawbacks still persist in integrating sustainability issues in building projects. This research therefore attempts to redress this imbalance.

This research is based on the premise that to achieve sustainability in architecture and the construction sector, there is need for a holistic approach for integrating sustainability principles into facade assessment and selection process at different stages of building project.

This chapter describes the research background, aim and objectives, thesis main features, methodology, as well as the thesis organization.

1.2. Research background

Due to the significant economic, environmental and social impacts of the construction industry on society, various sectors of the building industry have put a lot of effort in improving the primarily the environmental performance of buildings (Pitney, 1993; Spence and Mulligan, 1995; Hill and Bowen, 1997; Ofori *et al.*, 2000; Halliday, 2008). The sustainable construction practice aims at establishing an equilibrium among economic, social, and environmental performances in implementing construction projects (Shen *et al.*, 2010) (Fig.1.1.).

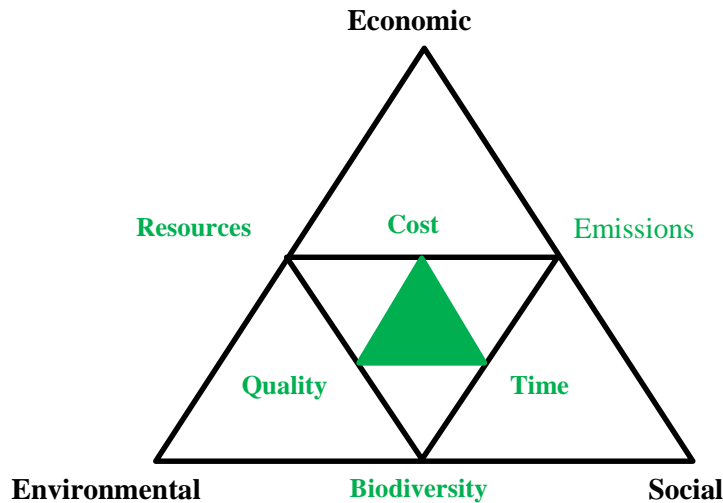


Fig.1.1. The concept of sustainable construction (adapted from Huovila, 2001)

While the majority of the existing literature report on sustainability assessment of buildings as a whole, (Spence and Mulligan, 1995; Ofori and Chan, 1998; Bourdeau, 1999; Myers *et al.*, 2008; Reed *et al.*, 2009; Abidin, 2010), research on the sustainability performance of building independent components (ex., beams, columns, walls, facades) is insufficient. One of the main and largest building's components is facade, which can considerably influence the sustainability performance of the whole building.

1.2.1. Buildings' facades and sustainability

According to the previous literature (Deilmann *et al.*, 1987, Rivard, 1995; Allen, 1997; Emmanuel, 2004; Lee & Tiong, 2007; Gu *et al.*, 2008; Taborianski and Prado, 2012; Aksamija, 2013; Harirchian *et al.*, 2013; Schuetze *et al.*, 2015; Azari and Palomera, 2015; Martabid and Mourgues, 2015; Garmston, 2017; Hartman *et al.*, 2019), facades may contribute to the whole building sustainability through minimizing the negative impacts on the three pillars.

Facades, as the first line of defense against the undesirable external impact, can reduce the level of heat and cooling energy needed in edifices. Facades can also secure inside against outdoor environmental impacts such as pollution, wind, rain, and lighting load among others (Lee and Tiong, 2007; Green Building, 2011); thus, minimizing the environmental impact on both the building and on the environment. According to Stansfield (2001) building sustainability could be achieved through its facade by reducing

environmental impacts on building as well as building impacts on the environment (Fig.1.2.).

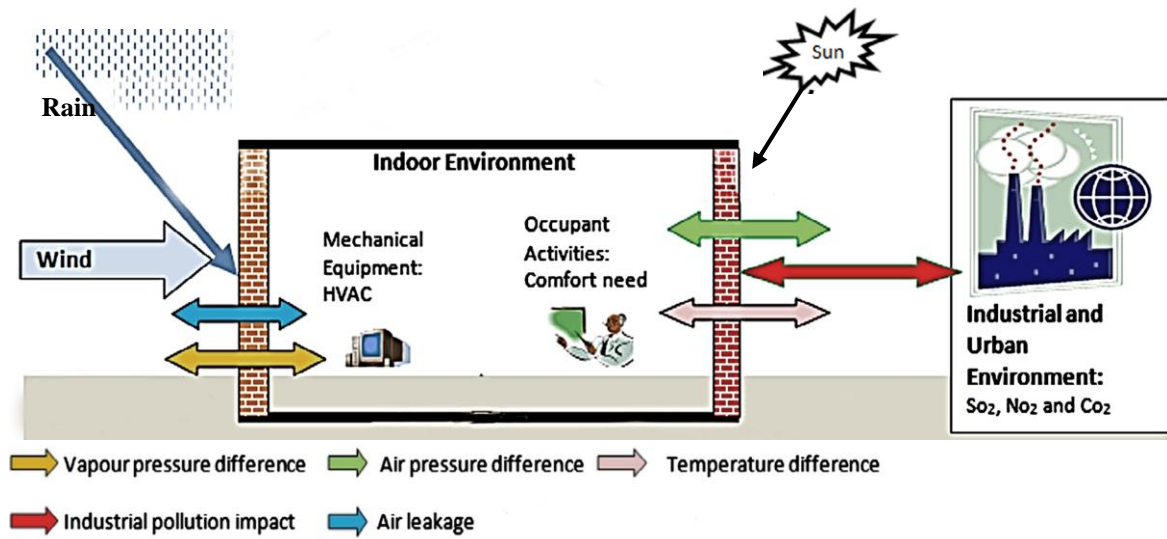


Fig.1.2. Environmental loads on buildings' facades (adapted from Iwaro & Mwashu, 2013)

On the other hand, facades could also have some economic and social effects. Around 25% up to 40% of the total construction cost is related to buildings' facades (Kragh, 2011; Layzell and Ledbetter, 1998; Wigginton and Harris, 2002). Besides, high-performance facade systems can significantly reduce the buildings' energy consumption so that decrease the operating energy cost of buildings. Facades can directly influence the urban landscape and image of city since these establish the character of buildings, towns and cities and all these issues can have positive influence on social attitude (Moughtin *et al.*, 1999; Utaberta *et al.*, 2012; Ghomeshi *et al.*, 2012). Fig. 1.3 summarizes these facades effects.

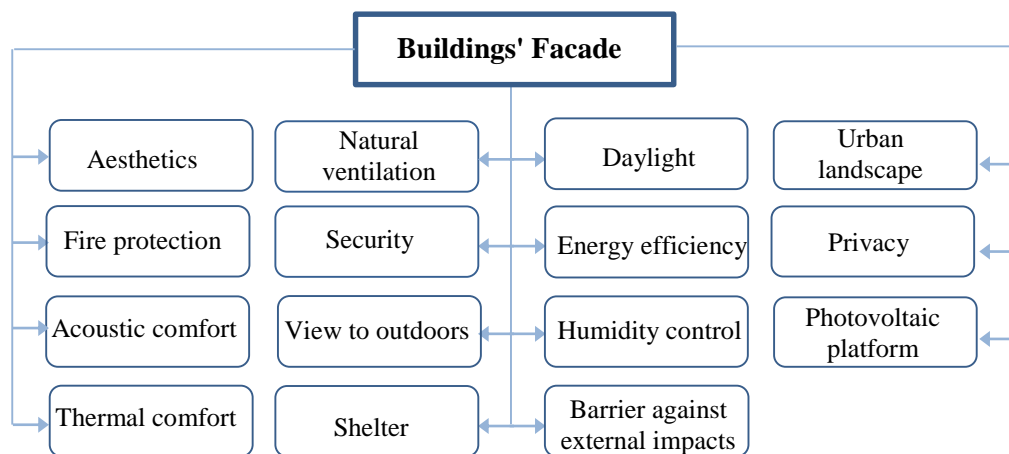


Fig.1.3. Functions of the buildings' façade

Despite the impact of facades on the three pillars of sustainability, most of the existing literature often dismisses all the sustainability indicators that govern the performance of these three pillars (Nadoushani, *et al.*, 2017) or, if considered, these

indicators are rather subjectively measured - especially those associated with the social aspect. This inadequate consideration of indicators may cause sub-optimal facade selection that can adversely affect the forthcoming project phases, causing delays, increased demand for labor in a building project, higher expenditure and poor client satisfaction (Passe and Nelson, 2012).

1.2.2. Decision-making processes for sustainable facades

Recently, growing number of commercial options and construction methods available for facades make it difficult, even challenging, to choose an optimal facade system. Each of these alternatives has its own economic, environmental and technical performances. Moreover, these difficulties increase due to the uncertainties caused by the numerous stakeholders involved, the indirect costs and other requirements that vary depending on each specific case (Jin & Overend, 2010). According to Singhaputtangkul *et al.* (2013), the success of a project is tied with an appropriate selection of the facade system that can satisfy the requirements of all the involved stakeholders.

Respectively, in order to establish an effective decision-making procedure for facades, it is important to take into account the economic, climatic and social conditions so that the requirements from the client - architectural, functional, comfort, etc. - can be fulfilled (Zavadskas *et al.*, 2013). Therefore, this is a multi-criteria decision problem.

On the other hand, the clients' preferences have to be considered into the decision-making process to guarantee the project success. However, these preferences might not always be aligned with those of other stakeholders such as the designer or contractor. Therefore, this is a multi-participant decision problem.

In terms of sustainability, this multi-criteria and multi-participant decision becomes a challenge when the most optimal facade system has to be selected. In this sense, in order to find out and evaluate the most sustainable facade alternative, decision makers should take into account all crucial sustainability issues as well as satisfaction of the involved stakeholders.

According to previous studies (Pohekar & Ramachandran, 2004; Opricovic & Tzeng, 2007; Zavadskas *et al.*, 2008; Simanaviciene and Ustinovicius, 2012; Triantaphyllou, 2000; Hopfe *et al.*, 2013; Balali *et al.*, 2014a,b; Pons *et al.*, 2016; Alhumaid *et al.*, 2018; Moghtadernejad *et al.*, 2018; Hosseini *et al.*, 2019), most of the existing tools have not fulfilled all the aforementioned requirements. Some of those consist of indicators difficult to be quantified and assessed and, in some, cases even misinterpreted. In addition, almost none of those take into account the stakeholders' satisfaction in the assessment and selection process of facade systems. These tools and the applicability in assessing the sustainability of facades are studied in depth in Chapter 2.

Moreover, most of the existing sustainability assessment rating tools have some drawbacks and limitations being as follows:

- These consider the wholeness of the building, these not being focused on specific components such as facade as one of the most important components of buildings.
- In these tools, the overall performance score is obtained by aggregation of all the points awarded to each criterion. In fact, all criteria are assumed to be of equal

importance, while the reality is that the relative importance - weights - of each criterion can differ according the economic situation of the country, cultural aspects and sensitivity towards environmental aspects (Akadiri, 2011). This simplification may restrict the existing methods in achieving sustainability goals.

- Most of the existing building assessment methods tend to be as comprehensive as possible. For example, the rating tools BREEAM comprises 49 criteria, the BEPAC comprises 30 criteria and GBTool comprises 120 criteria (Cole & Larsson, 1999). This approach has led to complex systems which require large quantities of detailed information to be assembled and analyzed. This may affect their usefulness in providing a clear direction for assessments. In fact, there should be a balance between completeness in the coverage and simplicity of use in existing assessment tools in order to be effective, representative and efficient in its implementation.
- The building assessment methods mainly focus on several issues including resource consumption (such as energy, land, water and materials), environmental loading, indoor comfort and longevity. Some assessment rating tools do not include financial consideration in the evaluation framework (Shi & Xie 2009), while cost minimizing is fundamental as one of the main principles of building project because a project may be environmentally friendly but very expensive to build. Therefore, environmental and financial aspects should be considered in parallel as parts of the evaluation framework when making decisions (Langdon, 2007; Ding, 2008). The previously mentioned social pillar of sustainability should be considered as well.

1.3. Aims and objectives

Previous studies have indicated that currently, there is a lack for comprehensive multi-criteria and multi-participant sustainability assessment tools for buildings' facades.

In this respect, the **main objective** of this research is to provide a platform to decision-makers for the assessment and selection process of buildings' facades by considering the representative indicators that govern the sustainability performance of this component.

This platform should be flexible and adaptable to any locations and conditions while guaranteeing sustainable solutions and considering the stakeholders' preferences.

To achieve the research aim, the following **specific objectives** were established:

1. To identify the most appropriate sustainability assessment tool for facades by means of an exhaustive investigation of the existing literature.
2. To identify and quantify the main sustainability indicators relevant to buildings' facades for modelling decision-making process in building projects.
3. To develop a new comprehensive approach which enables decision-makers to: 1) accurately and objectively assess the sustainability of the facades by considering all the important sustainability requirements and indicators, 2) consider the satisfaction level of all stakeholders involved in the decision making procedure,

in order to select the most optimal facade system, 3) take into account the weight - importance - of each indicator in the assessment procedure.

4. To validate the effectiveness, feasibility and accuracy of the proposed approach by means of case studies.

1.4. Research methodology

This study is generally organized into two main parts: Descriptive and Operational, as shown in Fig. 1.4.

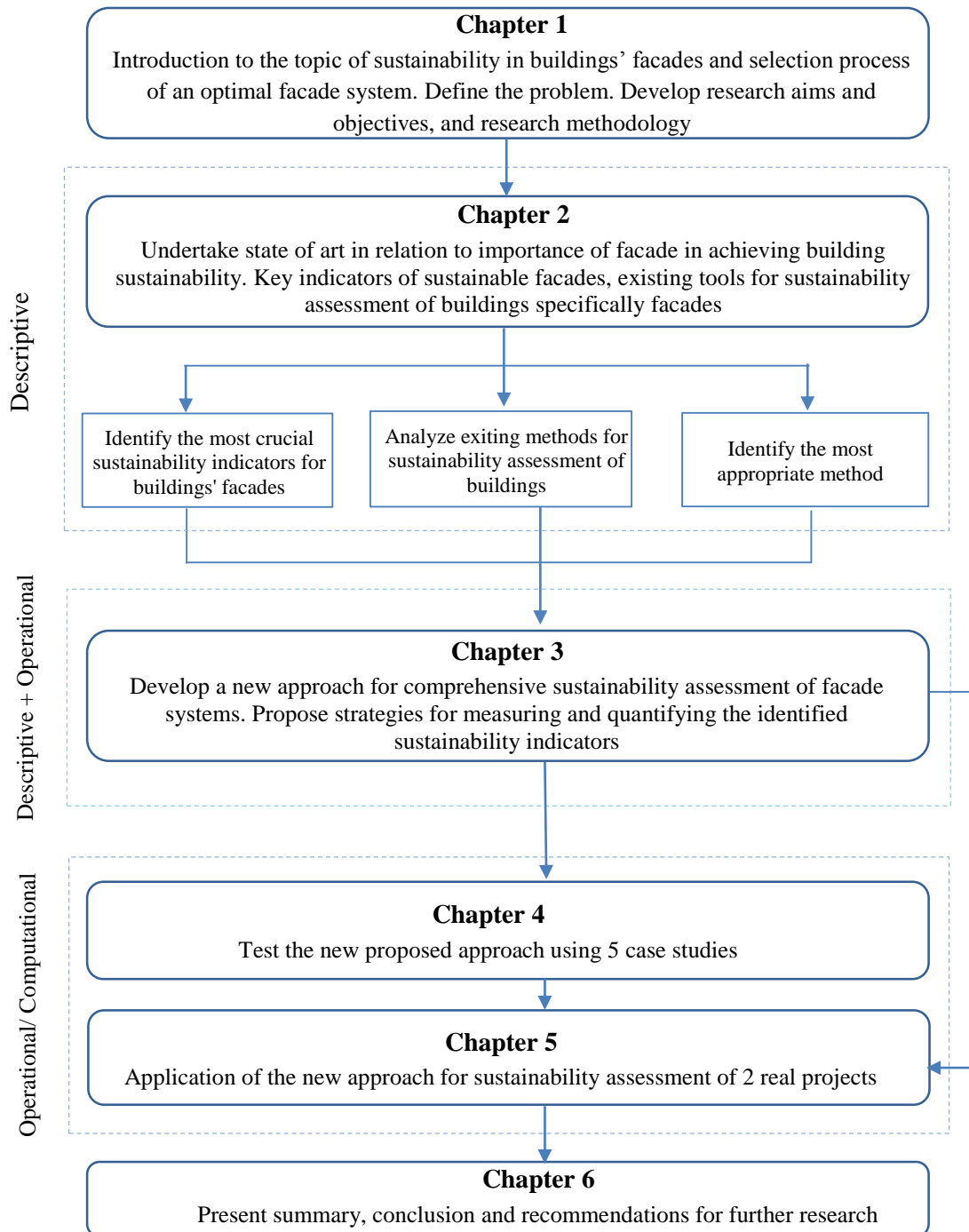


Fig. 1.4. Thesis organization

The descriptive section includes Chapter 2 and some parts of Chapter 3, as shown in Fig.1.4. This section mainly reviews and analyses the previous literature in order to achieve the research objectives, specifically the first and second objectives. The review of the literature has been extensively undertaken throughout the study to build up a solid theoretical base for the research area and a foundation for addressing the problems and achieving the research objectives. This review helped to identify gaps in knowledge and formed the basis for developing this thesis aim and objectives. Information have been sought from various sources including academic publications, university databases, internet, seminars, workshops and notes from attended conferences.

The operational section includes Chapter 4, Chapter 5 and some parts of Chapter 3 as shown in Fig.1.4. In this section, the new approach will be developed and applied for case studies in order to achieve the research objectives. The data collection method is based on questionnaire surveys, seminars, national and international environmental and economic databases, national technical building codes, obtained data from architectural companies as well as academic publications - those already studied in the literature review as well as other publications more related to this operational part.

1.5. Structure of the thesis

The thesis structure is presented in Fig.1.4 and the specific chapter descriptions are as follows:

Chapter 1

This chapter introduces the research background. It explains why this research is important and identifies the exiting problem and gaps. The aim and objectives of the study as well as the methodology are also highlighted.

Chapter 2

This chapter builds a theoretical foundation for the research by reviewing literature and previous research. It provides information and argument for the importance of incorporating sustainability principles in the design, assessment and selection procedure of facades. It presents the most important sustainability indicators for facades. This chapter also critically reviews and analyzes the previous methods applied for sustainability assessment of buildings, particularly the facades.

Chapter 3

This chapter proposes a new approach for comprehensive sustainability assessment of facade systems that attempts to cover all the drawbacks, problems and gaps identified in the previous chapters. This approach is based on MIVES (Integrated Value Model for Sustainability Assessment), which enables decision-makers to objectively assess the sustainability of facades with considering all the indicators belonging to the three pillars of sustainability as well as well as stakeholders' needs in the decision-making process.

Chapter 4

This chapter validates the effectiveness, feasibility, workability and accuracy of the new proposed approach by means of the analysis of the five most commonly used residential facade systems in Barcelona, Spain.

Chapter 5

In this section, the application of the novel MIVES-based approach is considered for assessing the sustainability of two real high-performance residential blocks in Barcelona, in order to: 1) prove the applicability of the approach, 2) identify the challenges when facing its application, 3) demonstrate how it enables decision makers to identify the strengths and weakness of facade system from economic, environmental and social points of view to improve the sustainability of facades and/or select the most sustainable ones.

Chapter 6

This chapter considers the specific and general conclusions of all chapters as well as a future perspective, which is expected to be followed in future research projects.

Chapter 2

State-of-the-Art

2.1. Introduction

This chapter is focused on the review and analysis of the existing literature related with the research. In general, the main questions proposed for this part of the dissertation are:

1. Why it is important to consider sustainability in the assessment and selection process of facades?
2. What are the key indicators of sustainable facades?
3. How previous studies have assessed the sustainability of facades?
4. What is the most suitable method for sustainability assessment of facades?

Taking into account the multifaceted nature of this thesis, the literature review is organized in four sections regarding to the aforementioned 4 questions. The first section, after a brief overview of the sustainability concept, focuses on facades and the impacts that facades have on the sustainability performance of the whole building (question 1).

The second section identifies the indicators that are crucial to satisfy for the design and construction of sustainable facades. To this end, through an extensive overview of previous literature, the most important indicators that sustainable facades ought to achieve will be extracted and presented (question 2). The third section presents the tools that have been already applied for assessing the sustainability of facades and determines the weaknesses and strengths of these tools (question 3). The last part assesses other possible methods - in addition to the previously-used tools compared in the third section - and presents the most suitable method for sustainability assessment of facade systems (question 4). Fig. 2.1 presents the general strategy followed in this chapter to review relevant previous studies.

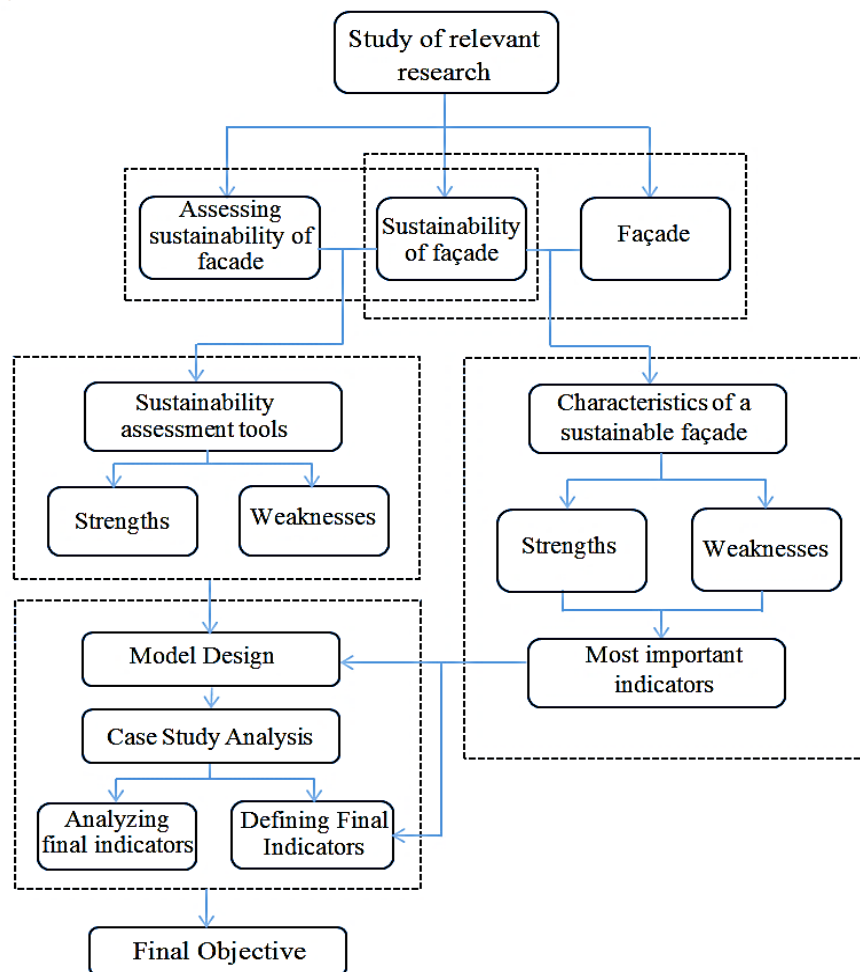


Fig.2.1. General strategy for literature review in this study

2.2. Considerations on the sustainability of the buildings' facades

2.2.1. The concept of sustainable development

The sustainable development concept known at present rose in the 1980s as a reaction to the destructive social and environmental impacts of the predominant approach to “economic growth”. The idea originated within the environmental movement. Perhaps, this concept has been firstly found in World Conservation Strategy jointly presented by the UN Environment Program, the World Wildlife Fund and the International Union for

conservation of nature and natural Resources (UNEP/WWF/IUCNNR, 1980). This early formulation emphasized that:

For development to be sustainable, it must take account of social and ecological factors, as well as economic ones; of the living and non-living resource base; and of the long-term as well as the short-term advantages and disadvantages of alternative actions (UNEP/WWF/IUCNNR, 1980 cited in Akadiri, 2011).

It includes three main priorities: the preservation of ecological processes; the sustainable use of resources; and the maintenance of genetic diversity. However, this concept gained a wider recognition only after the World Commission on Environment and development (WCED) which published its report “our common future” (also known as “the Brundtland Report”) in 1987. In this report, sustainable development was defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987). Besides, in order to change unsustainable trends, the WCED proposed the following seven actions to guarantee a good quality of life for people around the world (WCED, 1987):

- restore growth;
- change the quality of growth;
- meet essential needs and aspirations for jobs, food, energy, water and sanitation;
- ensure a sustainable level of population;
- protect and strengthen the resource base;
- reorient technology and manage risk; and
- include and combine environment and economic considerations in decision-making.

The main goal is to avoid environmental and/or social meltdown, thus ‘sustaining’ the existence of not only modern society, but the future generation.

Since the Brundtland report, a whole series of events and initiatives have resulted in the current wide-ranging interpretation of sustainable development. Undoubtedly, one of the key events was the United Nations Conference on environment and Development, known as the earth summit, held in Rio de Janeiro in 1992. At the earth summit, representatives of nearly 180 countries endorsed the Rio Declaration on Environment and Development which set out 27 principles supporting sustainable development. The assembled leaders also signed the Framework convention on Climate Change, the Convention on Biological Diversity, and the forest principles. They also agreed a global plan of action, Agenda 21, designed to deliver a more sustainable pattern of development and recommended that all countries should produce national sustainable development strategies (Akadiri, 2011).

Ten years later, at the World Summit on Sustainable Development (WSSD) held in Johannesburg in September 2002, representatives of 183 countries reaffirmed sustainable development as a key element of the international agenda. The governments agreed to a wide range of commitments and priorities for actions to meet sustainable development goals, including (WSSD, 2002):

- halving the proportion of people living in poverty by 2015;
- supporting and promoting the development of a 10-year framework of programs to accelerate the shift towards sustainable consumption and production;
- diversifying energy supply and significantly growing the global share of renewable energy sources in order to increase its contribution to total energy supply;
- improving access to affordable, economically viable, socially acceptable and environmentally sound energy services and resources;
- facilitating the development and dissemination of energy efficiency and energy conservation technologies, including the promotion of research and development;
- establishing water resource management and water efficiency plans by 2005; and
- achieving significant reduction in the current rate of loss of biological diversity by 2010.

2.2.1.1. Mapping the sustainable development

An ongoing debate about what sustainability truly means has created a plethora of definitions over the last three decades. Nonetheless, it has often been mentioned that there is no common understanding either on the definition of sustainable development or on the possible measures needed to be taken to achieve it (Gray and Bebbington, 2001; Bebbington, 2001; Livesey and Kearins, 2002; Islam *et al.*, 2003; Robinson, 2004). Previous research estimated the total numbers of definitions are in the range of 100 – 200 (Pezzey, 1989; Hill, 1998; Parkin, 2000; Moffatt *et al.*, 2001).

A wide variety of groups - ranging from businesses to national governments to international organization - have adopted the concept and given it their own interpretations.

Hill and Bowen (1997) define sustainable development as development that decrease potential negative environmental impacts while considering social needs. Postle (1998) goes further, suggesting that sustainability, as a concept, has a far wider reach than the environment, encompassing a whole range of social and ethical factors such as employment, social welfare, culture, and infrastructure as well as the economy. In other words, sustainability includes all the factors contributing to the long-term societal benefit to be taken into account in decision making. Lautso *et al.*, (2004) and Ding (2005) also support the idea that this concept promotes the balance of economic, social and ecological systems for any development. It means that sustainable development deals with the concepts of environment, futurity and equity, with the emphasis that the welfare of future generation must be considered in any decision-making process.

Furthermore, the International Institute of Sustainable Development (IISD) stipulates that sustainable development should also simultaneously consider the improvement of the economy. Beder (1996), Berggren (1999), Stigson (1999) and Rohrer (2001) all discuss the concept of sustainable development in the context of considering economic growth in addition to the social and environmental dimensions. Economic growth, with an emphasis on issues such as financial stability and material welfare creation, is the

primary objective for any government in order to guarantee rising standards of living and increase the capacity of providing goods and services to satisfy humans' needs.

The challenges of understanding what this idea of sustainable development may mean, and how people can work towards it, are evident in a brief analysis of the definition of sustainable development provided by the previously mentioned WCED commission. Moreover, the substantial challenges of operationalizing the concept of sustainable development were clear in the report of the WCED, back in 1987. Table 2.1 displays the critical objectives and the necessary conditions for sustainable development in the future identified by this commission.

Table 2.1. WCED critical objectives and necessary conditions for sustainable development (WCDE, 1987 cited in Akadiri, 2011, p.64)

Critical objectives
<ul style="list-style-type: none">▪ Reviving growth.▪ Changing the quality of growth.▪ Meeting essential needs for jobs, food, energy, water and sanitation.▪ Ensuring a sustainable level of population.▪ Conserving and enhancing the resource base.▪ Re-orientating technology and managing risk.▪ Merging environment and economics in decision-making.
Pursuit of sustainable development requires
<ul style="list-style-type: none">▪ A political system that secures effective citizen participation in decision-making.▪ An economic system that provides for solutions for tensions arising from disharmonious development.▪ A production system that respects the obligation to preserve the ecological base for development.▪ A technological system that fosters sustainable patterns of trade and finance.▪ An international system that fosters sustainable patterns of trade and finance.▪ An administrative system that is flexible and has the capacity for self-correction.

Note. Reprinted from " Development of a multi-criteria approach for the selection of sustainable materials for building projects", by Akadiri, O., 2011, Master thesis: University of Wolverhampton,UK.

Despite various perceptions about the precise meaning and the possible interpretation of the term 'sustainable development', it is widely accepted that a sustainable development must fulfill ecological, economic, social and ethical aspects of reality. It is also crucial that this development incorporates economics and ecology at urban planning level (Tisdell, 1993; Van Pelt, 1994; Spence and Mulligan, 1995; Berggren 1999; Stigson 1999). The divergence of opinion relating to the term proves that sustainability is such a broad idea that a single definition cannot adequately capture all meanings of the concept. While there is little consensus about a definition for sustainable development, there are certainly commonly accepted principles that can be used to guide the process of development (du Plessis, 1999). Sustainable development is a continuous process of dynamic balance instead of a fixed destination that must be reached at a certain time (Berggren, 1999; du Plessis, 1999).

To sum up, the concept of sustainable development must consist on the examination of economic, social and environmental aspects of a development. In addition, sustainable development consists of multiple facets of issues that concern people's present and future, instead of a one-dimensional development. This research relies on this complex concept

of sustainable development to develop a new sustainability model for assessing the sustainability of facade systems and selecting the most optimal one. This thesis considers that Brundtland report, although it gives an open definition, provides enough explanation of what sustainable development means. Moreover, to find a precise definition of sustainable development that satisfies all needs may be difficult. In this sense, this thesis considers more important to find ways to achieve sustainable goals to maintain and conserve the environment, so that future generations will not be disadvantaged. This doctoral dissertation considers also difficult to reach a definition that applies to all sectors; therefore, this thesis prioritizes to define the concept of sustainable development with particular reference to each sector and, in this specific case, to the construction sector.

2.2.1.2. Sustainable construction practices

Over the last three decades, the sustainability concept has emerged as a new framework in building and construction industries for achieving the sustainable development goal (Bragança *et al.*, 2010). Sustainable construction is considered as a way for the construction industry to move towards achieving sustainable development taking into account environmental, socio and economic issues (Pitney, 1993; Spence and Mulligan, 1995; Hill and Bowen, 1997; Ofori and Chan, 1998; Bourdeau, 1999; Ofori *et al.*, 2000; Ding, 2008; Abidin, 2010).

Within the broader context of sustainable development, construction has a prominent role. In fact, Buildings represent nearly 30% of final energy consumption, globally (IEA, 2011) and in the European Union (EU), these are responsible for up to 40% of the final total energy consumption (27% residential, 13% non-residential) and 35% of the associated carbon dioxide (CO₂) emissions (20% residential, 15% non-residential) (Eurostat databases, 2010). It also counts for a major share of the world's economy up to 45% including 6.5% and 9.5% of UK's and Australia's economy (Rhodes, 2015).

Such significant economic and environmental impacts of construction on society have led to a great deal of effort in various sectors of the building industry to improve the sustainability of buildings (Sadineni *et al.*, 2011). The promotion of sustainable construction practice is to pursue a balance among economic, social, and environmental performance in implementing construction projects (Shen *et al.*, 2010). In general, sustainable construction practice aims to minimize the negative impacts socially, economically and environmentally. In this case, various solutions have been proposed in the process of implementing construction projects that involve less harm to the environment - i.e. prevention of waste production (Ruggieri *et al.*, 2009); increased reuse of waste in the production of construction material - i.e. waste management (Asokan *et al.*, 2009; Tam, 2009); beneficial to the society, and profitable to the company (Tseng, *et al.*, 2009; Turk, 2009; Tam *et al.*, 2007).

The total environmental damage can be significantly reduced if the construction industry takes proper action to improve its environmental performance (Ofori and Chan, 1998; Ball, 2002) and this potential damage has to be analyzed when considering sustainable development (Bourdeau, 1999). According to Hill and Bowen (1997), sustainable construction starts at the planning stage of a building and continues

throughout its life to its eventual deconstruction and recycling of resources to reduce the waste stream associated with demolition.

Principles of Sustainable Construction

Various studies have been carried out (Kibert, 1994; Hill and Bowen, 1997; Robbert, 1995; Graham, 2000; Long, 2001; DETR, 2000; Ding, 2008) in order to enunciate the principles of sustainable construction. A few examples are presented in the table below (table 2.2).

Table 2.2. Principles of sustainable construction

Proposed principles for sustainable construction	References
Social issues: improve the quality of life, provision for social self-determination and cultural diversity, protect and promote human health through a healthy and safe working environment, etc. Economic issues: ensure financial affordability, employment creation, adopt full-cost accounting, and enhance competitiveness, sustainable supply chain management. Biophysical issues: waste management, prudent use of the four generic construction resources (water, energy, material and land), avoid environmental pollution, etc.	Hill and Bowen, 1997
Minimization of resource consumption, maximization of resources reuse, use of renewable and recyclable resources, protection of the natural environment, create a healthy and non-toxic environment, and pursue quality in creating the built environment.	Miyatake, 1996 ; CIB, 1999
Reduction of resources consumption (energy, land, water, materials), reduction of environmental loadings (airborne emissions, solid waste, liquid waste) and improvement in indoor environmental quality (air, thermal, visual and acoustic quality)	Cole & Larsson, 1999
Profitability and competitiveness, customers' and clients' satisfaction, respect and treat stakeholders fairly, enhance and protect the natural environment, and minimize impact on energy consumption and natural resources.	DETR, 2000

Note. adapted from " Development of a multi-criteria approach for the selection of sustainable materials for building projects", by Akadiri, O., 2011, Master thesis: University of Wolverhampton, UK.p.113

These principles can be utilized as a guideline in the process of building development at all levels and within all disciplines to assure that decisions made follow the road of sustainable development.

2.2.2. General overview of facades

The term facade has been originated from the Latin word 'facia' which means timbre, originated from the word 'face' in 14th century and from the French word 'façade' which means face in the 16th century. This word has meant apparent face of everything, what is seen from outside and exterior side or skin of a building. Krier (1992) also defines facade as the most essential architectural element capable of communicating the function and significance of a building.

In this study, facade refers to the vertical building envelope which comprises both opaque and transparent parts, the opaque part accounting for the wall system from exterior to interior layers while the transparent part includes the openings.

Facade through history

The evolution process of facades' form and function goes back to the history of humanity itself. Humans at the early ages discovered the importance of shelters that functioned as an enclosed envelope for protection and security. Then, gradually, suitable materials were identified, and construction skills were developed.

For several thousand years, load-bearing walls in Europe and elsewhere were built of masonry, wood, and/or stone among other materials. These walls were extremely stable and durable due to their size and massiveness and provide modicum of thermal protection through their natural heat storage and thermal insulation capability (Gadelhak, 2009). After the industrial revolution, the mass-production method became dominant in the construction sector. The technological approaches were firstly dominated in the mass-production of iron. Then, the usage of steel, concrete and curtain wall system followed the developing path of the iron as a building material.

An important example of this period was Crystal Palace designed by Joseph Paxton in 1851. This temporary building was constructed from prefabricated structural elements and glass for its exterior surface as shown in Fig. 2.2. All its structural elements and the exterior cover of construction were composed of lightweight, modular elements. The attempt of using glass for exterior surface transformed the massive quality of masonry into the lightweight cover for the enclosed space.

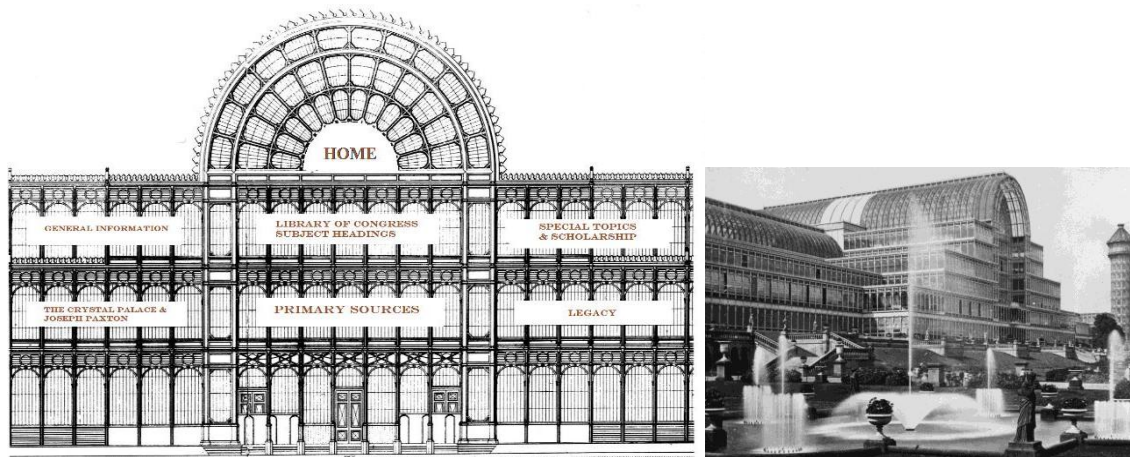


Fig.2.2. [photograph of Crystal Palace designed by Joseph Paxton] retrieved from <https://insidecroydon.com/2019/01/01/the-great-exhibition-of-1851-crystal-palace-museum-jan-15/>

Unlike the traditional buildings of the Renaissance made from heavy masonry, the lightweight materials were assembled on site. Therefore, the ‘construction speed’ was remarkable. In this respect, it was an important development for the designers of the revolutionary time that the basic concern was speed, economy and quality of the end product (Garner *et al.*, 1986).

In addition to iron and steel, concrete had also become to be one of the “expressing elements” in the basic building vocabularies for Modern Movement, especially in the works of Le Corbusier. In his works, the exterior face begins to be differentiated from the reinforced concrete structure of the building. The structure carries its own load by its own concrete columns and beams, while the walls have been freed from their load-bearing function. The independent character of the exterior surface has provided the independency to the disposition of openings on the wall in any size, in any shape and in any location. The Modern Movement started using concrete and glass as free-standing exterior surfaces in dwellings and explored the capacities of these new materials to organize the exterior skin, especially in the buildings that had corporate identity. Then, World War Two had great influence on using new technologies and new materials,

especially glass and metal curtain walls for facades in the Western tradition (Kelly & Johnson, 1998). The physical autonomy of the facades is much more obvious in this system compared to the other technologies. The system is produced as identical units in the dry construction site. Thus, manufacturing and assembly processes are continued in more precision. All these advantages also provide an economic strength in terms of mass production and reduced assembly time in construction (Oesterle *et al.*, 2001).

One of the greatest examples of this skeleton structure and curtain wall facade combination is Seagram Building, which was designed by Ludwig Mies Van der Rohe and constructed in 1954-1958 in New York. Mies used a steel frame on the interior of the curtain wall, but added a second structural facade on the exterior. On the exterior surface of the Seagram Building, there is a false structural system of bronze columns which are used to allude to the steel structure hidden behind it that required fire and durability protection. (Fig.2.3).

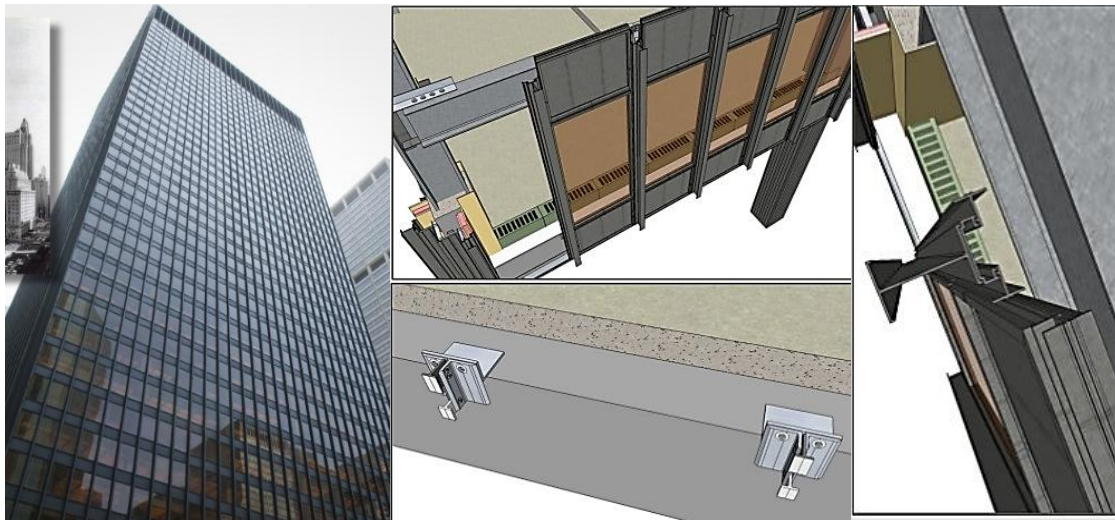


Fig.2.3. [photographs of Seagram building facade details] (2010) retrieved from <https://www.slideshare.net/amraladdin/100421-architectural-history-polimi>

Figure 2.4 shows how the structural column is hidden within the corner of the structure and cladled with the bronze T-brackets to the exterior.

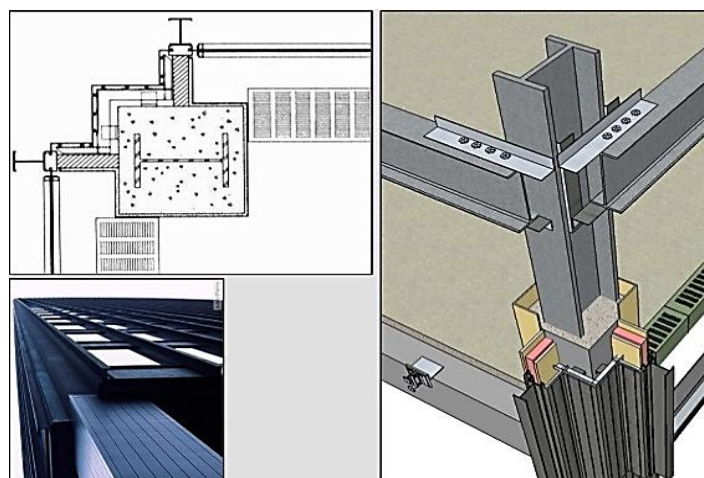


Fig.2.4. [photographs of Seagram Building, corners' detail] (2010) retrieved from <https://www.slideshare.net/amraladdin/100421-architectural-history-polimi>

The notion of 'Postmodernism' was originated as a critique of Modern Movement and to create architecture of "narrative contents". Postmodernism affected mostly the formation of the exterior surfaces with its main principles. This new movement of facades is regarded as representation grounds, which embellishes with historical elements arbitrarily to create an imagistic appearance (Klotz, 1988). The historical styles have begun to be integrated with the new techniques and materials. Thus, the exterior respond of the facade is totally distracted by "conscious ruination of styles and the cannibalization of the architectural form", because traditional usage of historical elements together with "the tendency of the production / consumption cycle" reduces the civic character of the exterior surface in terms of any kind of "consumerism and undermined traditional quality" (Frampton, 1992).

The abovementioned reveals that during different times, from pre-modern to present times, it has been always attempted to enhance the performance of facade systems from different aspects by using new materials and new construction technologies and new styles. This is due in part to the economic, environmental and social impacts of facade on the whole building performance, as will be explained in detail in the following section.

2.2.3. Impacts of facades on buildings sustainability performance

One of the main and largest components of a building is the facade, which can considerably affect the buildings' energy performance. Facade as a linkage between the interior of building and the external environment can decrease the level of heat/cooling energy needed in buildings. Vertical envelopes can protect the interior space against adverse environmental effects such as pollution, wind, rain, humidity, HVAC load and lighting load among others (Lee and Tiong, 2007; Building, 2011). According to Zavadskas *et al.* (2008), great part of the heat loss in building envelope occurs via the facade with a 60% while floor is only 15% and roof is 25%.

Previous studies (Utaberta *et al.*, 2012; Ghomeshi *et al.*, 2012) also indicate that facade plays an important role in urban landscape and image of city since it is always in the public attention and establishes the character of buildings, towns and cities. Therefore, all these can have positive influence on social attitude.

In general, according to Deilmann *et al.*, (1987), facade has four main functions: a) protection, b) linkage between exterior and interior, c) representativity and d) part of urban space.

a) Protection: The primary function of the building envelope is to protect the indoor environment against adverse environmental effects and provide thermal comfort of the inhabitants (Brock, 2005; Leung *et al.*, 2005; Lee & Tiong, 2007). Apart from its protective and regulatory functions, it has to control the penetration of snow, wind, rain and sun to the inside and to contain the desired indoor climate (Quirouette, 1982; Allen, 1997). One of the roles of the facade is the regulation of radiant heat flow from the sun. Interior surfaces of buildings should not get to a state of radiant discomfort. According to Allen (1997), a very cold interior surface will make people chilly being near the wall even if the air in the building is warm to a comfortable level. And, hot interior surface or direct sun light in summer can cause over heating of the body despite the coolness of the interior

air. These kinds of problems can be solved by using external sun shading devices, adequate thermal insulation and thermal breaks, and appropriate selection of glasses. On the other hand, the facade has to prevent water to penetrate into the inside of the building. Water in the form of snow, rain and ice is often driven by wind and can penetrate inside of the cladding or wall not just in a downward direction but in every direction, even upward (Çıkış, 2007).

b) Linkage between exterior and interior: Facades are also responsible to satisfy the psychological needs of the inhabitants. The openings as an important element of facades provide views to the outside and also sufficient natural lighting so as to avoid the feeling of isolation by the building occupants (Leung *et al.*, 2005).

c) Representability: In recent years, after highlighting the significance of public spaces and the value of urban life, facade has doubled in significance. People expect that facades introduce the status of residents of buildings. Vertical envelopes also represent a cultural status of the builders and promoters of each building. In fact, the beauty of a facade can be the best representative of the knowledge and quality of its architects, designers, engineers, etc. It indicates which values the authors have respected in their building (Kheirossadat, 2015).

d) Part of urban space: Aesthetic quality of a facade not only influences the visual quality of a building but also the visual quality of the city. According to various authors (Utaberta *et al.*, 2012; Hui, 2007; Moughtin *et al.*, 1999), facade plays an important role in urban landscape and image of the city. The facade is always in the public attention, so beauty is an inseparable part of it. Moreover, many buildings and groups of buildings are valued as much for their aesthetics as for their functional characteristics. Aesthetics distinguish one building from another, often controversially, and establish the character of buildings, neighborhoods, towns and cities.

In addition to the aforementioned issues that are environmental and social effects, facade may also have some economic impacts. According to Kragh (2011) and Layzell *et al.*, (1998), around 25% of the total construction cost is related to facade and sometimes even up to 40% of a total buildings cost (Wigginton & Harris, 2013). On the other hand, with the selection of an optimal facade system the level of heat/cooling energy needed in buildings could decrease significantly and it may directly affect the energy cost during operation phase.

According to the aforementioned social, economic and environmental impacts of facade, it can be stated that selection of an optimal facade system can considerably affect the whole building performance. In other words, a sustainable facade can significantly improve the total building sustainability through minimizing the negative impacts of sustainability requirements (social, economic and environmental).

In this respect, in the following section, the most crucial indicators that a sustainable facade must fulfill will be determined through an extensive review of previous literature.

2.3. Review of previous studies on sustainability of facades

Over the last three decades, a great deal of effort has been made in various sectors of the construction industry to improve the sustainability of buildings (Sadineni *et al.*, 2011).

Respectively, in the construction sector, many studies have focused on this issue (Segnestam *et al.*, 2003; Dasgupta, 2007; Myers *et al.*, 2008; Sobotka and Rolak, 2009; Reed *et al.*, 2009).

Although there exists a vast amount of literature on sustainability of buildings, there is still a lack of study about sustainability assessment of building components (ex., beams, columns, walls, facades) capable of accounting for the three aspects of sustainability. One of the main and largest components is facade, which can have considerable impact on the sustainability performance of the whole building as explained in section 2.2.3.

In the next section, the existing literature on sustainability of buildings' facades will be reviewed and analyzed in order to identify the strengths and weaknesses as well as the commonly-used indicators for sustainability assessment of facades.

2.3.1. Identification of sustainability indicators for buildings' facades: Review

A sustainable facade should cover the fundamental principles of sustainable development concept. Therefore, it could be stated that designing and building of a sustainable facade is a process that should meet optimized integration of the three main vertexes of the sustainability concept (Fig.2.5.). These three main vertexes are the sustainability requirements: (1) economic, (2) social and (3) environmental and each of the three requirements also includes some criteria and indicators. To achieve sustainability, the negative impacts of these requirements must be minimized.

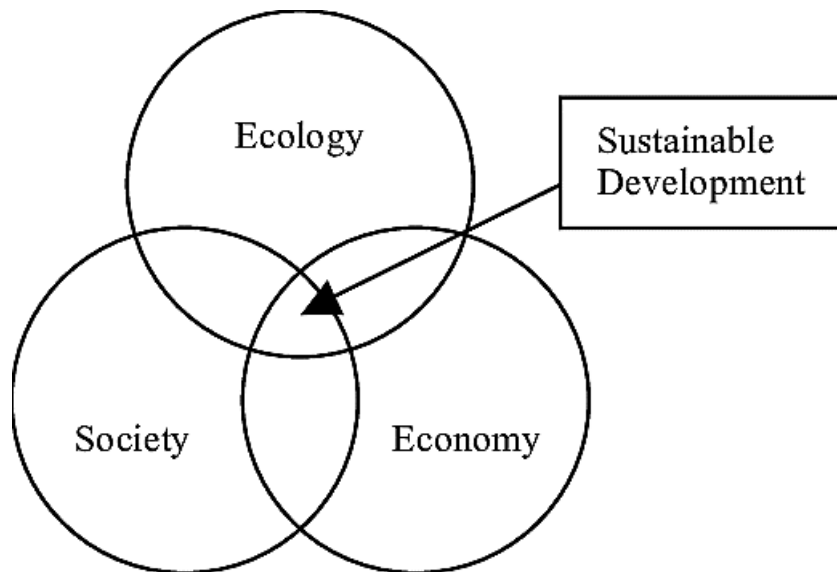


Fig.2. 5.Main requirements of sustainable facades.

As mentioned above, there have been few research projects focusing on what the concept sustainable facade means or identifying all required criteria for the selection of sustainable facade systems.

Table 2.3 summarizes in chronological order the main previous technical literature focusing on the sustainability performance of facades or its components (opaque part /openings). This table also presents 22 sustainability indicators that the author defined relying on the state of the art and seminars with experts. Table 2.3 also shows which of

these 22 indicators were analyzed in each of the around 100 studies from this literature review. The nine studies highlighted in grey are the ones that study the whole facade system, including both opaque and opening parts.

According to Table 2.3, since 2007, the attention on sustainability performance of facades has increased considerably. Nevertheless, most of these projects primarily focus on economic and environmental indicators

Table 2.3. Literature on the sustainability performance of facade systems: summary.

Authors		Criteria																					
		C1. Construction Cost (material & installation cost)	C2. Maintenance Cost	C3. Demolition/ disassembly Cost	C4. Reusability/ recyclability Potential	C5. Waste	C6. Environmental Impact (energy consumption(CO2))	C7. Water Consumption	C8. Suitability To Climate	C9. thermal performance	C10. Material Quality	C11. Moisture Resistance	C12. resistance to decay	C13. Fire Safety	C14. Flexibility	C15. Ease Of Construction (construction speed/ time)	C16. Durability Of The System	C17. acoustic performance	C18. Daylight	C19. Indoor Air Quality	C20. Aesthetics	C21. Harmony With Surrounding	C22. Risk For Labors
1995	Rivard <i>et al.</i> [112]																						
1998	Hassanain & Harkness																						
2000	Bouchlaghem [113]																						
2002	Campante&Paschoal																						
2003	Warren [115]																						
2004	Emmanuel [116]																						
	Oral <i>et al.</i> [117]																						
	Unver <i>et al.</i> [118]																						
	Kolokotroni <i>et al.</i> [119]																						
2005	Leung <i>et al.</i> [121]																						
	Brock, L. [122]																						
	Hien <i>et al.</i> [120]																						
	Wang <i>et al.</i> [123]																						
	Haase & Amato[124]																						
2006	Manioglu & Yilmaza (a)																						
	Manioglu & Yilmaz (b)																						
	Liping & Hien																						
2007	Horner <i>et al.</i> [128]																						
	Wang <i>et al.</i> [129]																						
	Avellaneda <i>et al.</i> [130]																						
	Çıkış [131]																						
	Wong Wan Sie [132]																						
	Brunoro [133]																						
2008	Zavadskas <i>et al.</i> [10]																						
	Yu <i>et al.</i> [134]																						
	Yang <i>et al.</i> [135]																						
	Høseggen <i>et al.</i> [136]																						
	Radhi [137]																						
2009	Yu <i>et al.</i> [138]																						
	Pulselli <i>et al.</i> [139]																						
	Kahhat <i>et al.</i> [35]																						
	Turskis <i>et al.</i> [47]																						
	Ochoa and Capeluto																						

Authors		Criteria																					
		C1. Construction Cost (material & installation cost)	C2. Maintenance Cost	C3. Demolition / disassembly Cost	C4. Reusability/ recyclability Potential	C5. Waste	C6. Environmental Impact (energy consumption/ CO2)	C7. Water Consumption	C8. Suitability To Climate	C9. thermal performance	C10. Material Quality	C11. Moisture Resistance	C12. resistance to decay	C13. Fire Safety	C14. Flexibility	C15. Ease Of Construction (construction speed / time)	C16. Durability Of The System	C17. acoustic performance	C18. Daylight	C19. Indoor Air Quality	C20. Aesthetics	C21. Harmony With Surrounding	C22. Risk For Labors
2010	Zheng <i>et al.</i> [141]																						
	Hashemi <i>et al.</i> [142]																						
	Frenette <i>et al.</i> [44]																						
	Sozer [143]																						
	Su & Zhang[144]																						
	Šaparauskas <i>et al.</i> [46]																						
	Ebbert [145]																						
	Chua And Chou [146]																						
2011	Ogwezi <i>et al.</i> [147]																						
	Mora <i>et al.</i> [148]																						
	Kim [149]																						
	Pellegrino <i>et al.</i> [150]																						
	Ottel� <i>et al.</i> [151]																						
	Oliveira and Melhado																						
	Singhaputtangkul <i>et al.</i>																						
	Jin <i>et al.</i> [154]																						
	Sheweka & Magdy[155]																						
	Mwasha <i>et al.</i> [156]																						
2012	Ghameshi <i>et al.</i> [22]																						
	Haggag <i>et al.</i> [157]																						
	H�kkinen [77]																						
	Orondo & Bedoya [158]																						
	Stazi <i>et al.</i> [159]																						
	Taborianski & Prado																						
	Monteiro and Freire [33]																						
	Garmston <i>et al.</i> [161]																						
	2013	Iwano & Mwasha [38]																					
		Eren & Erturan[162]																					
Ghameshi & Jusan [163]																							
Ritzen <i>et al.</i> [164]																							
Granadeiro <i>et al.</i> [165]																							
Perini & Rosasco [166]																							
Harirchian <i>et al.</i> [167]																							
Zavadskas <i>et al.</i> [42]																							
Singhaputtangkul <i>et al.</i>																							
2014		Cetiner & Edis [36]																					
	Saberi [168]																						
	Alshamrani & Alkass																						
	Sief[170]																						
	Azari [32]																						
	Islam <i>et al.</i> [171]																						
	Ksi�zek <i>et al.</i> [172]																						
	Barecka <i>et al.</i> [173]																						
	Broun <i>et al.</i> [174]																						

Authors		C1. Construction Cost (material & installation cost)	C2. Maintenance Cost	C3. Demolition / disassembly Cost	C4. Reusability/ recyclability Potential	C5. Waste	C6. Environmental Impact (energy consumption/CO2)	C7. Water Consumption	C8. Suitability To Climate	C9. thermal performance	C10. Material Quality	C11. Moisture Resistance	C12. resistance to decay	C13. Fire Safety	C14. Flexibility	C15. Ease Of Construction (construction speed / time)	C16. Durability Of The System	C17. acoustic performance	C18. Daylight	C19. Indoor Air Quality	C20. Aesthetics	C21. Harmony With Surrounding	C22. Risk For Labors
	Markelj <i>et al.</i> [41]																						
	Iwano <i>et al.</i> [175]																						
	Iwano <i>et al.</i> [176]																						
2015	Kassem and Mitchell																						
	Han <i>et al.</i> [178]																						
	Aksamija [179]																						
	Alshamrani[180]																						
	Schuetze <i>et al.</i> [181]																						
	Martabid & Mourgues																						
	Kanniyapana <i>et al.</i> [182]																						
	Crutchik [47]																						
	2016	Friedrich & Luible [52]																					
Kovacic <i>et al.</i> [48]																							
Silva <i>et al.</i> [183]																							
Ahmed <i>et al.</i> [184]																							
Sierra-Pérez <i>et al.</i> [185]																							
Rochikashvili & Bongaerts																							
2017	Garmston [187]																						
	Udawatha & Halwatura																						
	Nadoushani <i>et al.</i> [23]																						
2018	Saleem <i>et al.</i> [188]																						
	Moghtadernejad <i>et al.</i>																						
2019	Hartman <i>et al.</i> [189]																						

Through this holistic overview of around 100 studies about the sustainability performance of facades (Table 2.3), it can be stated that 60% of the studies have focused on environmental criteria by evaluating the life cycle environmental impact of different facade systems. Aksamija (2013) describes the environmental characteristics of sustainable facades as: (1) heat storage possibility; (2) avoiding heat transfer from exterior to interior; (3) avoiding moisture transfer through the facade; and (4) allowing natural ventilation through the facade. Kim (2011) showed that glass curtain walls have a considerably higher environmental impact than transparent composite facade systems. Han *et al.*, (2015) indicated that ceramic facade panels have better environmental performance than typical curtain wall system, i.e. glass and aluminum. Taborianski and Prado (2012) reported that among the various facade alternatives investigated in that study, the highest and lowest CO₂ emissions were associated with structural glazing with uncolored glass and brickwork with mortar coating facade systems, respectively. Ottele *et al.*, (2011) showed that in Mediterranean climate, the energy saving benefit of green facades is roughly twice more than that of conventional European brick facades. There are also various similar comparative studies that have analyzed different types of exterior walls (Azari and Palomera, 2015; Azari, 2014; Monteiro and Freire, 2012). Ingrao *et al.*,

(2016) proved that ventilated facade systems have higher environmental performance compared to the standard wall compositions through environmental impact assessment of four wall systems. (Fig.2.6)

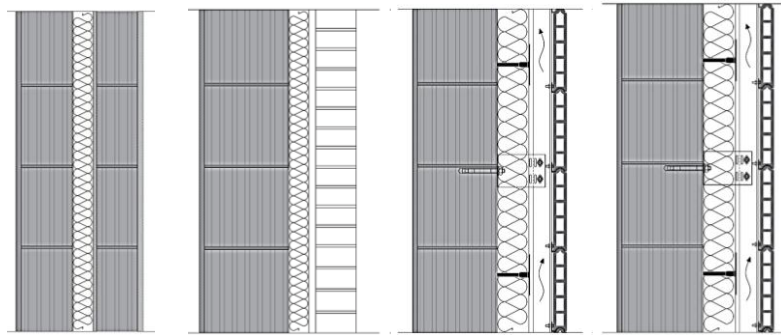


Fig .2.6. The four wall systems studied by Ingaro *et al.*, (2016)

Kahhat *et al.*, (2009) also applied ATHENA, a life-cycle assessment tool, to compare different wall systems for a residential building and concluded that, in order to select the best wall system, overall life-cycle environmental impacts should be considered rather than individual phases of environmental impacts.

In addition, 30% of these research projects have attempted to consider both economic and environmental impacts of different facade systems aiming at providing a more holistic sustainability assessment (Gu *et al.*, 2008; Cetiner and Edis, 2014; Iwaro and Mwashu, 2013). Zavadskas *et al.*, (2008) selected the effective dwelling house walls based on wall durability, thermal transmittance, costs, weight, and duration. Chua and Chou (2010) considered energy efficiency and cost savings as the main criteria in selecting facade systems.

Meanwhile, as indicated in Table 2.3, only 10% of the available literature integrated the economic, environmental and social impacts of facades. In fact, despite the emphasis on selection of sustainable facades, the available literature has focused mainly on accounting for environmental and/or economic impacts of facades, overlooking the third important component of sustainability, i.e. social impacts, as well as the tradeoff between social impacts and environmental and economic impacts. According to Martabid and Mourgues (2015), inadequate consideration of criteria may lead to the selection of suboptimal facade systems that can have adverse impact on the subsequent project phases, causing delays, increased expenses, increased manpower requirements for a building project, and poor client satisfaction.

By realizing this issue, several attempts have been made to develop a list of major economic, social and environmental sustainability criteria for the selection of facade and envelope systems. For instance, Singhaputtangkul *et al.*, (2013) carried out a more comprehensive research and identified 18 criteria for achieving sustainability and buildability in exterior wall cladding materials in Singapore. Martabid and Mourgues (2015) also identified eight criteria as the most commonly considered factors in Chilean practice.

As previously explained and indicated in Fig. 2.7, the most recurrent criteria have been identified through reviewing the previous literature as well as the frequency in which each criterion has been considered in these studies.

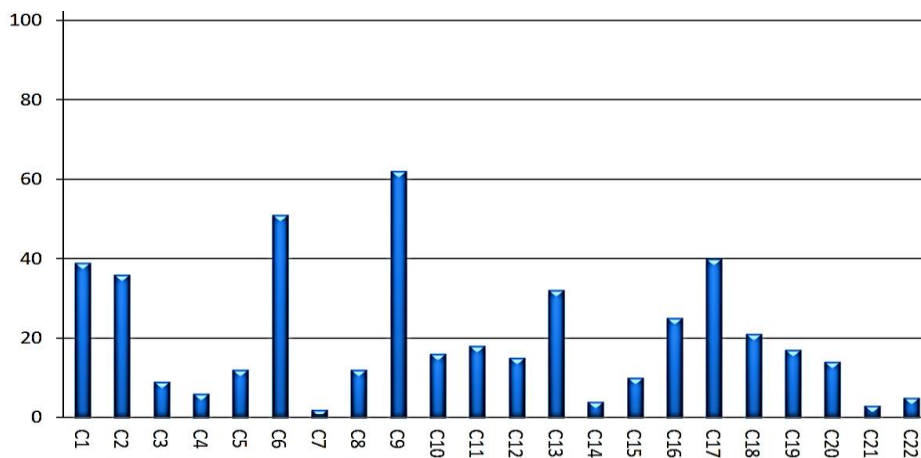


Fig.2.7. Frequency of considering each criterion in the studied technical literature.

According to Fig. 2.7, the criteria included in more studies are thermal performance - 62 studies - and environmental impact - 51 studies -, both related to the environmental aspect. Construction and maintenance cost are also frequently considered; these being related to economic requirements. Noise, which can be seen as a social (users' comfort), is often included into analyses in the economic impact (cost of materials and thickness to guarantee a certain noise damping level). The criteria less frequently taken into account in studies are those related to social aspects: flexibility, aesthetics, harmony with surrounding, risk for labors and labor availability. It can also be stated that the end-of-life stage of buildings' facades has been not included in most of the studies.

In order to assess the sustainability of facades, the present dissertation considers that firstly, the most crucial environmental, economic and social indicators of a sustainable facade have to be defined. In this sense, this section mainly focused on identifying these main indicators for sustainable facades. In the next section, previously-used methods applied for the sustainability assessment of facades are going to be studied and discussed.

2.4. Methods for sustainability assessment of facades

According to Markelj *et al* (2014), the selection of the suitable facade system can govern the sustainability performance of the whole building. This selection is becoming increasingly difficult, even challenging, due to the growing number of commercial options and construction methods available for facades, each of these alternatives with its own environmental, economic and technical performance. This complexity increases with the uncertainties due to the numerous stakeholders involved, the indirect costs and other technical requirements that vary according to the project to be dealt with (Jin and Overend, 2010).

To establish an effective decision-making process, it is essential to consider the rational estimation of climatic, economic and social conditions so that architectural, functional, comfort and other requirements of the client can be satisfied (Zavadskas *et al.*, 2013). Therefore, this is a multi-criteria decision problem.

On the other hand, it is vital to consider the clients' preferences into the decision-making process to ensure the project success. But, these preferences might not always be aligned with those of other stakeholders such as the designer or contractor. For example, clients demand the project to cover all technological, architectural and comfort requirements with minimum cost. While, stakeholders of the construction chain can be interested in maximizing profits, company growth and market share. Consequently, the selection of the best alternative becomes a considerable problem (Ginevičius *et al.*, 2008). This is a multi-participant decision-making problem.

This multi-criteria and multi-participant decision establishes a challenge for the selection of the most preferable facade system in terms of sustainability (Fig.2.8).

More recently, developments in computer science and numerical procedures have promoted the development of multiple decision analysis tools such as linear or dynamic programming, inventory control, hypothesis testing, and operation control. These tools enable decision makers to make the best decision and select the most preferable alternatives.

Multi-Criteria Decision-Making (MCDM) methods, as a branch of operational research, are gaining importance as potential tools for analyzing and solving complex problems due to their inherent ability to evaluate different alternatives with respect to various criteria for possible selection of the best alternative (Chakraborty *et al.*, 2015).

Before identifying an appropriate MCDM method, one must define the problem and consider the decision-making elements shown in Fig. 2.8, this commencing by defining the main sustainability indicators for a facade system based on local conditions and clients' needs and expectations.

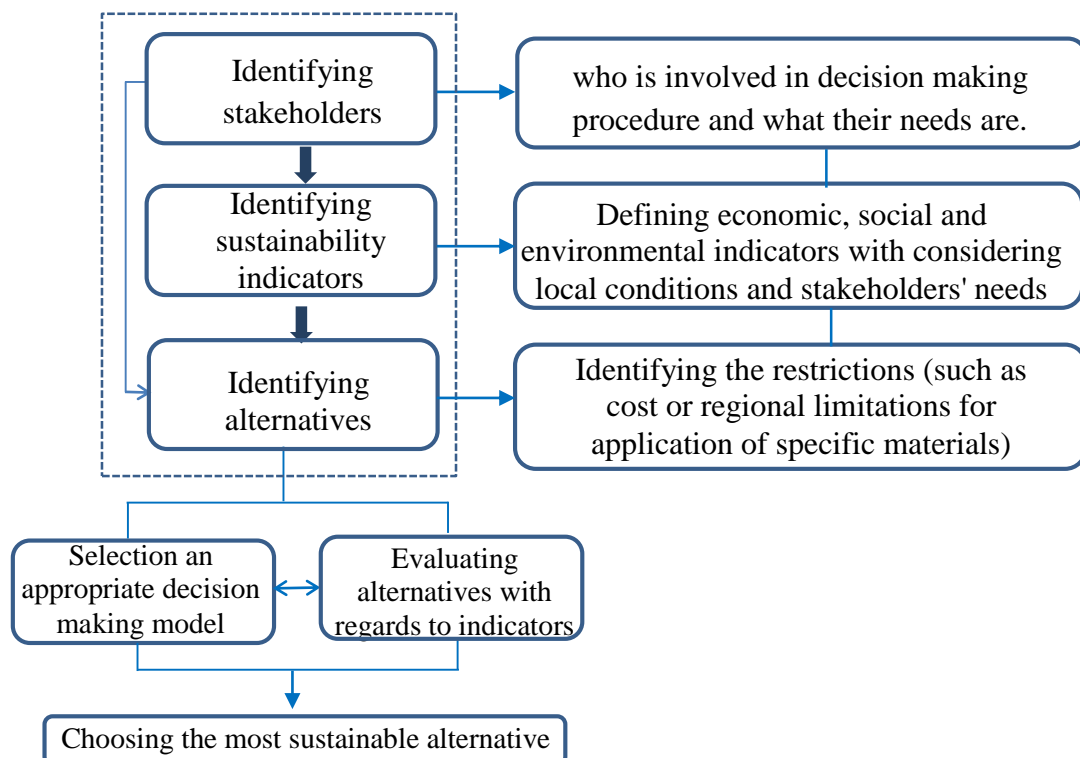


Fig .2.8. Decision making procedure for selection of sustainable facades

2.4.1. Multi-Criteria Decision-Making Models (MCDM)

Selecting an appropriate Decision-Making Model is a complex task. Each method has strengths and weaknesses; while some methods are better grounded in mathematical theory, others may be easier to implement (Kiker *et al.*, 2005). For choosing a particular MCDM approach, it is essential to consider the complexity of the decision in terms of scientific, technical and social factors, as well as understanding the process needs and the availability of information and/or knowledge about the problem space (Huang *et al.*, 2011).

Multi-criteria decision-making has a relatively short history. Many researches dedicated their time to the development of new MCDM models and techniques between 1950s and 1960s, when foundations of modern MCDM methods were laid (Zavadskas *et al.*, 2014).

MCDM methods are usually categorized with regards to their problem-solving technique (value-based, outranking or CBA methods), or their mathematical nature (MODM, MADM or a combination of both) as illustrated in Fig. 2.9.

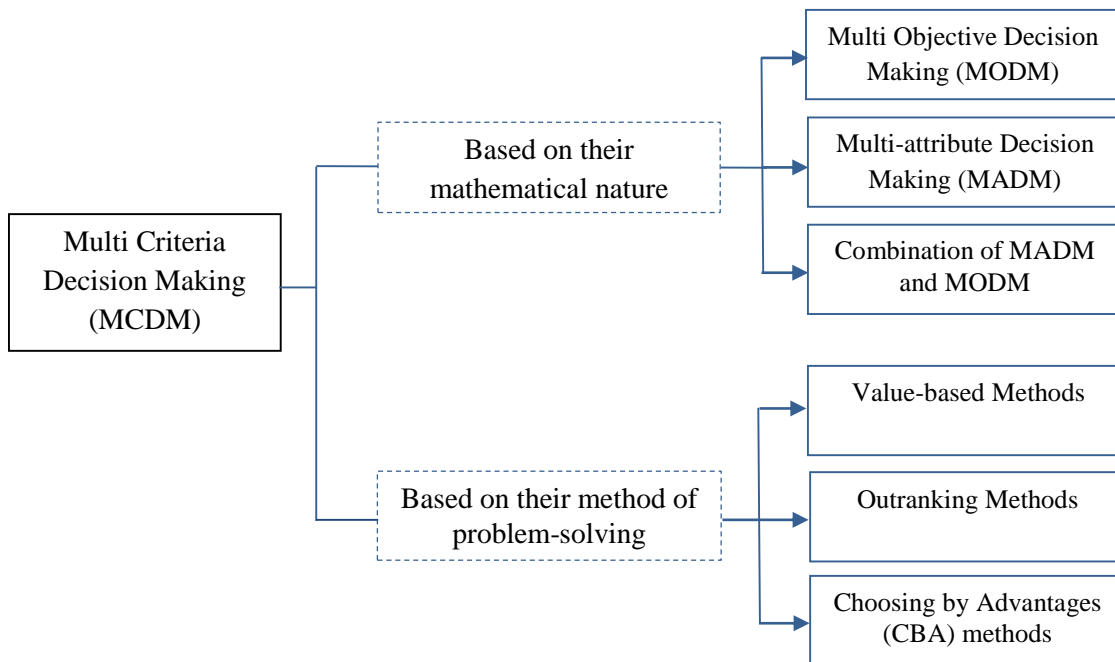


Fig.2.9. Most common categorization of MCDM methods.

Value-based methods are based on partial or total compensation of the different factors involved (Arroyo, 2014). For example, a good energy efficiency performance can compensate a bad performance on the initial costs factor. In these methods, numerical scores are constructed for each criterion or factor, and then the decision makers utilize an aggregation model to select their preferences according to the weights of the various criteria.

In Outranking methods, first alternatives would be compared in terms of each criterion, and then aggregated the preferences, support selection of one alternative over the other.

In Choosing by Advantages (CBA) methods, decisions are only based on advantages of alternatives, and not on the advantages and disadvantages. It enables decision makers

to avoid double counting of factors. Once, the advantages of each alternative have been identified, these methods determine the importance of the advantages by making comparisons among those. CBA methods are not suitable for facade design problems where the number of alternatives and decision criteria are high, some of those with time consuming evaluation need and with subjectivity endorsed. In addition, cost cannot be a factor in CBA, while it is an important decision criterion and cannot be discarded as merely a design constraint (Arroyo, 2014).

MODM methods assume continuous solution spaces and are based on continuous mathematical spaces (Triantaphyllou, 2000). The objective of these methods is to define the optimal trade-offs and solve the problem as a mathematical programming model. The main weakness of these methods is having limited value for the designers because in reality, mathematical programming does not solve most of MCDM-problems.

MADM methods are based on discrete mathematics and solve problems in discrete decision spaces, where the decision alternatives are predetermined.

Lately, several MCDM methods have been applied for solving problems in the areas of sustainable engineering (Zolfani *et al.*, 2018; Zavadskas *et al.*, 2018; Liu *et al.*, 2018; Kianpour *et al.*, 2017; Mardani *et al.*, 2016; Yazdani *et al.*, 2018). Stojcic *et al.*, (2018) conducted a review paper about the application of MCDM methods in the field of sustainable engineering in the period of 2008–2018. After reviewing 329 articles in the Web of Science Core Collection database, it has been noticed that the most of articles belongs to the field of civil engineering (61), and the smallest number belongs to the field of urban studies (6) (Fig. 2.10). Moreover, AHP was the most frequently-use method among other MCDM methods in this area. It was also revealed that a few number of the studied articles were related to the application of MCDM methods in sustainable engineering before 2008.

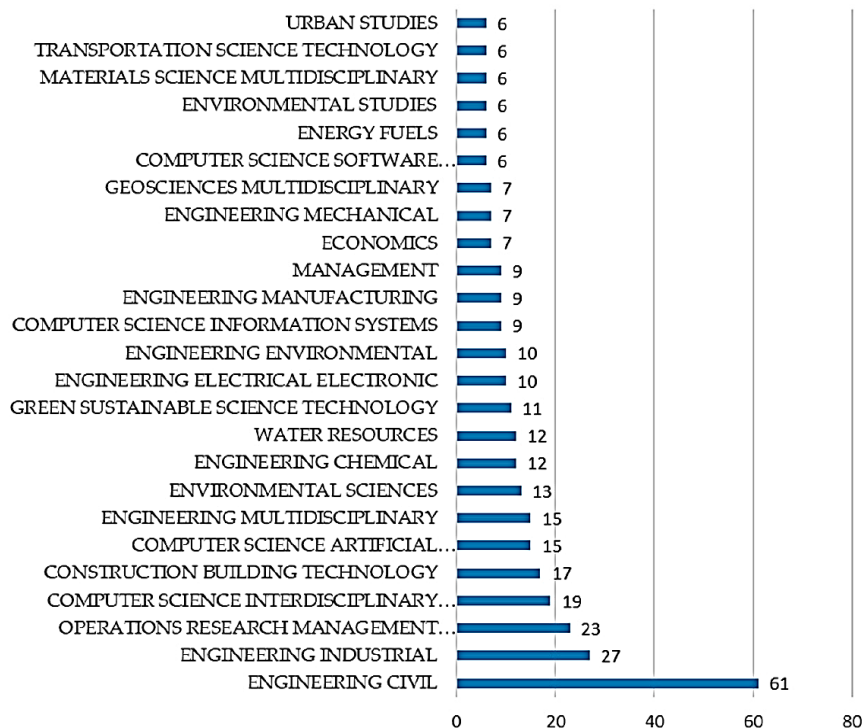


Fig.2.10. Number of articles on the application of MCDM methods in sustainable engineering from Stojcic *et al.* (2018)

Therefore, over the last decade, as indicated by Stojcic *et al.*, (2019), attentions towards sustainability have considerably increased in the domain of architecture and engineering. However, a few number of MCDM methods are favored by researchers in this domain (Birgani and Yazdandoost, 2018; Alhumaid *et al.*, 2018; Jia *et al.*, 2018; Formisano and Mazzolani, 2015; Akhtar *et al.*, 2015; Tsai *et al.*, 2013). Particularly, their application in the facade assessment is very limited in research and almost non-existent in practice.

2.4.2. Overview of previously used methods for sustainability assessment of facades

As already mentioned, there are a few studies on developing a methodology for global sustainability assessment of the whole facade system. This section aims to review and analyze the existing literature in order to identify previously-used methods for sustainability assessment of facades as well as their strengths and weaknesses. Table 2.4 summarizes the main technical literature on these methods.

Table 2.4. Overview of decision-making models applied for sustainability assessment of facades.

Method	Area of study*	Reference
ELECTRE	Wall System	Frenette <i>et al.</i> , 2010
COPRAS	Wall System	Zavadskas <i>et al.</i> , 2008
WPM	Wall system	Zavadskas <i>et al.</i> , 2013
WASPAS	Wall system	Zavadskas <i>et al.</i> , 2013
AHP	Wall system	Nadoushani <i>et al.</i> , 2017; Książek <i>et al.</i> , 2014
SAW	Wall System	Crutchik & Esteban, 2015; Zavadskas <i>et al.</i> 2013
QFD	External cladding material	Singhaputtangkul <i>et al.</i> , 2013
SAW	External cladding material	Friedrich & Luible, 2016
TOPSIS, AHP	External cladding material	Moghtadernejad <i>et al.</i> , 2018
CHOQUET integral	External cladding material	Moghtadernejad <i>et al.</i> , 2018
VIKOR	Wall insulation	Ginevičius <i>et al.</i> , 2008
COPRAS	Windows	Kaklauskas <i>et al.</i> , 2006

* In this paper, the term facade includes both opaque and transparent part. Opaque part accounting for the wall system from exterior layer to interior and transparent part is all the openings.

As indicated in Table 2.4, previous decision-making models applied to facades focused on wall systems (opaque part), disregarding the transparent areas. Nevertheless, glazed elements have always been considered as a critical component (Lori *et al.*, 2019). According to Planas (2018), the heating and cooling demand of the buildings depend directly on the percentage of openings of the facade and, consequently, on its level of solar control. In addition, the openings' performance directly affects the indoor natural lighting as well as air-borne sound transmission through facades. Form and composition of the windows can also have a significant impact on the beauty of the whole facade. Therefore, it can be stated that none of the previous methods fulfill all the criteria related to the whole facade system.

In the following section, each method will be explained in detail in order identify their positive and negative points.

2.4.3. Analyzing previously used methods for sustainability assessment of facades

Table 2.5 shows the strengths and weaknesses of each method through a comparison and then, Table 2.6 summarizes the aforementioned methods in a chronological order. Both tables are the updated and completed version of a table taken from a research made by Moghtadernejad *et al.*, (2018).

According to Zanakis *et al.*, (1998), it is very difficult to determine which method is the most suitable for a specific problem. And this applies to facade selection as well.

In this respect, through a comparison, the strengths and weaknesses of the aforementioned MCDM methods have been identified and presented in Table 2.5 in order to determine the suitability of each method.

Table 2.5. Strengths and weaknesses of previously-used MCDM for sustainability assessment of facades.

Methods	Description	Strengths	Weaknesses	References
ELECTRE	An outranking method based on concordance analysis. It selects the alternatives that are favored over most of the criteria and do not have an unacceptable performance in any of the other criteria.	Deals with both quantitative and qualitative criteria. Takes uncertainty and vagueness into account.	Time consuming, Complex application. Despite having 4 revisions it is still not perfect, and sometimes cannot identify an optimal alternative. It only provides a better view of the available alternatives by discarding the less favorable ones. Outranking causes the strengths & weaknesses of alternatives not to be directly identified	Aruldoss <i>et al.</i> , 2013; Triantaphyllou, 2000; Hosseini <i>et al.</i> , 2019;
TOPSIS	An alternative to the ELECTRE method and is based on distance of an alternative from the ideal solution.	Works with fundamental rankings and makes full use of allocated information. Easy to use. Clearness. Simple mathematical form.	Its use of Euclidean Distance does not consider the correlation of attributes. Difficult to weight and keep consistency of judgment.	Stanujkic <i>et al.</i> , 2013; Triantaphyllou, 2000; Velasquez and Hester, 2013
VIKOR	It ranks the alternatives based on their distance from ideal solution. It can generate multiple solutions instead of one; which occurs when none of the alternatives stands out, and there are several alternatives as close to the ideal solution as the one that is the closest.	It has become more interactive and allows the decision maker to adjust the weights via the information generated by a trade-off analysis.	It needs some modifications, as it is sometimes difficult to model a real-time model. Difficulty of dealing with conflicting situations. Lack of consideration of interactions among criteria.	Opricovic & Tzeng, 2007; Moghtadernejad <i>et al.</i> , 2018
COPRAS	Ranking alternatives based on several criteria by using criteria weights and utility degree of alternatives. The selection of the best alternative is based on considering ideal and anti-ideal solutions.	Evaluating both maximizing & minimizing criteria values separately. Simple computation process. Less computational time. Ranking alternatives in terms of significance.	Less stable than other methods in the case of data variation. Results obtained by COPRAS depend on the number of minimizing criteria and their values.	Podvezko, 2011; Ayrim, <i>et al.</i> , 2018; Moghtadernejad <i>et al.</i> , 2018
SAW	Earliest and most commonly used MCDM approach. In SAW; a value function is established based on a simple addition of scores that represent the goal achievement under each criterion, multiplied by the particular weights.	Simple computation. Understandable. Ability to compensate among criteria. Intuitive for decision makers.	Estimates revealed do not always reflect the real situation. Difficulty in multi-dimensional problems where the criteria units are different and their numerical values are occasionally several orders of magnitude apart. Illogical results may be obtained.	Triantaphyllou & Mann, 1989
WPM	Similar to SAW. The main difference is that instead of addition, ranking of alternatives is based on a multiplicative measure. It was proposed as an alternative to overcome the single dimensionality problem of SAW	It can be used in single and multi-dimensional decision-making problems. Instead of the actual values it can use relative ones. It's dimensionless.	It priorities or deprioritizes the alternative which is far from average. The normalization approach considers only two performance values, i.e. minimum (for non-beneficial attributes) and maximum (for beneficial attributes), and does not consider all the values.	Mulliner <i>et al.</i> , 2016; Moghtadernejad <i>et al.</i> , 2018

WASPAS	This method is a MCDM approach combining the results of two different models, namely weighted sum model (SAW) and weighted product model (WPM).	Easy to use. Combination of WPM and SAW leads to higher-ranking accuracy. More generalized equation for determining the total relative importance of alternatives. Successfully applied in various areas.	Beneficial and non-beneficial criteria are treated equally. The Normalization approach considers only two values, i.e. minimum (for non-beneficial attributes) & maximum (for beneficial attributes), and does not consider all the values.	Mulliner <i>et al.</i> , 2016; Zavadskas <i>et al.</i> , 2013; Chakraborty & Zavadskas, 2014
Choquet Integral	Choquet Integral is an aggregation function defined with respect to the fuzzy measure. It is capable of representing interactions between the criteria.	Can be used for both single & multifaceted decision-making problems. Considers the interaction among criteria. Can deal with qualitative & quantitative criteria. Mathematically not demanding.	Time consuming. difficulty of Assigning weights, this depends on the subjective input from a panel of experts. It is almost impossible to assign weights when the number of criteria increases.	Schuck & Blasch, 2010; Moghtadernejad <i>et al.</i> , 2018;
QFD	It is a systematic, user-driven quality assurance and improvement method that focuses on meeting customers' demands in the process of product development. It evaluates the quality of a system through House of Quality to achieve the targets of a project.	Meets the demand of users in design quality. Structured tool to systematically deal with customer's demands and to precisely define their requirements. Linking the customers' requirements to engineering characteristics.	Complex application. Time-consuming. Difficulty in manually recording the QFD matrix in a paper form. Qualitative and subjective decision-making process. Lack of the techniques to deal with qualitative and subjective requirements. Lack of knowledge-based decision making.	Yang <i>et al.</i> , 2003; Singhaputtangkul <i>et al.</i> , 2013
AHP	Breaks a complex MCDM problem into a system of hierarchies.	Intuitive & verifiable for inconsistencies. Easy to use. Applicable for either single or multi-faceted Decision making problems. Ranking irregularities. Suitable method for defining weights of criteria. Computationally non-demanding.	Subjective nature of AHP may not guarantee the decision as definitely true. Rank reversals. Linear equations. It is based on both probability and possibility measures. Difficulty of considering uncertainties associated with judgments. Interdependency between criteria and alternatives; can lead to inconsistencies between judgment and ranking criteria.	Pohekar & Ramachandran, 2004; Hosseini <i>et al.</i> , 2019

Note. Adapted from " Multi-criteria decision-making methods for preliminary design of sustainable facades", by Moghtadernejad S, Chouinard LE, Mirza MS., 2018, *Journal of Building Engineering*. 1; 19:181-90.

Table 2.6. Table summarizing the MCDM previously applied for sustainability assessment of facades.

Methods	Steps	References
Weighted Product Method (WPM)	$P(A_i) = \prod_{j=1}^n (a_{ij})^{w_j}$ <p>where $P(A_i)$ is the WPM score of each alternative, with n decision criteria, a_{ij} is the actual value of the i^{th} alternative in terms of the j^{th} criterion, and w_j is the weight of importance of the j^{th} criterion.</p>	Zavadskas <i>et al.</i> , 2013
Choquet Integral	$C_{\mu}^K(x_1, \dots, x_n) = \sum_{i=1}^n (x_{(i)} - x_{(i-1)})\mu(A_i)$ <p>where μ denotes the fuzzy measures, (i) is the permuted rank of a criteria such that $0 \leq x_{(1)} \leq x_{(2)} \leq \dots \leq x_{(n)}$, $x_{(0)} = 0$ and $A_{(i)} = \{x_{(i)}, \dots, x_{(n)}\}$.</p>	Moghtadernejad <i>et al.</i> , 2018
Quality Function Deployment (QFD)	<ol style="list-style-type: none"> 1. Composition of House of Quality (HOQ) 2. Articulation among the Components of HOQ $rt_j = \left(\frac{at_j}{\sum_{j=1}^n at_j} \right) \times 100\%, j = 1.2. \dots . n \cdot at_j = \sum_{i=1}^m r_{ij} \times d_i, j = 1.2. \dots . n \cdot$ <p>d_i is the judgment on the importance of the i th demand from customers, r_{ij} represents the contribution and influence on the i th customer demand from the j th technical demand, at_j is absolute weight of technical measures and rt_j is relative weight of technical measures.</p>	Singhaputtangkul <i>et al.</i> , 2013

Weighted Sum Method (SAW)	$A_{WSM} = \sum_{j=1}^n a_{ij}w_j$ <p>where A_{SAW} is the SAW score of each alternative, with n decision criteria, a_{ij} is the actual value of the i^{th} alternative in terms of the j^{th} criterion, and w_j is the weight of importance of the j^{th} criterion.</p>	Zavadskas <i>et al.</i> , 2013; Crutchik & Esteban, 2015; Friedrich & Luible, 2016
Elimination and Choice Translating Reality (ELECTRE)	<p>Associating appropriate weights to the matrix, determination of the concordance and discordance sets and construction of the related matrices, determination of the concordance and discordance dominance matrices and the aggregate dominance matrix and finally elimination of the less favorable alternatives. If alternative A_l is preferred to A_k:</p> $C_{lk} = \frac{\sum_{j=1}^n w_j c_j(A_l A_k)}{\sum_{j=1}^n w_j}$ <p>where W_j is the weight associated with j^{th} criterion.</p>	Frenette <i>et al.</i> , 2010
Analytic Hierarchy Process (AHP)	$A_{AHP-score} = \sum_{j=1}^n a_{ij}w_j$ <p>where a_{ij} are elements of the matrix A, and w_j is the weight assigned to the j^{th} criterion, using pairwise comparisons and calculating the priority vector (normalized principal Eigen vector).</p>	Nadoushani <i>et al.</i> , 2017; Książek <i>et al.</i> , 2014; Moghtadernejad <i>et al.</i> , 2018
Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS)	$S_i^* = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^*)^2}, \text{ and } S_i^- = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2} \cdot C_i^* = \frac{S_i^-}{S_i^- + S_i^*}$ <p>Where S_i^* and S_i^-, are ideal and negative-ideal solutions respectively, and v_{ij} is the weighted normalized value of i^{th} alternative. v_j^* and v_j^- are respectively the best and the worst scores of j^{th} criterion among alternatives. C_i^* corresponds to the relative closeness to the ideal solution which is the basis for ranking the alternatives.</p>	Moghtadernejad <i>et al.</i> , 2018
Complex Proportional Assessment (COPRAS)	$N_j = \frac{Q_j}{Q_{max}} \cdot 100\% \cdot Q_j = S_{+j} + \frac{S_{-min} \cdot \sum_{j=1}^n S_{-j}}{S_{-j} \cdot \sum_{j=1}^n \frac{S_{-min}}{S_{-j}}}, j = \overline{1, n}$ <p>Where N_j is the utility degree of j^{th} alternative, Q_j is the Relative significance of j^{th} alternative, Q_{max} is the most efficient alternative from the set of alternatives, S_{+j} is the sum of „pluses” of each j^{th} alternative, S_{-j} is the sum of „minuses” of each j^{th} alternative, S_{-min} is the minimum of S_{-j} and n – number of alternatives.</p>	Zavadskas <i>et al.</i> , 2008
VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR)	$S_i = \sum_{j=1}^n \left[\frac{w_j (f_j^* - f_{ij})}{(f_j^* - f_j^-)} \right], R_i = \max_j \left[\frac{w_j (f_j^* - f_{ij})}{(f_j^* - f_j^-)} \right]$ <p>Where w_j is the weight of the j^{th} criteria, and i is the number of alternatives. Q_i values determine of the ranking order of alternatives.</p> $Q_i = \frac{v(S_i - S^*)}{(S^- - S^*)} + \frac{(1-v)(R_i - R^*)}{(R^- - R^*)}$ <p>$S^* = \min S_i, S^- = \max S_i, R^* = \min R_i, R^- = \max R_i$</p> <p>where v is the weight of the maximum group utility which is in the range of $[0, 1]$ and is usually considered as 0.5.</p>	Ginevičius <i>et al.</i> , 2008
Weighted Aggregated Sum Product Assessment (WASPAS)	$Q_i = \lambda \sum_{j=1}^n \bar{x}_{ij} w_j + (1 - \lambda) \prod_{j=1}^n (\bar{x}_{ij})^{w_j}, \lambda = 0, \dots, 1.$ <p>Q_i is relative importance of alternative i, \bar{x}_{ij} stands for the performance value of alternative i when it is evaluated in terms of criterion j and w_j is relative significance (weight) of the criterion j.</p>	Zavadskas <i>et al.</i> , 2013

Note. adapted from " Multi-criteria decision-making methods for preliminary design of sustainable facades", by Moghtadernejad S, Chouinard LE, Mirza MS., 2018, Journal of Building Engineering. 1; 19:181-90.

As indicated in Table 2.6, the basic approaches of WSM, WPM, WASPAS, AHP and Choquet integrals are similar. SAW, as one of the simplest and widely used MCDM methods, has difficulties in apprehending stakeholder preference adequately due to its

subjective nature. Then, AHP, which was firstly introduced by Saaty (1990), improves over WSM and WPM by using dimensionless scores (relative values instead of actual ones) and does not prioritize or deprioritize alternatives which are far from the average alternative. The AHP method uses pairwise comparisons to assess decision maker preferences regarding alternatives as well as criteria importance. It is one of the most preferred methods in academic papers dealing with MCDM problems in civil engineering (Arroyo, 2014). However, the subjective nature of AHP may not guarantee the decisions as definitely true. Nonetheless, the AHP method enables the most consistent weighting judgments (Pons *et al.*, 2016; Hopfe *et al.*, 2013). Therefore, it may be a useful method for assigning weights to design criteria.

The Choquet aggregation function, proposed by the French mathematician Choquet (1954), is also not an appropriate method to be used for facade sustainability assessment because the number of objective and subjective criteria for sustainability assessment of facades is large and assigning fuzzy measures would be too time-consuming and almost impossible in this case.

Another well-known method is TOPSIS that was introduced by Huang and Yoon (1981) as an alternative to improve the weaknesses of the ELECTRE method which is time-consuming and cannot always identify an optimal alternative. However, decisions provided by COPRAS are more efficient and less biased than those provided by TOPSIS (Simanaviciene and Ustinovicius, 2012) since it considers the utility degree of alternatives. COPRAS, developed by Zavadskas and Kaklauskas in 1996, has a simpler and transparent computation process than TOPSIS. Although it has some advantages, but the obtained results by COPRAS could be unstable due to the number of minimizing criteria and their values. So, it may not be a suitable method for facade sustainability assessment due to the various minimizing criteria needed for facade assessment.

VIKOR is also not as favored and needs some modifications. Difficulty of dealing with conflicting situations and modeling a real-time model are the main drawbacks of this method.

2.4.4. Finding the most suitable method for sustainability assessment of facades

All the aforementioned models have both positive and negative points that enable them to be used for facades sustainability assessment. But, this study aims to select the most suitable method that allows decision makers assessing the sustainability of the whole facade from economic, environmental and social points of view.

In this respect, previous studies have been reviewed (Pohekar & Ramachandran, 2004; Balali *et al.*, 2014a, b; Moghtadernejad *et al.*, 2018; Hosseini *et al.*, 2019) in order to identify other possible MCDM methods. The two commonly-used MCDM methods, specifically in the domain of architecture and construction, are MIVES and PROMETHEE which have not been already used for facade assessment.

Preference Ranking Organization Method (PROMETHEE) is an outranking method for ranking a finite set of alternative actions based on pairwise comparisons of the alternatives (Behzadian *et al.*, 2010). This method, like other MCDM methods, has both strengths and weaknesses. According to Moghtadernejad *et al.*, (2018), this method can

deal with both qualitative and quantitative information. But PROMETHEE assessment process is time consuming and complex, which discourages decision makers to use it. Another reason that can make it inappropriate for facade evaluation is that PROMETHEE does not provide the possibility to structure a decision problem. In the case of many criteria and options, it thus may become difficult for the decision maker to obtain a clear view of the problem and to evaluate the results; therefore, non-representative results may be obtained.

The Integrated Value Model for Sustainable Assessment (MIVES) is a MCDM model that integrates the main sustainability requirements (economic, environmental and social). This method is capable of carrying out specialized and holistic sustainability assessments while obtaining global sustainability indexes (Lombera & Aprea, 2010; Aguado *et al.*, 2012). One of the main characteristics of MIVES that makes it unique among other MCDM methods is the use of value functions to measure the satisfaction grade of various stakeholders involved in the decision-making procedure. As previously mentioned, the selection of the best facade system is a multi-criteria and multi participant procedure. Therefore, in order to assess and select the most sustainable facade system, all the sustainability criteria as well as satisfaction of all stakeholders involved in decision making procedure should be considered. And, this method can give decision makers this necessity to consider the two parameters (multi-criteria / multi participant) in the assessment and selection process of an optimal facade system. Moreover, in MIVES, weights are determined by experts using AHP which, as mentioned before (refer to section 2.4.3), enables the most consistent weighting judgments. AHP helps to organize the process efficiently, to reduce the model complexity and subjectivity and decrease possible disagreements between the team members (del Caño *et al.*, 2015).

2.4.5. Towards the most suitable method for sustainability assessment of facades

Since this study aims to choose the most appropriate method for facades sustainability assessment, another possible MCDM have been also analyzed rather than previously-used MCDM applied for facade sustainability assessment.

Consequently, by considering all the strengths and weaknesses of the abovementioned methods, sustainable facades essential features as well as the requirements of a suitable model that makes it eligible for the sustainability assessment of facades, MIVES has been selected as the most appropriate method due to the following reasons:

- Although all assessed tools have had the ability to deal with facade systems, MIVES is the only method that incorporates value functions to assess the satisfaction level of the different stakeholders involved in the decision-making process.
- MIVES is capable of minimizing the subjectivity in the assessment by introducing AHP in the seminars of experts.
- MIVES covers the basic principles of the sustainable development concept because it is capable of considering essential environmental, economic and social indicators for

facade assessment, as well as all stakeholders' satisfactions and necessities in the decision-making process.

- MIVES enables decision-makers to objectively quantify both quantitative and qualitative indicators belonging to the three pillars of sustainability and, therefore, with different units by means of applying value functions.
- MIVES has already been satisfactorily applied within the framework of different real projects of architecture and civil engineering.
- The MIVES methodology can be applied for 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.
- It gives global sustainability indexes so decision-makers can detect the best alternative(s), it ranks all alternatives, and it also identifies the major characteristics as well as the strengths and weaknesses of each alternative and for each requirement and criteria.

2.5. Conclusion

This chapter was mainly categorized into 4 parts:

- Importance of considering sustainability in facades,
- Indicators of sustainable facades,
- Assessing the sustainability performance of facades, and
- Selecting the most appropriate method for sustainability assessment of facades.

Through reviewing and analyzing the previous literature on the aforementioned parts, the following results have been obtained:

As previous studies indicated (refer to section 2.2.3), facades can have considerable economic, environmental and social impacts on the whole building performance, these being;

- protecting the indoor environment against adverse environmental effects,
- decreasing the level of heat/cooling energy needed in buildings. Actually, 60% of heat loss in building envelope occurs via facade,
- regulating radiant heat flow from the sun,
- providing thermal comfort for inhabitants,
- acting as a Linkage between exterior and interior, providing views to the outside and also sufficient daylight for interior spaces, therefore, avoiding the feeling of isolation by the building occupants,
- playing an important role in urban landscape and image of city,
- decreasing the energy cost during operation phase, and
- 25% up to 40% of the total construction cost is related to building facade.

Therefore, sustainability of facades significantly affects the sustainability of buildings through minimizing negative impacts on sustainability. Despite the importance of facades, 90% of the existing literature mainly focused on environmental and economic

aspects, disregarding the third pillar of sustainability, which is the social aspect (section 2.3.1). On the other hand, there is still lack of a comprehensive sustainability assessment approach which is applicable for any type of facades.

Based on the extensive review of previous literature presented in this chapter, it can be stated that a suitable model, that makes it possible to determine sustainable facade alternatives based on the defined priorities, should generally be:

1. Easy understandable,
2. Customizable,
3. Quick enforceable,
4. Able to consider satisfaction level of all the stakeholders involved in the decision-making procedure,
5. Able to consider diverse quantitative or qualitative indicators with different units,
6. Able to cover 3 main pillars of sustainability,
7. Able to assess alternatives objectively,
8. Able to incorporate the utility theory,
9. Flexible to incorporate changes,
10. Previous studies-proved model,
11. Able to be specified.

Existing sustainability assessment tools such as LEED, BREEAM, CASBEE and etc. consider buildings as a whole. Moreover, these are not universal and these are typically designed with one country and applied to other areas as well without being adjusted to take into account the local climate or cultural differences. In fact, when a sustainability assessment requires a specialized tool for a particular study case, the aforementioned tools are scarcely representative.

On the other hand, as indicated in section 2.4.3, none of the previously-used decision-making models applied for sustainability assessment of facades fulfill all the aforementioned requirements. Some of them like AHP, SAW, WPM have a subjective nature which may not guarantee the decision as definitely true. Some of them have complicated and time-consuming application procedure such as QFD and ELECTRE. Furthermore, none of them consider the satisfaction degree of all the stakeholders involved in the decision-making procedure, which is an important parameter for assessing and selecting the most sustainable facade system (section 2.4). In this respect, other possible MCDM methods, that have not already been used for facade assessment, were also determined (section 2.4.4) in order to choose the most suitable method.

Finally, MIVES was considered as the most appropriate DM model due to its well-organized structure and use of value function (section 2.4.5). Although it can be slightly time-consuming, it covers all the aforementioned requirements for assessing sustainability of facade systems.

As a consequence, it can be stated that there is still the need to develop an approach for holistic sustainability assessment of facade systems with considering all the aforementioned requirements. In this respect, the following chapter sets out the methodology for addressing this goal.

Chapter 3

A new approach for sustainability assessment of buildings' facades

3.1. Introduction

In the previous chapter, it was explained that despite the impact of facades on the three pillars of the sustainability - economic, environmental and social -, most existing studies are mainly focused on the environmental aspect (60%), dismissing the other pillars. And the few studies that do otherwise, measure the other two sustainability pillars rather subjectively (especially those associated with the social requirement). On the other hand, previously used methods for sustainability assessment of facades did not cover all the parameters required for sustainability assessment (refer to section 2.4).

Therefore, there is still a lack of a systematic framework for the assessment and selection of optimal facade systems in terms of sustainability. In this respect, this chapter

is aimed at proposing a new approach for comprehensive sustainability assessment of facades that covers all the existing drawbacks and deficiencies.

The proposed approach is based on MIVES. As indicated in Chapter 2, MIVES was considered as the most suitable method, which makes it possible to objectively assess the sustainability of facades. Moreover, MIVES is unique among other MCDM methods due to the use of value function which indirectly allows measuring the satisfaction grade of various stakeholders involved in the decision-making procedure. On the other hand, as explained in previous chapter, in order to select the most sustainable facade system, all the sustainability criteria as well as satisfaction of all stakeholders involved in decision making procedure should be considered. And, MIVES can provide decision makers a solution for considering these requirements in the assessment and selection process of an optimal facade system.

This method has already been satisfactorily applied for real projects in the domain of architecture and civil engineering. Table 3.1 presents the application of MIVES in different areas.

Table 3.1. Studies where MIVES methodology was applied.

Area of study	Sustainability assessment	Year	Reference
Urban	1.Choice of the optimal tunnel diameter for Barcelona subway system	2008	<i>Ormazabal et al.</i>
	2.Assessing sustainability of concrete & plastic sewerage pipes	2016	<i>de la Fuente et al.</i>
	3. Sustainability assessment of alternatives for pavements systems	2014	<i>Jato-Espino et al.</i>
	4. Sustainable site location of post-disaster temporary housing	2016	<i>Hosseini et al.</i>
	5. Developing a sustainable prioritization index for urban investments	2017	<i>Pujadas et al.</i>
	6. Sustainable alternatives for manufacturing the segmental tunnel lining	2017	<i>De la Fuente et al.</i>
	7.Assessing urban-pavement conditions in Barcelona	2019	<i>Pujadas et al.</i>
Building Elements & Systems	8.Sustainability assessment method applied to structural concrete columns	2013	<i>Pons & de la Fuente</i>
	9. Sustainability assessment of concrete structures	2012	<i>Aguado et al.</i>
	10.Sustainability assessment of slabs	2011	<i>Ballester et al</i>
	11. Sustainability assessment of concrete slabs	2019	<i>de la Fuente et al</i>
Building Functions	12.Sustainable assessment applied to technologies used to build schools	2012	<i>Pons & Aguado</i>
	13.Sustainability of post-disaster temporary housing units' technologies	2016	<i>Hosseini et al.</i>
	14. Environmental analysis of industrial buildings	2010	<i>Lombera , Aprea</i>
Energy	15. Sustainability index of wind-turbine support systems	2016	<i>de la Fuente et al.</i>
	16. Sustainability assessment of energy sub-systems	2015	<i>Del Caño et al.</i>
	17. Sustainability assessment of different types of power plants	2015	<i>Barros et al.</i>
	18. Optimal selection of a domestic water-heating system	2018	<i>Casanovas & Armengou</i>
Others	19. developing probabilistic method MIVES–EHEm–Mcarlo, to give the likelihood of reaching the sustainable objective during the project phase	2012	<i>del Caño et al.</i>
	20. Sustainability assessment of construction industry based on occupational health and safety criteria	2014	<i>Reyes et al.</i>
	21. occupational safety assessment based on the project design	2014	<i>Casanovas et al.</i>

In general, the proposed MIVES-based approach, which will be explained in detail in the following sections, enables decision-makers to develop tools that:

- Incorporate all the economic, environmental and social indicators required for sustainability assessment of facade systems.
- Consider both qualitative and quantitative indicator with different units.
- Quantify, as objectively as possible, the sustainability of each facade system.
- Take into account the satisfaction level of all the stakeholders involved in the decision-making procedure.

3.2. A new MIVES-based approach for sustainability assessment of facades

As mentioned above, the proposed approach is based on MIVES (Integrated Value Model for Sustainable Assessment), a Multi Criteria Decision Making (MCDM) model, which allows quantifying indicators belonging to the three pillars of sustainability. These indicators have different units and, in order to deal with this aspect, the indicators are normalized by means of applying value functions (Lombera & García-Tornel, 2008; Alarcon *et al.*, 2011; Viñolas, 2011). In other words, the use of value functions allows researchers transforming the results obtained by each indicator, which might have different measurement units, to a non-dimensional magnitude value. This magnitude is intended to measure the satisfaction grade of the stakeholders.

3.2.1. Stages of the approach

The MIVES-based approach proposed herein for assessing sustainability of facades consists of 3 phases as shown in Fig. 3.1, these being:

- In phase 1, first, the main objective and all existing boundaries are defined and quantified, respectively. Then, a decision-making tree is built based on a theoretical framework to identify the most representative indicators (see section 3.3 for a detailed explanation on the decision-making tree).
- In phase 2, after determining the quantification procedure for each indicator and the databases to be considered, value functions are calibrated to normalize the magnitudes of the indicators. For this purpose, a scale from 0 to 1, where 0 indicates minimum satisfaction (S_{\min}) and 1 indicates maximum satisfaction (S_{\max}), is considered. More details on the characteristics and application of value functions can be found in section 3.4.2. The final step of this phase consists in establishing the different components that conform the multi-criteria decision tree, to this end the AHP (Saaty, 1990) method has proven to be the most suitable; however, other methods (ex., DELPHI) can be alternatively used (Casanovas-Rubio & Armengou, 2018).
- In phase 3, the Sustainability Index (SI) of each alternative to be assessed is derived from applying this approach. The SI is computed based on a formula that is presented in section 3.5. A sensitivity analysis can be finally 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 can be finally used to prioritize and assist the stakeholders in making the decision.

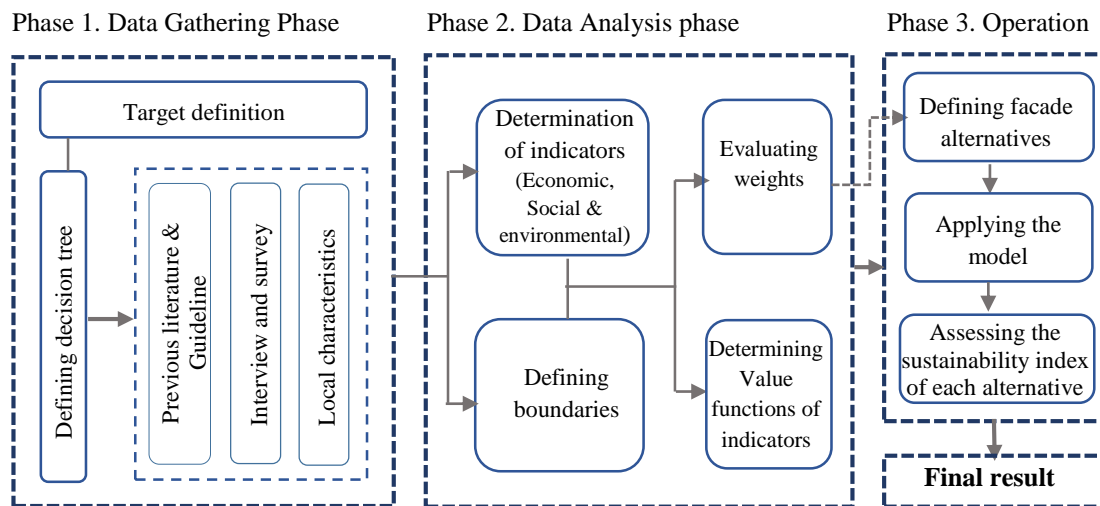


Fig. 3.1. Proposed tool for sustainability assessment of Facade systems based on MIVES.

It should be noted that the proposed approach is applicable for any type of facade such as office buildings, commercial centers and other uses and for different locations and countries. In this study, this approach is specifically optimized for the sustainability assessment of residential building facades; nonetheless, the applicability of the proposed is also extendable to other uses.

The reason for focusing on residential buildings is that housing sector is responsible of relevant impacts from the sustainability point of view. For instance, in the European Union (EU) the building sector accounts for around 37% of the final total energy consumption (Eurostat databases, 2010; EPBD, 2010; Pérez-Lombard *et al.*, 2008), while residential buildings alone represent 27% of final energy demand, which makes those one of the largest single energy-consuming sectors. It also represents 20% out of 35% of the total associated carbon dioxide (CO₂) emissions in the EU building sector (Eurostat databases, 2010). According to Lowry (1990), providing more and better housing is a cost-effective way of improving people's health and physical wellbeing.

3.3. First phase of the proposed approach

In the proposed approach, the first step is to define the aim and boundaries clearly in order to have an accurate assessment.

The second step is to define a decision-making tree that includes the most important criteria and indicators, so that this tree permits assess the satisfaction and sustainability of a specific process, system and product, and make decisions with the obtained results.

The decision-making tree is a hierarchical diagram in which the most significant indicators of alternatives are defined in an organized manner, normally at three levels: requirements, criteria, and indicators (Fig. 3.2). 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; this allowing, on the one hand: (1) having a global view of the problem; (2) organizing the ideas and (3) facilitating the comprehension of the model to any stakeholder involved in the decision process. On the other hand, the tree is useful to carry out the subsequent mathematical analysis.

The tree is previously fixed and agreed by the involved stakeholders. Some indicators can be found determining or negligible according to the stakeholders' preferences. For instance, natural disaster risk should be considered as an important indicator for the earthquake prone countries while, in Barcelona, this indicator can be discarded since the seismicity in Spain (except in the South) is low. On the other hand, the final number of criteria and indicators in each tree branch shall be the minimum and the most important so that overlapping among indicators is avoided. Likewise, this approach permits to discard indicators with low relative weight (namely <5%) with low impact into the final SI but that, if considered, could imply time-consuming and difficult processes (and sometimes with high uncertainties).

According to the above-mentioned explanations, the following decision-making tree was developed that includes the most representative indicators for sustainability assessment of residential facades (Fig. 3.2). This tree can be applied in different stages of design, construction and renovation of residential facade systems. However, its application is recommendable at early stages since the results may lead to improved comfort, energy efficiency, health and safety in buildings (Šaparauskas *et al.*, 2011).

The criteria and indicators presented in Fig. 3.2, as the most principal indicators of the residential building facades, were defined in 2 phases;

First, initial set of indicators were identified through the extensive review of previous studies explained in detail in section 2.3.1 (Table 2.1).

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

Finally, as indicated in Fig.3.2, 13 indicators were selected as those most representative and independent from each other.

The life-cycle period considered in this study is fixed to be 50 years, this embracing all those stages comprised from the extraction of the constituent materials of the facade up to the recycling.

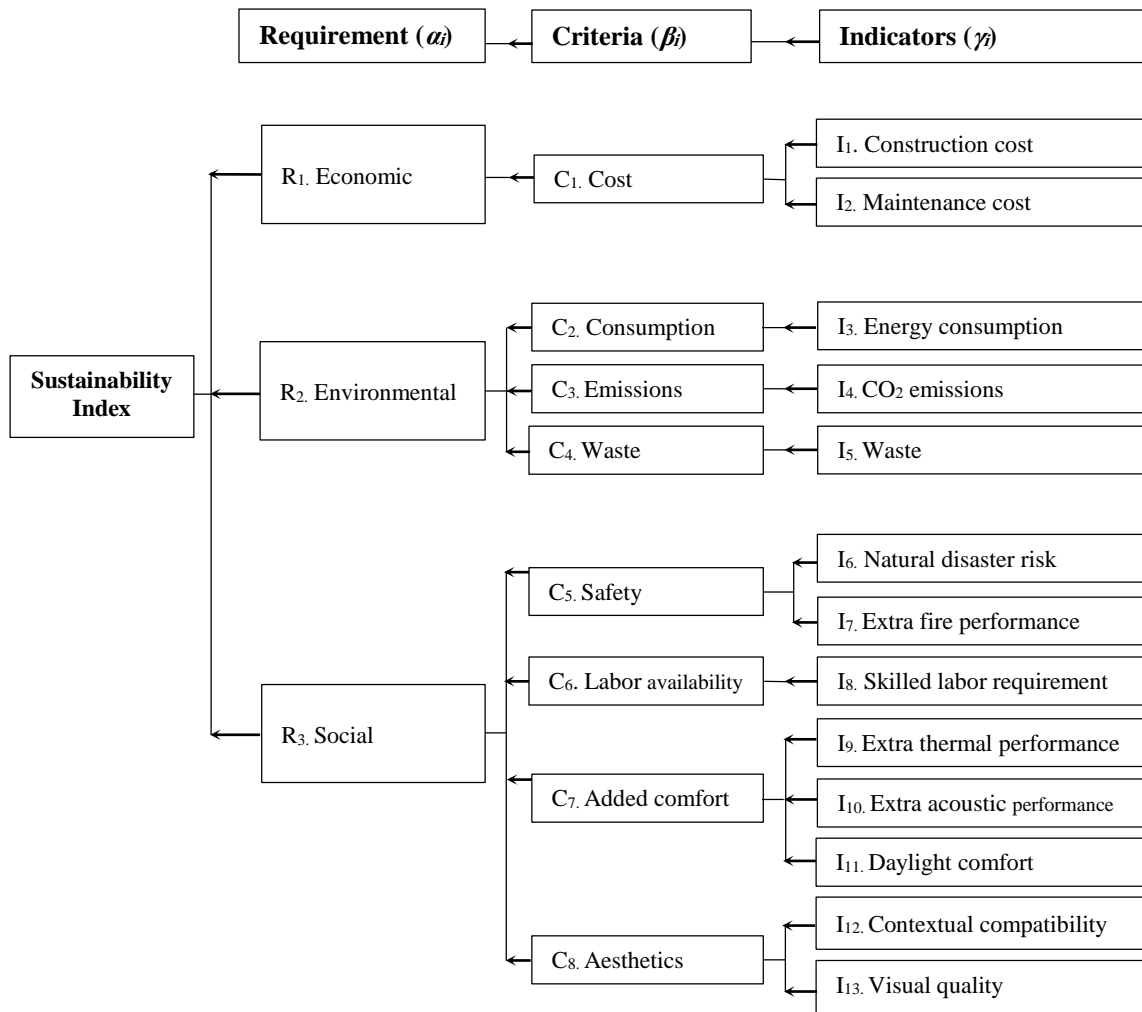


Fig.3.2. Decision-making tree for sustainability assessment of residential facades.

It should be noted that the aforementioned decision-tree can be used for different locations since it includes the most important indicators required for sustainability assessment of residential facades. This possible extended use should be proceeded by studying each new location particular context so to weight the hypothetical necessity to include or exclude some indicators and updated the decision-tree according to the location and/or stakeholders' particularities.

The following sections present all the information about each of the 13 indicators as well as other potential indicators that were discarded during the definition of the decision-tree.

3.4. Second phase of the proposed approach

3.4.1. Quantification procedure for each indicator

This section is focused on the definition of each indicator as well as the way that each indicator is going to be evaluated.

Economic Requirement

The *economic requirement* (R_1) takes into account the economic impacts of the facade over the whole life-cycle established during the first step by means of two indicators.

I₁ assesses the *construction costs*, both direct and indirect. According to the case studies' location, local costs databases should be preferably used for evaluation in order to guarantee accuracy and representativeness of the results.

I₂ covers the *maintenance costs* expected during the life span of facade systems. The life-cycle of facades is considered to be 50 years so maintenance cost will be calculated considering this interval. Other service life periods (ex., extension to 100 years, or more) can be considered depending on factors as ownership (private or public), importance, use (and potential future reconversions) and environmental exposure of the building.

In order to estimate the maintenance cost, first a maintenance plan has to be defined. Maintenance plan is a document that anticipates maintenance actions, according to different time ranges, with minimal interference in the regular functioning of the building (Auteri & Macci, 2003). Some countries have extensive studies on the definition of building's maintenance plans, and legislation to oblige builders and/or homeowners to implement those, like France, Italy and Spain (Madeira *et al.*, 2017).

In this sense, in order to estimate the maintenance cost, this study proposed a maintenance plan for facades (Table 3.2), based on the existing literature and several technical documents (Manteniment de l'edifici, 1991; CIRIA, 1999; Marteinsson & Jónsson, 1999; Silva & Falorca, 2009; Shohet & Paciuk, 2004; Silva *et al.*, 2012). The proposed plan includes facade elements subjected to maintenance, maintenance actions as well as the maintenance operations frequency for facade elements.

According to Table 3.2, the main facade elements subjected to maintenance are divided into two parts: cladding (as the most exterior layer of the building) and openings (ASTM, 2013; Madureira *et al.*, 2017). As explained in Chapter 2, in this study, facade refers to the vertical building envelope which includes both opaque and transparent parts, the opaque part accounting for the wall system from exterior (cladding) to interior layers while the transparent part includes the openings (windows and doors). In fact, cladding as the most exterior layer of the opaque part, is directly exposed to agents causing degradation. It is therefore more prone to suffer anomalies, with direct consequences on the quality of the urban space, on users' comfort, and on the costs of maintenance and repair (Kirkham and Boussabaine, 2005). In addition, the degradation of cladding is one of the major concerns of building owners and maintenance managers since in most cases maintenance actions are often based on the outward appearance of the buildings, for example building aesthetics (Balaras *et al.*, 2005).

On the other hand, through reviewing previous literature, the three most important maintenance actions were identified for facade elements as cleaning, repairing and replacing. The aforementioned actions were defined based on the four main anomalies that occur in facade claddings that are: aesthetical, adhesion loss, fastening defects and defects in openings (Neto & de Brito, 2012; Madureira *et al.*, 2017). The most common

cladding and opening materials used for facades as well as the operation frequency of their maintenance actions are also presented in Table 3.2.

Table.3.2. Proposed maintenance plan for residential facades.

Facade maintenance elements		Maintenance operations			References	
		Cleaning	Repairing	Replacing		
Cladding	Continuous	Paint	NA	NA	Every 5 to 10 ^{1,2} or every 15 years ³	1.Magalhães, 2008 2.Flores & de Brito, 2010 3.Manteniment de l'edifici,1991 4.Madureira, 2017 5. ASTM E 2136-04 2013 6.RICS, 2000 7.HAPM, 1992 8. BPG, 1999 9.Perret, 1995 10. Silva <i>et al.</i> , 2012 11. Leite, 2009 12. Barbosa, 2009 13. Equitone Product brochure
		Renders	Every 5 years ^{1,3}	Every 10 years ^{1,4,3}	Every 50 years ^{5,6,7,8}	
	Discontinuous	Stone	Every 10 years ^{9,4} or 20 years ³	Every 15 years ^{9,4,10}	When necessary ^{3,9,10} or every 45 years ^{5,6,7,8}	
		Brick	Every 20 years ³	When necessary ^{3,9}	When necessary ^{3,9} , every 55 years ^{5,6,7,8}	
		Ceramic	Every 10 years ⁴ 20 years ³	Every 13 years ^{2,9,4}	When necessary ^{4,9} , every 35 years ^{5,6,7,8}	
		Al composite panel	Every 20 year ³	When necessary ^{3,11}	When necessary ^{3,11} , every 45 years ^{5,6,7,8}	
		Wood	Annual ⁹	Every 5 year ^{9,12}	When necessary ^{9,12} , 40 years ^{3,5,6,7,8}	
		Concrete panel	Every 20 year ³	When necessary ³	When necessary ³ , every 50 years ^{5,6,7,8}	
		Cement panel	If needed ^{3,13}	When necessary ^{3,13}	When necessary ^{3,13} , every 45 years ^{5,6,7,8}	
Openings	Frame	Al	Biannual ¹²	Every 13 years ^{3,12}	When necessary ³ or every 35 years ^{5,6,7,8}	
		PVC	Biannual ^{4,12} 5 years ³	When necessary ^{4,11,12}	When necessary ^{4,12} , every 30 years ^{5,6,7,8}	
		Wood	Biannual ^{4,12}	Every 5 years ^{9,4,12}	When necessary ^{4,12} , every 40 years ^{3,5,6,7,8}	
	Glass	Biannual ¹² annual ³	NA	When necessary ^{3,12}		

Legend: NA: Not applicable; Al: Aluminium.

Based on the proposed maintenance plan, the maintenance cost of facade systems can be estimated at a 50-year interval following previous experiences, guidelines and recommendations.

A particular mention should be made for *demolition cost*. This cost was discarded due to the lack of representativeness, since the life expectancy of facades are often around or even more than 50 years and facades are mostly renovated by repairing or replacing some of the cladding components during the life-span or afterwards rather than demolition (Udawattha & Halwatura, 2017; Madureira *et al.*, 2017). Should this indicator be determining, this could be included as an additional indicator within the criteria C₁.

Environmental Requirement

The *environmental requirement* (R₂) assesses the impact of facades on the environment considering the following four life cycle phases of the building: (1) manufacturing; (2) construction; (3) operation and (4) demolition (Bribián *et al.*, 2009; Mosteiro-Romero *et al.*, 2014). These four indicators can be defined as a simplified is a

version of the Life Cycle Assessment (LCA) methods (ISO, 2006; Lecouls, 1999). This approach is meant to optimize time-efforts and cost of the assessment without compromising the rigorousness. For assessing this indicator, environmental databases (BEDEC, 2019; Hammond & Jones, 2011), Environmental Product declaration (EPD) of the materials as well as energy simulation Software (LIDER, 2010) can be used.

Indicator **I₃** *energy consumption* accounts for the amount of energy consumed according to this simplified LCA and embracing two of the four phases: *manufacturing* and *construction*. This indicator excludes energy consumption during operation phase, because this is considered in the thermal performance indicator (**I₈**). This is because indicators should be independent from each other. Energy consumption during demolition phase is reported by Pons & Aguado (2012) and Wadel & Pons (2011) to be negligible when compared to that associated with the previous phases, these being less than a 3%.

Indicator **I₄** *CO₂ Emissions* stands for the amount of CO₂ emissions produced during the same two phases considered for **I₃** (manufacturing and construction).

Indicator **I₅** *Waste* assesses the total amount of waste material remaining from the construction (assembly) and demolition (disassembly) phases.

Water consumption associated to the production and construction of the facade is minor, below 0.01%, when compared with that consumed during the use phase of the building (Crawford & Pullen, 2011; Pons & Aguado, 2012). In consequence, this indicator was excluded from the decision-making tree due to the lack of representativeness.

Social Requirement

The social requirement (**R₃**) assesses the impact of facades on users' health and comfort as well as the involved third parties. The social requirement consists of four criteria and seven indicators.

Safety indicators are aimed at assessing the robustness of the facade against natural and man-made disasters.

The indicator *natural disaster risk* (**I₆**) evaluates the resilience of facade systems against natural disasters such as earthquake, typhoon, tsunami, etc. This indicator is directly related to the case study's location. In some countries and cities that are not prone to serious disasters the relative importance of this indicator (weight) can be reduced, or even discarded. While, it should be considered as an important indicator in the countries which can be subjected to natural disasters. Depending on the location and the related potential disaster or disasters, decision maker should propose suitable strategy for evaluating this indicator.

The indicator *extra fire performance* (**I₇**) is considered in this study as one of the most important man-made disasters. **I₇** is meant to add value and promote those facade alternatives with higher fire resistance above that established by the standards. In most of the national and international standards, fire resistance is mainly measured in minutes and expresses the durability of the building components - such as exterior walls - that are exposed to fire.

In this study, the added value for fire performance of facades is suggested to be evaluated through Equation (3.1.):

$$\Delta_{\text{red.}} = T_{\text{alt}} - T_{\text{ref}} \quad (3.1)$$

- T_{alt} : Fire resistance of the alternative (min)
 T_{ref} : Minimum fire resistance taken as reference based on standards (min)

If the result became a negative number, it means that the alternative does not even meet minimum standards and consequently satisfaction would be zero.

It should be mentioned that the author agrees with many researchers who believe that sustainability approach goes beyond the minimum code requirements (Persily and Emmerich, 2012; Spellerberg *et al.*, 2012; Figge and Hahn, 2004). In fact, it would be meaningless to assess sustainability of a building that does not even meet minimum standards. According to Wes Sullens (2018), director of codes technical development at USGBC, it is necessary to step forward beyond existing codes-mandated minimums in order to achieve the aim of greening all buildings within this generation. Spellerberg *et al.*, (2012) in their book also mentioned that even rating tools aim to go beyond the existing building code to set a new definition of standard practice in the industry.

In this respect, this study considered the added value for the sustainability assessment of the indicators that are related to building codes and minimum standards have been established for them. For example, this is the case of fire, noise and heat transfer. In this way, a facade system that goes beyond the current building codes will receive higher sustainability rate than another facade that is constructed satisfying minimum standards.

Is *skilled labor requirement* indicator assesses the need of on-site skilled labor for assembling facade systems. This indicator is intended to evaluate the construction time-efforts and assembly easiness of facade systems. The latter is related to advanced technology and automatization of the construction process. Therefore, a system that requires the minimum number of on-site skilled labors is the most self-sufficient (Wallbaum *et al.*, 2012). According to Patman *et al.*, (1968), industrialized building systems have demonstrated their ability to utilize unskilled or semi-skilled manpower with comparatively limited training; therefore, these can offer substantially increasing of the construction output with only modest increase in the total on-site labor force.

In order to assess this indicator, the following questionnaire was proposed based on seminars with multidisciplinary engineers who collaborate in the construction sector, including: architects, engineers, contractors and project managers. A measurable scale of 0 to 10 is used to rate the need for on-site skilled labor for assembling facade systems. The higher the score, the higher need for on-site skilled labor is and thus, the lower satisfaction level of stakeholders.

Table 3.3 presents this questionnaire, which enables decision makers to carry out a quick and precise assessment.

Table 3.3. Proposed questionnaire for assessing the on-site skilled labor indicator.

Assessing the need for on-site skilled labor	Score
Is the assembly/construction of the facade based on a traditional or a prefabricated system? <input type="radio"/> 100% industrialized (0.0) <input type="radio"/> 30% traditional-70% industrialized (0.5) <input type="radio"/> 50/50 (1.0) <input type="radio"/> 70% traditional-30 % industrialized (1.5) <input type="radio"/> 100% traditional (2.0)	0.0-2.0
Does the labor (installer) need specialized training for construction/installation of the facade? <input type="radio"/> No (0.0) <input type="radio"/> Yes (2.0)	0.0-2.0
Does the labor (installer) need work experience for the installation of facade systems? <input type="radio"/> No need (0.0) <input type="radio"/> 1-3year (0.5) <input type="radio"/> 3-5 years (1.0) <input type="radio"/> 5-7years (1.5) <input type="radio"/> More than 7 years (2.0)	0.0-2.0
Rate of detail and complexity of the studied facade system assembly process <input type="radio"/> No complexity (0.0) <input type="radio"/> Low (0.5) <input type="radio"/> Average (1.0) <input type="radio"/> High (1.5) <input type="radio"/> Very high (2.0)	0.0-2.0
How many skilled labors are needed for the assembly process of the facade? <input type="radio"/> No need (0.0) <input type="radio"/> 1 skilled labor (0.5) <input type="radio"/> 2 skilled labors + 1 simple (1.0) <input type="radio"/> 2 skilled labors (1.5) <input type="radio"/> More than 2 (2.0)	0.0-2.0

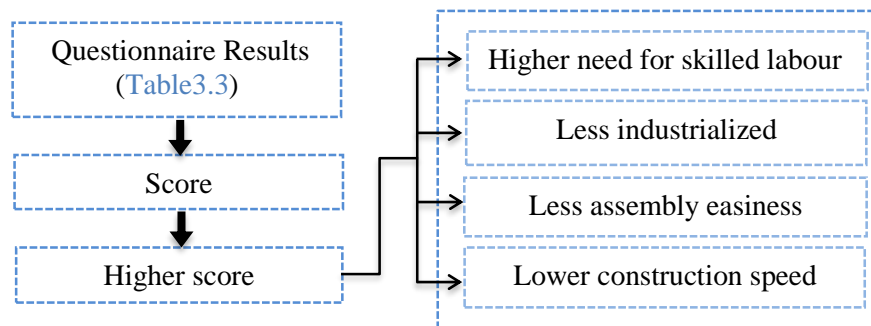


Fig.3.3. Interpretation of the results obtains from Table 3.3.

Io *extra thermal performance* indicator is meant to add value and promote those facade alternatives with higher resistance to heat flow above that established by standards. As already explained, thermal performance of the facade systems can have a significant impact on reducing annual energy demand (Iribarren *et al.*, 2016; Monge-Barrio & Sánchez-Ostiz, 2015). The transfer of heat and air infiltration through facades affects the hydrothermal conditions of the indoor environment and consequently, this transfer affects the energy consumption of HVAC systems to achieve and maintain the comfort levels demanded by users (Fanger, 1970; Aznar *et al.*, 2018)

In this study, the added value for thermal performance of facade systems is going to be evaluated through the Equation (3.2):

$$\frac{\Delta_{\text{red}}}{\Delta_{\text{req}}} = \frac{U_{\text{ref}} - U_{\text{alt}}}{U_{\text{ref}}} \times 100 \quad (3.2)$$

- U_{alt}** : U-value (heat transfer coefficient) of the alternative (W/m²K).
U_{ref} : Maximum heat transfer coefficient (Max U-value) based on standards

If the result became a negative number, it means that the alternative would not meet minimum standards and consequently satisfaction would be zero.

I₁₀ extra acoustic performance indicator considers the added value for noise damping capacity of facade alternatives by comparing the air-borne soundproofing with that required into the standard of reference. Therefore, this indicator has an approach similar to I₆ and I₈ Equation (3.3).

$$\Delta_{\text{red}} = \text{NoiseDC}_{\text{alt}} - \text{Noise DC}_{\text{ref}} \quad (3.3)$$

- DC_{alt}** : Noise damping capacity of the alternative (dB).
DC_{ref} : Minimum Noise Damping Capacity based on standards (dB)

If the result became a negative number, it means that the alternative would not meet minimum standards and consequently satisfaction would be zero.

I₁₁ day light comfort indicator measures whether the sufficiency of the daylight for occupants to carry out normal activities during the day. Daylighting provides many benefits on various aspects such as reducing energy demand, enhancing human productivity, and supporting human health and well-being (Boyce *et al.*, 2003; Leslie, 2003; Van Bommel & Van den Beld, 2004).

One of the oldest approach for daylight assessment is Daylight Factor(DF) (refer to Equation (3.4), defined as the ratio between the light levels inside a structure to the light level outside the structure under CIE standard overcast sky conditions (Baker & Steemers, 2002).

$$DF = (E_i / E_o) \times 100\% \quad (3.4)$$

- E_i** : Illuminance due to daylight at a point on the indoors working plane.
E_o : Simultaneous outdoor illuminance on a horizontal plane from an unobstructed hemisphere of overcast sky.

Calculating Daylight Factor requires complex repetition of calculations and this is generally undertaken using a complex software tool such as Radiance, a lighting simulation program with vigorous validation (Mardaljevic, 1995), which includes a

renderer as well as other tools for measuring simulated light levels. This approach is too high time consuming to be applied in this sustainability assessment tool for the assessment of residential buildings.

Another way to assess daylight is to use Average Daylight Factor (ADF), which is easier and faster than the previously mentioned computer-based approach Daylight Factor.

ADF is defined by Littlefair (1991) as;

“Ratio of total daylight flux incident on the working plane to the area of the working plane, expressed as a percentage of the outdoor illuminance on a horizontal plane due to an unobstructed CIE Standard Overcast Sky”.

It can be calculated through Equation (3.5) proposed by Crisp & Littlefair (1984) from the BRE (Building Research Establishment, UK). Previous studies studied the accuracy of this formula and claimed that this formula gave results with a standard error of $\pm 10\%$ of the measured values (Bonaiuti & Wilson, 2007).

$$\text{BRE ADF} = \frac{T A_w \theta}{A (1-R^2)} \% \quad (3.5)$$

- T** : Diffuse visible transmittance of the glazing.
A_w : Net glazed area of the window (m²).
θ : The angle of visible sky(°).
A : Total area of the room surfaces: ceiling floor, walls and windows (m²).
R : Their average reflectance of room surfaces i.e. walls, floors, ceilings.

ADF is measured in percentage and categorized into 3 parts (Yarham & Wilson, 1999):

- Under 2% – Not adequately lit and, in consequence, artificial lighting is required.
- Between 2% and 5% – Adequately lit but artificial lighting may be needed part of the time.
- Over 5% – Well lit and artificial lighting is generally not required, except at dawn and dusk.

ADF it is now widely used for daylight assessment by various rating tools such as BREEAM (Building Research Establishment Environmental Assessment Method) as the most recognized method for sustainable design rating and sustainability assessment. It is also used in the British Standard Code of Practice for daylighting (British Standard, 1992) as a means for assessing the daylight in a space as well as CIBSE (The Chartered Institution of Building Services Engineers).

Considering all the aforementioned, this thesis uses the BRE ADF to quantify the daylight quality in interior spaces because it allows decision makers a quicker way to assess the daylight performance of interior spaces.

I12 contextual compatibility indicator evaluates the rate of harmony between the facade alternative and its neighborhood by considering physical and objective parameters that can affect the visual compatibility of facade.

According to Brown *et al.*, (2003), contextual compatibility can considerably affect many aspects of the urban experience, including urban quality, urban landscape, urban housing and urban neighborhood. Many authors and designers (Cullen, 1961; Brolin, 1980; Tugnutt & Robertson, 1987) have also commented on the need to fit new buildings into existing visual contexts. Brown *et al.*, (2003), in his book mentioned that contextual compatibility between individual houses and their surrounding houses are usually more important than the attributes of the houses themselves. He also indicated that people mainly like homogeneous blocks over blocks with different buildings even if, in isolation, they prefer each or some of the different buildings in particular.

As Previous studies (Groat, 1988; Utaberta *et al.*, 2012) indicated, facade is one of the main building components that can considerably affect impressions of contextual compatibility. In this respect, this indicator aims to investigate the rate of compatibility between the facade and its neighborhood.

To this end, a questionnaire was defined in 2 phases as explained below;

First, through reviewing previous literature (Nasar, 1994; Topcu & Kubat, 2009; Stamps, 1991; Sanoff, 1991; Berlyne & Madsen, 1973; Hui, 2007) the main elements, which when used will create harmony between new and existing buildings were determined as shown in [Table 3.4](#). This identified elements can have significant impact on achieving visual connectivity between new and existing buildings. For example, Hui (2007), through conducting a survey of public evaluation toward the city image in China, revealed that style, color, volume and material of the facades are challenging and crucial visual elements that can have considerable effects on judgments of compatibility.

Then, based on seminars with architects - both practitioners and researchers -, the following questionnaire was proposed ([Table 3.4](#)). A measurable scale of 0-5 is used to rate the compatibility of facade with its built neighborhood. The higher the score, the more compatibility is established between the facade alternative and its nearby buildings. This questionnaire enables decision makers to evaluate the rate of harmony between the facade alternative and its built neighborhood quickly and precisely.

Table 3.4. Proposed questionnaire for assessing the contextual compatibility between facade alternatives and its nearby buildings.

Objective parameters that can affect the visual compatibility facade-neighborhood	Score
<p>1. Form: Similarity between the facade alternative and other facade systems in the neighborhood in terms of form. In the process of scoring, the following issues are considered:</p> <ul style="list-style-type: none"> - Facade form - Shape and size of the openings. - Projections and recesses from the facade plane, considering the form and size of terraces, balconies. <ul style="list-style-type: none"> ○ $X < 25\%$ (0) ○ $25\% \leq X \leq 75\%$ (0.5) ○ $X > 75\%$ (1) 	0-1
<p>2. Color and texture Similarity between the facade alternative and other facade systems in the neighborhood in terms of color & texture.</p> <ul style="list-style-type: none"> ○ $X < 25\%$ (0) ○ $25\% \leq X \leq 75\%$ (0.5) ○ $X > 75\%$ (1) 	0-1
<p>3. Scale (size): Similarity between the facade alternative and other facade systems in the neighborhood in terms of size.</p> <ul style="list-style-type: none"> ○ $X < 25\%$ (0) ○ $25\% \leq X \leq 75\%$ (0.5) ○ $X > 75\%$ (1) 	0-1
<p>4. Material Similarity between the facade alternative and other facade systems in the neighborhood in terms of material.</p> <ul style="list-style-type: none"> ○ $X < 25\%$ (0) ○ $25\% \leq X \leq 75\%$ (0.5) ○ $X > 75\%$ (1) 	0-1
<p>5. Design Style and decoration Similarity between the facade alternative and other facades in the neighborhood in terms of architectural style.</p> <ul style="list-style-type: none"> ○ $X < 25\%$ (0) ○ $25\% \leq X \leq 75\%$ (0.5) ○ $X > 75\%$ (1) 	0-1
X= amount of similarity between the Facade alternative and other facade systems in the neighborhood	0-5

I13 *visual quality* indicator aims to assess and rate the visual quality of the facade alternative through a questionnaire survey as well. In other words, this indicator assesses the factors that have positive affect on aesthetic preferences of observers and users and enhance the visual quality of facades.

In this respect, as a first step, through an extensive review of previous literature, the most preferred factors that could greatly influence the observers' aesthetic judgments were identified; these being medium complexity, originality, details quality and proportionality (Table 3.5).

Medium complexity is defined as neither very simple facade nor very complex that could lead to chaos (Berlyne, 1971; 1974). Berlyne (1971) was probably the first person who investigated the effect of complexity on aesthetic preference and proposed the existence of an Inverted-U-shaped relationship between the two. This researcher hypothesized that objects with a medium level of complexity are preferred over very complex or very simple objects.

Many studies have been carried out to assess the relation between aesthetic preference and complexity and most of them confirmed Berlyne's hypothesis (Ilbeigi & Ghomeishi, 2017; Imamoglo, 2000; Wohlwill, 1975; Akalin *et al.*, 2010; Munsinger and Kessen, 1964; Aitken, 1974; Vitz, 1966; Nasar, 2002; Roberts, 2007; Saklofske, 1975; Gifford *et al.*, 2002; Ulrich, 1983; Kaplan, 1987). Imamoglu (2000) in his study indicated that for both architects and non-architects, medium complexity produces highest satisfaction, whereas low or high complexity produces the lowest. Nasar (2002) also did a research on the relation between attractiveness and complexity and revealed that people had tended to rate intermediately complex buildings as the most attractive, and that they had rated simple and highly complex buildings as less attractive. He concluded that these results support Berlyne's prediction concerning the relation between preference and complexity.

According to previous studies (Berlyne *et al.*, 1968; Roberts, 2007; Nicki and Moss, 1975), there are 3 main aspects that can contribute to the subjective impression of complexity:

- Amount and variety of elements, in terms of colors and 3-dimensional appearance.
- Organization: related with how the elements are grouped to form identifiable objects and how these are organized into a coherent scene.
- Asymmetry.

These aspects can be considered for assessing medium complexity of facade alternatives.

Originality in previous studies is mainly defined as a positive innovation and change of an established trend, style and ornament among others (Gifford, 2000; Ghomeshi *et al.*, 2012; Nasar, 1994; Brown & Gifford, 2001; Nadoushani *et al.*, 2018).

Ibeigia and Ghomeishia (2017) demonstrated in their study that innovativeness and simplicity are the most important preferred factors influencing the aesthetic preference of building's facade for both architects and non-architects. They also mentioned that this simplicity does not mean absence of complexity in the facade; it rather indicates medium complexity of a facade. Their study actually confirms the studies carried out by Gifford (2000) and Ghomeshi *et al.*, (2012) whom suggested that originality greatly influence the non-architects' total aesthetics judgment.

Details quality stands for the quality of the installation and assembly of materials in the facade systems (da Luz Reis & Dias, 2010; Zinas & Jusan, 2012; Hui, 2007; Nadoushani *et al.*, 2018).

Proportionality refers to the right and harmonious relationship from one part to another or the whole as a good unity visually. In this study, this factor prioritizes those solutions that satisfy the observers' sense of proportion between different parts of a facade (Stamps, 1999; Hui, 2007).

In the explanations above, this thesis identified the four factors that can positively affect the visual quality of facades. Then, the questionnaire presented in [Table 3.5](#) was designed based on seminars with architects - both practitioners and researchers. A

measurable scale of 0-4 is used to rate the visual quality of facade alternatives with its built neighborhood. This questionnaire can help decision makers to quickly and objectively evaluate the visual quality of facade alternatives.

Table 3.5. Proposed questionnaire for assessing the visual quality of facade in its neighborhood

Factors affecting the observers' facade aesthetic judgments	Score
Originality X= level of innovation of the facade alternative in comparison to other facades in the neighborhood. <ul style="list-style-type: none"> ○ $X < 25\%$ (0) ○ $25\% \leq X \leq 75\%$ (0.5) ○ $X > 75\%$ (1) 	0-1
Medium complexity <ul style="list-style-type: none"> ○ Simple / very complex (0) ○ Medium level of complexity (1) 	0-1
Details quality X= Percentage of high-quality details in the facade alternative. <ul style="list-style-type: none"> ○ $X < 25\%$ (0) ○ $25\% \leq X \leq 75\%$ (0.5) ○ $X > 75\%$ (1) 	0-1
Proportionality: X (%) = Level of proportionality between different parts of the facade alternative. <ul style="list-style-type: none"> ○ $X < 25\%$ (0) ○ $25\% \leq X \leq 75\%$ (0.5) ○ $X > 75\%$ (1) 	0-1
	0-4

It should be mentioned that the aesthetic criteria (C7), that includes 2 indicators of contextual compatibility (related to urban housing) and visual quality (related to facade itself), has always been a never end subject of discussion in architectural theory because it deals with problems of perception, taste, and judgment. In the proposed MIVES-based approach, the author aimed to propose objective and reliable solutions for assessing the aforementioned indicators through extensive review of previous literature. This approach aims to enable decision-makers to carry out a fast and precise evaluation that lets them to make the best decision.

All the proposed strategies explained in this section are applicable to any locations. Nevertheless, it should be noted that, for assessing environmental and economic indicators, regarding to other locations, an appropriate local database has to be used in each location.

3.4.2. Value functions

The main objective of a value functions is to homogenize the indicators units and facilitate the satisfaction (value) assessment of the indicators, including the minimization of subjectivity of this procedure. Defining the value function implies establish preferences or the degree of satisfaction produced by a certain alternative option for a certain variable, the indicator.

Incorporating value functions and satisfaction concepts makes MIVES different from other available MCDMs. Moreover, through translating the stakeholders' needs and

satisfaction by means of the value functions, MIVES covers the sustainable development crucial concept which aims to satisfy human needs for present and future generations.

To determine the satisfaction value for an indicator, the MIVES model (Ministerio de Ciencia y Educacion, 2005, 2009, 2010; Pons *et al.*, 2016) outlines a procedure consisting of:

- Stage 1. Definition of the tendency of the value function: increasing or decreasing.
- Stage 2. Definition of the points corresponding to S_{min} and S_{max} .
- Stage 3. Definition of the value function's shape: linear, concave, convex or S-shaped among
- Stage 4. Definition of the mathematical expression of the value function.

Stage 1: Definition of the tendency of the value function: increasing or decreasing.

The value function (Fig.3.4) can be increasing or decreasing depending on the nature of the indicator (or variable) to be evaluated. An increasing function is used when an increase in the variable results in an increase in the decision-maker's satisfaction. In contrast, a decreasing value function shows that an increase in the measurement unit causes a decrease in satisfaction.

Examples of indicators with a decreasing tendency include economic cost, or emissions to the environment.

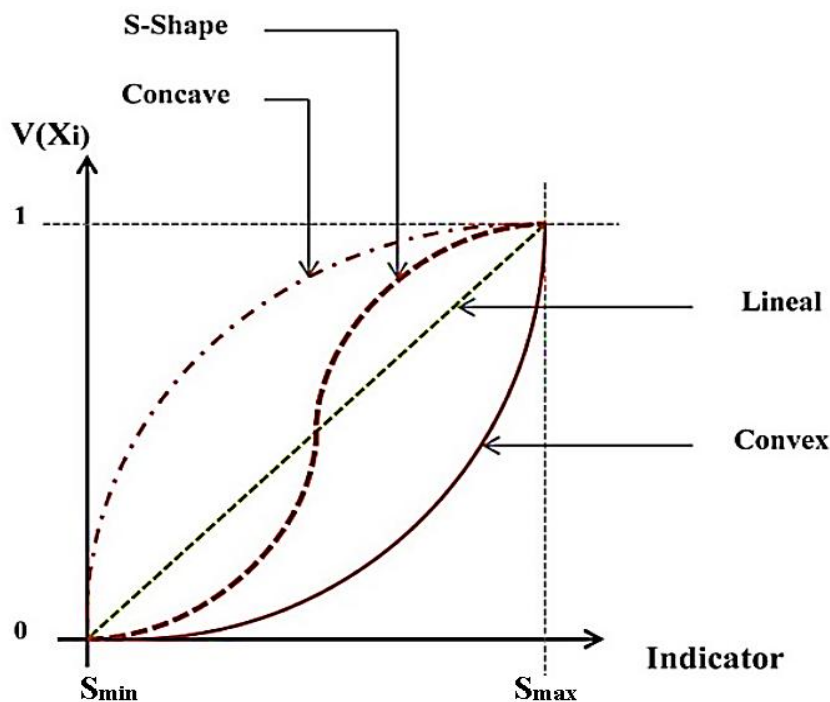


Fig. 3.4. Different shapes of value functions. Adapted from "Multi-criteria decision-making method for assessing the sustainability of post-disaster temporary housing units technologies: A case study in Bam, 2003" by Hosseini *et al.*2015.

Other value functions could have a mixed tendency (ex., increase at first but later decrease). This type of function is characteristic of indicators with two points of minimum satisfaction and one maximum in between, as explained in the following section.

Stage 2: Definition of the points of minimum (S_{min}) and maximum satisfaction (S_{max})

The points of minimum and maximum satisfaction define the limits of the value function on the x -axis: S_{min} and S_{max} , points of minimum and maximum satisfaction, respectively. These points have a satisfaction value of 0.0 (S_{min}) and 1.0 (S_{max}). These limits correspond to the satisfaction values and not necessarily to the minimum and maximum values of the measurement variables, which may have (and will generally have) a wider range.

These points are usually established according to three criteria: (1) existing rules and regulations; (2) experience with previous projects, and (3) the value produced by the different alternatives with respect to the indicator.

Fig.3.5 presents the value function of the indicator comfort temperature for offices buildings. This indicator has two points of minimum satisfaction and only one maximum.

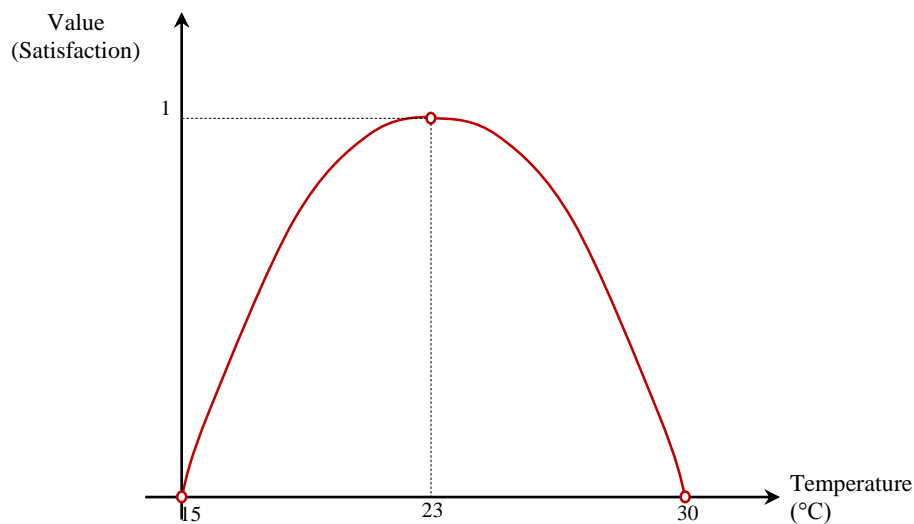


Fig. 3.5. Function with two minimum points and only one maximum. Adapted from " A Value Function for Assessing Sustainability: Application to Industrial Buildings" by Alarcon *et al.* 2011.

Stage 3: Definition of the value function shape (linear, concave, convex, S-shaped)

Given that so far two coordinate points, S_{min} and S_{max} , have been defined, the objective of this stage is to connect these using functions. Four types of functions (Fig. 3.4) are suggested: concave, convex, linear and S-shaped. These four curves represent the most common relationships that can be found in practice. These allow modeling different behaviors of stakeholders regarding the indifference, aversion or attraction to risk with respect to the decisions to be made, in addition to the different strategies that can be defined in order to promote improvement of indicators.

A concave curve is used when, starting from a minimum condition, satisfaction rapidly increases at first in relation to the indicator. In this case, this functions lead to satisfaction to be very sensitive to small changes around the point that generates minimum satisfaction. This type of relationship is chosen when it is more important to move away from the point of minimum satisfaction than to approach the point of maximum satisfaction.

A convex function is appropriate when there is hardly any increase in satisfaction for small changes around the point that generates minimum satisfaction. It is used when it is more important to approach the point of maximum satisfaction than to move away from the point of minimum satisfaction. This type is often used for economic or environmental indicators since the aim is to ensure that the alternatives are located as close to the point of maximum satisfaction as possible.

A linear function reflects a steady increase in the satisfaction produced by the alternatives. There is a proportional relationship throughout the range. This function is the default option when no specific criteria can be defined.

An S-shaped function is a combination of the concave and convex functions. A significant increase in satisfaction is detected at central values, while satisfaction changes little as the minimum and maximum points are approached.

Stage 4. Definition of the mathematical expression of the value function

MIVES uses Equation (3.6) as the basis for defining individual value functions V_i .

$$V_i = K_i \cdot \left[1 - e^{-m_i \cdot \left(\frac{|S_{i,x} - S_{i,min}|}{n_i} \right)^{A_i}} \right] \quad (3.6)$$

In Equation (3.7), variable K_i is a factor that ensures that the value function will remain within the range of [0.0-1.0] and that the best response is associated with a value equal to the unit (see Equation (3.7)).

$$K_i = \frac{1}{1 - e^{-m_i \cdot (|S_{i,max} - S_{i,min}|/n_i)^{A_i}}} \quad (3.7)$$

In Equation (3.6) and (3.7):

- $S_{i,max}$ & $S_{i,min}$** : maximum & minimum points in the scale of the indicator under consideration.
- $S_{i,x}$** : the score of alternative x that is under assessment, with respect to indicator i under consideration, which is between $S_{i,min}$ and $S_{i,max}$. This score generates a value that is equal to $V_i(S_{i,x})$, which has to be calculated
- A_i** : the shape factor that defines approximately, in this case, whether the curve is *concave* ($A_i < 1.0$), whether it tends to be a *straight line* ($A_i \approx 1.0$), or whether it is *convex* or *S-shaped* ($A_i > 1.0$).
- n_i** : the value that is used, if $A_i > 1.0$, to build *convex* or *S-shaped* curves as it coincides approximately with the value of the abscissa on which the inflection point occurs
- m_i** : the value of the ordinate for point n_i , in the former case where $A_i > 1.0$.

Once fixed the shape of the value function, in case the slope is unclear, it may be defined by a working group. When this is the case, several value functions may initially be defined according to the proposals given by each or some of the members of the group for the measurement variable (indicator). This means that rather than a single function, a family of functions is obtained (Fig.3.6).

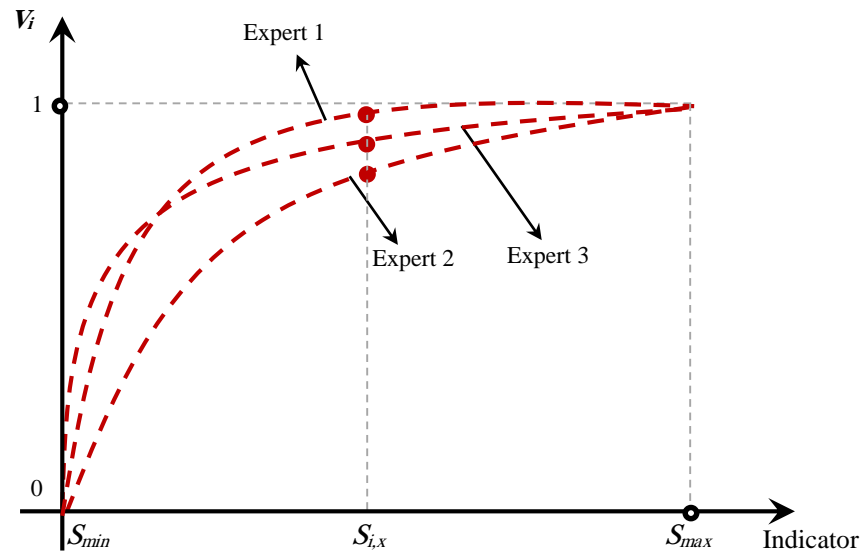


Fig.3.6. Value function generated by a working group composed of different decision-makers. Adapted from "A Value Function for Assessing Sustainability: Application to Industrial Buildings" by Alarcon *et al.* 2011.

As shown in Fig.3.6, several values on the y-axis - one for each initial value function - correspond to the value labeled $S_{i,x}$. As these values are obtained, it is necessary to establish another value that allows each alternative to be evaluated. The simplest way to do this is to take the mean of the different values, after excluding extreme cases if needed. The parameters A_i , n_i and m_i can then be estimated through a minimum squares approach. It is also possible to work with a range of values in such a way that two values correspond to each y-value: the mean and the standard deviation. This would call for a statistical approach in the subsequent decision-making process.

According to the above-mentioned explanations, the value function for each defined indicator was determined which will be discussed in detail in Chapter 4.

3.4.3. Weights assignment

Once the value functions have been defined, as the third step, it is necessary to estimate weights α_i , β_i , and γ_i for each branch of the requirements tree (Fig.3.2), these representing the preference, respectively, of certain indicator (γ_i), criterion (β_i), and requirement (α_i).

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). Alternatively, (or even complimentary), other methods (ex., DELPHI) can be alternatively used (Casanovas-Rubio & Armengou, 2018).

As explained in section 2.4.3, the AHP method enables the most consistent weighting judgments (Pons *et al.*, 2016; Hopfe *et al.*, 2013). Applying AHP helps to organize the process efficiently, to reduce the model complexity and subjectivity and decrease possible disagreements between the team members (Del Caño *et al.*, 2015). To this end, the participation of all stakeholders in the decision-making process is required (Kapucu & Garayev, 2011). Afterward, to compensate for possible subjective bias, a subsequent process of analyzing, comparing, and—if appropriate—modifying the resultant weights is recommended.

In this study, in order to facilitate decision makers task, a questionnaire was defined for assigning weights to the parameter of the tree which is fully explained in [Appendix A](#). This questionnaire would be applicable for any location.

3.5. Third phase of the proposed approach

In the last phase of the proposed MIVES based approach, after defining the alternatives and applying all the aforementioned stages, the Sustainability Index (SI) of each alternative is computed by means of using Equation (3.8):

$$SI = \sum_{i=1}^{i=N} \alpha_i \cdot \beta_i \cdot \gamma_i \cdot V_i(S_{i,x}) \quad (3.8)$$

- α_i, β_i and γ_i : The weights of each requirement, criterion and indicator.
- $V_i(S_{i,x})$: The value of the alternative x with respect to a given indicator i
- N : The total number of indicators.

In general, all the aforementioned phases - the multi-criteria tree and the weights - should be determined before assessing the alternatives for the sake of the objectivity and transparency of this method. Once these elements are established, each alternative can be assessed to derive an integrated sustainability.

3.6. Conclusion

This third chapter of the thesis presents a MIVES-based approach oriented to objectively assess the sustainability of facades, considering and quantifying those representative indicators belonging to the economic, environmental and social pillars.

The proposed approach would be an appropriate method for facade assessment since it fulfills all the requirements for a facade assessment tool. In fact, since the selection of an optimal facade system is a multi-criteria and multi participant procedure, applying the proposed approach enables decision-makers to consider both parameters - multi-criteria and multi participant - in the assessment and selection process of facade systems. Moreover, the proposed approach covers the basic principles of the sustainable development concept through considering the three pillars of sustainability for facade assessments, as well as stakeholders' needs and satisfaction in the decision-making process.

The overall proposed approach, which includes three main phases, is applicable for any type of facade in any country with diverse characteristics. In this study, it was specifically optimized for sustainability assessment of residential building facades.

The first phase aims to identify the most important indicators for sustainability assessment of the facade alternatives. In this case, the 13 most representative indicators were identified for the sustainability assessment of residential facades.

The second phase aims to define and propose some strategies for calculating the identified indicators as well as defining the indicators value functions and the decision-making tree weights. In this case, the author proposed some strategies for calculating all 13 indicators. The proposed strategies are based on the extensive review of previous literature as well as consulting with experts, including professors, multidisciplinary engineers and practitioners from the construction sector. Therefore, these calculating strategies are reliable and other researcher can apply them for facade assessment in any location. This second phase also explained in detail the value functions calculation procedure (section 3.4.2) as well as the weighting system (section 3.4.3).

The last phase enables to compute the Sustainability Index (SI) of each alternative via the proposed formula (section 3.5). Besides calculating the overall sustainability index of the alternatives, this model also makes it possible to calculate economic, social and environmental satisfaction indexes separately. In this case, weaknesses and strengths of each alternative can be identified from economic, environmental and social points of view.

In the next chapter, the proposed MIVES-based approach is applied for the sustainability assessment of residential facade systems in Barcelona as an example of application as well as to validate and calibrate the proposed approach.

Chapter 4

Sustainability assessment of the residential facades in Barcelona to validate the MIVES-based approach proposed in Chapter 3

4.1. Introduction

In the previous chapter, a novel MIVES-based approach was designed for assessing the sustainability of facade systems, which has been specifically optimized for residential building facades. This chapter aims to validate both the suitability and effectiveness of the proposed approach by means of the analysis of the five most commonly used residential facade systems in Barcelona, Spain.

As mentioned, this approach was optimized for residential buildings since the housing sector has proven to be the most representative sector from the sustainability point of view (Pérez-Lombard *et al.*, 2008; Lowry, 1990; EPBD, 2010). Nonetheless, the applicability of the proposed approach is also extendable to other uses (ex., offices,

commercial centers, among others) and other locations by including the appropriate indicators and adjusting the weights to the involved stakeholders' preferences.

On the other hand, the case studies were selected from Barcelona since this city along with its metropolitan area is one of the biggest city in Spain and also one of the largest metropolises in Europe and the Mediterranean area (Trullen & Boix, 2008; Montagut, 2012; Barna, 2018).

4.2. Case study: Facade systems in the residential buildings of Barcelona

In this study, 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. With the objective of validating the approach, 5 facade systems were identified as the most commonly used facade systems (FS, hereinafter) for residential uses in Barcelona (CTE, 2006; Loga *et al.*, 2012, 2010; Häkkinen, 2012; Pérez-Bella *et al.*, 2015); these systems are listed below:

- FS-A, Fig.4.1.a: single-leaf wall of solid brick masonry with double glazed aluminum windows.
- FS-B, Fig.4.1.b: brick cavity wall without insulation with double glazed aluminum windows.
- FS-C, Fig.4.1.c: brick cavity wall with insulation with double glazed aluminum windows.
- FS-D, Fig.4.1.d: concrete block cavity walls with insulation & double-glazed aluminum windows.
- FS-E, Fig. 4.1.e: precast concrete panel with double glazed aluminum windows.

The composition of the opaque parts of the FSs are explained in detail in Fig.4.1.

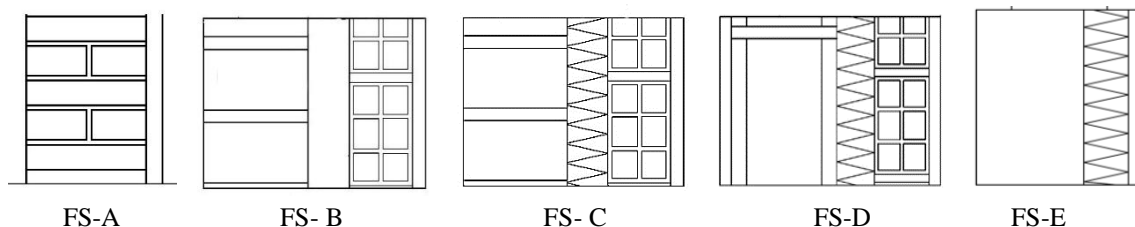


Fig.4.1. Theoretical layers of the opaque part from outside to inside (a) 30 cm solid brick wall, 1.5 cm gypsum plaster; (b) 11.5 cm perforated facing brick, 4 cm air cavity without insulation, 7 cm hollow clay brick, 1.5 cm gypsum plaster; (c) 11.5 cm perforated facing brick, 6 cm expanded polystyrene (EPS), 7 cm hollow clay brick, 1.5 cm gypsum plaster; (d) 1.5 cm cement plaster, 12 cm AAC block, 6 cm polyurethane (PUR), 7 cm hollow clay brick, 1.5 cm gypsum plaster; (e) 12 cm prefabricated concrete panel, 6 cm extruded polystyrene(XPS), 1.5 cm plaster board

In general, Spanish residential building stock – and Barcelona in particular - can be classified into three categories based on the construction periods: (i) prior to 1980, when there was no thermal protection for buildings or building units; (ii) 1981-2007, when buildings or building units were built under NBE-CT 79 (Spain, 1979); and (iii) after 2008, when buildings or building units were erected under the Technical Building Code (Spain, 2006) (Table 4.1).

Table 4.1. residential building examples in different periods

Before 1980		
	<p>[Puig i Cadafalch, 1903-1905: <i>Casa de les Punxes</i>, Massive 30cm brick wall (FS-A)]. Retrieved from http://www.arxiusarquitectura.cat/arquitectura_det.php?id=723</p>	<p>[Lluís Nadal, 1966-1968: <i>Habitatges La Vinya</i>. Masonry wall without insulation (FS-B)]. Retrieved from http://www.arxiusarquitectura.cat/arquitectura_det.php?id=397</p>
1981-2008		
	<p>[d'Alfons Soldevila, 1984: <i>casa Riera MR6</i>. Masonry walls with insulation (FS-D)]. Retrieved from http://arquitectures234.blogspot.com/2010/11/casa-riera-mr6</p>	<p>[BST Arquitectos, 2004: <i>Illa del Llac</i>. prefabricated concrete panels (FS-E)]. Retrieved from https://www.escofet.com/en/projects/architectural-concrete/illa-del-llac</p>
After 2008		
	<p>[SV Arquitectura, 2010: <i>Bon Pastor</i>. Masonry wall with insulation (FS-C)]. Retrieved from http://www.arxiusarquitectura.cat/arquitectura_det.php?id=1050</p>	

FS-A and FS-B were mainly constructed before 1980 (first category), when there was no thermal protection for buildings (Gaspar *et al.*, 2016) (Table 4.1). According to Häkkinen (2012), in the 75% of the existing Spanish building stock both types were installed and these need adaptations to meet the current standards. FS-C, -D and -E were

installed mainly after 2008 (third category), when buildings were erected under the Technical Building Code (CTE, 2006; 2013; Gangolells *et al.*, 2016) (Table 4.1).

To select the case study, the following issues were taken into account:

- The FSs were just selected for a validation purpose to assess the feasibility, adequacy, accuracy and clarity of the approach, and ensure that it is reasonably robust.
- To evaluate the 5 wall systems, these systems were theoretically applied to the same reference building, and these five applications were assessed. This reference building is a real residential block onto which the 5 wall systems were theoretically considered as replacement of the existing opaque part, whilst the rest of the building was considered unaltered. This reference residential block is Neinor project, located at Nou Barris district in Barcelona, Spain. All the information regarding this project is presented in detail in the next chapter.

In consequence, only the opaque parts are different, while the opening systems are the same.

The characteristics of the materials that compose the analyzed FSs are reported in Table 4.2.

Table 4.2. 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	0.57	26.93	4.65	CTE, 2013; BEDEC, 2019
Cement mortar (1:6)	1650	0.8	19.45	3.61	
Gypsum board	800	0.25	99.4	6.55	
AAC block	500	0.16	370.80	35.52	Hammond & Jones, 2011; BEDEC, 2019
Perforated facing brick	1550	0.4	36.12	23.22	
Hollow clay brick	1200	0.35	223.62	16.96	
Prefabricated concrete panel	2100	1.44	759.42	71.51	CTE,2013; BEDEC, 2019
Polyurethane(PUR)	24	0.04	352.8	52.07	
EPS	23	0.039	147.42	21.76	
XPS	35	0.033	221	32.64	
Double glazed AL window (4/12/6)	-	0.042	4559	504	

4.3. Application of the proposed sustainability assessment approach to the case studies

As mentioned in the previous chapter, the proposed approach includes three main phases. In the following sections, the results obtained from the application of each phase on the 5 FSs will be explained in detail.

4.3.1. Phase one: definition of the decision-making tree

The aim is to assess sustainability of commonly used residential FSs in Barcelona. Regarding the decision-making tree, this was defined in Chapter 3 (Fig.3.2), which includes the most representative indicators for sustainability assessment of residential building facades. It should be noted that the indicator *natural disaster risk* was discarded since Barcelona, in the current context, is not prone to any serious natural disaster (Table 4.3).

Table 4.3. Decision-making tree for sustainability assessment of residential building facades in Barcelona

Requirement (α_i)	Criteria (β_i)	Indicators (γ_i)
R ₁ . Economic (0.34)	C ₁ . Cost (1.00)	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 (1.00)
	C ₃ . Emissions (0.32)	I ₄ . CO ₂ emissions (1.00)
	C ₄ . Waste (0.29)	I ₅ . Total solid waste (1.00)
	C ₅ . Safety (0.29)	I ₆ . Extra fire performance (1.00)
R ₃ . Social (0.33)	C ₆ . Labor availability (0.18)	I ₇ . Skilled labor requirement (1.00)
	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)	

4.3.2. Phase 2: quantification of the decision-making tree components

As explained in Chapter 3, this phase includes the following 3 items:

- defining each indicator and determining the measurement approach
- defining a value function for each indicator
- assigning weights to all parameters of the decision-making tree.

The results from each item will be explained in detail in the following sections.

a) *Quantification of the indicators*

The definition and quantification procedure was explained in detail in section 3.4.1. In this part, the proposed strategies are applied for measuring the indicators related to each FS. The results are presented in Table 4.4.

It is worth to mention that I₁₁ and I₁₂ were quantified based on the questionnaires proposed in Chapter 3 (Table. 3.4 and 3.5). The questionnaire survey was conducted among 17 architects and then, Grubbs' test was used to identify the outliers (Grubbs, 1950). The results of the questionnaire surveys can be found in Appendix B.

Table 4.4. Obtained results from the quantification of each indicator related to each facade system based on the proposed strategies in the previous chapter.

Indicators		FS-A	FS-B	FS-C	FS-D	FS-E	References
I ₁ (€/m ²)		184	177	188	205	190	BEDEC, 2019
I ₂ (€/m ²)		465	435	435	390	298	BEDEC, 2019; informal seminars with maintenance service of Campus Nord, UPC
I ₃ (MJ/m ²)	Opaque	1160	832	875	1027	1072	BEDEC, 2019. Hammond & Jones, 2011
	Opening	4379	4379	4379	4379	4379	
I ₄ (kgCO ₂ /m ²)	Opaque	93	68	81	101	89	
	Opening	482	482	482	482	482	
I ₅ (kg/m ²)	Opaque	13.9	16.3	18	14.5	2.8	BEDEC, 2019
	Opening	0.09	0.09	0.09	0.09	0.09	
I ₆ (min)		-	-	0.0	0.0	0.0	CTE, 2013; Based on the proposed strategy in Chapter 3 (Eq. (3.1))

I₇ (points)		6.2	7.3	7.8	6.5	2.6	Based on proposed questionnaire in Chapter 3 (Table 3.3)
I₈ (%)	Opaque	-	-	18%	33%	11%	CTE, 2013; Based on the proposed strategy in Chapter 3 (Eq. (3.2))
	Opening	38%	38%	38%	38%	38%	
I₉ (dB)		2.0	2.0	2.0	2.0	2.0	CTE, 2013; Based on the proposed strategy in Chapter 3 (Eq. (3.3))
I₁₀ (%)		6.8%	6.8%	6.8%	6.8%	6.8%	Yarham & Wilson, 1999; Based on the proposed strategy in Chapter 3 (Eq. (3.5))
I₁₁ (points)		2.8	4.0	4.0	2.9	2.7	Proposed questionnaire (Table 3.4), Appendix B
I₁₂ (points)		1.0	1.6	1.6	1.3	2.3	Proposed questionnaire (Table 3.5), Appendix B

b) *Value functions for the indicators*

This part aims to determine the value function (satisfaction value) for each indicator to homogenize the indicators units and minimize the subjectivity in the assessment. The satisfaction values are defined through a procedure consisting of 4 stages (refer to 3.4.2).

Economic indicators

Basic data corresponding to each economic indicator value function is shown in Table 4.5. The values of S_{min} , S_{max} , and the function shapes were established based on: Spanish BEDEC database (BEDEC, 2019), scientific literature, and the background of experts, including professors and multidisciplinary engineers and practitioners from the construction sector.

Table 4.5. Basic data of each economic indicator value function.

Indicators	unit	S_{max}	S_{min}	C	K	P	shape	References
I₁. Construction cost	€/m ²	480	100	240	0.8	4.3	DS	BEDEC, 2019
I₂. maintenance cost	€/m ²	1100	130	400	0.05	1.1	DL	Madureira et al, 2017; Pons & Aguado, 2012; BEDEC, 2019

Regarding the Indicator I₁, minimum and maximum construction cost (S_{min} , S_{max}) were defined through evaluating a set of 615 FSs (opaque part) and 300 openings (transparent part) gathered in BEDEC database (BEDEC, 2019) (Table 4.6) as well as holding 2 seminars with experts who collaborate with the Spanish construction industry.

Table 4.6. Obtained results from BEDEC regarding the construction cost of facade systems.

Facade components	Type of facade	Number of facades	Cost (€/m ²)		Number of facades	Cost (€/m ²)
Opaque part (615 facade systems)	Masonry walls	295 FS	70	<	280FS	< 110
			110	<	15FS	< 150
	Dry walls composed of boards	320 FS	110	<	30FS	< 150
			150	<	290FS	< 210
Transparent part (300 openings)	Openings	300 openings	150	<	openings	< 650

Likewise, since satisfaction decreases drastically when the building cost increases, a decreasing S-shape (DS) was assigned (Fig. 4.2). The curvature of the function was established according to the existing construction market in Barcelona, which is extremely competitive and costs above 150 €/m² lead to sharp reductions of stakeholders' satisfaction.

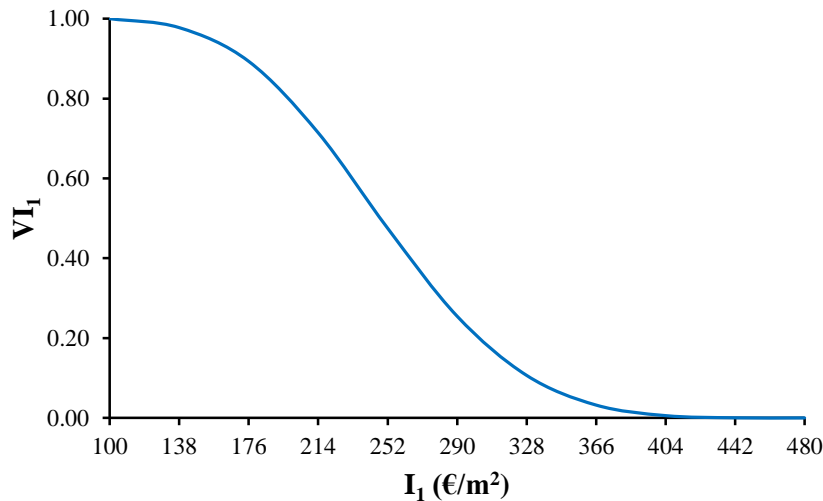


Fig. 4.2. Value function of construction cost indicator (I_1)

In regard to I_2 , S_{min} , S_{max} and shape were defined according to the maintenance plan proposed for a 50-year life span of FSs (refer to Table 3.2.). This value function definition also relied on BEDEC database (BEDEC, 2019), as well as meetings with the members of maintenance service of Campus Nord, UPC. Besides, since satisfaction decreases when the cost increases, a decreasing Linear shape (DL) was assigned (Fig. 4.3). The linear function was chosen as a default option due to the lack of information about an acceptable range of maintenance cost and reaction of stakeholders regarding the maintenance cost of facades.

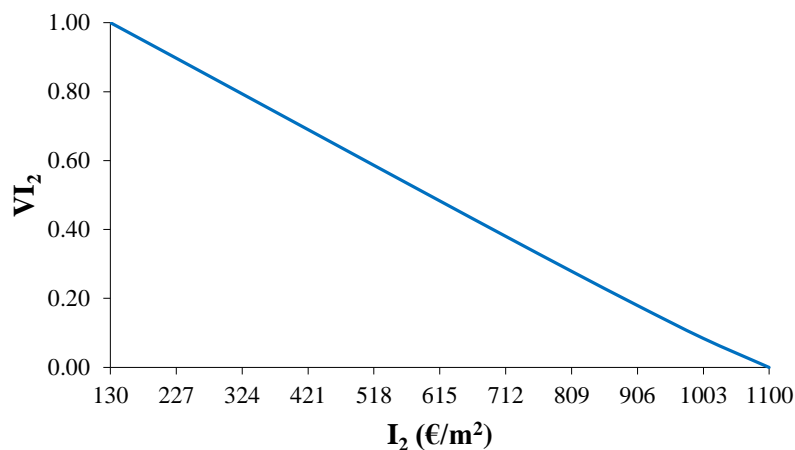


Fig.4.3. Value function of maintenance cost indicator (I_2).

Environmental indicators

Table 4.7 presents the information relating to each environmental indicator value function. As shown in Table 4.7, these three indicators and its opaque and opening parts had: 4 decrease S-shape (DS) and 2 decrease convexly (DC_{vx}). It should be mentioned

that since details, functions and environmental impacts of the opaque and opening parts are different in these indicators, in order to have a more precise evaluation, two value functions were considered for each indicator; one for the opaque and another one for the transparent part.

Table 4.7. Basic data of each environmental indicator value function.

Indicators	Unit	S _{max}	S _{min}	C	K	P	Shape	References	
I3	Opaque	MJ/m ²	1500	500	1100	8	3.5	DS	BEDEC, 2019 Hammond & Jones, 2011
	Openings		7000	700	3000	0.35	4	DS	
I4	Opaque	Kg CO ₂ /m ²	130	30	110	8.5	4	DS	BEDEC, 2019; Hammond & Jones, 2011
	Opening		700	30	445	0.9	4.3	DS	
I5	Opaque	kg/m ²	20	0	19	1	3	DC _{vX}	BEDEC, 2019
	Openings	Gr/m ²	330	0	165	0.15	2	DC _{vX}	

The values of S_{min} and S_{max} for I3, I4 and I5 were established – similarly to the previous economic indicators - through evaluating the environmental impacts of 615 FSs (opaque part) and 300 openings (transparent part) gathered in BEDEC database (BEDEC, 2019). ICE database (Hammond & Jones, 2011) and Environmental Product Declaration (EPD) of materials were used to complete the information from BEDEC database (Table 4.8).

Table 4.8. Obtained result from BEDEC regarding the environmental performance of facade systems.

Environmental indicators	Facade components	Number of facades	MJ/m ²	Number of facades	MJ/m ²	
Energy Consumption (MJ/m²)	Opaque	615 FS	500	<	32 FS	< 700
			700	<	463 FS	< 1000
			1000	<	120 FS	< 1500
	Transparent	300 openings	700	<	30 windows	< 2500
			2500	<	70 windows	< 4000
			4000	<	200 windows	< 7000
CO₂ Emissions (kg CO₂/m²)	Opaque	615 FS	30	<	30 FS	< 50
			50	<	485 FS	< 70
			70	<	100 FS	< 130
	Transparent	300 openings	30	<	40 windows	< 130
			130	<	60 windows	< 400
			400	<	200 windows	< 700
Waste (kg/m²)	Opaque	615 FS	0	<	615 FS	< 20
	Transparent	300 openings	0	<	300 window	< 0.33

A decreasing S-shape (DS) was chosen for I₃ and I₄ since satisfaction decreases rapidly to a residual value once a certain value of the indicator is reached (Figs. 4.4 - 4.7). Regarding I₅, a decreasing convex shape (DC_{vX}) was assigned to promote the reduction of waste production (Fig.4.8 and 4.9). In other words, it is more important to approach the point of minimum waste production (maximum satisfaction) than to move away from the point of maximum waste production (minimum satisfaction).

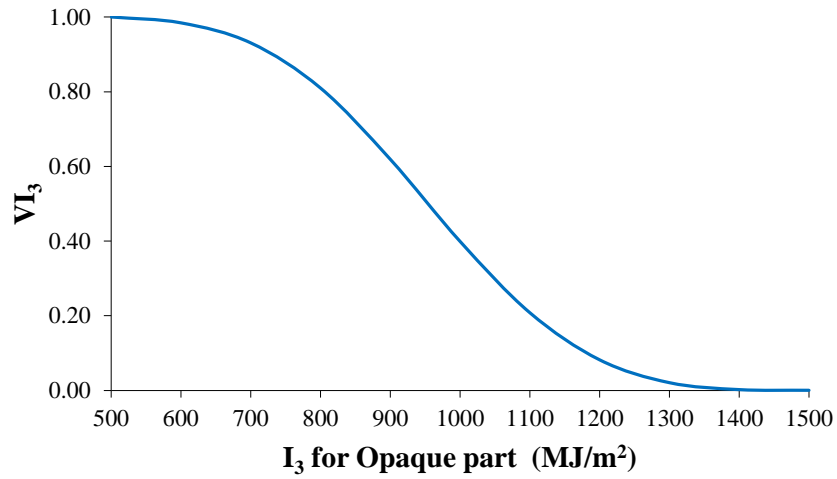


Fig. 4.4. Value function of energy consumption indicator for opaque part (I_3)

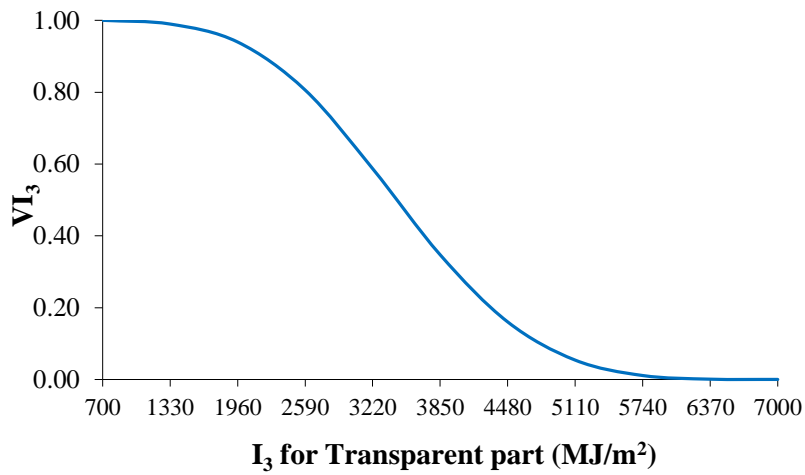


Fig. 4.5. Value function of energy consumption indicator for transparent part (I_3).

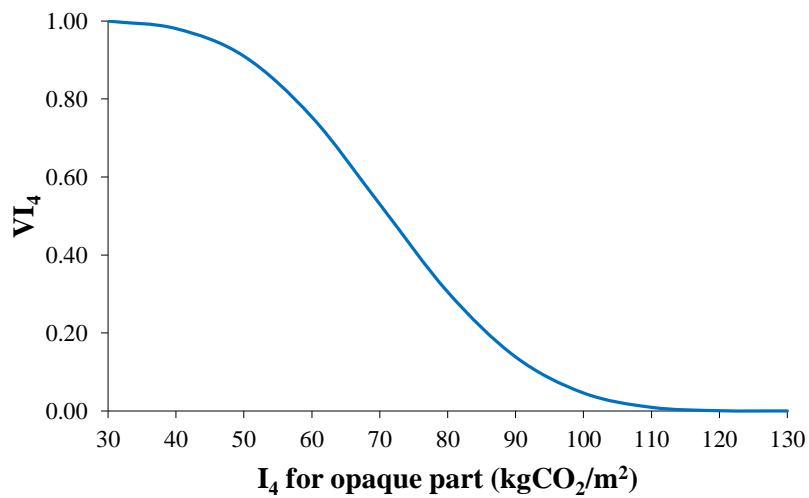


Fig. 4.6. Value function of CO_2 emissions indicator for opaque part (I_4)

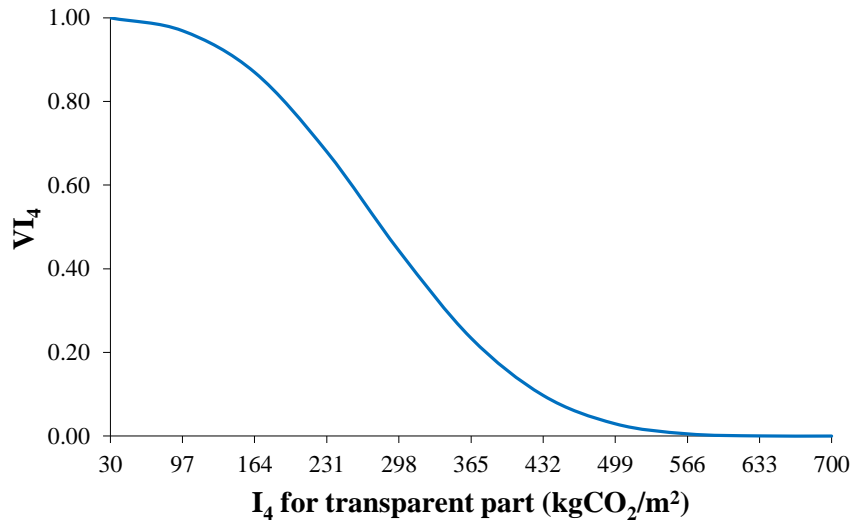


Fig.4.7. Value function of CO₂ emissions indicator for transparent part (I₄).

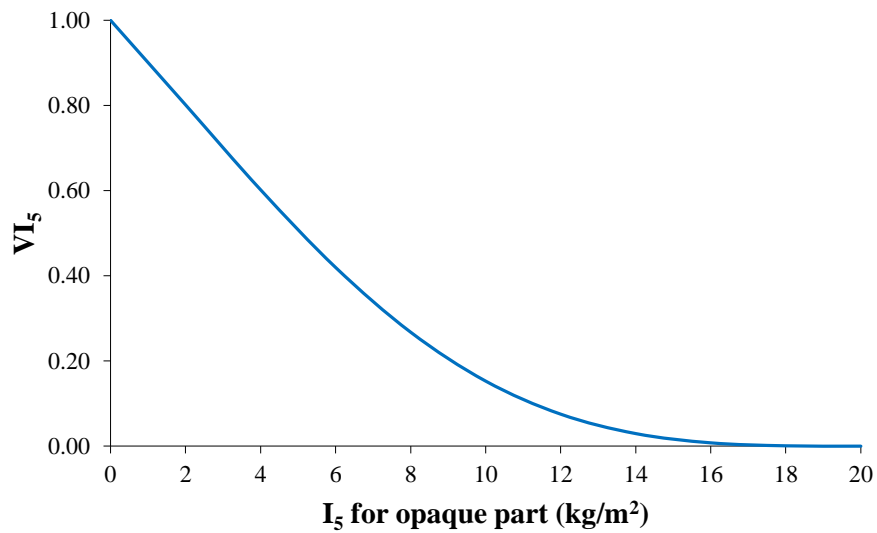


Fig.4.8. Value function of waste indicator for opaque part (I₅).

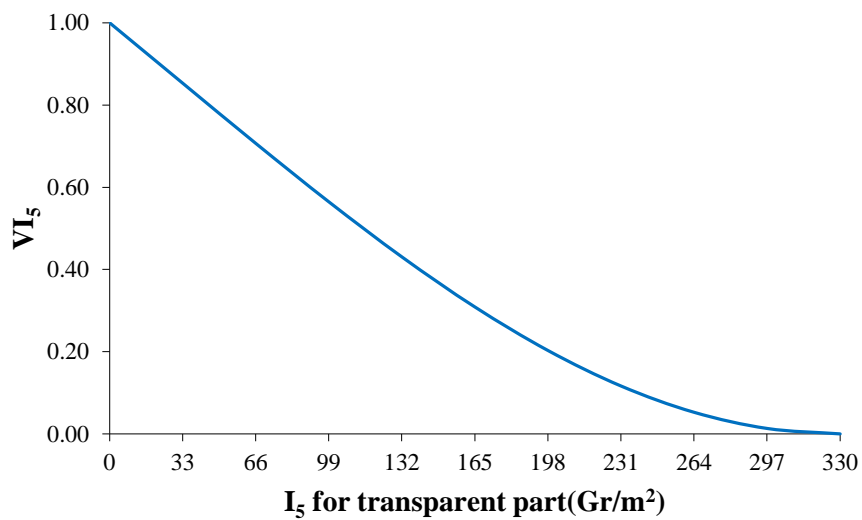


Fig.4.9. Value function of waste indicator for transparent part (I₅).

Social Indicators

Data corresponding to each social indicator value function is presented in Table 4.9. As indicated in Table 4.9, from the seven indicators – from which I₈ had different value functions for opaque and openings -, 3 functions are increasing with a S-shape (IS), 4 increase concavely (IC_{CV}) and 1 decrease S-shape (DS).

Table 4.9. Basic data of each social indicator value function.

Indicators	Unit	S _{max}	S _{min}	C	K	P	Shape	References
I ₆	Min	30	-4	6.5	0.6	0.47	IC _{CV}	CTE, 2013; strategy from Chapter 3 (Eq.3.1)
I ₇	Points	10	0	7.5	2.45	3.5	DS	Al-Anbari <i>et al.</i> , 2015 ; Isaac & Edrei, 2016 ; Questionnaire (Table 3.3)
I ₈	opaque	100	-11	1.7	4.5	0.7	IC _{CV}	Strategy from Chapter 3 (Eq.3.2), CTE,2013
	openings	100	-11	1.4	5	0.8	IC _{CV}	
I ₉	dB	5	-1	2.2	0.8	0.65	IC _{CV}	CTE, 2013; Strategy from Chapter 3 (Eq.3.3)
I ₁₀	%	5	2	1.9	1.3	3	IS	Naeem & Wilson, 2007; Yarham & Wilson, 1999
I ₁₁	Points	5	0	2.9	1.25	3	IS	Questionnaire (Table 3.4)
I ₁₂	Points	4	0	1.9	0.71	3.1	IS	Questionnaire (Table 3.5)

For I₆, I₈ and I₉, an increasing concave shape (IC_{CV}) was assigned since satisfaction increases when the thermal, acoustic and fire performance of facade systems improve. The concave shape was established since moving away from minimum condition, satisfaction drastically increases at first in relation to these indicators values (Figs. 4.10 – 4.13). Regarding I₈, it should be mentioned that, since thermal performance of the opaque (Fig. 4.11) and opening (Fig. 4.12) parts are different, two value functions were considered for this indicator in order to achieve representativeness. Likewise, S_{min} and S_{max} were demarcated according to the references presented in Table 4.9.

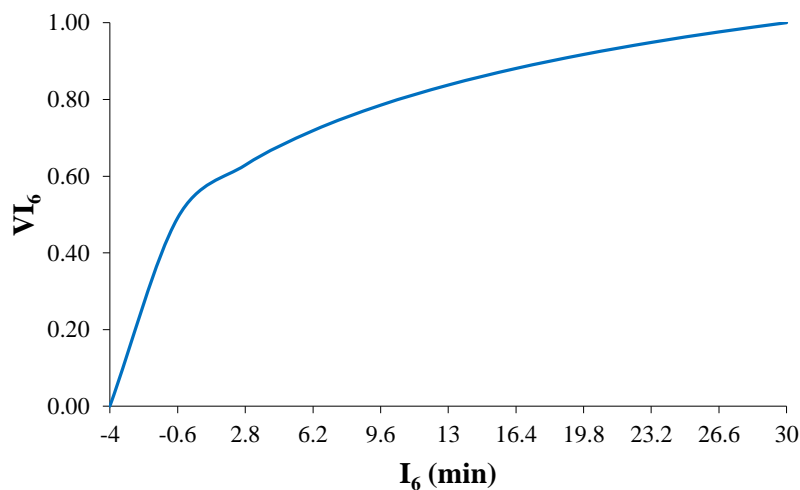


Fig. 4.10. Value function of extra fire performance indicator (I₆).

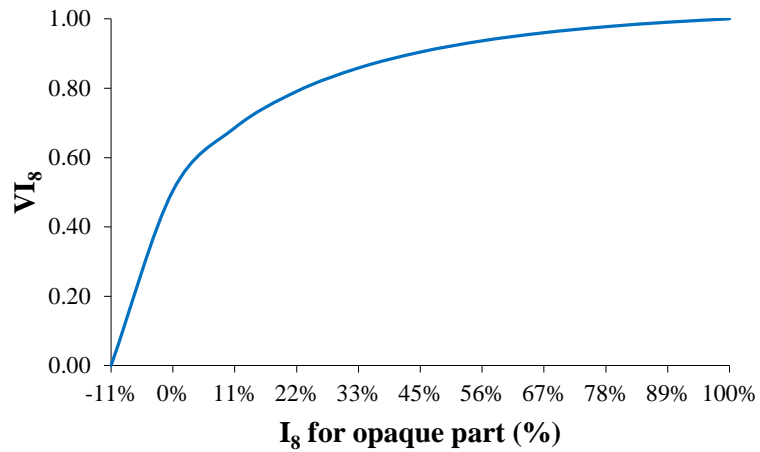


fig.4.11. Value function of extra thermal performance indicator for opaque part (I_8)

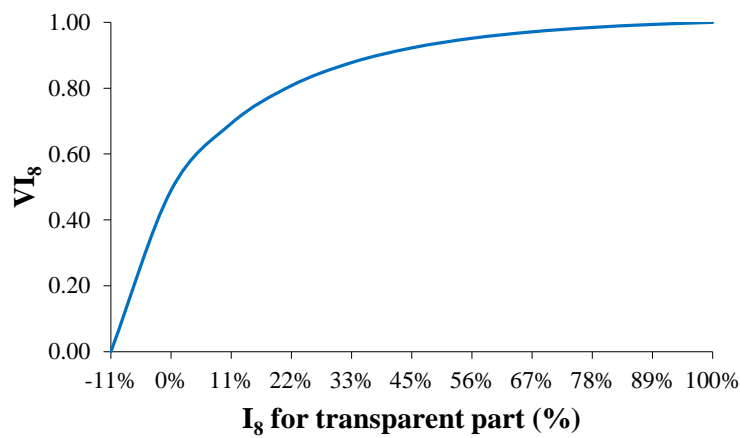


Fig.4.12. Value function of extra thermal performance indicator for transparent part (I_8)

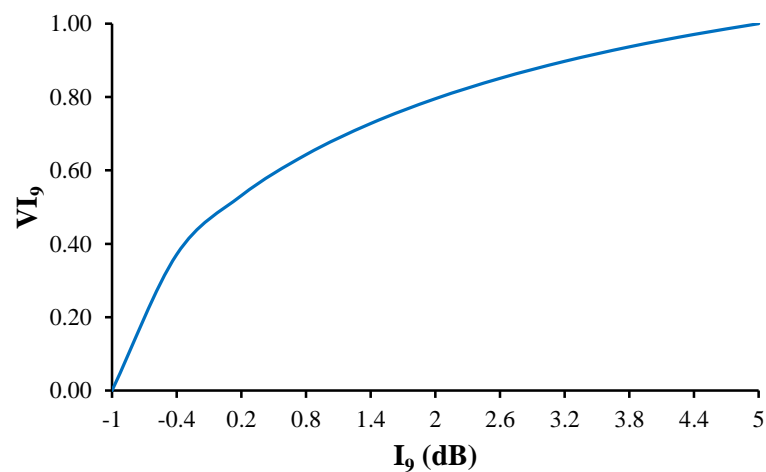


Fig.4.13. Value function of extra acoustic performance indicator (I_9).

In regard to I_7 , S_{\min} and S_{\max} were defined according to the proposed questionnaire presented in Chapter 3 for assessing the need of on-site skilled labor for assembling the facade system (Table 3.3). Finally, a DS function was chosen since up to a certain value of the indicator the satisfaction is relatively high and then, satisfaction decreases rapidly to a residual value (Fig. 4.14).

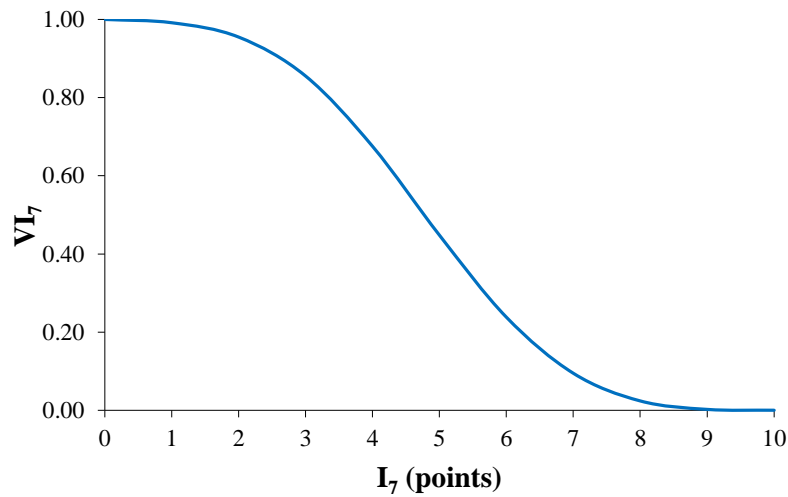


Fig.4.14. Value function of skilled labor requirement indicator (I₇)

An increasing S-shape (IS) was chosen for I₁₀, I₁₁ and I₁₂ since satisfaction is relatively low up to a certain value of the indicators and then, there is a drastic increase in satisfaction. In addition, the values of S_{min} and S_{max} were fixed according to the references presented in Table 4.9. (Figs. 4.15- 4.17).

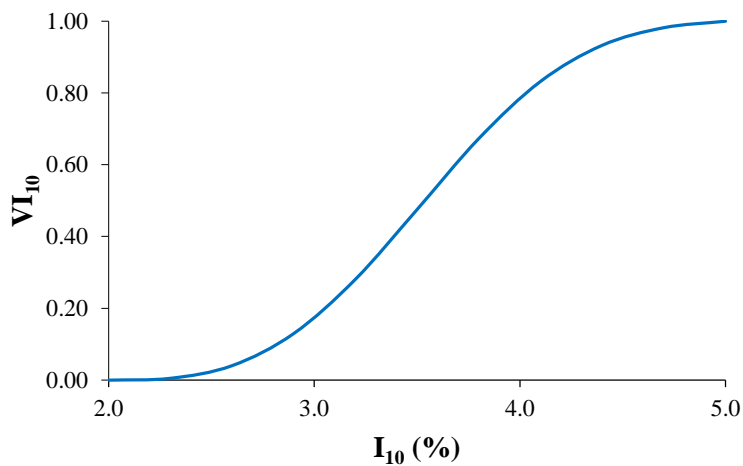


Fig.4.15. Value function of daylight comfort indicator (I₁₀)

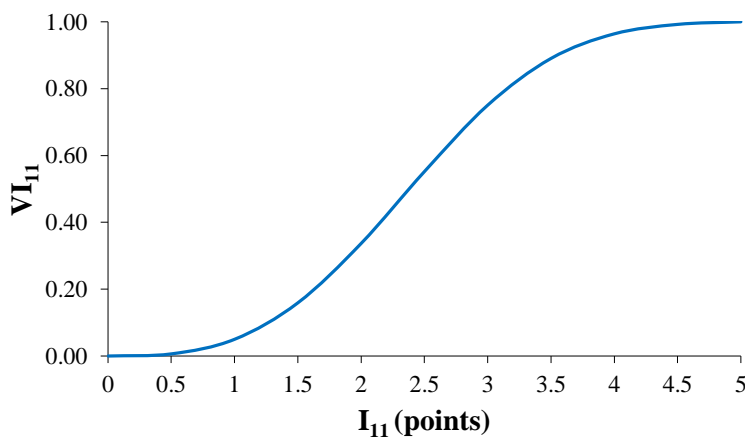


Fig.4.16. Value function of contextual compatibility indicator (I₁₁)

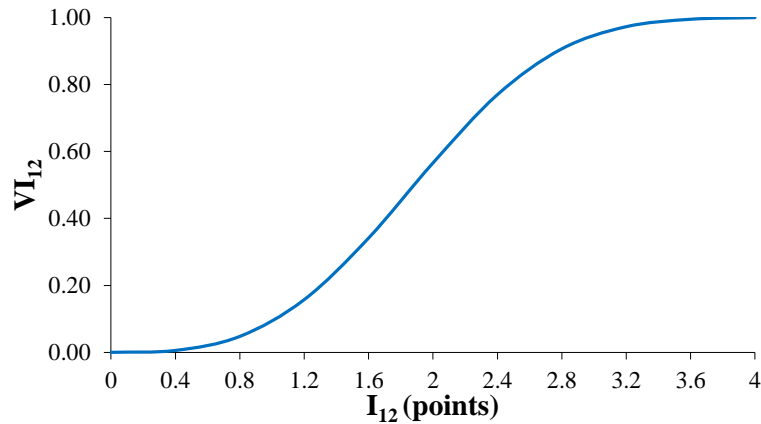


Fig.4.17. Value function of visual quality indicator (I12).

It should be noted that the defined value functions, associated parameters and charts can be taken as reference and used for any facade system in any country with diverse characteristics; nevertheless, these can be updated according to the specific case and preferences of the stakeholders involved in the decision procedure.

c) Weights' sets for the decision-making tree components

The weights were assigned for each requirement (α_i), criteria (β_i) and indicator (γ_i) using the analytic hierarchy process (AHP) (Saaty, 1990) (Table 4.3) based on the questionnaire proposed in prior chapter (for more detail refer to Appendix A). The questionnaire survey was conducted among 23 respondents consisting of: 14 architects, 3 facade consultants who collaborate in Spanish construction industry as well as 6 experts from the university. 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.

In previous sections, the results of the first and second phase of the proposed MIVES-based approach were explained in detail. In the following section, results obtained from the last phase will be discussed.

4.3.3. Results from phase three: sustainability index of each facade system

In the last phase, the 5 case studies indicated in Fig.4.1 were analyzed with the proposed approach to determine each sustainability performance. The functional unit fixed for evaluation is 1.0 m² facade.

The Sustainability Index (SI) of each alternative was computed through Equation (3.6).

Apart from the SI value of each alternative, value of each requirement (V_R), criteria (V_C), and indicator (V_I) for each FS were also obtained (Table 4.10). These magnitudes are the elements upon which the decision-making process is made. In this regard, after a sensitivity analysis, the most sustainable alternative can be identified. The optimum alternative must have a balanced and robust performance in each of the requirements and with a high value of SI (not necessarily the highest).

Table 4.10. Values of SI, V_R , V_C and V_I 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}
FS- A	0.43	0.78	0.15	0.34	0.78	0.15	0.08	0.23	0.00	0.2	0.69	0.4
FS- B	0.52	0.80	0.39	0.37	0.80	0.53	0.37	0.22	0.00	0.06	0.69	0.69
FS- C	0.56	0.78	0.31	0.57	0.78	0.49	0.19	0.21	0.49	0.03	0.87	0.69
FS- D	0.49	0.75	0.19	0.54	0.75	0.28	0.04	0.23	0.49	0.1	0.89	0.48
FS- E	0.62	0.83	0.32	0.71	0.83	0.22	0.1	0.71	0.49	0.89	0.85	0.67

	V_{I1}	V_{I2}	V_{I3}	V_{I4}	V_{I5}	V_{I6}	V_{I7}	V_{I8}	V_{I9}	V_{I10}	V_{I11}	V_{I12}
FS- A	0.86	0.65	0.15	0.08	0.24	0.00	0.2	0.32	0.80	1.00	0.67	0.07
FS- B	0.88	0.67	0.53	0.37	0.22	0.00	0.06	0.32	0.80	1.00	0.96	0.35
FS- C	0.85	0.67	0.49	0.19	0.21	0.49	0.03	0.8	0.80	1.00	0.96	0.35
FS- D	0.77	0.71	0.28	0.04	0.23	0.49	0.10	0.85	0.80	1.00	0.71	0.20
FS- E	0.83	0.82	0.22	0.10	0.71	0.49	0.89	0.75	0.80	1.00	0.63	0.72

4.4. Analysis of the results

After measuring the sustainability index of each FS with the proposed MIVES-based approach, in this section, the results will be analyzed in order to prove both suitability for the purpose and robustness of the results as well as to quantify the SI of each alternative.

To this end, the sustainability and requirements performance for each alternative are presented in Fig. 4.18.

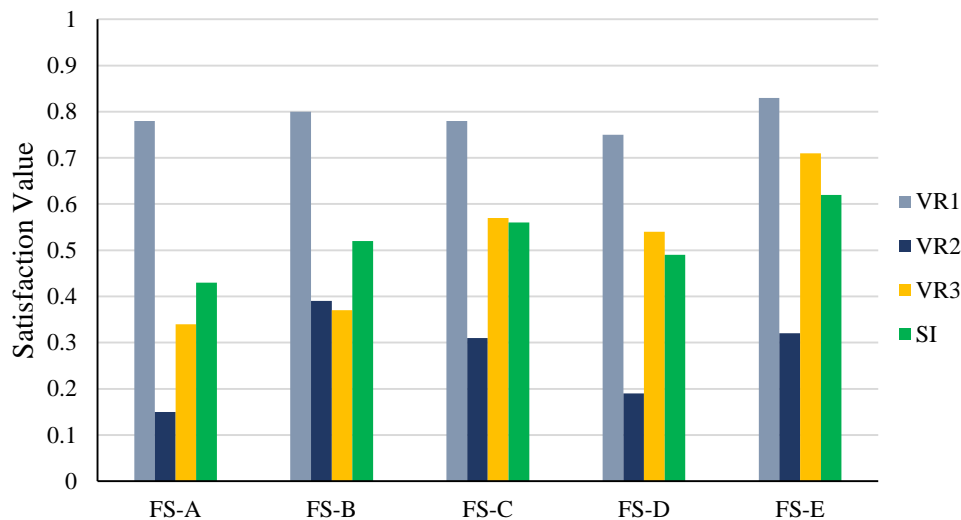


Fig.4.18. Total sustainability index and requirements values for the five facade systems.

From both Fig. 4.18 and Table 4.10, it can be remarked that the SI of the alternatives ranged from 0.43 (FS-A) to 0.62 (FS-E) when considering a balanced requirements' weights set ($\alpha_i = 0.33$, $i = 1$ to 3). FS-A performed with the lowest SI (0.43) and FS-E with the highest SI (0.62) since FS-A was mainly designed and constructed before 1980. At that time, building standards and regulations were, besides these being more conservative in terms of structural design, less sensitive towards environmental and social aspects. Likewise, the sustainability concept was still not sufficiently consolidated. Regarding FS-E, due to the high assembly easiness, low waste production and low need for on-site skilled labor, it was expected to obtain higher score comparing to other alternatives specifically in social aspect. On the other hand, since openings were

considered the same for the five studied FSs - see section 4.2 - the resulting values for the indicators related to the transparent part (36%) were same for all five FSs. Nevertheless, the obtained results are still satisfactory and reliable, and it proves the representativeness of the results.

Regarding the alternatives, there is still important room for improving the sustainability of the commonly used FSs in Barcelona. From a general perspective, the SIs of facade systems FS-B, FS-C, FS-D and FS-E fell within the obtained range, the performance of these still being below respect to a minimum target value to be achieved (namely $SI \geq 0.75$) according to the current standards and demands. This is a fact that allows confirming that most of the environmental and social indicators included into the proposed approach were not directly considered in the design phase, but these were considered implicitly and most probably from a subjective point of view (ex., aesthetics). This result was, however, expectable since this MIVES-based approach oriented to facade is the first, according to the authors' knowledge, that embraces all these governing indicators for the sustainability assessment.

It is worth to mention that the FSs analyzed had a high economic requirement (R_1) performance ($V_{R1} \geq 0.75$), this also being a symptom that economic aspects drove the decision-making process. This can be confirmed by noticing the low social performance values that were detected for FS-A (0.34) and FS-B (0.37). This pattern can be observed for the environmental performances.

In terms of environmental requirement (R_2), FS-B, FS-C and FS-E performed equivalently ($0.31 \leq V_{R2} \leq 0.39$) and FS-A obtained the lowest environmental value ($V_{R2} = 0.15$), see Fig. 4.18. In general, low environmental performance of all FSs ($V_{R2} \leq 0.39$) confirms that environmental indicators included into the proposed approach were not considered in any of the alternatives and also highlights the need of providing improvements orientated to enhance the environmental performance. As indicated in Fig.4.19, performance of waste indicator (I_5) is low for all FSs ($VI_5 \leq 0.24$) except FS-E with $VI_5 = 0.71$ which consists of prefabricated systems that significantly affect waste production. Regarding CO_2 emissions indicator (I_4), although all the alternatives obtained very low values ($VI_4 \leq 0.37$), it is worth to note a point about FS-B with $VI_4 = 0.37$ and FS-C with $VI_4 = 0.19$; as shown in Fig.4.1, the only difference between these two FSs is the use of polystyrene insulation in the opaque part of FS-C, while the value of I_4 in FS-C is almost half of the FS-B and it confirms that insulations can considerably affect the environmental performance of building facades.

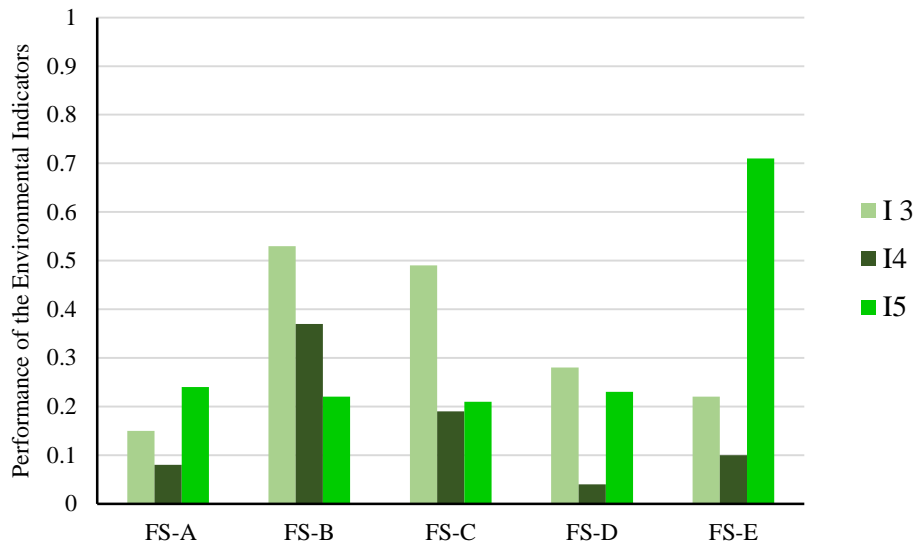


Fig.4.19. Performance of the environmental indicators for each facade system.

As for the social requirement (R_3), FS-A obtained the lowest social performance ($V_{R3} = 0.34$) due to the insufficient thermal resistance of the opaque part ($0.37 \text{ m}^2\text{K/W}$) according to the current Spanish regulations (CTE, 2013) (Minimum R-value for opaque part: $1.33 \text{ m}^2\text{K/W}$) as well as higher need for on-site skilled labor and low visual quality. Contrarily, FS-C, FS-D and FS-E presented both high thermal ($0.75 \leq V_{I8} \leq 0.85$) and fire ($V_{I6} \approx 0.50$) performances. Regarding the aesthetics criterion (C_8), FS-C obtained the maximum contextual compatibility ($V_{II1} = 0.96$) with a rather low visual quality ($V_{II2} = 0.35$) whilst the FS-E showed less duality the V_{II1} and V_{II2} indicators values being 0.63 and 0.72, respectively. Finally, it should be highlighted that the skilled-labor requirements (I_7) for the facade technologies analyzed resulted to be high, except the FS-E, which consists of prefabricated systems and requires low on-site skilled labor-force for construction. This indicator performance can be enhanced by using technologies similar to those often installed in pre- and post-disaster housing (Hosseini *et al.*, 2016); however, the use of those could compromise the performance of other indicators.

Finally, FS-E performed with the higher SI ($SI_{FS-E} = 0.62$). In this sense, FS-E achieved the highest economic ($VR_1 = 0.83$) and social ($V_{R3} = 0.71$) requirement values whilst FS-B obtained the better environmental performance value ($VR_1 = 0.39$). As no insulation is installed in FS-B, energy consumption and CO_2 emissions decreased and consequently, environmental performance value was slightly higher. But, instead, social performance decreased due to the low thermal and fire performance values as well as high need for on-site skilled labor, see Table 4.10. By adding insulation to FS-B, this resulting in FS-C, the social requirement value increased significantly (64%) and, in consequence, this led to an alternative with higher SI. Respect to the latter, should a decision have to be made this would not be possible by directly comparing the obtained SI, since the differences are negligible and non-decisive in this case, which is due to the weights established and alternatives analyzed. Nonetheless, the results are valid and helpful to: (1) quantify, as objectively as possible, the sustainability of each facade system analyzed,

and (2), identify strengths and weaknesses that would allow implementing improving measures.

A sensitivity analysis of the results (see Fig. 4.20) was carried out by considering 18 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, for example: global depressed and/or economic crisis period, and/or excessive importance in the decision-making process of those stakeholders whose driver is solely economic. Contrarily, scenarios in which the involved stakeholders are aligned and compromised with a balanced importance of the sustainability requirements or even prioritizing the environmental and social pillars, are represented by values of α_2 and α_3 greater than those assigned to α_1 .

On the other hand, the highlighted point on the horizontal axis -economic 0.34, environmental 0.33 and social 0.33 - indicates the sustainability indexes of FSs that were based on the weights obtained through questionnaire survey.

It must be remarked that other stochastic-based approaches - as that proposed by Caño *et al.*, (2012) - could have been applied; these, however, fall out of both the scope and objective of this research.

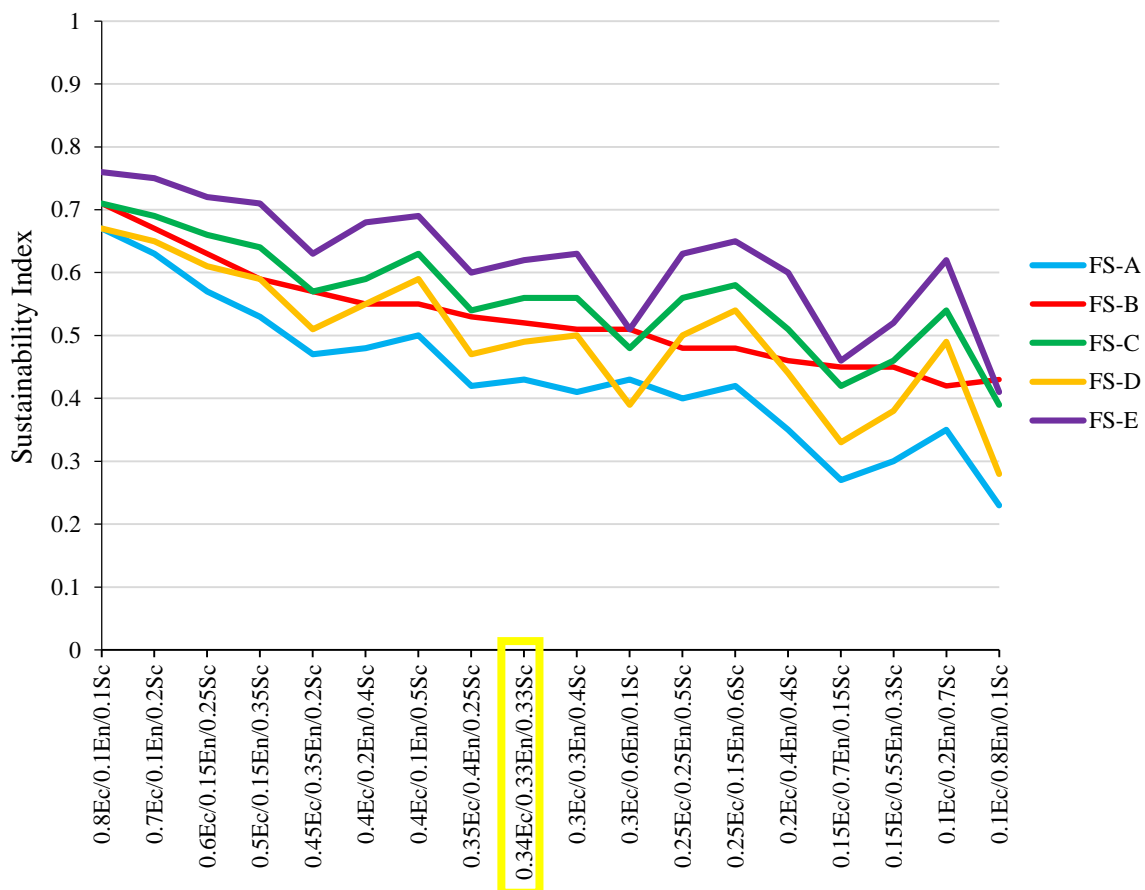


Fig. 4.20. Sustainability indexes of the six alternatives considering different requirements' weights sets: economic (Ec), environmental (En) and social (Sc).

The results depicted in Fig. 4.20. confirm that:

- Economy was the governing design condition of the facades since a range of $0.67 < SIs < 0.76$, for $\alpha_1 = 0.80$, was derived from scenarios with great values of α_1 . On the contrary, for greater values of α_2 , the SI tends to decrease.
- FS-E obtained higher SI value in most of the scenarios ($SI > 0.60$) specifically when the economic weight increases such the point with economic 0.7, environmental 0.1 and social 0.2. Thus, this alternative comparing to others resulted to be the most suitable from the sustainability perspective.

These results can also be explained by resorting to the technical literature. In this sense, the thermal performance of building envelopes has improved considerably in Spain from 1980, especially since 2008 due to the obligatory consideration of the Technical Building Code (CTE, 2006). Improvements can be noticed if the FS-A and FS-E are compared. The former was mainly installed prior to 1980, and no thermal protection for buildings or building units was mandatory whilst FS-E was mainly built after 2008, the Technical Building Code (CTE, 2006) being already regulating the building construction sector.

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

4.5. Conclusions

In this chapter, the proposed MIVES-based approach was applied to assess the sustainability of 5 commonly used FSs in Barcelona to validate the suitability and robustness of the method. The 5 FSs were applied to the same reference building, which is a real residential block in Barcelona. The following conclusions can be drawn:

- The obtained results proved the feasibility, applicability and clarity of the approach. In fact, as expected, FS-A performed with the lowest sustainability index (0.43) and FS-E with the highest sustainability index (0.62) since FS-A was mainly designed and constructed before 1980. At that time, building standards and regulations were, besides these being more conservative in terms of structural design, less sensitive towards environmental and social aspects. Likewise, the sustainability concept was still not sufficiently consolidated.
- The sustainability assessment of the five FSs analyzed with the proposed approach highlights that: (1) there is a wide room for improvement of several indicators, especially those related to environmental aspects, since the sustainability indexes (SI) were below 0.40; (2) the design driven criteria of these FSs was primarily the economic performance since great weights to this requirement led to the highest SIs; and (3) FSs consisting of precast concrete panel with double glazed aluminum windows (FS-E) and brick cavity wall with insulation with double glazed

aluminum windows (FS-C) were those that better performed in terms of sustainability, with a balanced weighting strategy of 33% for each requirement.

These results and conclusions were expectable but not previously quantified and reported, confirm that the great majority - namely 75% - of the installed FSs in Barcelona present an intermediate sustainability performance - $0.43 < SI < 0.62$ - according the multi-criteria approach developed herein. The aspects to be improved were identified with the approach and these can be considered in the renovation plan of the Barcelona's built stock and for new buildings.

It must be mentioned that the proposed approach can be extended to other building facade types (ex., offices, commercial centers) and other boundary conditions (ex., country, standards and recommendations) by including the proper indicators and adjusting the weights to the involved stakeholder's preferences provided a robust, clear and transparent procedure is applied.

Chapter 5

Sustainability MIVES-based assessment of Neinor and Lepant residential blocks of Barcelona

5.1. Introduction

In the previous chapter, it was proved that the proposed MIVES-based approach is a feasible and robust method for assessing the sustainability of buildings' facades. This chapter aims at applying the MIVES model for assessing the sustainability of real buildings in order to identify and quantify the challenges when the sustainability assessment in real cases. In addition, capabilities, and potentials of this approach for improving FSs will be also identified. In this respect, two high-performance energy-efficient residential blocks placed at Barcelona were selected as study cases.

5.2. Study cases: residential building facades in Barcelona

The two selected study cases are energy-efficient residential buildings. One received the BREEAM (Building Research Establishment Environmental Assessment Method) certification, and another one is currently waiting for VERDE (Valoración de Eficiencia de Referencia de Edificios) certification. In this sense, the sustainability assessment approach proposed herein goes beyond the minimum code requirements so that buildings that fail at meeting minimum standards would be disqualified in terms of sustainability. This was decision-driver for selecting both study cases, since both projects considered sustainability issues from the initial design phases.

5.2.1. Case 1: Neinor residential building

It is a 5-storey multi-family residential building that consists of 34 houses located in Nou Barris district (Porta neighborhood) in Barcelona, Spain. It was designed by Picharchitects group in 2015 and built in 2018. As indicated in Fig.5.1, this building is open to all sides and not attached to any construction. The northeast facade faces to the street and the southwest faces to a pedestrian public space. This residential building received its BREEAM certificate in good level (Fig.5.1).



Fig.5.1. Location of the Neinor residential block

The main architectural drawings of Neinor project, including floor plans and elevations are presented in Appendix D.

Regarding the facades of this building, the total area of the facades (both opaque and transparent parts) is 2275 m²; the opaque part with 1450 m² (64%) and transparent part with 825 m² (36%). The opaque part, which is fully industrialized, consists of 4 types of wall systems and the transparent part includes 4 metal doors and 36 types of aluminum

double glazed windows. All the information related to the Neinor facades, its facade system (FS-case1 herein after) and its components are presented in Table 5.1.

Table 5.1. Facade components and related areas

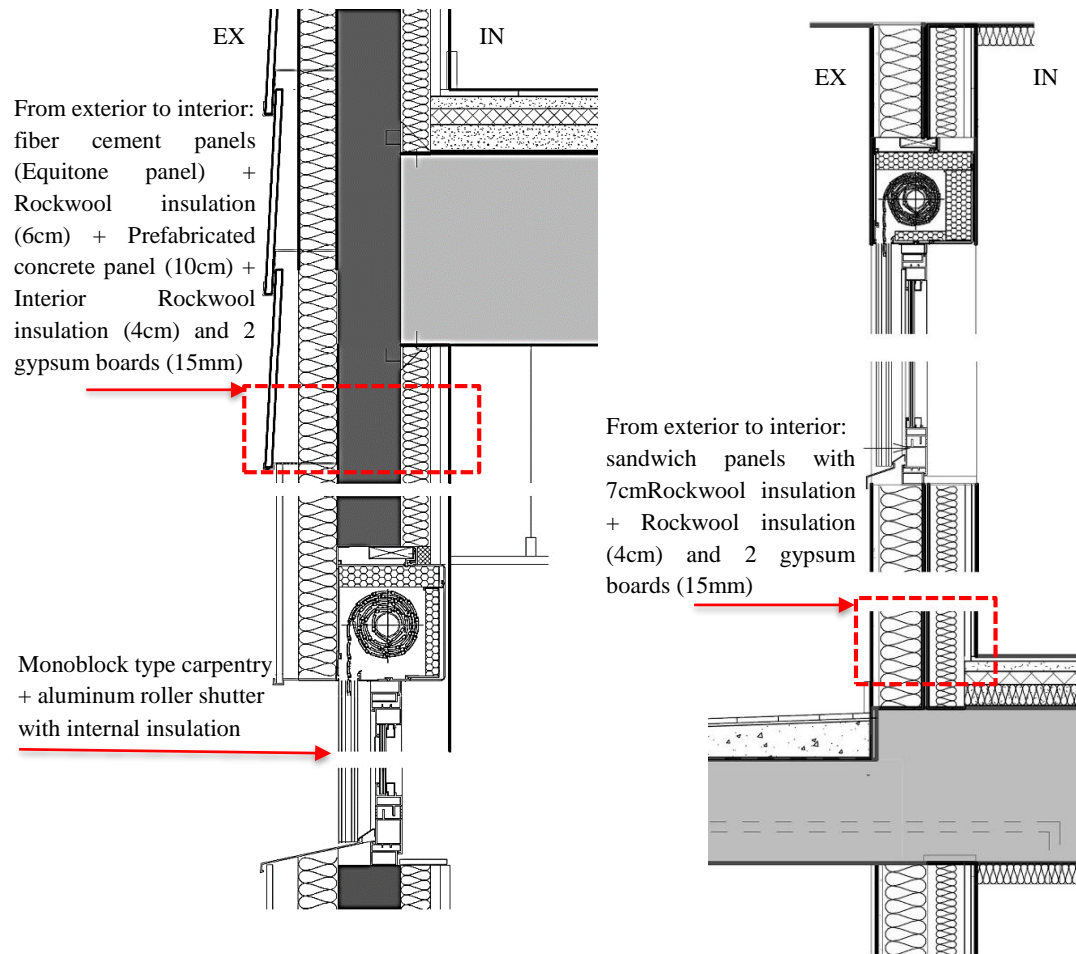
Material		Total Amount (m ²)
Opaque Part (64%)		1450
WS-N-1	Equitone Panels (fiber cement panels)	1000
	6cm Rock Wool Insulation	1000
	Concrete Panel 10 Cm	967
	Dry Wall System: 2 Gypsum Boards of 15mm + 4cm Rock Wool insulation	950
	Paint	950
		44%
WS-N-2	Sandwich Panel Europerfil NILHO 903 + 7cm Rock Wool	280
		12%
WS-N-3	Sandwich Panel Europerfil NILHO 903 + 7cm Rock Wool	80
	Dry Wall System: 2layers Gypsum Board 15mm (2 standard) +4cm Rock Wool	80
	Paint	80
		3.5%
WS-N-4	Equitone Panels (fiber cement panels)	90
	6cm Rock Wool Insulation	90
	Concrete Panel 10 Cm	90
	Dry Wall System: Gypsum Board of 15mm +4cm Rock Wool insulation	90
	Tile	90
		4.5%
Transparent Part (36%)		825
Openings	Metal Doors (Jansen 50)	47.5
	Windows: Al frame + double glazing 3+3-12-4 + Al roller window shutter with inside insulation	777.5
		34%

Legend: WS: wall system; WS-N-1: Neinor wall system 1; WS-N-2: Neinor wall system 2; WS-N-3: Neinor wall system 3; WS-N-4: Neinor wall system 4; Al: Aluminium.

The north, east and west facades were mainly made up of WS-N-1 and WS-N-4, while the south facade was mainly made up of WS-N-2 and WS-N-3. On the other hand, in the whole facade, windows had the same features (double glazed aluminum windows) with different sizes. In the following table, the details related to the FS-case1 are presented for more clarification (Table 5.2).

Table 5.2. Details and information related to FS-case1





Facade detail: WS-N-1 and 4

Facade detail: WS-N- 3

Regarding WS-N-2 ; it only includes sandwich panel as explained in Table 5.1

The main features of FS-case1 is reported in Table 5.3.

Table 5.3. Important features of FS-case1

	U Value (w/m ² k)		Fire resistance (min)	Noise insulation (dB)	construction cost (€/m ²)	Maintenance cost (€/m ²)
	Opaque	Transparent				
FS-Case1	0.33	1.92	60	34	200	254
References	Project's report		Project's report	Project's report	Project's bill of quantities, which was adjusted according to the Cost Prices Index (CPI) 2019	Project's Maintenance plan; Ingenieros, C.Y.P.E., SA, 2018; consulting with maintenance service of Campus Nord, UPC

5.2.2. Case 2: Lepant residential building

This is a 6-storey multifamily residential building that consists of 10 apartments, with a ground floor used for commercial purposes. It is located in Eixample district (Sagrada familia neighborhood) in Barcelona, Spain and designed by Picharchitects group in 2017. It is in preconstruction phase (Fig.5.2). This project was evaluated by the company itself based on the VERDE criteria and estimated the score of "4 Hojas" level for it. It is now under submission for VERDE certification.



Fig.5.2. Location of the Lepant residential building

The main architectural drawings including floor plans and elevations are presented in [Appendix E](#).

Regarding the facades of this project, the total area (both opaque and transparent parts) is 261 m²; the opaque part with 119 m² (45.6%) and transparent part with 142 m² (54.4%). The opaque part consists of 2 types of wall systems and the transparent part includes a curtain wall system and 2 types of aluminum double glazed windows. All the information related to the Lepant facade system (FS-case2 herein after) and its components is presented in [Table 5.4](#).

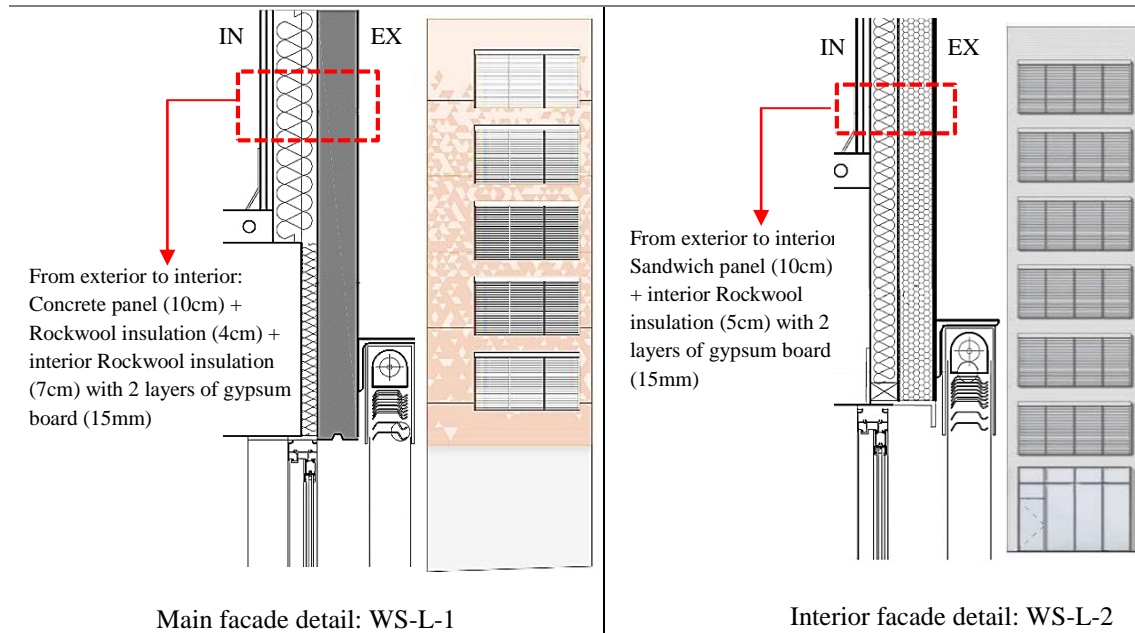
Table 5.4. Facade components and related areas

Material		Total Amount (m ²)	
Opaque Part: 45.6%		119	
WS-L-1	Concrete panel 10 cm	71.5	
	4cm Rockwool Insulation	71.5	
	2 layers of Gypsum Board 15 mm + 7 cm Rockwool insulation	71.5	
	Paint	71.5	
		27.6%	
WS-L-2	Sandwich Panel Europerfil NILHO with Rockwool insulation(10cm)	47.5	
	2 layers of Gypsum Board 15 mm +5 cm Rockwool insulation	47.5	
	Paint	47.5	
		18%	
Transparent Part: 54.4%		142	
Openings	Curtain wall (main façade)	35.5	
			13.4%
	Window type 1: Al frame U= 2.7 W/m ² K + low emissive glass 6+16+4	15.5	
	Window type 2: Al frame U= 2.7 W/m ² K + low emissive glass 6+16+4 + Al adjustable shutter	91	
		35%	

Legend: WS: wall system; WS-L-1: Lepant wall system 1; WS-L-2: Lepant wall system 2; Al: Aluminium.

The main facade (north facade), which faces to the street, is mainly built using WS-L-1 while the south facade is interior and constructed using WS-L-2. According to the project's description, the main facade is designed to be fully integrated into the environment and traditional facades of the Eixample district. Beige color prefabricated concrete panels are considered for the main facade to achieve the continuity and compatibility of the project's facade with the other facades of the street (Table 5.5). The details related to the FS-case 2 is presented in Table 5.5 for more clarification.

Table 5.5. Details related to FS-case2



The main features of FS-case2 is reported in Table 5.6.

Table 5.6. Important features of the FS-case2

	U Value (w/m ² k)		Fire resistance (min)	Noise insulation (dB)	construction cost (€/m ²)	Maintenance cost (€/m ²)
	Opaque	Transparent				
FS-case2	0.29	2	120	45	235	290
Reference	Project's report		Project's report	Project's report	BEDEC, 2019	Proposed maintenance plan (refer to Table 3.2); Ingenieros, C.Y.P.E., SA, 2018; consulting with maintenance service of Campus Nord, UPC

5.2.3. General considerations

After presenting the 2 above-mentioned case studies in detail, the MIVES-based approach is applied for assessing the sustainability of each building's facade and the results presented within the next sections.

As an important boundary condition, it should be mentioned that in this study, facade as a vertical building envelope is considered for evaluation, excluding other attached elements such as balconied. However, effects of these elements will be considered in the indicators.

5.3. Results derived from the sustainability assessment

The results obtained from the sustainability assessment of FS-case1 and FS-case2 are reported in this section.

This assessment considered the decision-making tree already defined and detailed in the previous chapter (section 4.3.1).

The quantification of each indicator, value functions and weights assignment, were as follows:

- The identified indicators were quantified for the FS-case1 and FS-case2 based on the strategies proposed in Chapter 3 for measuring the indicators and presented in Table 5.7. About the environmental indicators (I_3 - I_5), for the sake of clarity, the quantification procedure for FS-case1 and FS-case2 was also reported in Table 5.8 and Table 5.9.
- Regarding the social indicators (I_6 - I_{12}), the following was considered:
 - *Extra thermal performance* indicator (I_8). In case of the facade is composed by different systems, each with different U-values (W/m^2K), the highest value, which is the worst condition, it is the value considered for assessment. However, depending on the project and the decision makers' preference, other solutions can be also proposed and used (ex., compute the equivalent U-value by using numerical methods and/or experimental testing).
 - *Extra acoustic performance* indicator (I_9). In case of the facade consists of several systems with different sound insulation performance, depending on the project and the decision makers' preference, the worse performance value can be considered as representative for the evaluation (from the safe side). It should be noted that buildings under evaluation should meet minimum standards since sustainability approach goes beyond the minimum code requirements, so it would be meaningless to assess the sustainability of a building that does not meet minimum standards. For instance, in FS-case2, the main and back facades had different noise damping capacity and the critical situation that was considered for evaluation was the bedrooms facing to the main street. Since this project exceeds the minimum standards, the sound insulation performance of the bedrooms as the most critical location was considered as a reference for the assessment.

Table 5.7. Quantification of all indicators for FS-case1 and FS-case2

Indicators		FS-case1	FS-case2	References
I_1 (€/m ²)		200	235	BEDEC, 2019
I_2 (€/m ²)		254	290	Ingenieros, C.Y.P.E., SA, 2018; informal seminars with maintenance service of Campus Nord, UPC
I_3 (MJ/m ²)	Opaque	1156	1033	BEDEC, 2019
	Opening	4379	4660	
I_4 (kgCO ₂ /m ²)	Opaque	91	77.5	BEDEC, 2019
	Opening	482	530	
I_5 (kg/m ²)	Opaque	2.82	1.8	BEDEC, 2019
	Opening	0.09	0.12	
I_6 (min)		0	30	CTE, 2013; proposed strategy in Chapter 3 (Eq.(3.1))
I_7 (point)		3.5	2.5	Based on proposed questionnaire in Chapter 3 (Table3.3)
I_8 (%)	Opaque	56	61	CTE, 2013;the proposed strategy in Chapter 3 (Eq. (3.2))
	Opening	38	35	
I_9 (dB)		2	4	CTE, 2013; the proposed strategy in Chapter 3(Eq. (3.3))

I₁₀ (%)	6.7	4.8	Based on the proposed strategy in Chapter 3 (Eq.(3.5))
I₁₁ (point)	2.8	4.5	Proposed questionnaire (Table 3.4), Appendix F
I₁₂ (point)	2.5	2	Proposed questionnaire (Table 3.5), Appendix F

Table 5.8. Quantification of environmental indicators for FS-case1

Material		Total surface (m ²)	Energy consumption (MJ/m ²)	Emissions KgCO ₂ /m ²	Waste kg/m ²	
Opaque Part		1450				
WS-N-1	Equitone Panels	1000	1000	346	2.1	
	6cm Rockwool Insulation	1000		107.55	6.94	
	Concrete Panel 10 Cm	967		570	49	
	2 layers Gypsum Board 15 mm+ 4cm Rockwool insulation	950		280	18	
	Paint	950		22.18	3.27	
Total Environmental Impact Of WS-N-1		69%	1325×69%=914	67	2.6	
WS-N-2	Sandwich Panel NILHO 903 + 7cm Rockwool insulation	280	489.96	57.83	0.59	
Total Environmental Impact Of WS-N-2		19.5%	589.96×19.5%=95	11.5	0.11	
WS-N-3	Sandwich Panel + 7cm Rockwool insulation	80	489.96	57.83	0.59	
	2layers Gypsum Board 15mm+ 4cm Rockwool insulation	80	280	18	1.15	
	Paint	80	22.18	3.27	0.032	
Total Environmental Impact Of WS-N-3		5.5%	809×5.5%=43.5	4.5	0.1	
WS-N-4	Equitone Panels	90	346	20.2	2.10	
	6cm Rock Wool Insulation	90	107.55	6.94	0.29	
	Concrete Panel 10 Cm	90	570	49	0.56	
	2 layers Gypsum Board 15mm + 4cm Rockwool insulation	90	458.49	32.91	0.78	
	Tile	90	264.89	21.21	1.15	
Total Environmental Impact Of WS-N-4		6%	1746×6%=104	8	0.42	
Total Environmental Impact of opaque part /m²			1156	91	2.82	
Transparent Part		825				
Openings	Doors	47.5	1710	102.3	0.014	
	Total Environmental Impact of doors		5.5%	1710×5.5%=94	5.62	0.0007
	Window: Al frame + shutter + double glazed glass	777.5	4559	504	0.1	
	Total Environmental Impact of windows		94.5%	4285.5	476.3	0.09
Total Environmental Impact of transparent part / m²			4379.5	482	0.09	

Table 5.9. Quantification of environmental indicators for FS-case2

Material		Total surface (m ²)	Energy consumption (MJ/m ²)	Emissions (KgCO ₂ /m ²)	Waste (kg/m ²)	
Opaque Part		119				
WS-L-1	Concrete panel 10cm	71.5	570	49	0.56	
	4 cm Rock Wool Insulation	71.5	80	3.2	0.08	
	2 layers Gypsum Board 15 mm + 7cm Rockwool	71.5	430	22	1.2	
	Paint	71.5	22.18	3.27	0.032	
Total Environmental Impact of WS-L-1		60%	1274×60% = 661	46	1	
WS-L-2	10 cm Sandwich Panel	47.5	580	58.4	0.8	
	2 layers Gypsum Board 15mm +5cm Rockwool	47.5	330	18	1.15	
	Paint	47.5	22.18	3.27	0.032	
Total Environmental Impact of WS-L-2		40%	1156.24×40%=372	31.5	0.8	
Total environmental impact of opaque part /m²			1033	77.5	1.8	
Transparent Part		142				
Openings	Curtain wall	35.5	1671	98	0.26	
	Total Environmental Impact		25%	417.75	24.5	0.06
	Window type 1 (Al frame+ double glazed glass)	15.5	3399.628	438	0.043	
	Total Environmental Impact		11%	373.96	48.18	0.005
	type 2: Al frame+ shutter+ double glazed glass	91	6044	714.5	0.1	
Total Environmental Impact		64%	3868.16	457.28	0.06	
Total Environmental Impact of transparent part/m²			4659.87	529.96	0.12	

After quantifying the indicators, in order to homogenize the indicators units, the value function of each indicator was applied (Figs. 4.2 – 4.17). The obtained results are presented in Table 5.10.

The final item of the second phase is to assign weights for each parameter of the decision-making tree, which was already carried out in Chapter 4 through a questionnaire survey (Appendices 3.A and 4.A). The final weights were presented in Table 4.2.

Regarding the last phase of this MIVES-based approach, the Sustainability Index (SI) of each FS was computed through the equation (3.6). Apart from the SI value of each case, the satisfaction value of each requirement (V_R), criteria (V_C), and indicators (V_I) of each facade system was also obtained (Table 5.10). These magnitudes are the elements upon which the decision-making process is made. In this regard, after a sensitivity analysis, the most sustainable alternative can be identified as this alternative proves to have a balanced and robust performance in each of the requirements and with a high value of SI.

In fact, a sensitivity analysis can be carried out to identify the elements - weights and requirements - that govern the sustainability performance so that specific measures can be taken to enhance this performance.

Table 5.10. Values of SI, V_R , V_C and V_I for each study case

Alternatives	SI	V_{R1}	V_{R2}	V_{R3}	V_{C1}	V_{C2}	V_{C3}	V_{C4}	V_{C5}	V_{C6}	V_{C7}	V_{C8}
FS-case1	0.63	0.82	0.31	0.75	0.82	0.16	0.1	0.73	0.54	0.79	0.92	0.75
FS-case 2	0.66	0.70	0.34	0.94	0.70	0.22	0.18	0.68	1.00	0.94	0.96	0.81
	V_{I1}	V_{I2}	V_{I3}	V_{I4}	V_{I5}	V_{I6}	V_{I7}	V_{I8}	V_{I9}	V_{I10}	V_{I11}	V_{I12}
FS-case1	0.79	0.87	0.16	0.10	0.73	0.54	0.79	0.94	0.80	1.00	0.69	0.83
FS-case2	0.6	0.85	0.22	0.18	0.68	1.00	0.94	0.93	0.95	1.00	1.00	0.57

5.4. Analysis of the results

The results obtained in the previous section – SI of FS-case1 and FS-case2 – are presented herein. This part aims at evaluating the sustainability performance of the assessed FSs and identify potential weaknesses and strengths so that to the capabilities of this novel MIVES-based approach can be confirmed

To this end, the sustainability and requirements performance for each FS are presented in Fig. 5.3.

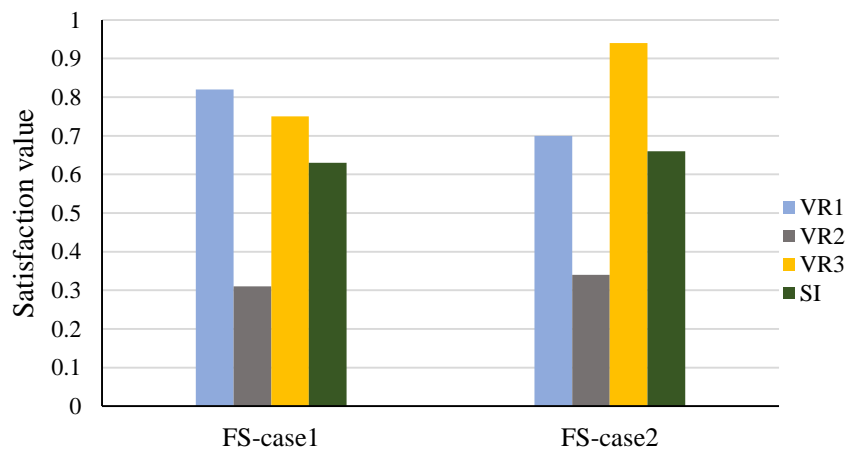


Fig. 5.3. Total sustainability index and requirements values for case studies

From a general perspective, as indicated in both [Table 5.10](#) and [Fig. 5.3](#), FS-case1 and FS-case2 performed equivalently ($SI_{case1} = 0.63$, $SI_{case2} = 0.66$) when considering a balanced requirements' weights set ($\alpha_i = 0.33$, $i = 1$ to 3). The performance of these still being below respect to a minimum target value to be achieved (namely $SI \geq 0.75$). This is a fact that allows confirming that most of the environmental indicators included into the MIVES-based approach were not directly considered in the design phase. On the other hand, both case studies had high economic and social requirement performances.

It is worth to mention that the FSs analyzed had a relatively high economic requirement (R_1) performance ($VR_{1, case1} = 0.82$, $VR_{1, case2} = 0.70$), this being a symptom that one of the main aspects that could drive the decision-making process was the economic aspect. This pattern was also observed in previous chapter for most commonly used FSs in Barcelona ([Fig.4.18](#)).

In terms of environmental requirement (R_2), both FSs obtained low value ($VR_{2, case1} = 0.31$, $VR_{2, case2} = 0.34$) that confirms that environmental indicators included into the approach, particularly *energy consumption* (**I3**) and *CO₂ emissions* (**I4**), were not considered in the design phase.

Regarding the indicator **I3** and **I4**, as explained in Chapter 3, manufacturing, and construction phases were considered for the LCA. Operation phase was excluded since this was already considered in the *extra thermal performance* indicator (**I8**); so that overlapping between indicators was avoided (section 3.4.1.2). According to [Table 5.10](#), the performance of the **I8** for both FSs was high ($VI_{8, case1} = 0.94$, $VI_{8, case2} = 0.93$), whilst both **I3** and **I4** obtained a very low value ($VI_{3, case1} = 0.16$, $VI_{3, case2} = 0.22$) ($VI_{4, case1} = 0.1$, $VI_{4, case2} = 0.18$) ([Fig.5.4](#)). These satisfaction values confirm that the operation phase was taken into high consideration regarding the **I8**, while manufacturing and construction phases were mainly disregarded in both case studies. These results highlight the need of providing improvements orientated to enhance the environmental performance, particularly **I3** and **I4**. Since 30% of the total energy consumption is used in manufacturing and construction phases (Wadel et al., 2011), these two phases can considerably affect the total energy consumption and should be considered in design phase, during the selection process of material and facade systems.

Contrarily to indicators **I3** and **I4**, the performance of *waste* indicator (**I5**) was relatively high for both FSs due to the use of prefabricated systems that significantly affect waste production ([Fig. 5.4](#)).

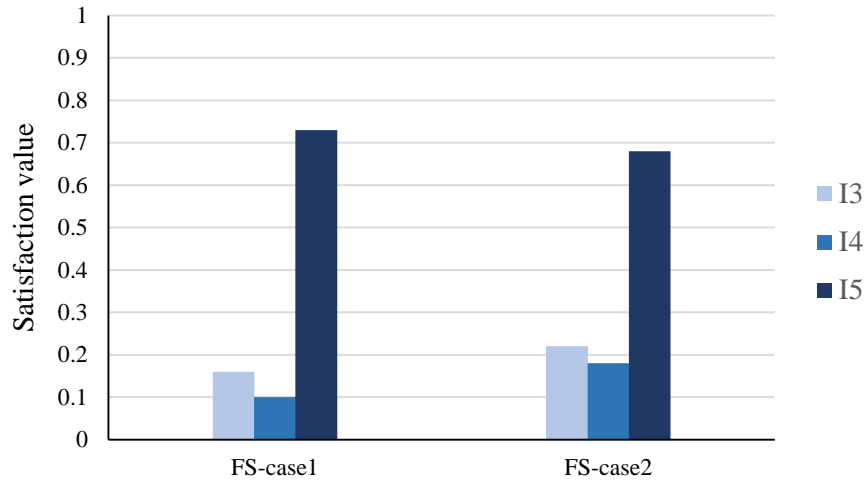


Fig. 5.4. Performance of the environmental indicators for each case study

It is worth noting that both study cases had an attractive high social requirement (R_3) performance, particularly FS-case2 ($VR_{3, \text{case1}}=0.75$ and $VR_{3, \text{case2}}=0.94$). Since both projects were high-performance buildings which were designed beyond the minimum code requirements, most of the social indicators obtained very high values (refer to Table 5.10) particularly the indicators *thermal performance* (I_8), *acoustic performance* (I_9) and *daylight comfort* (I_{10}).

Regarding the aesthetics criterion (C_8), the FS-case2 obtained the maximum contextual compatibility ($V_{I11} \approx 1.00$) with a rather low visual quality ($V_{I12} = 0.57$) whilst the FS-case1 showed less duality the V_{I11} and V_{I12} indicators values being 0.69 and 0.83, respectively.

It should be mentioned that the *skilled-labor requirements* (I_7) for the facade technologies analyzed resulted to be low due to the use of prefabricated systems for both FSs. As consequence, the performance value of this indicator is high ($VI_{7, \text{case1}} = 0.79$, $VI_{7, \text{case2}} = 0.94$). As previously explained, prefabricated building systems can be constructed using unskilled or semi-skilled manpower with comparatively limited training. Therefore, these prefabricated systems can offer substantially increasing of the construction output with only modest increase in the total on-site labor force (Patman *et al.*, 1968).

Regarding the indicator *extra fire performance* (I_6), It should be highlighted that one of the main reasons FS-case1 achieved lower social requirement value comparing to FS-case2 was due the fire performance value ($VI_{6, \text{case1}}=0.54$, $VI_{6, \text{case2}}=1.00$). In fact, fire resistance of FS-case1 provided minimum standards whilst fire performance of FS-case2 exceeded the minimum established standards.

Consequently, both FSs performed equivalently ($SI_{\text{case1}}=0.63$, $SI_{\text{case2}}=0.66$) and slightly below respect to a minimum target value (namely $SI \geq 0.75$) due to the low environmental performance values, which affected the total sustainability index (SI). Nonetheless, both achieved relatively high economic ($VR_{1, \text{case1}}=0.82$, $VR_{1, \text{case2}}=0.70$) and social ($VR_{3, \text{case1}}=0.75$ and $VR_{3, \text{case2}}=0.94$) performance values. In terms of social requirement (R_3), FS-case2 obtained higher value ($VR_{3, \text{case2}}=0.94$) while FS-case1 performed better economically ($VR_{1, \text{case1}}=0.82$).

The obtained results allow proving various potentials and capabilities of this MIVES-based approach, which allowed to: (1) quantify, as objectively as possible, the sustainability of FSs, and (2), identify strengths and weaknesses that would allow implementing improving measures.

A sensitivity analysis of the results (see Fig. 5.5) was also carried out by considering 16 scenarios simulated by adapting the requirements' weights (α_i ; $i = 1$ to 3). In this regard, high values of α_1 (max. 0.75) would represent scenarios in which economic aspects are determining, for example: global depressed and/or economic crisis period, and/or excessive importance in the decision-making process of those stakeholders whose driver is solely economic. Contrarily, scenarios in which the involved stakeholders are aligned and compromised with a balanced importance of the sustainability requirements or even prioritizing the environmental and social pillars, are represented by values of α_2 and α_3 greater than those assigned to α_1 .

On the other hand, the highlighted point on the horizontal axis -economic 0.34, environmental 0.33 and social 0.33 - indicates the sustainability indexes of FSs that were based on the weights obtained through questionnaire survey.

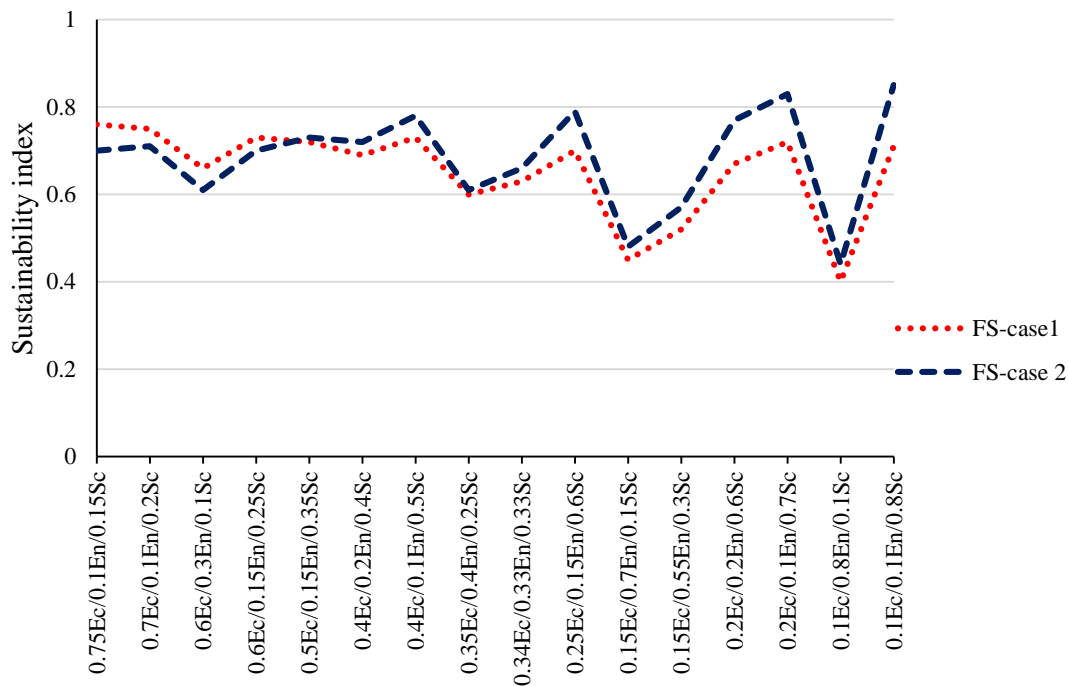


Fig. 5.5. Sustainability indexes of the study cases considering different requirements' weights sets: economic (Ec), environmental (En) and social (Sc).

These results depicted in Fig. 5.5. confirm that:

- Increasing the weights of economic (α_1) and social (α_3) requirements increase the SI of both study cases: for $\alpha_1 = 0.7$, the $SI_{case1} = 0.76$ and $SI_{case2} = 0.71$; for $\alpha_3 = 0.7$, the $SI_{case1} = 0.72$ and $SI_{case2} = 0.83$. This confirms that economy issues and stakeholders comfort in use phase were prioritized in the design and selection phase of the FSs.
- On the contrary, for greater values of α_2 , the SI tends to decrease significantly. As indicated in Fig. 5.5, the lowest SI_s were obtained when α_2 increased: for $\alpha_2 = 0.8$, the

$SI_{\text{case1}} = 0.4$ and $SI_{\text{case2}} = 0.44$ while for $\alpha_2 = 0.1$, the $SI_{\text{case1}} = 0.71$ and $SI_{\text{case2}} = 0.85$. This fact is a consequence of the low values of environmental indicators of both FSs (see Fig. 5.4), that indicates that environmental indicators were mainly disregarded in the design phase. FS-case2 obtained a little higher SI value in most of the scenarios ($SI > 0.70$) comparing to FS-case1, specifically when the social weight increases such the point with economic 0.20, environmental 0.10 and social 0.70.

5.5. Discussion

The main weakness of both study cases' FSs was the disregard of environmental indicators included into the approach in the design phase, particularly **I₃** and **I₄** which account for the amount of energy consumed and CO₂ emissions produced during manufacturing and construction phase. In other words, some of the selected materials in both study cases performed poorly regarding energy consumption and CO₂ emissions in these two phases, as shown in Table 5.8 and Table 5.9. However, both FSs achieved high social and economic requirements value.

On the other hand, according to the obtained results, it can be stated that openings could have a considerable impact on the performance of all indicators. For instance, according to Table 5.8 and 5.9, the large share of energy consumption and CO₂ emissions was related to the transparent part (almost 4 times more than opaque part), particularly aluminum windows, in both study cases. In fact, after evaluating 300 openings in BEDEC database, it was observed that AL windows had low environmental performance in manufacturing and construction phase, particularly in terms of energy consumption and CO₂ emissions.

In case of changing the aluminum windows for timber windows in both study cases in order to quantify the effect of this change on the economic (**R₁**), environmental (**R₂**) and social (**R₃**) performance values as well as the SI.

The reason for focusing on timber windows is that timber is considered a natural, renewable and environmentally friendly material with a very low embodied energy, although it requires high maintenance (Lawson, 1995; Scharai-Rad & Welling, 2002; Asif *et al.*, 2005; Abeysondra *et al.*, 2008; Menzies, 2013). According to Asif *et al.*, (2002), timber windows exhibit the least value of embodied energy comparing to Aluminum and PVC because processing and production of timber frames do not impose any significant loads on the environment.

To carry out a reliable evaluation, the author selected timber frames that had similar technical characteristics to AL window frames. It should also be mentioned that, for evaluation, only the window frames were changed and the rest (opaque part, window shutters, glasses etc.) remains the same.

Once more, the three phases of MIVES-based approach were applied for assessing the sustainability of both FSs with timber windows and the obtained results will be explained in the following paragraphs.

Table 5.11 gathers the quantification of each indicator for the FS-case1 and FS-case2 with timber windows. As indicated, changing the AL window frames into timber mainly affected the economic and environmental indicators, while most of the social indicators remained unchanged.

Table 5.11. Quantification of all indicators for FS-case1 and FS-case2 with timber frames

Indicators		FS-case 1	FS-case 2	References
I₁ (€/m²)		240	272	BEDEC, 2019
I₂ (€/m²)		712	810	Ingenieros, C.Y.P.E., SA (2018)
I₃ (MJ/m²)	Opaque	1156	1033	BEDEC, 2019; EPD of timber windows
	Opening	1579	1537	
I₄ (kgCO₂/m²)	Opaque	91	77.5	BEDEC, 2019; EPD of timber windows
	Opening	97	96	
I₅ (kg/m²)	Opaque	2.8	1.8	BEDEC, 2019
	Opening	0.07	0.1	
I₆ (min)		0	0	CTE, 2013; Based on the proposed strategy in Chapter 3 (Eq. (3.1))
I₇ (point)		3.5	2.5	Based on proposed questionnaire in Chapter 3 (Table3.3)
I₈ (%)	Opaque	56	61	CTE, 2013; Based on the proposed strategy in Chapter 3 (Eq. (3.2))
	Opening	38	35	
I₉ (dB)		2	4	CTE, 2013; Based on the proposed strategy in Chapter 3 (Eq. (3.3))
I₁₀ (%)		6.7	4.8	Proposed strategy in Chapter 3 (Eq.(3.5))
I₁₁ (point)		2.6	4.5	Proposed questionnaire (Table 3.4), Appendix G
I₁₂ (point)		2.75	2.2	Proposed questionnaire (Table 3.5), Appendix G

After establishing the value of each indicator (V_I), criteria (V_C) and requirements (V_R) as well as measuring the SI of both study cases (Table 5.12), the final results including the sustainability and requirements performance for each FS are presented in Fig. 5.6.

Table 5.12. Values of SI, V_R , V_C and V_I for FS-case1 and FS-case2 with timber frames

Alternatives	SI	V_{R1}	V_{R2}	V_{R3}	V_{C1}	V_{C2}	V_{C3}	V_{C4}	V_{C5}	V_{C6}	V_{C7}	V_{C8}
FS-Case1	0.6	0.49	0.55	0.75	0.49	0.47	0.45	0.76	0.54	0.79	0.92	0.73
FS-Case2	0.62	0.33	0.73	0.81	0.33	0.73	0.74	0.71	0.54	0.94	0.96	0.86

	V_{I1}	V_{I2}	V_{I3}	V_{I4}	V_{I5}	V_{I6}	V_{I7}	V_{I8}	V_{I9}	V_{I10}	V_{I11}	V_{I12}
FS-Case1	0.56	0.39	0.47	0.45	0.76	0.54	0.79	0.94	0.8	1.00	0.59	0.91
FS-Case2	0.36	0.28	0.73	0.74	0.71	0.54	0.94	0.93	0.95	1	1	0.69

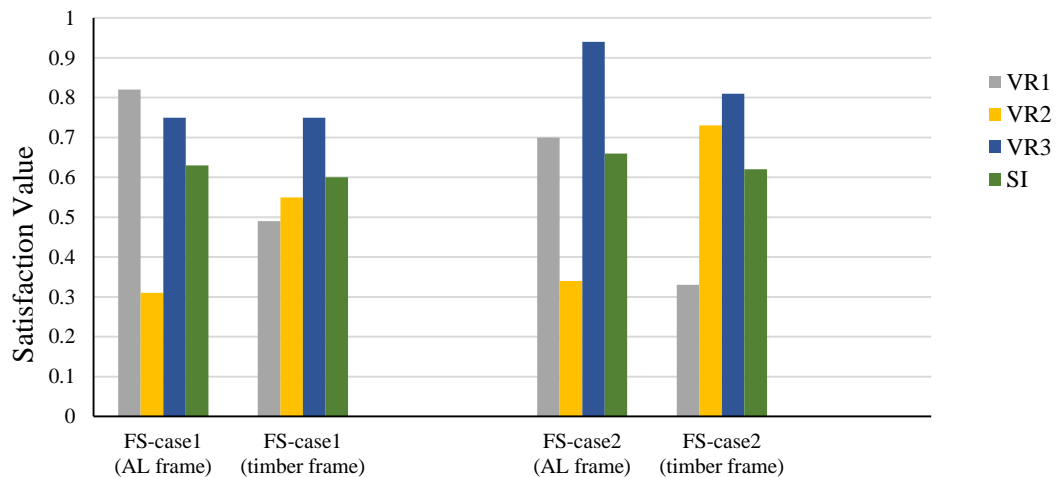


Fig.5.6. Total sustainability index and requirements values for study cases with timber windows

Comparing the obtained results from FSs with timber windows with the FSs with AL windows (Fig. 5.6 and Table 5.12) allows stating that:

- The economic performance value (R_1) of FSs with timber windows decreased significantly ($V_{R1} \geq 47\%$) comparing to FSs with AL windows. The main reason is due the high maintenance cost of timber frames. In fact, timber windows are less durable than AL windows and the resistance and performance can be affected by various factors such as weathering and decay, termites, infestation, fire and etc. Therefore, maintenance actions and treatment processes must be carried out periodically to preserve the timber for a longer service life.
- On the contrary, the environmental requirement satisfaction value (R_2) of FSs with timber windows increased considerably ($V_{R1} \geq 50\%$) comparing to the AL windows, although the rest of facade systems (opaque part, window shutters, glasses and etc.) remained unchanged. This allows stating that timber frames perform very well environmentally, particularly in terms of energy consumption (I_3) and CO₂ emissions (I_4), both in manufacturing and construction phase.
- Regarding the social performance value (R_3), as indicated in Fig.5.6, the values remained partially unchanged (e.g., R_3 with AL windows = 0.75, with timber frame= 0.75) because changing the frames did not affect most of the social indicators. The unique indicator, which is mainly affected by this change would be the *fire performance* indicator (I_6). However, this effect can be removed/reduced through the application of as fire retardant and fire-resistant coating technologies.
- From a general perspective, as shown in both Fig. 5.6, SI value of FSs with timber windows slightly decreased comparing to FSs with AL windows. In other words, FS_{case1} with timber windows and FS_{case1} with AL windows performed similarly, these having a slightly better sustainability performance in AL windows cases ($SI_{case1, timber\ window} = 0.60$, $SI_{case1, AL-window} = 0.63$). This pattern was also observed in FS-case2 as well ($SI_{case2, timber-window} = 0.62$, $SI_{case2, AL-window} = 0.66$). This is due the fact that although environmental performance (R_2) of FSs with timber windows improved considerably but these down-performed in terms of economic requirement (R_1) and economy was one of the governing design condition of FSs so that the SI values remained partially unchanged comparing to AL-windows.

As a consequence, it can be stated that sustainability performance of FSs with timber windows is still lower respect to the minimum target value to be achieved (namely $SI \geq 0.75$) due to the reduced economic performance values. In fact, economy is the governing design condition of FSs. Therefore, low value of economic requirement significantly affects the total SI of FSs.

5.6. Conclusions

In this chapter, the MIVES-based approach developed in this doctoral thesis was applied for the sustainability assessment of two energy-efficient residential buildings in Barcelona aiming at confirming the suitability of the approach for the purpose and to identify aspects of improvement of both buildings (ex., reduction of U-values ($\text{W}/\text{m}^2\text{K}$) or higher sound insulation performances).

After assessing the sustainability of the case studies with this novel approach, the following conclusions can be drawn:

- The sustainability assessment of the study cases highlights that: 1) both FSs achieved high economic (R_1) and social (R_3) performance values while they performed poorly regarding environmental requirement (R_2); 2) in terms of SI value, both FSs performed equivalently ($SI_{\text{case1}} = 0.63$, $SI_{\text{case2}} = 0.66$) (with a balanced weighting strategy of 33% for each requirement) and partially below respect to a minimum target value (namely $SI \geq 0.75$) due to their low environmental performance values; and 3) the design driven criteria of these FSs were the economic and social performances since great weights to these requirements led to the highest SIs.
- Both study cases' FSs obtained low environmental requirement values due to the disregard of environmental indicators included into the approach in the design phase. This was particularly the case of the environmental indicators I_3 and I_4 , which account for energy consumed and CO_2 emissions produced during manufacturing and construction phase. This confirms that the environmental impacts in manufacturing and construction phase were mainly disregarded in both FSs, while operation phase was taken into high consideration.
- The results also demonstrated that openings could considerably affect the performance of economic, social, and environmental indicators. As demonstrated in section 5.5. only changing the AL windows into timber windows could change the economic (R_1) and environmental (R_2) values even more than 50%, therefore they must be carefully designed and selected. However, the SI of timber and aluminum windows was similar.
- FS-case1 was already received BREEAM certification (score of 2 out of 5 categories) and FS-case2 is under submission for VERDE certification (estimated score of 4 out of 5). According to the criteria considered in both rating tools, both case studies are energy –efficient with high quality of indoor environment in terms of natural illumination, indoor air quality and acoustic insulation. In addition, both obtained high score in land use and transportation criteria. These certificates and the scores are related to the sustainability performance of the whole building not specifically the facades, although a few indicators can include the facade as well. But, with considering the obtained scores from the rating tools, it is worth noting the SI values obtained from the application of MIVES-based approach (FS-case1 obtained lower SI value than FS-case2), which follows the same pattern. This could confirm the impact of the facades on the whole building sustainability performance.

All the above-mentioned results and conclusions confirm various capabilities and potentials of this approach, which allows to: (1) quantify, objectively, the sustainability of facade systems, (2), identify strengths and weaknesses that would allow implementing improving measures. It would be also if there is only one case study for assessment, and 3) carry out sensitivity analysis to identify the elements (weights and indicators) that govern the sustainability performance so that specific measures can be taken to enhance this performance. It also makes it possible to introduce changes to the alternatives and repeat the analysis keeping the non-variable indicators, as indicated in section 5.

Chapter 6

Conclusions

6.1. Introduction

Acknowledging the importance of sustainability in facade systems (FSs), this research was aimed at highlighting the problems and drawbacks associated with this aspect, define the key indicators of sustainable facades and identify those factors that are critical for developing a model for the sustainability assessment of FSs. This research also investigated and analyzed the existing building assessment methods to identify the deficiencies and strengths as tools for evaluating the sustainability performance of FSs.

Finally, after considering all the facades essential features, strengths and weaknesses of the existing methods as well as the requirements that a sustainability assessment model should incorporate, a new comprehensive approach was proposed. This approach is based on MIVES (Integrated Value Model for Sustainable Assessment), which is a Multi

Criteria Decision Making (MCDM) model that was already successfully applied to develop tools to assess other building components.

This final chapter is aimed to present and discuss the conclusions of this doctoral dissertation. In addition, several uncovered topics are proposed in the second part of this chapter as future research lines.

6.2. Main conclusions

The critical analysis of the results derived from this research permit to establish the following conclusions:

- A new MIVES-based approach to assess and rank the sustainability of residential FSs was successfully developed and validated by analyzing five commonly-used residential FSs in Barcelona. The representativeness of the results obtained from this approach allows confirming that this is a suitable approach, which enables decision-makers to accurately and objectively quantify the sustainability of FSs by considering the satisfaction level of the involved stakeholders. This leads to facilitate decision-makers' tasks as well as maximize the stakeholders' satisfaction since local conditions can be objectively considered by using MIVES.
- Thirteen (13) indicators were found as the most representative for the sustainability assessment of residential facade systems. This conclusion relies on the conferences, multidisciplinary seminars as well as technical literature described and studied in this doctoral dissertation, which led to identifying the 22 crucial indicators of sustainable facades in general.
- This new approach is applicable for any type of facade - i.e., offices, commercial centers- as well as various locations and countries. Particularly, it was optimized for residential building facades. Furthermore, it can be applied in different stages of design, construction, and renovation, as indicated in Chapter 5.
- The obtained results permitted to prove that decision-makers can apply this approach for the whole FS - both opaque and opening parts - and for specific parts - i.e., cladding layer, window glasses, and frames.

Hence, this approach can be used as the basis for benchmarking buildings' facades allowing decisions to be made to enhance the quality of the built environment. The benchmarks of the thirteen indicators developed in this research can be set as a common target for comparison. The development of this approach also helps to make better decisions as sustainability requirements are successfully measured and incorporated into the decision-making process.

6.3. Specific conclusions

This study was conducted following the descriptive and operational methods explained in Chapter 1. The combination of both methods allowed overcoming the problems and presenting a new approach for assessing the sustainability of residential FSs.

In this regard, the specific conclusions derived from the descriptive section are as follows:

- Through a holistic overview of around 100 studies about sustainability performance of FSs, it was demonstrated that 60% of the studies were focused on environmental criteria, while only 10% of the available literature incorporated all the 3 pillars of sustainability - economic, environmental and social.
- Thermal performance and environmental impacts - energy consumption and CO₂ emissions - indicators were considered as the mostly-used ones with 66 and 51 studies respectively.
- Through a deep review and analysis of the existing methods, it was concluded that most evaluation tools fail in considering the satisfaction of all stakeholders involved in the decision-making procedure.
- The Integrated Value Model for Sustainable Assessment (MIVES) proved to be suitable for taking into account, objectively, the satisfaction of the stakeholders involved in the decision-making process for selecting FSs.

Besides, in the operational section of this research, the new MIVES-based approach was presented and applied for the case studies. The results and findings derived from the application of the approach led to the following conclusions:

- The design driven criteria of these FSs was primarily the economic performance while the environmental and social indicators, if considered, the relative importance associated to those was minor.
- The results emphasized the need for renovation and/or improvement of the facades mainly built before 1980 in Barcelona in order to meet not only minimum standards but also go beyond the existing buildings codes and meet more advanced and strict sustainable development goals.
- After applying the proposed approach for two real high-performance residential blocks, it was found that in operation phase the environmental impacts - energy consumption and CO₂ emissions - were taken into high consideration in both FSs, while in the manufacturing and construction phases these environmental issues were mainly disregarded. In other words, some of the selected materials in both study cases performed poorly regarding energy consumption and CO₂ emissions in these two phases.
- The openings can considerably affect the performances of FSs. It was indicated that only changing the aluminum windows into timber windows could change the economic (R_1) and environmental (R_2) performance values even more than 50%; this reflecting the importance of the design and selection of facade openings.

6.4. Future perspectives

In this research, an in-depth investigation was carried out in relation to sustainability of FSs and integrating sustainable development goals into decision making framework for the design, assessment, and selection of sustainable residential building facades in an objective manner. However, there are still numerous aspects to be covered in future research lines:

- This research focused on residential buildings. Further research can be carried out by adapting this approach to focus on other building typologies - i.e., offices, commercial centers, educational centers and etc. - as well as promoting sustainable practices among building stakeholders. To this end, the indicators and weights should be adjusted to the new requirements and stakeholders' preferences.
- This area of research can be expanded to other countries and cities, besides Spain and Barcelona, bringing the opportunity to draw interesting international comparisons. This possibility should be proceeded by studying each new location particular context in order to verify all components. The developing and testing of this approach through using projects from different countries will enable more interesting comparisons to be made and to consolidate the robustness of the approach.
- Integrating Artificial Intelligence (AI) techniques with the MIVES-based Approach to reduce human errors and make the evaluation procedure faster and easier.
- Developing a digital App for this approach, which would be useful for public and private stakeholders - i.e. architects, construction firms and facade consultants among others. In this sense, the architectural offices that participated in this new approach definition, among other experts, already showed their interest for this app to be used in their projects.

The research, whilst completed at this stage, has opened up opportunities for further research in many other areas including an international application. The findings in this research can be further extended to accomplish the ultimate goal of promoting and improving sustainable practices in architecture and the construction sector.

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Appendix A. Questionnaire survey sample for weights assignment

Section 1. Cover letter for postal questionnaire survey

A Copy of the cover letter sent to experts

Dear Sir or Madam,

Research into sustainability assessment of facades in residential buildings of Barcelona

You are kindly asked to evaluate the parameters in the following diagram(tree) by assigning weights to them through pairwise comparison.

The tree includes the most representative and important indicators of a sustainable facade, which have been organized at three levels of; indicators, criteria, and requirements.

For weighting the parameters, it would be helpful to know the opinion of a set of professionals in construction sector. Therefore, this questionnaire was designed to achieve this goal.

This has been designed in a way that you can make suggestions as part of your invaluable contributions to this work. All of data collected from you will be used only for academic purpose.

We do appreciate that the questionnaire will take some of your valuable time but without your kind and expert input the research objectives aimed at improving sustainability implementation cannot be realized. To this end, we would like to thank you very much for your valued and kind consideration.

If you would like any further information about the research, please let me know.

Golshid Gilani

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Section.2. Professional profile of each expert

Professional Profile	
Title	
Professional Activities	
Years of Experience	

Section.3. Direction

Please fill the cells out based on your opinion.

In each cell, define the relative weights (importance) of each branch of the Tree. In other words, in each branch, which parameter is more important and has higher weight.

For weights assignment, the order should be as:

- First, determining the requirements' weights.
- Then, within each requirement, weights for the criteria are determined.
- Finally, within each criterion, weights for the indicators have to be defined.

Sum of the coefficients within each branch must be 1.

Proposed Sheet for collecting the weights by each Expert

REQUIREMENTS	CRITERIA	INDICATORS
$\lambda R1 =$ <input type="text"/> R1 Economic	$\lambda C1 =$ 1 C1. Cost	$\lambda I1 =$ <input type="text"/> I1. Construction Cost $\lambda I2 =$ <input type="text"/> I2. Maintenance Cost SUM * <input type="text" value="1"/>
$\lambda R2 =$ <input type="text"/> R2 Environmental	$\lambda C2 =$ <input type="text"/> C2. Consumption $\lambda C3 =$ <input type="text"/> C3. Emission $\lambda C4 =$ <input type="text"/> C4. Waste SUM * <input type="text" value="1"/>	$\lambda I3 =$ 1 I3. Energy Consumption $\lambda I4 =$ 1 I4. Co2 Emission $\lambda I5 =$ 1 I5. Total Solid Wastes
$\lambda R3 =$ <input type="text"/> R3 Social	$\lambda C5 =$ <input type="text"/> C5. Safety $\lambda C6 =$ <input type="text"/> C6. Labor availability $\lambda C7 =$ <input type="text"/> C7. User Added Comfort $\lambda C8 =$ <input type="text"/> C8. Aesthetics SUM * <input type="text" value="1"/>	$\lambda I6 =$ 1 I6. Extra Fire performance $\lambda I7 =$ 1 I7. Labor skilled requirement $\lambda I8 =$ <input type="text"/> I8. Extra thermal performance $\lambda I9 =$ <input type="text"/> I9. Extra acoustic performance $\lambda I10 =$ <input type="text"/> I10. Daylight comfort SUM * <input type="text" value="1"/>
SUM * <input type="text" value="1"/>		$\lambda I11 =$ <input type="text"/> I11. contextual compatibility $\lambda I12 =$ <input type="text"/> I12. Visual quality SUM * <input type="text" value="1"/>

* must be = 1

Observations:

please add your comments and suggestions for improvement of the study

Example of a completed sheet; the proposed weights by an expert

REQUIREMENTS	CRITERIA	INDICATORS
$\lambda_{R1} = 0.2$ R1 Economic	$\lambda_{C1} = 1$ C1. Cost	$\lambda_{I1} = 0.7$ I1. Construction Cost $\lambda_{I2} = 0.3$ I2. Maintenance Cost SUM * 1
$\lambda_{R2} = 0.4$ R2 Environmental	$\lambda_{C2} = 0.2$ C2. Consumption $\lambda_{C3} = 0.4$ C3. Emission $\lambda_{C4} = 0.4$ C4. Waste SUM * 1	$\lambda_{I3} = 1$ I3. Energy Consumption $\lambda_{I4} = 1$ I4. Co2 Emission $\lambda_{I5} = 1$ I5. Total Solid Wastes
$\lambda_{R3} = 0.4$ R3 Social	$\lambda_{C5} = 0.4$ C5. Safty $\lambda_{C6} = 0.1$ C6. Labor availability $\lambda_{C7} = 0.3$ C7. User Added Comfort	$\lambda_{I6} = 1$ I6. Extra Fire performance $\lambda_{I7} = 1$ I7. Labor skilled requirement
SUM * 1	$\lambda_{C8} = 0.2$ C8. Aesthetics SUM * 1	$\lambda_{I8} = 0.4$ I8. Extra thermal performance $\lambda_{I9} = 0.3$ I9. Extra acoustic performance $\lambda_{I10} = 0.3$ I10. Daylight comfort SUM * 1
		$\lambda_{I11} = 0.6$ I11. contextual compatibility $\lambda_{I12} = 0.4$ I12. Visual quality SUM * 1

Appendix B. Results of the questionnaire survey used for evaluating I₁₁ (contextual compatibility) and I₁₂ (visual quality) related to the five commonly-used facade systems in Barcelona

The questionnaires presented in Chapter 3 (Table 3.4 and 3.5) were sent to the respondents and then, the PhD candidate interviewed these respondents in order to fill out the questionnaires.

Results obtained from the questionnaire survey regarding I₁₁

	X_{min}	X_{max}	Average	Deviation	Number of outliers out of 17
FS-A	2	4	2.8	0.53	1
FS-B	3.5	4.5	4	0.43	0
FS-C	3.5	4.5	4	0.43	0
FS-D	2.5	4	2.9	0.44	0
FS-E	2	3.5	2.70	0.49	0

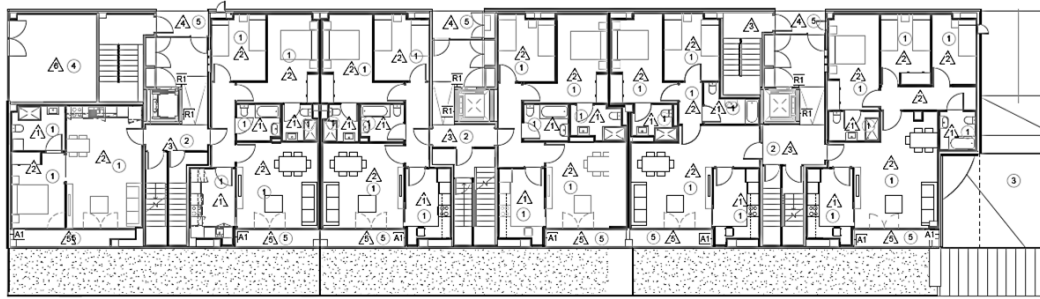
Results obtained from the questionnaire survey regarding I₁₂

	X_{min}	X_{max}	Average	Deviation	Number of outliers out of 17
FS-A	0.5	1.5	1	0.3	0
FS-B	1	2.5	1.6	0.37	0
FS-C	1	2.5	1.6	0.37	0
FS-D	1	2	1.3	0.39	0
FS-E	2	3	2.3	0.35	0

Appendix C. Obtained results from the questionnaire survey regarding weights assignment

Parameters		Min Weight	Max Weight	Average	Deviation	Number of outliers out of 23
Requirements	Economic	0.20	0.55	0.33	0.1	0
	Environmental	0.15	0.7	0.35	0.12	1
	Social	0.10	0.5	0.32	0.09	0
Criteria	Cost	1.00	1	1	0	0
	Consumption	0.20	0.6	0.37	0.12	0
	Emission	0.15	0.7	0.34	0.12	1
	Waste	0.05	0.5	0.28	0.14	0
	Safety	0.00	0.45	0.28	0.1	0
	Constructability	0.00	0.3	0.18	0.07	0
	User added comfort	0.7	0.1	0.34	0.12	1
	Aesthetics	0	0.4	0.21	0.09	0
	Construction cost	0.3	0.95	0.61	0.18	0
	Maintenance cost	0.05	0.7	0.39	0.18	0
Indicators	Energy consumption	1	1	1	0	0
	CO2 emission	1	1	1	0	0
	Total solid waste	1	1	1	0	0
	Extra fire performance	1	1	1	0	0
	skilled labor requirement	1	1	1	0	0
	Extra thermal performance	0.1	0.6	0.38	0.1	0
	Extra acoustic performance	0.15	0.45	0.28	0.07	0
	Daylight comfort	0.2	0.6	0.34	0.1	0
	Contextual compatibility	0.2	1	0.55	0.19	0
	Visual quality	0	0.8	0.45	0.19	0

Appendix D. Architectural drawings from Neinor project (FS-case1)

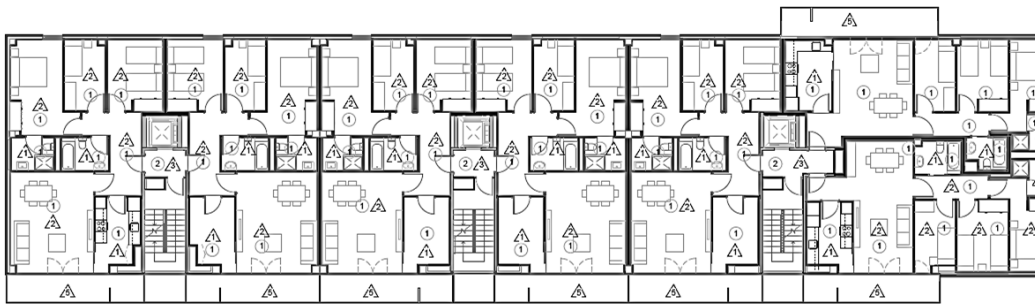


Ground floor plan

FLOOR PLANS



First and third floor plan

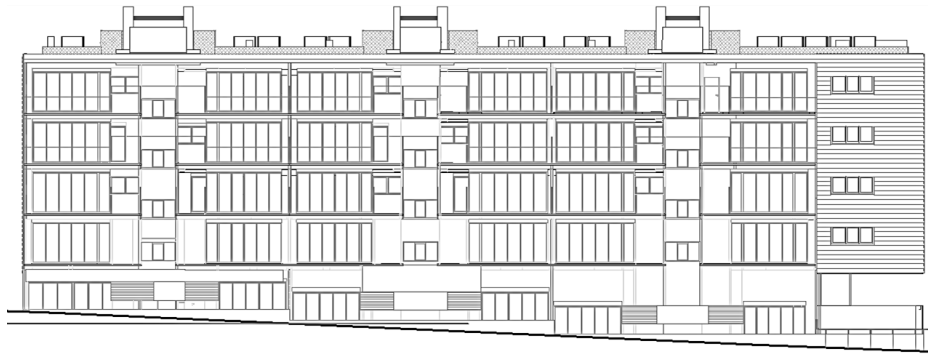


Second and fourth floor plan

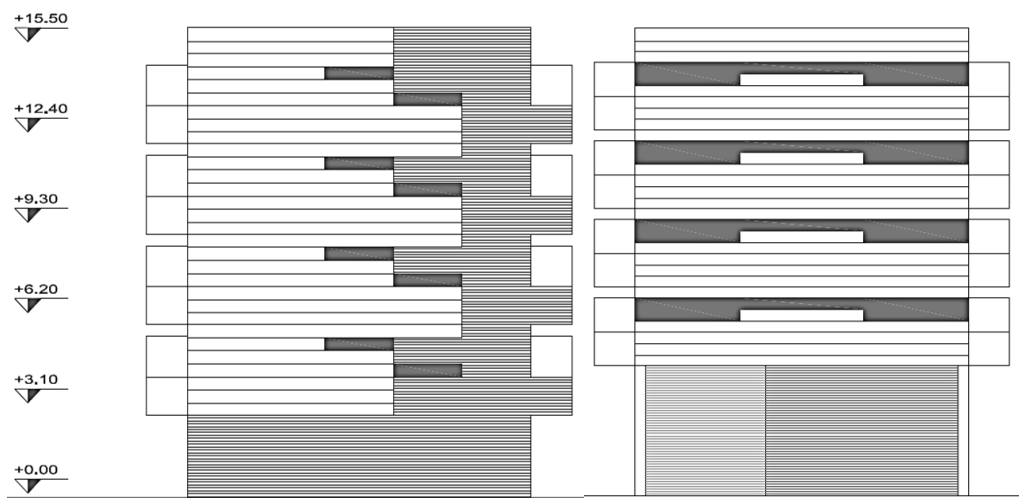
FACADES



North Facade



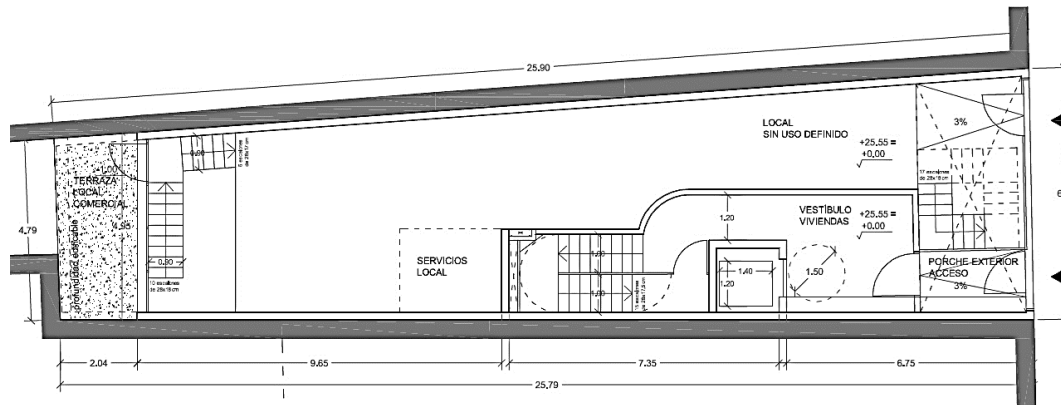
South facade



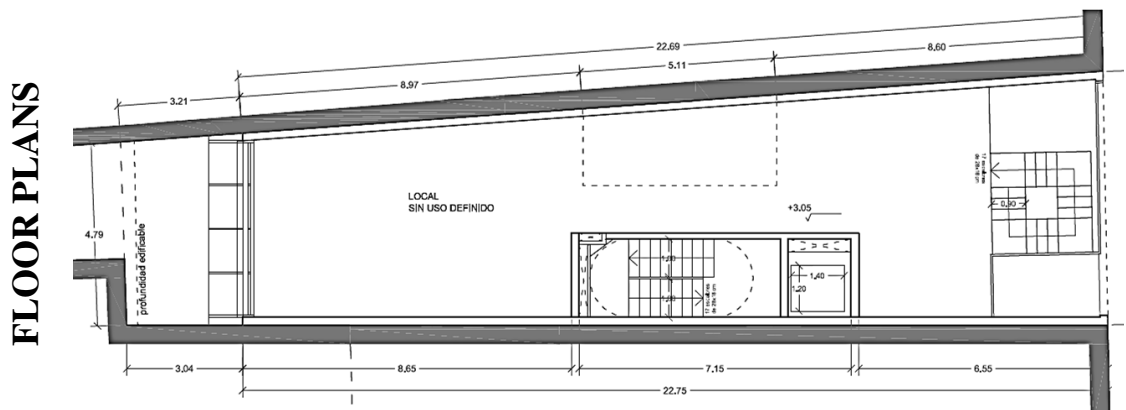
West facade

East facade

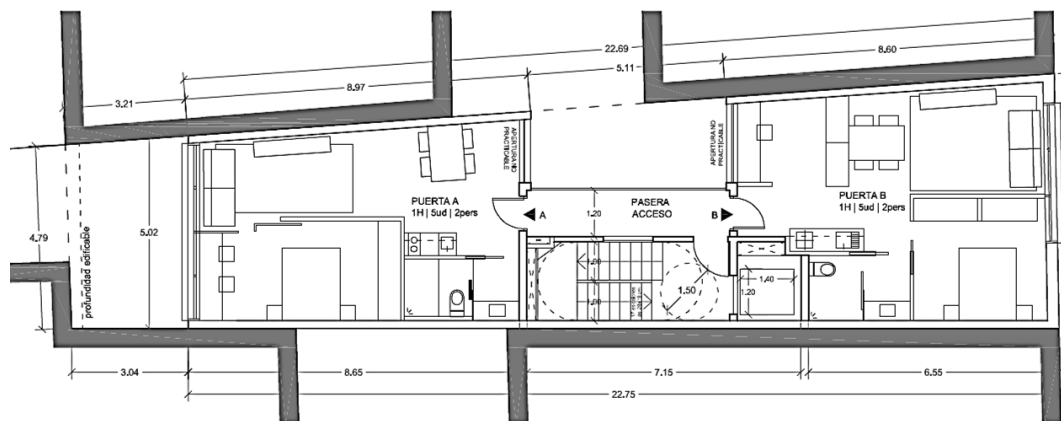
Appendix E. Architectural drawings from Lepant project (FS-case2)



Ground floor plan



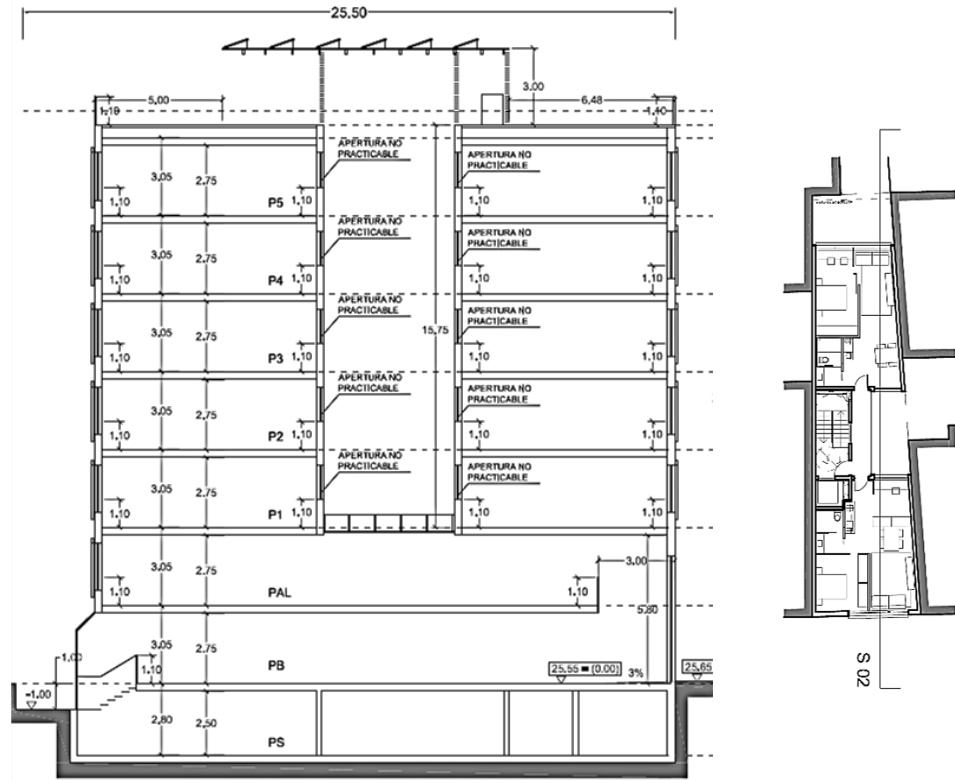
Mezzanine plan



First to fifth floor plan

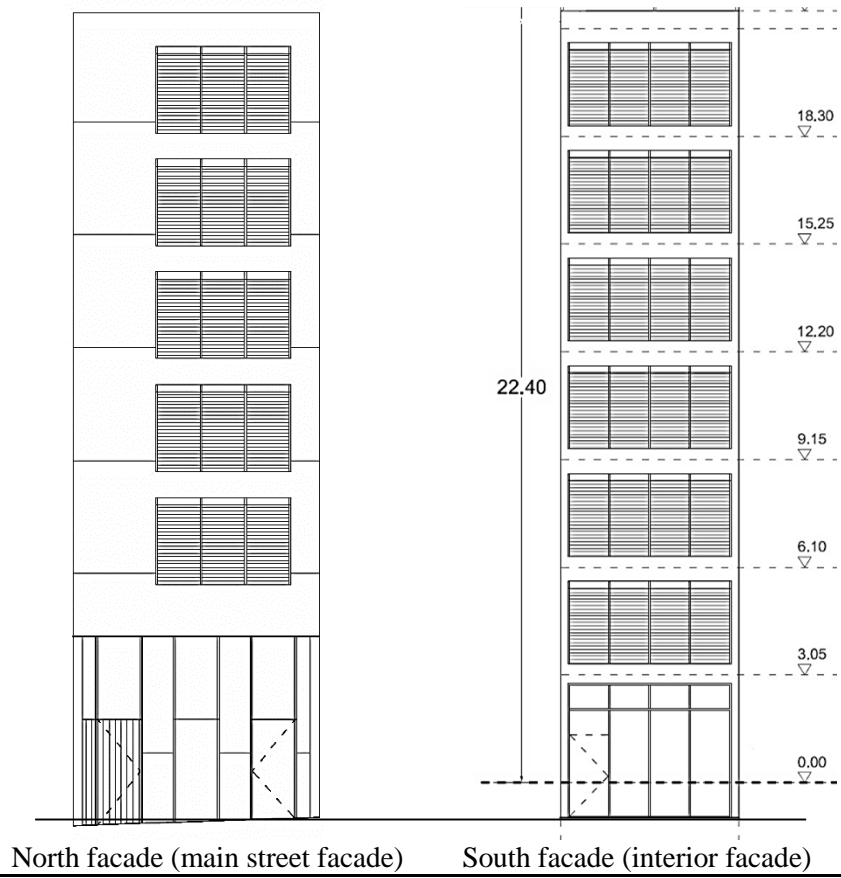
FLOOR PLANS

SECTION



Longitudinal section

FACADES



North facade (main street facade)

South facade (interior facade)

Appendix F. Results of the questionnaire survey used for evaluating I₁₁ and I₁₂ related to the FS-case1 and FS-case2 with AL windows

The process of evaluation was the same as Appendix B. The proposed questionnaires (Table 3.4 and 3.5) were sent to the respondents and completed via an interview.

Results obtained from the questionnaire survey regarding I₁₁

	X_{min}	X_{max}	Average	Deviation	Number of outliers out of 17
FS-case1	2.5	3.5	2.8	0.35	0
FS-case2	4	5	4.5	0.35	0

Results obtained from the questionnaire survey regarding I₁₂

	X_{min}	X_{max}	Average	Deviation	Number of outliers out of 17
FS-case1	2	4	2.5	0.55	1
FS-case2	1.5	2.5	2	0.39	0

Appendix G. Results of the questionnaire survey used for evaluating I_{11} and I_{12} related to the FS-case1 and FS-case2 with Timber windows.

Results obtained from the questionnaire survey regarding I_{11}

	X_{\min}	X_{\max}	Average	Deviation	Number of outliers out of 17
FS-case1	2	3	2.6	0.38	0
FS-case2	4	5	4.5	0.35	0

Results obtained from the questionnaire survey regarding I_{12}

	X_{\min}	X_{\max}	Average	Deviation	Number of outliers out of 17
FS-case1	2.5	4	2.75	0.40	1
FS-case2	1.5	2.5	2.20	0.31	0