# Towards the Façades of the Future: A New Sustainability Assessment Approach

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**Abstract.** While the majority of the recent studies report on sustainability assessment of buildings as a whole, research on the sustainable performance of building independent elements (e.g., envelope and façades) is scarce. Façades, as the first line of defense against the undesirable external impact, may contribute to the building sustainability by reducing the amount of energy consumption and providing thermal comfort for the inhabitants, thus minimizing the environmental impact on both the building and on the environment. Despite the significance of this issue, there are a few studies that focus on sustainability assessment of façades that consider economic, environmental and social aspects; however, these aspects are generally taken into account in a decoupled manner and, often, not objectively measured. In this respect, a set of criteria and indicators for assessing sustainability of residential façade systems is presented and discussed in detail herein. In addition, a new model for assessing objectively sustainability of building façades is also presented. This approach has been obtained by using MIVES, a Multi-Criteria Decision Making model that integrates the main sustainability requirements (economic, environmental and social) and includes the concept of value functions.

## 1. Introduction

The concept of sustainable development was first defined in Brundtland Commission in 1987. Before that, little efforts were made to achieve sustainability while after that, many studies have concentrated on this issue in construction sector [1-5] and various building performance assessment methods have been introduced for measuring building sustainability such as BREEAM (UK,1991) which was pioneer of all other building performance assessment methods, LEED, CASBEE, HQE, Green Globe, Green Star, GBC.

But, there is still a lack of study on sustainability assessment of building elements especially the ones that can have considerable impact on sustainability of the whole building such as building envelope and façade. According to Stansfield [6] building sustainability could be achieved through building facade by reducing environmental impacts on building as well as building impacts on the environment. Façade as a linkage between the interior of building and the external environment can decrease the level of heat/cooling energy needed in building. It can protect the interior space against adverse environmental effects such as pollution, climate change, temperature, humidity, HVAC load, lighting load, etc. Apart

from its protective, environmental and regulatory functions, building envelope may control the indoor air quality, fire, and acoustic effects on buildings and provide comfort for the inhabitants [7]. Furthermore, façade 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 and all these have positive influence on social aspects as well [8].

All the aforementioned studies reveal the importance of façade and its role in the sustainability performance of the building. Respectively, this study aims to present a new model for assessing the sustainability of different façades systems from environmental, social, economic points of view. In addition, the most relevant and representative indicators for assessing the sustainability of residential façades are also proposed and described.

In this study, the focus is on façade of residential buildings because housing sector is responsible for adverse environmental, social and economic impacts. For instance, in EU the building sector accounts for 35 %–40 % of the final total energy consumption (25 %–27 % residential, 10 %–13 % non-residential) and 25 %–40 % of the associated carbon dioxide ($CO_2$) emissions (15 %–27 % residential, 11 %–21 % non-residential) [9].

## 2. Conceptual Model for Sustainability Assessment of Façades

The proposed model is based on MIVES (Integrated Value Model for Sustainable Assessment), which is a Multi Criteria Decision Making (MCDM) tool that makes it possible to assess and quantify objectively indicators belonging to the three aspects of sustainability (economic, environmental and social) by means of the value function concept [10–12]. The use of value functions, which is presented in Figure 1, allows 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. MIVES can be calibrated to a certain time period and used for different locations with diverse characteristics and local living standards without being limited by the present conjuncture. This model has already been satisfactorily applied in various studies in different fields of architecture and civil engineering [13–24].

In the following subsection, the process of evaluation with MIVES is explained in detail.

### 2.1. Procedure

MIVES includes the following phases for assessing sustainability:

*Phase 1: Define the problem to be solved and the decisions to be made*

In this case, phase 1 consist in assessing the sustainability index of three types of façades for a residential building in Barcelona in order to decide which one is the most sustainable one with considering the boundary conditions (environmental factors of the city, orientation of the building, use of the building….).

*Phase 2: Establish a requirements tree that may include qualitative and quantitative parameters*

Requirements' tree is a diagram that includes the most representative criteria and indicators that permit assess satisfaction and sustainability of a specific process, system and product, and make decisions with the obtained results. This requirements' tree is previously fixed and filtered according to the involved stakeholders' preferences, and it is unique for each decision-making process and sustainability assessment (e.g., façades, columns, beams, and foundations in case of buildings). Although, as different locations have different standards and requirements some indicators can be eliminated or changed based on the local characteristics. 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 it is not representative. On other hand, the final number of criteria and indicators in each tree branch shall be the minimum number and they should be independent from each other so some indicators should be disregarded due to either their lack of representativeness or due to certain overlapping with other indicators already considered.

Based on the aforementioned explanations, the following requirement tree has been developed to assess the sustainability of façade systems in contemporary residential buildings in Barcelona (Table 1). The obtained criteria and indicators are based on extensive review of previous literature: a thesis about the sustainable buildings [25], a thesis about selection of sustainable building materials [26] and numerous related bibliography [27–29], seminars with multidisciplinary engineers who collaborate in Construction Industry (civil engineers, architects, contractors, project managers, building inspectors) and/or researchers as well as standards. It has been tried to select the most representative indicators which are independent from each other. In section 3, description of each indicator is presented in detail.

**Table 1.** Requirement tree for sustainability assessment of residential façades

| Requirements | Criteria | Indicators | Units |
|---|---|---|---|
| $R_1$.**Environmental** | $C_1$.Consumption | $I_1$.Energy Consumption | MJ/m2 |
| | | $I_2$.Water Consumption | Kg/m2 |
| | $C_2$.Waste | $I_3$.Total Solid Wastes | kg/m2 |
| | $C_3$.Emission | $I_4$.$CO_2$ Emission | $Kgco^2/m^2$ |
| $R_2$.**Economic** | $C_4$.Cost | $I_5$.Construction Cost | €/m$^2$ |
| | | $I_6$.Maintenance Cost | €/m$^2$ |
| $R_3$.**Social** | $C_5$.Safety | $I_7$.Risk For Public | Points |
| | | $I_8$.Risk For Labors | |
| | | $I_9$.Risk Resistance | h(s) |
| | $C_6$.Comfort | $I_{10}$.Heat Transfer | m$^2$ k/w |
| | | $I_{11}$.Acoustic Comfort | Points |
| | | $I_{12}$.Automatic/Manual Control | |
| | $C_7$.Aesthetics | $I_{13}$.Visual Quality | Points |
| | | $I_{14}$.Consistency with Surrounding | |

*Phase 3: Define the relative weight of each parameter*
After defining the requirements tree, weights should be assigned for each branch of the requirements. First, weights for the various requirements are calculated. Then, within each requirement weights for the criteria are calculated, and finally, the same thing is done for each criteria to obtain the indicators weights. The weightings of the tree's components are also defined at seminars, using the analytic hierarchy process (AHP) [30] and/or direct assignment.

*Phase 4: Establish value functions to convert all parameters into a set of variables with same units*
Afterwards, value function has to be defined for each indicator in order to homogenize the indicators units. These values represent minimum and maximum degree of satisfaction in terms of sustainability, which vary from 0 to 1, respectively [17].
To determine the satisfaction value for each indicator, the following stages should be done in the MIVES model:
    Stage 1. Definition of the tendency (increase or decrease) of the value function.
    Stage 2. Definition of the points corresponding to $P_{min}$ and $P_{max}$.
    Stage 3. Definition of the shape of the value functions (linear, concave, convex, S-shape)
    Stage 4. Definition of the mathematical expression of the value function.

According to Alarcon, et al [11], when satisfaction increases rapidly or decreases slightly, a concave-shaped function is the most suitable. The convex function is used when the satisfaction tendency is contrary to the concave curve case. If satisfaction increases/decreases steadily, a linear function is presented. An S-shaped function is used when the satisfaction tendency contains a combination of concave and convex functions, as shown in Figure 1.

The parameters, tendency and shape of the value function for each indicator are determined from international guidelines, scientific literature, National Building Regulations, and the background of experts participated in the seminars.
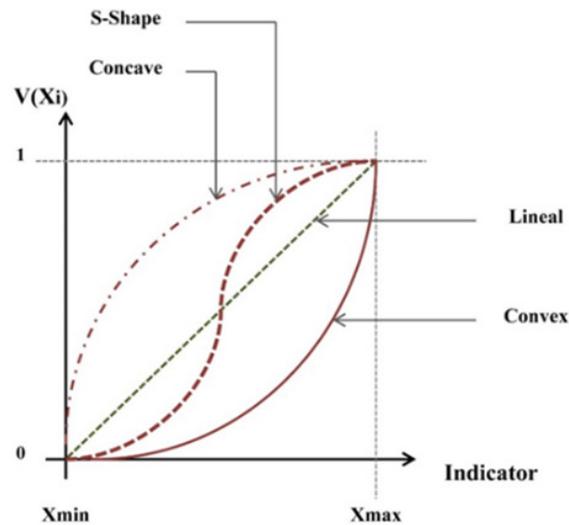


**Figure 1.** Different value function shapes.

For instance, to evaluate the sustainability value of the construction cost indicator (I5):

$P_{min}$ = 50 €/m$^2$ and $P_{max}$=700 €/m$^2$; these prices have been considered as minimum and maximum construction cost of a façade system in contemporary residential buildings in Barcelona. To estimate the prices; 620 façade system have been evaluated through the online BEDEC database from the Technological Institute of Catalonia (ITeC) [31]. Additionally, since satisfaction decreases rapidly when the building cost increases, a decreasing S-shape curve is assigned for the tendency of this indicator value function as shown in figure.2. S-shape curve has been selected because according to the existing construction market in Barcelona, rising the construction price from 50€ to 150€ does not affect the satisfaction rate of stakeholders a lot while after that the satisfaction decreases rapidly.
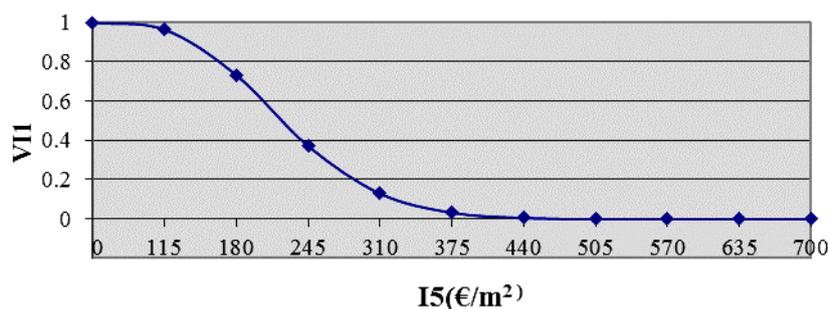


**Figure 2.** Value function of construction cost indicator (I5).

In Table 2, indicators' tendency and shape have been defined based on numerous bibliography entries including one dissertations [32], Barcelona building regulations and standards, international and local databases, and several meetings with experts. From the 14 value functions, three increase S-shape (IS), two increase concavely (IC$_{CV}$), 3 decrease concavely (DCcv), one decrease S-shape (DS), four decrease convexly (DCvx) and one decrease lineally (DL).

MIVES uses Eq. (1) as the basis for defining individual value functions $Vi$.:

$$V_i = K_i \cdot \left[ 1 - e^{-m_i \cdot (|P_{i,x} - P_{i,min}|/n_i)^{A_i}} \right] \tag{1}$$

In Eq. (2), 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.

$$K_i = \frac{1}{1 - e^{-m_i \cdot (|P_{i,max} - P_{i,min}|/n_i)^{A_i}}} \tag{2}$$

In Eqs. (1) and (2):

**a)** $P_{i,max}$ and $P_{i,min}$ are the maximum and minimum points in the scale of the indicator under consideration.

**b)** $P_{i,x}$ is the score of alternative $x$ that is under assessment, with respect to indicator $i$ under consideration, which is between $P_{i,min}$ and $P_{i,max}$. This score generates a value that is equal to $V_i(P_{i,x})$, which has to be calculated.

**c)** $A_i$ is 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* ($A_i > 1.0$). This field will be cover in the next section

**d)** $n_i$ is 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.

**e)** $m_i$ defines the value of the ordinate for point $n_i$, in the former case where $A_i > 1.0$.

*Phase 5: Assess the alternatives by using the established model.*
In this phase, the sustainability index of each alternative is evaluated by using the following Formula.

$$V(P_x) = \sum_{i=1}^{i=N} \alpha_i \cdot \beta_i \cdot \gamma_i \cdot V_i(P_{i,x}) \tag{3}$$

*Phase 6: Make the right decisions*
Finally, according to the sustainability index of each alternative, the stakeholders involved in the decision-making process should choose the alternative that best meets all the requirements. This does not necessarily mean that they will choose the alternative with the highest sustainability index, because there may be another alternative that has a sufficiently high rate and that better meets various other requirements.

## 3. Main criteria for sustainability assessment of residential façades

The requirements tree presented in Table 1 includes three main sustainability criteria which are divided into 7 sub-criteria and 14 indicators. The Economic Criteria ($R_1$) takes into account the economic impacts of façade, both direct and indirect; over its entire life cycle. The environmental impacts of façade during the entire life cycle are evaluated in Environmental Criteria ($R_2$). The social Criteria (R3) is used to assess the impact of each parameter on the comfort and health of society. In the following table, a Short description of each indicator has been presented as well.

**Table 2.** Description of the new model chosen indicators.

| Indicators | Units | Value Functions shape |
|---|---|---|
| $I_1$.Energy Consumption | $MJ/m^2$ | $DC_{VX}$ |

This indicator evaluates the amount of energy consumed in two phases of production and construction of façade systems based on LCA. For assessment; Referring to national and international databases such as ICE

| | | |
|---|---|---|
| $I_2$.Water Consumption | $Kg/m^2$ | $DC_{VX}$ |

Amount of water usage during the whole life of façade system is assessed.
It is determined based on Wuppertal Institute for Climate, Environment and Energy, 2011[33].

| | | |
|---|---|---|
| $I_3$.Total Solid Wastes | $kg/m^2$ | $DC_{Vx}$ |

The total amount of waste material remaining from the construction (assembly) & demolition (disassembly) phases is going to be calculated in this indicator.
To quantify the weight (kg) of C&D waste generated, BEDEC database is used [31].

| | | |
|---|---|---|
| $I_4$.Co$_2$ Emission | $Kgco^2/m^2$ | $DC_{VX}$ |

The amount of CO2 emissions in two phases of production and construction of any façade alternatives is calculated.
For assessment; Referring to national and international databases such as ICE

| | | |
|---|---|---|
| $I_5$.Construction Cost | $€/m^2$ | DS |

Material and installation cost of the façade systems is calculated in this indicator.
BEDEC databases is used for assessment

| | | |
|---|---|---|
| $I_6$.Maintenance Cost | $€/m^2$ | DL |

Calculating the cost of any maintenance action during the life cycle of façade such as repairing, replacing. 50 years' maintenance is considered for evaluation

| | | |
|---|---|---|
| $I_7$.Risk For Public | pts | $DC_{CV}$ |

Probability of any accident affecting the public during construction and assembly of façade is going to be assessed through questionnaire survey

| | | |
|---|---|---|
| $I_8$.Risk For Labors | pts | $DC_{CV}$ |

Probability of any accident for labors during construction and assembly of façade is going to be assessed through questionnaire survey by providing a checklist for project risk assessment

| | | |
|---|---|---|
| $I_9$.Risk Resistance | h(s) | $IC_{CV}$ |

This indicator assess the strength of façade against fire
For assessment: referring to national standards and regulations

| | | |
|---|---|---|
| $I_{10}$.Heat Transfer | $m^2$ k/w | $DC_{CV}$ |

This indicator assesses the amount of the heat transfer through exterior walls
For assessment: referring to national standards and regulations

| | | |
|---|---|---|
| $I_{11}$.Acoustic Comfort | pts | $IC_{CV}$ |

This indicator assesses the rate of air-borne sound proofing of each façade alternative.
For assessment: referring to national standards and regulations such as STC

| | | |
|---|---|---|
| $I_{12}$.Automatic/Manual Control | pts | IS |

This indicator assesses the rate of user involvement on façade components to make himself comfortable in terms of air flow, daylight, and view to the outside and providing privacy.

| | | |
|---|---|---|
| $I_{13}$.Visual Quality | pts | IS |

This indicator Assesses perceptional properties that influence aesthetic preference of observers through questionnaire survey

| | | |
|---|---|---|
| $I_{14}$.Consistency with Surrounding | pts | IS |

This indicator assesses the rate of compatibility of the façade with its surrounding from various aspects such as appearance, architectural style, culture, climate and others

Legend: pts: points…

## 4. Summary and Discussion

In this research, an MCDM approach has been proposed based on MIVES to quantify the sustainability of building façades. The model presented permits to assess the sustainability of these elements by considering 14 relevant indicators that represent economic, environmental and social requirements. This model is conceptually presented herein, while a real case study is being prepared to serve an example of application within the context of the PhD thesis of the first author.

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