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# A multi-criteria decision-making framework for residential building renovation using pairwise comparison and TOPSIS methods

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ABSTRACT

The rate at which buildings are renovated across Europe is expected to increase in the upcoming years. However, selecting renovation solutions for residential buildings is still a challenging task due to the participation of multiple stakeholders, lack of clear decision-making procedures, and diverse effects resulting from the renovation alternatives. Most of the existing approaches do not consider multiple stakeholders and focus mainly on weighting criteria and performing simulations to quantify alternatives' performance. Therefore, this paper presents a more complete Multi-criteria decision-making (MCDM) framework to support the decision-making process in renovation. To illustrate and validate the framework, it is implemented in two case studies based on a five-story building located in Spain. Each case includes five stakeholders. Two weighting settings are analysed to study the robustness and sensitivity of the proposed approach. The main contributions correspond to: 1) an MCDM enabling the participation of multiple stakeholders using the Pairwise comparison method; supporting the setting of objectives and criteria, promoting a comprehensive evaluation of the alternatives; and facilitating the integration of criteria weights and alternatives' performance through the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method; and 2) the validation of the proposed framework, especially the implementation of TOPSIS to evaluate renovation alternatives. Promoting the setting of objectives and criteria can enable discussions and encourage a broader and more complete analysis of renovation alternatives. In the two case studies, stakeholders included social aspects and assigned in total weights around 20% to this category. The Pairwise comparison and TOPSIS methods integrated the perspectives of stakeholders with different interests and the alternatives' performance to obtain a shared view of the renovation and a final ranking of the alternatives to differentiate them accordingly and make a better-informed decision.

## 1. Introduction

In Europe, building renovation rates are expected to increase due to the large number of existing buildings that require to be renovated. Around 75% of existing buildings are considered inefficient according to current standards [1]. 85–95% of the existing building stock will still be standing in 2050 [2]. Typically, in residential renovation projects, complex governance and ownership structures, legal structures, and other challenges impact the initiation and execution of the renovation activities [3]. Some of these

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aspects lead towards complex decision-making processes to select the final renovation solution. Strategies and tools need to be developed to support stakeholders to overcome these barriers.

In the building renovation field, there is a lack of consensus regarding the main criteria, applicable renovation methodologies, and tools to support the decision-making process [4]. Despite the involvement of multiple stakeholders in such projects, most of the existing approaches are limited to cases where the decision is made by a single stakeholder. Nevertheless, in these projects, additional stakeholders such as tenants and building managers may get involved [5], influencing the decision-making process. Around 49% of the housing stock in Europe corresponds to multi-family units, and the average share of rented units is 30%, reaching levels around 70% in countries such as Germany [3]. Therefore, a decision-making strategy in the context of residential renovation should support the participation of multiple and diverse stakeholders, which may have different rights and obligations [6].

A renovation initiative for a residential building should address multiple environmental, economic, and social elements. Nevertheless, Pombo et al. [7] emphasized that most of the studies in this field have focused on economic and environmental aspects, meanwhile social elements are scarcely considered. This perspective can lead to top-down views on people and energy use that cannot consider heterogeneity, social structure, or interests beyond energy and economy [8]. Moreover, decision-making approaches in this field often focused only on energy-related measures. In practice, these projects usually include other kinds of renovation activities [9,10]. For instance, Pohoryles et al. [11] studied energy and seismic renovation measures in conjunction, showing that a combined renovation scheme brings benefits in moderate to high seismicity regions. Covering all these different aspects could lead to better and informed decision-making, satisfying the needs of multiple stakeholders. Decision-making approaches should enable and encourage the identification of comprehensive objectives and criteria to evaluate potential renovation alternatives following a more complete perspective.

The main goal of this paper is to present a more complete Multi-criteria decision-making (MCDM) framework covering these and additional aspects and requirements of the decision-making in residential renovation projects. The proposed framework is based on the pairwise comparison method to enable the participation of multiple stakeholders, a predefined comprehensive decision tree and complementary activities to support the objectives and criteria setting, and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to integrate the criteria weights and alternatives' performance. Particularly, TOPSIS has proven to be simple and quick to identify the ranking of alternatives [12]. These characteristics and its ability to maintain the same number of steps regardless of the problem size can be beneficial in the context of renovation projects where new alternatives could be included during the decision-making process. TOPSIS has been also frequently used to review other methods [13]. It has been implemented in related areas, for instance, de Angelis et al. [14] used it to evaluate different types of floors in the context of building design. Complementary strategies are proposed for other stages of the decision-making process as well. To show how the framework can enable the participation of multiple stakeholders and facilitate the integration of criteria weights and alternatives' performance, the framework is applied to two case studies including multiple stakeholders in each case.

The contributions of this paper can be summarized as follows: 1) an MCDM that aims at enabling the participation of multiple stakeholders; supporting the setting of objectives and criteria, promoting a comprehensive evaluation of the alternatives; and facilitating the integration of criteria weights and alternatives' performance; and 2) the validation of the proposed framework, especially the implementation of the TOPSIS method to evaluate different renovation alternatives. The remainder of the paper is structured as follows: Section 2 presents the background, research motivation, and introduces the proposed MCDM framework. Section 3 summarizes the methodology to illustrate and validate the proposed approach. Section 4 presents the results from two case studies. Finally, the discussion and conclusions are synthesized in Sections 5 and 6, respectively.

## 2. Background and research motivation

### 2.1. Decision-making in building renovation and MCDM frameworks

The decision-making process in renovation projects encounters different scenarios [15]. Cases such as an owner living in a single-family house, a housing company and its experts renovating dwelling units occupied by tenants, or a more complex scenario of a multi-family building with multiple owners, and units occupied by tenants often demand the participation of multiple and diverse stakeholders. Nevertheless, most of the existing decision-making approaches for renovation [4,16–24] did not consider the participation of multiple stakeholders in the process. Taillandier et al. [25] included multiple stakeholders in the definition of criteria, nevertheless, the case analysed in their study included a single owner making the decision. The studies presented in Refs. [5,26]

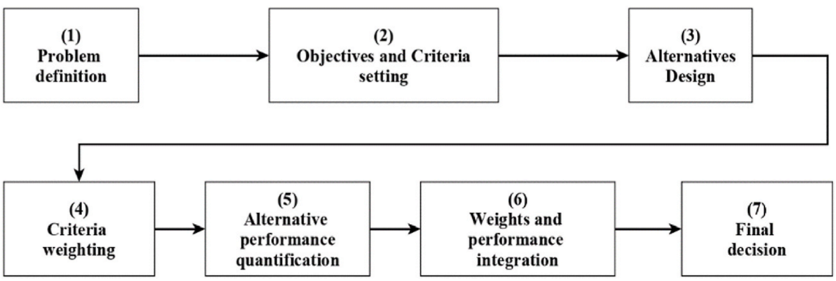


**Fig. 1.** General steps of MCDM frameworks.

**Table 1**
Review of existing decision-making approaches for renovation.

| | Particularities | a) Multiple Stakeholders | b) Objectives and criteria setting | c) Criteria set scope | d) Weights and performance integration |
|---|---|---|---|---|---|
| **Proposed approach** | Structured decision-making framework covering the different stages. | Multiple stakeholders using the Pairwise comparison method. | Based on a predefined flexible criteria tree. Value-focused thinking, complementary activities. | Triple bottom line sustainability. | TOPSIS. |
| [27] | Structured decision-making framework covering the different stages. | General approach. Multiple stakeholders. | Root definition + CATWOE analysis + Conceptual models. | Suggests using the results from Ref. [4]. | Suggested AHP-TOPSIS but did not implement them. |
| [26] | Decision at the building portfolio level. | Multiple professional stakeholders. | Discussion between stakeholders through a dialogue tool. | No suggestion. Stakeholders define them. | Own method. |
| [5] | Evaluation of renovation projects, not alternatives. | Large scale projects. Multiple stakeholders. | Through interviews with stakeholders for each case. | Criteria are defined to evaluate renovation projects not alternatives. | Spider net diagram. |
| [4] | The proposal of new objectives and criteria categories for sustainability | No strategy to enable participation of multiple stakeholders is discussed. | General objectives and criteria are fixed and predefined. | Three general categories: functionality, accountability, and feasibility. | Spider net diagram. |
| [25] | Main focus, the quantification of alternatives performance. | Multiple stakeholders. The case presented included one single owner. | Criteria are fixed and predefined. | Triple bottom line sustainability. | ELECTRE III. |
| [16] | Main focus, the quantification of alternatives performance. | No strategy to enable participation of multiple stakeholders is discussed. | Criteria are fixed and predefined. | Environmental and economic aspects. | None. |
| [17] | Comparison of the performance of buildings with different potential to be renovated. | No strategy to enable participation of multiple stakeholders is discussed. | Criteria are fixed and predefined. | Mainly indoor conditions and energy consumption. | WASPAS, ARAS, TOPSIS modified. |
| [18] | Validation of a functional prototype to support the decision-making process. | No strategy to enable participation of multiple stakeholders is discussed. | Criteria are fixed and predefined. | Energy and CO2 emissions. | None. |
| [19] | Main focus, life cycle assessment. | No strategy to enable participation of multiple stakeholders is discussed. | Criteria are fixed and predefined. | Life cycle assessment. | Pareto front. |
| [34] | Support of home owners throughout the decision-making | No strategy to enable participation of multiple stakeholders is discussed. | Criteria are fixed and predefined. | Triple bottom line sustainability. | Own method. |
| [20] | Main focus, the quantification of alternatives performance. | No strategy to enable participation of multiple stakeholders is discussed. | Criteria are fixed and predefined. | Environmental and economic aspects. | Matrix, Pareto front. |
| [21] | Main focus, economic sustainability and energy efficiency according to a specific local context. | No strategy to enable participation of multiple stakeholders is discussed. | Criteria are fixed and predefined. | Environmental and economic aspects. | Colours code, based on cost. |
| [22] | Main focus, combination of renovation and electrical mobility strategies. | No strategy to enable participation of multiple stakeholders is discussed. | Criteria are fixed and predefined. | Environmental and economic aspects. | TOPSIS. |
| [23] | Genetic algorithm to optimize the building envelope and support the decision-making process. | No strategy to enable participation of multiple stakeholders is discussed. | Criteria are fixed and predefined. | Environmental and economic aspects, and thermal comfort. | Pareto front. |
| [24] | Spatial decision support system at the neighbourhood level. | No strategy to enable participation of multiple stakeholders is discussed. | General objectives and criteria are fixed and predefined. | Comprehensive criteria set based on six general objectives. | Hermione. |
| [28] | Decision at the district and building level. | A focus group for the criteria weighting. | Criteria are fixed and predefined. | Triple bottom line sustainability. | PROMEETHEE. |

discussed the participation of multiple stakeholders but focused on evaluating the renovation project itself and the renovation of a building portfolio, respectively. Only few studies [5,26–28] considered explicitly strategies to enable the participation of multiple stakeholders in the context of renovation projects at the building level.

Besides supporting the participation of multiple stakeholders, an MCDM for renovation should support different steps to conduct the decision-making procedure. MCDM approaches are intended to provide stakeholders with a structured framework to deal with decision-making processes, especially in the presence of multiple and conflicting objectives and criteria [29]. In general, an MCDM framework usually comprises the steps presented in Fig. 1 [30,31]. In the renovation field, the existing approaches have focused mainly on steps 4 and 5, weighting criteria and performing simulations to quantify alternatives' performance [32]. Meanwhile, only few studies have included key elements such as setting objectives and criteria (step 2) and integrating weights and alternatives' performance (step 6).

Establishing objectives and criteria is a key step for the entire process [33], it is the starting point for all the following decision-making phases, especially to define characteristics of alternatives. Nielsen et al. [32] highlighted that only a few studies encompassed the values of stakeholders as a departing point for renovation, even though setting objectives and choosing criteria are important elements in the decision-making process. Most of the existing approaches [4,16–25,28,34] did not discuss the setting of objectives or focused mainly on fixed pre-established environmental or economic goals. This may result in the definition of objectives and criteria that do not evaluate the renovation alternatives with a comprehensive approach. Only few approaches [5,26,27] considered a basis for dialogue among stakeholders in the formulation of objectives.

According to Hashempour et al. [35], most of the existing approaches have given more relevance to environmental and economic elements. Meanwhile, social aspects have been briefly considered even though the reasons to renovate often differ from energy and money savings [36]. The strategies presented in Refs. [16,18–22] integrated only environmental and economic aspects such as energy efficiency, greenhouse gas emissions, and investment cost. Meanwhile, the approaches presented in Refs. [17,23] considered also some aspects of the indoor conditions of the building. Riera et al. [24] classified the criteria based on six general objectives. However, their approach is developed for the neighbourhood level. Even though some of the criteria can be relevant at the building level, elements such as indoor conditions and operational and maintenance costs, and among others were not included. Only few approaches [25,28,34] followed the triple bottom line sustainability including environmental, economic, and social aspects including some of the criteria already mentioned and other elements such as water saving, tax detraction, aesthetics, durability, social image and awareness. Meanwhile, Kamari et al. [4] proposed a criteria set using Accountability, Functionality, and Feasibility as general categories for a sustainability approach.

Besides the objectives and criteria setting, and their scope, the integration of criteria weights and alternatives' performance has not been studied in detail in the renovation field. This integration allows calculating a global performance score for each renovation alternative to rank and compare them according. It is a key step for the comparison of multiple alternatives in terms of multiple criteria. In the context of building renovation, existing approaches such as the ones presented in Refs. [4,5,16,18,21] did not include explicitly a criteria weighting strategy, and the integration of stakeholders' preferences and the alternatives' performance is not discussed. Some of them [4,5,21] included strategies based on spider nets or colour codes to characterize the alternatives' performance. The strategies proposed in Refs. [19,20,23] analysed the alternatives through Pareto fronts, focusing only on two characteristics at a time, which can be a limitation considering that evaluating renovation alternatives requires assessing multiple criteria. Other strategies [26,34] implemented their own method. Only some approaches [17,22,24,25,28] implemented well-established methods such as Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE), Elimination and Choice Expressing Reality (ELECTRE) III, and TOPSIS.

Particularly, TOPSIS simplicity can be an advantage to encourage transparency in the decision-making process and facilitate the engagement of some of the stakeholders that do not have a technical background. Moreover, its sensitivity and capability to represent differences between alternatives [17], can be an advantage to compare renovation alternatives, which may vary in single components and have similar characteristics. Nevertheless, its application in building renovation has not been studied in detail. From the related literature, two studies [17,22] included TOPSIS in their approaches. However, Zavadskas et al. [17] did not implement it to compare renovation alternatives but the performance of thirteen apartments. Only Perera et al. [22] used TOPSIS to evaluate renovation alternatives, though from a general perspective, in the context of policies and incentives.

Table 1 summarizes the characteristics of existing approaches identified from the related literature according to the four aspects previously discussed: a) the participation of multiple stakeholders, b) objectives and criteria setting step, c) scope of the criteria set to evaluate the renovation alternatives, and d) weights and performance integration strategy. The main goal of this paper is to present a more complete MCDM framework for the decision-making process in renovation projects covering these aspects. Compared to the existing approaches, it could be considered that the most complete strategy is the one proposed by Kamari et al. [27] since it defined a complete set of steps and strategies to support the decision-making process in renovation. It covered the participation of multiple stakeholders and the setting of objectives and criteria with a broad view of the alternatives. They also proposed the implementation of methods such as Analytical Hierarchy Process (AHP) and TOPSIS, nevertheless, they did not implement them in the validation. As presented in the first row of Table 1, the proposed approach in this paper includes the Pairwise comparison method to enable the participation of multiple stakeholders (a), supports the objectives and criteria setting based on a predefined comprehensive decision tree and complementary activities (b and c), and integrates the criteria weights and alternatives' performance through the TOPSIS method (d). More details and the entire structure of the proposed MCDM are discussed in the following section.

### *2.2. An MCDM for building renovation*

The proposed MCDM framework presented in Fig. 2 follows the general accepted steps described in Section 2.1. The approach aims at enabling the participation of multiple stakeholders; supporting the setting of objectives and criteria, promoting a comprehensive evaluation of the alternatives; and facilitating the integration of criteria weights and alternatives' performance. The proposed approach is intended to support the decision-making process in different scenarios encountered in residential building renovation projects. Whether there is a single decision-maker like in the case of a single owner or multiple stakeholders like in the case of multiple experts deciding on the renovation alternatives, multiple owners in a multi-family building, or other cases including multiple investors or external stakeholders such as municipalities. The criteria included in the predefined tree of the framework aim at covering the perspectives of diverse stakeholders by including criteria such as *Property value increment*, which is relevant in cases where the owner occupies the dwelling unit, or the *Rent increment* which is relevant in cases involving tenants. More details of each of the steps of the proposed approach are summarized in the following subsections.

### *2.2.1. Problem definition*

At the first stage, the project's general aspects should be identified: stakeholders, their role and rights in the process (e.g. decision-maker, advisor, only informed), restrictions regarding budget, local regulation, existing conditions of the building, etc. This stage can benefit from diagnostic techniques, building technical inspections, inhabitants' questionnaires, and other strategies to characterize the project and its context.

### *2.2.2. Objectives and criteria setting*

At the second stage, stakeholders should reflect on the decision tree, select objectives that represent their goals and define the criteria for the project. Keeney [37] suggested strategies based on value-focused thinking: creating a wish list, thinking about alternatives, checking problems and shortcomings, studying consequences, and others. The framework incorporates the predefined decision tree presented in Fig. 3 as the starting point to promote the discussion about the objectives of the project in conjunction with a set of criteria covering not only environmental and economic aspects but also social elements. It has been shown that using a tool to set objectives and criteria helps the stakeholders to understand sustainability aspects in a deeper sense and facilitates problem-solving, adding value to the process [38].

The decision tree in Fig. 3 includes the three categories of sustainability. Each category comprises potential objectives for renovation projects. At the third level, different criteria are proposed to measure the degree to which an objective is achieved. The objectives and criteria were identified from related literature [4,5,7,15,17,25,32,34,39], technical guidelines [40], and the results from European research initiatives [41,42]. A preliminary decision tree was presented to six experts including architects and civil engineers involved in six renovation projects in five European countries. They indicated whether they found each of the objectives and criteria Relevant, Relevant in some cases, or Irrelevant. The criteria marked with [*] were proposed by the experts.

Since each project has specific requirements, decision-making approaches should be flexible regarding objectives and criteria. The proposed general decision tree is intended to be a starting point to support stakeholders to identify objectives and criteria that are equivalent or represent their own goals. Nevertheless, stakeholders can add or remove elements from the decision tree according to the context of the project. To reach a consensus on the decision tree, strategies such as the Delphi method [43] can be implemented.

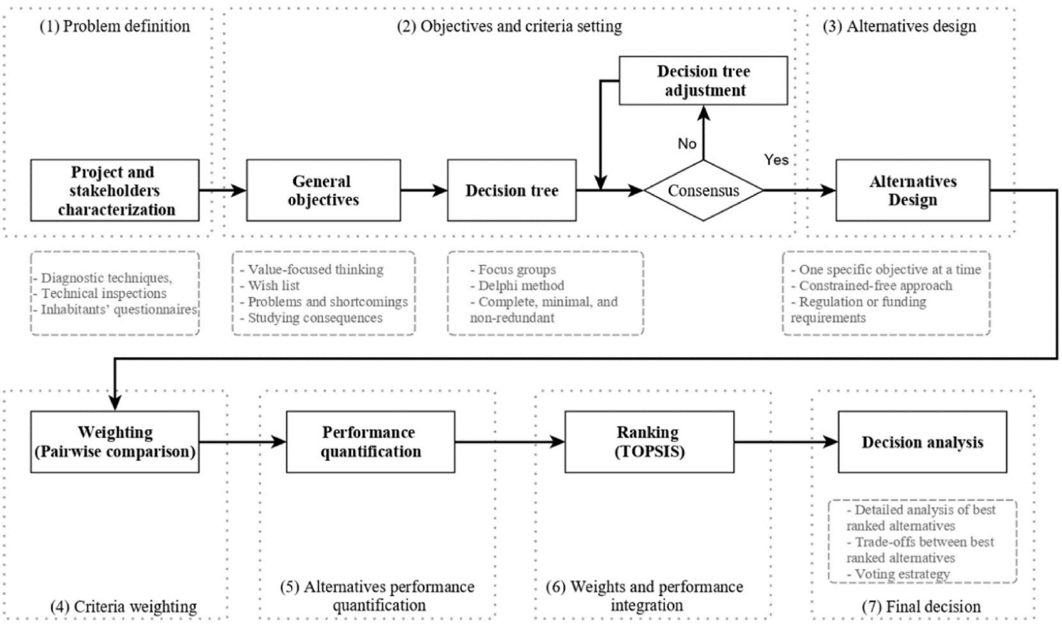


**Fig. 2.** MCDM framework for residential building projects.

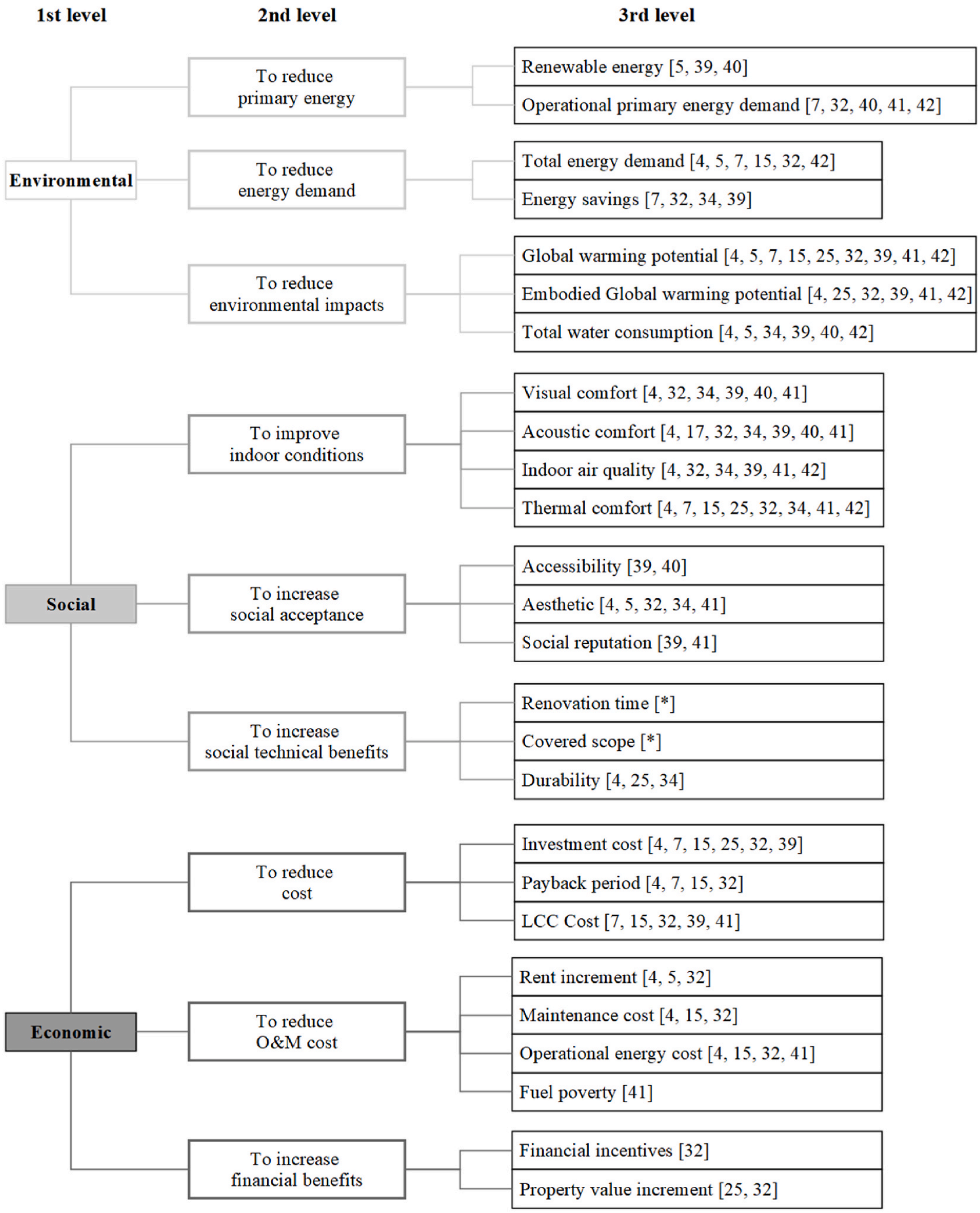


**Fig. 3.** Proposed general decision tree.

### 2.2.3. *Alternatives design*

Once the stakeholders agree on the decision tree, the renovation alternatives are designed at the third stage of the proposed framework. The design of alternatives is out of the scope of this paper, nevertheless, some strategies include focusing on one specific objective at a time, once multiple alternatives are generated with this approach, they are combined and diversified [37].

### 2.2.4. *Criteria weighting*

The fourth stage focuses on capturing the preferences of the stakeholders in the form of criteria weights. These weights can derive from stakeholders' judgments or mathematical models [44]. We included the Pairwise comparison method since it has particular application in decision-making processes involving multiple stakeholders and has been used in multiple disciplines [30]. Gade et al. [26] compared the Pairwise comparison and Weighting Rating and Calculating (WRC) methods. The users involved in their research preferred the Pairwise comparison method since it provided a useful foundation for dialogue among the stakeholders. Pairwise comparison is a well-developed method to order criteria, which asks stakeholders to compare two criteria at a time, encouraging them to consider thoroughly all elements in the criteria set [45]. This characteristic can facilitate the elicitation of the criteria, especially for non-expert stakeholders which may experience difficulties expressing their preferences. The general procedure requires comparing pairs of criteria to indicate their level of importance according to the 1–9 scale developed by Saaty [46] as presented in Fig. 4. Once the comparisons are completed, the weights are calculated. The mathematical details can be found in Refs. [12,44]. The method assesses also the consistency of the stakeholders' judgment as described in Ref. [12].

To apply the method on the three levels of the decision tree, elements sharing the same stem are compared. For instance, in Fig. 5, *Objectives 1* and *2* at the second level share the same stem (*Environmental* category), then, they are compared together. A similar approach is followed for *Criterion 1* and *2*, at the third level, which have *Objective 1* as their stem. Once the weights are obtained, the final aggregated weights of each criterion at the third level are quantified by multiplying the weights from the first level with the weights of the elements associated with them at the other levels as presented in Fig. 5. When multiple stakeholders have the right to vote (e.g. multiple owners, multiple experts in a design team), each stakeholder performs the pairwise comparisons individually. Then, the corresponding sets of weights from each stakeholder group are calculated. To integrate the preferences of the stakeholders, the average value from the weights is calculated.

### 2.2.5. *Alternatives performance quantification*

At the fifth stage, the performances of the alternatives are quantified. It should be guaranteed that methods, tools, and assumptions are the same or equivalent for all the alternatives to ensure a transparent and fair comparison between them. These calculations can include building energy, cost, thermal, acoustic, structural, life cycle and other analyses, using spreadsheets, specialized software such as Energy Plus, BIM-based tools and other approaches.

### 2.2.6. *Weights and performance integration*

At the sixth stage, the aggregated criteria weights and alternatives' performances are integrated. We included the TOPSIS method for this purpose. Nevertheless, any other method such as the PROMETHEE method could be implemented. TOPSIS identifies the alternatives that are closest to the best ideal solution and farthest to the negative ideal solution in a multi-dimensional space [47]. The method determines the Ideal and Negative-Ideal solutions. The former indicates the most preferable alternative, which gathers the best performances according to the criteria. The latter indicates the least preferable alternative, which gathers the worst performances. An example of a two-criteria problem is shown in Fig. 6. The final score for each alternative is obtained based on the relative closeness to the ideal solution, the first positions are occupied for the alternatives that have the shortest distance to it. More information describing the mathematical details of the TOPSIS method can be found in Ref. [45]. TOPSIS simplicity, sensitivity and capability to differentiate alternatives, and ability to maintain the same number of steps regardless of the number of alternatives can be an advantage to support the decision-making process in renovation projects.

### 2.2.7. *Final decision*

At the last stage, the framework provides stakeholders with the final ranking of the alternatives. This enables stakeholders to analyze them and their trade-offs to make a better-informed decision to select the solution that fulfils the project requirements and attempt to meet the preferences of the multiple stakeholders. It is important to notice that even though the implementation of different methods and steps within decision-making frameworks allows identifying the best alternative or a ranking of alternatives, one strategy should not strive to take over the role of the stakeholders or the means they use, but serve as an aid to managing the complexity of the decisions throughout the process [32]. To illustrate and validate the proposed MCDM framework, it was applied to two case studies as described in the following section.

## 3. Case studies, illustration, and validation

To illustrate and validate the proposed MCDM framework, it was applied to two case studies. It was implemented in a spreadsheet including a workspace comprising the description of the steps, a project characterization area, stakeholders' specification, slide bars to perform the pairwise comparisons, and the final ranking. The interface and navigation are designed to be easy to operate by users. In each case study, a separate group of five students from different construction engineering master programs used the proposed MCDM framework to select the renovation solution for the five-story residential building presented in Fig. 7. The building is one of the main demonstration cases from the European project BIM-SPEED. It is located in northern Spain and has eight dwelling units in total. Its main structure is made of reinforced concrete. The façade and rooftop do not have any insulation; therefore, energy and acoustic performances are low. The housing company leading the renovation project highlighted that this is a typical case often encountered in the country and it is relevant to promote the replication of lessons learned in other similar buildings in the region.

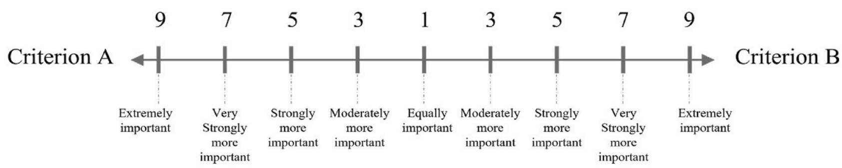


**Fig. 4.** Pairwise comparison scale.

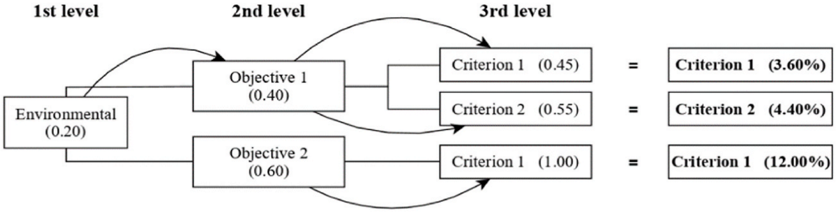


**Fig. 5.** Weighting aggregation process.

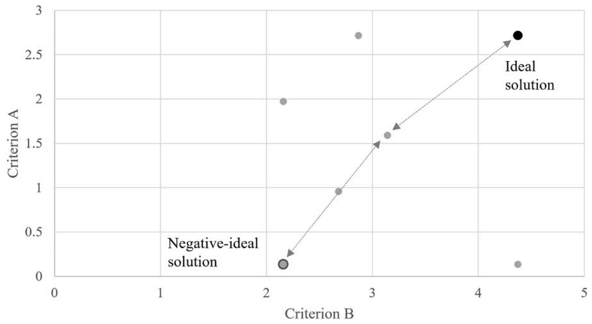


**Fig. 6.** General concept of the TOPSIS method.

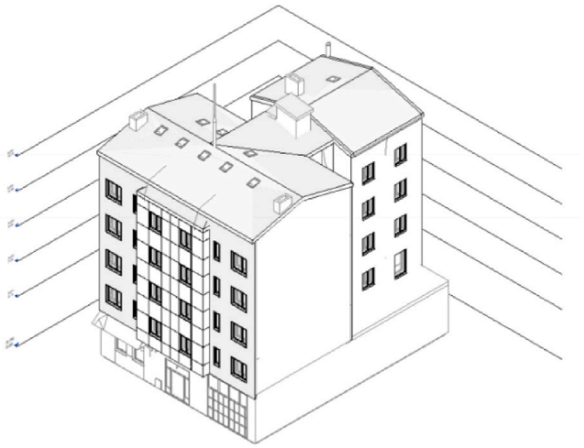

**Fig. 7.** Building for the two case studies analysed.

The two case studies are intended to show how the proposed framework can enable the participation of multiple stakeholders and facilitate the integration of criteria weights and alternatives' performance to support the stakeholders to make a better-informed decision. In each case, each of the students played the role of an expert from a certain field according to their program of studies and expertise. For instance, the first group included a structural designer, acoustic specialist, life cycle analyst, energy specialist, and cost and planning engineer. The second group comprised a structural designer, architectural designer, cost analyst, energy specialist, and geotechnical designer. In both cases, each of the stakeholders provided their preferences on the criteria, according to their perspectives and experiences. Particularly, the two case studies can represent the scenario where a social housing company and its group of experts from different domains design and select the renovation solution for a certain building. Nevertheless, from a general perspective, the two case studies are intended to represent the participation of multiple stakeholders with different and sometimes conflicting interests to study how the proposed approach allows gathering their perspectives. Therefore, these cases can also partially represent other scenarios where multiple owners, investors, or additional stakeholders with different points of view participate in the process and their perspectives should be gathered to reach a unified evaluation of the renovation alternatives.

The spreadsheet prototype of the framework was presented to each group during two individual workshops. In each case, they adjusted the objectives and criteria to define the decision tree according to the project requirements and designed a set of five renovation alternatives. Their preferences as stakeholders were captured through the Pairwise comparison method. When necessary, they adjusted their comparisons to make them consistent. In each case, the framework gathered the preferences from the stakeholders involved to obtain the aggregated weights representing their integrated perspective. We provided the two groups with a detailed Building Information Model (BIM) of the building to support the design of renovation alternatives and the criteria calculations. Most of the criteria calculations were conducted using tools such as Autodesk Revit [48], COMSOL [49], Excel spreadsheets, and One-click LCA [50]. Once the criteria were calculated, the TOPSIS method was applied to integrate the criteria weights and alternatives' performances to obtain the final ranking to support the stakeholders. In both cases, it was considered that all the stakeholders involved have the same influence on the decision, i.e. their opinion and vote count equally on the final choice.

The validation stage also includes a sensitivity analysis to study the robustness of the proposed framework. An important aspect of decision-making approaches is their ability to return a result insensitive to local variations (uncertainties) of the data [51]. To understand how the resulting rankings vary according to the criteria weights representing the stakeholders' preferences, we analysed two weighting settings in both case studies. In setting I, we studied the final ranking considering the preferences of each stakeholder individually, i.e. the ranking is obtained based on the preferences of one stakeholder at a time. This also allows analysing the differences between the stakeholders' perspectives and how the participation of all of them and the integration of their perspectives can support the decision-making process. In weighting setting II, we aim at evaluating how the rankings are sensitive to predefined variations. In one scenario, the criteria are equally weighted to represent the case where their level of importance is equivalent. For the other scenarios, one criterion is considered the most important with a weight of 60%, meanwhile, the others are equally weighted. For instance, in a case with five criteria, a weight equal to 60% is assigned to one criterion and each of the remaining four criteria is weighted with 10%. The proposed framework is presented in the following section.

## 4. Illustration and validation

### 4.1. First case study, general results

#### 4.1.1. Objectives and criteria

In the first case, five stakeholders selected two environmental objectives, two social objectives, and an economic objective for the renovation of a five-story residential building. They adjusted the objectives and criteria to define the decision tree according to the project (a preliminary evaluation of the building, available data, etc.). The final decision tree includes five criteria as presented in Fig. 8.

Since the building had no envelope insulation, its energy demand was very high, therefore the criterion *Total energy demand* was selected to evaluate the alternatives. To quantify the environmental impacts, the stakeholders included the *Environmental cost* of the new elements added to the building. They also included the *Sound damping* measure after observing that the existing external building walls provide a soundproof capacity lower than typical levels [52]. *Additional dead load* was included to quantify the loads added to the building structure due to new components of the renovation. Stakeholders included the *Internal rate of return* to evaluate the economic aspects of the project. Four of the criteria were not included in the general decision tree proposed in Section 2.2, however, three of them are directly linked to the criteria proposed in the framework. *Sound damping* is related to *Acoustic comfort index*, *Environmental cost* to *Embodied global warming potential*, and *Internal rate of return* to *Payback period*.

#### 4.1.2. Weighting and integration

Each stakeholder entered their preferences on the criteria following the Pairwise comparison method at each level of the criteria tree. The criteria weights were quantified according to the pairwise comparison method. Since it was considered that the vote of each of the five stakeholders counted equally on the final decision, to integrate their preferences, the average value from the weights was calculated as described in Section 2.2. Table 2 summarizes the stakeholders' perspectives in the form of the aggregated weights. *Total energy demand* (37.5%) and *Internal rate of return* (33.8%) are the most important criteria for the stakeholders. The least relevant

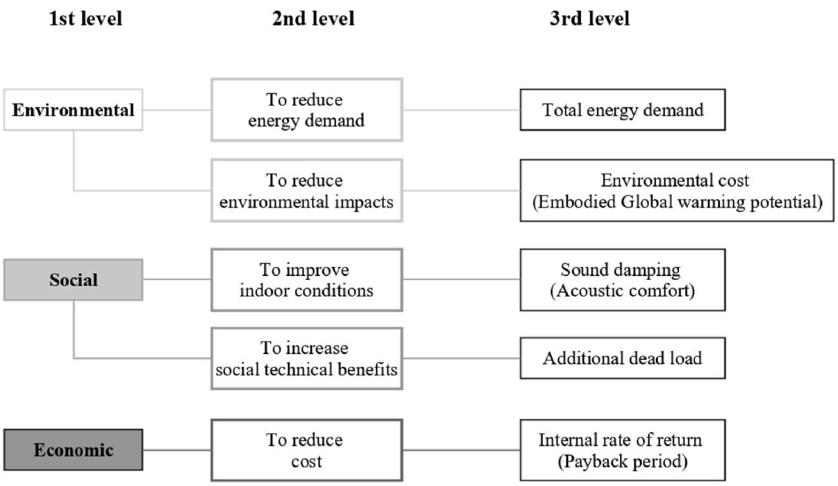


**Fig. 8.** Decision tree, first case study.

**Table 2**
First case study, aggregated criteria weights.

| Category | 1st level Weights | Objective | 2nd level Weights | Criteria | 3rd level Weights | Aggregated Weights |
|---|---|---|---|---|---|---|
| Environmental | 0.501 | To reduce energy demand | 0.750 | Total energy demand | 1.000 | **37.5%** |
| | | To reduce environmental impacts | 0.250 | Environmental cost | 1.000 | **12.5%** |
| Social | 0.161 | To improve indoor conditions | 0.358 | Sound damping | 1.000 | **5.8%** |
| | | To increase social technical benefits | 0.642 | Additional dead load | 1.000 | **10.3%** |
| Economic | 0.338 | To reduce cost | 1.000 | Internal rate of return | 1.000 | **33.8%** |

criterion is *Sound damping* (5.8%). In general, the level of importance assigned to environmental aspects correspond to 50.1%, social criteria 16.1%, and economic aspects 33.8%.

The stakeholders considered five alternatives for the building, focusing mainly on the insulation of the envelope: A) cellulose insulation (It is a cost-efficient option but may have lower insulating properties for energy as well as acoustic); B) fibreglass insulation (It might have much good insulation properties but may have a larger impact on the environment); C) mineral wool insulation (It is a lightweight material that could be good from a structural point of view); D) cellulose insulation + triple glazing windows (The new windows are included to homogenise the characteristics of the existing building windows since some of them are outdated and present large heat losses); and E) cellulose insulation + triple glazing windows + extra rooftop cellulose insulation (The existing rooftop has no insulation, this options aims for a more integral renovation solution). Table 3 summarizes the results of calculations and simulations that quantified the performance of the alternatives using BIM-based tools and Excel spreadsheets as described in Section 3. The best performance on each criterion is presented in bold font. The spreadsheet prototype integrated these results with the criteria weights to apply the TOPSIS method as described in Section 2.2.

The final ranking of the alternatives was displayed to the stakeholders on the spreadsheet prototype. In terms of the two most important (*Total energy demand* (37.5%) and *Internal rate of return* (33.8%)), the most complete renovation alternatives (D and E) performed the best according to *Total energy demand* and *Sound damping* as expected. However, they have a low *Internal rate of return*. Their *Environmental cost* and *Additional dead load* are high, then in general, they were located in the middle positions of the ranking. Alternative C (mineral wool insulation) was ranked in the first place. Mineral wool provides energy performance improvements with a low investment. In this case, it had the highest *Internal rate of return* (80%) which is one of the most important criteria according to the stakeholders' preferences (weight 33.8%). Mineral wool is a lightweight material, adding the lowest dead load (44.65 kN) to the building structure. This alternative had also the second-best performance on *Environmental cost* and a medium performance in the other two criteria. The stakeholders selected this alternative as the final renovation solution for the building.

### *4.2. Second case study, general results*

#### *4.2.1. Objectives and criteria*

In the second case study, another group of five stakeholders took part in the process to select a renovation solution for the same five-story residential building. They defined the decision tree including five objectives and eight criteria as presented in Fig. 9. Since the energy performance of the building was very low, stakeholders selected *Energy savings* as a criterion. They included *Embodied global warming potential* to evaluate the environmental impacts. In this case, the stakeholders pursued an improvement of the indoor conditions of the building, they incorporated *Glazing area ratio* and *Useable area* as criteria to measure how the alternatives enhance the natural lighting and functional area of the dwelling units. The stakeholders also included *Settlement* and *Existing structure preservation*. The former is related to the reinforcement of the existing building foundation, meanwhile, the latter measures how much of the existing building structure is preserved by each renovation alternative. Finally, the stakeholders selected *Renovation time* to reduce the disruption on the building inhabitants and *Investment cost* to assess the economic aspects of the alternatives.

#### *4.2.2. Weighting and integration*

The five stakeholders provided their preferences and the criteria weights were calculated according to the Pairwise comparison method. The average value from the weights was calculated as described in Section 2.2 to integrate the stakeholders' preferences. The results are summarized in Table 4. *Embodied global warming potential* (32.5%) potential and *Investment cost* (23.7%) are the two most important criteria. The two least relevant criteria for the stakeholders are *Settlement* (1.3%) and *Renovation time* (0.7%). Environmental

**Table 3**
First case study, general results.

| Alternative | Total energy demand [kWh/m$^2$/y] (37.5%) | Environmental cost [€] (12.5%) | Sound damping [−] (5.8%) | Additional dead load [kN] (10.3%) | Internal rate of return [%] (33.8%) | Ranking |
|---|---|---|---|---|---|---|
| A | 264 | **37.9** | 1.0011 | 70.74 | 44 | 2 |
| B | 268 | 168.0 | 1.0011 | 90.24 | 16 | 5 |
| C | 267 | 65.0 | 1.0020 | **44.65** | **80** | 1 |
| D | 262 | 272.0 | 1.0041 | 70.74 | 27 | 3 |
| E | **260** | 293.0 | **1.0044** | 74.50 | 25 | 4 |

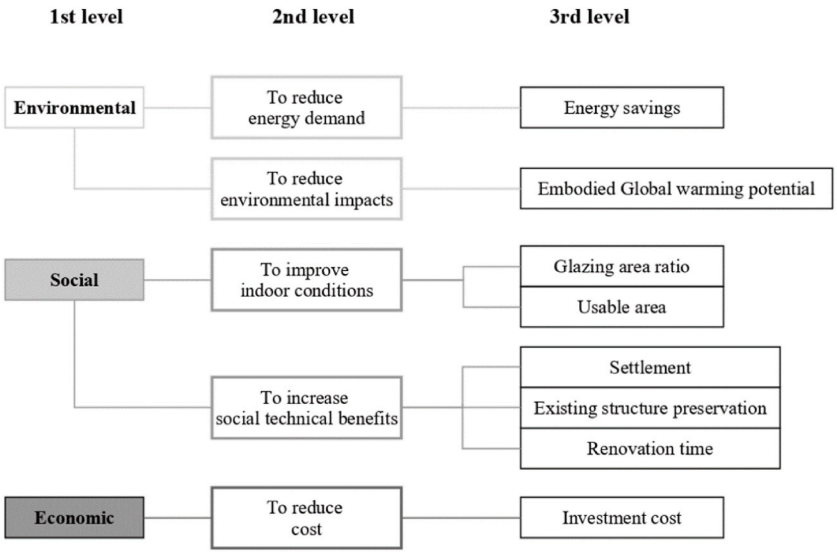


**Fig. 9.** Decision tree, second case study.

**Table 4**
Second case study, aggregate criteria weights.

| Category | 1st level Weights | Objective | 2nd level Weights | Criteria | 3rd level Weights | Aggregated Weights |
|---|---|---|---|---|---|---|
| Environmental | 0.534 | To reduce energy demand | 0.392 | Energy savings | 1.000 | **20.9%** |
| | | To reduce environmental impacts | 0.608 | Embodied global warming potential | 1.000 | **32.5%** |
| Social | 0.229 | To improve indoor conditions | 0.808 | Glazing area ratio | 0.245 | **4.5%** |
| | | | | Useable area | 0.755 | **14.0%** |
| | | To increase social technical benefits | 0.192 | Settlement | 0.300 | **1.3%** |
| | | | | Existing structure preservation | 0.542 | **2.4%** |
| | | | | Renovation time | 0.157 | **0.7%** |
| Economic | 0.237 | To reduce cost | 1.000 | Investment cost | 1.000 | **23.7%** |

aspects correspond to 53.4% of the level of importance, social criteria 22.9%, and economic aspects 23.7%.

The alternatives for this case could be considered more complex since they have an impact on different aspects of the building and the dwelling units. In this case, the stakeholders addressed the insulation problem using a commonly used insulation technology, and focused on adding different options of new balconies and rearranging the functional areas of the building: A) expanded polystyrene insulation + separated enclosed balconies; B) expanded polystyrene insulation + shared non-enclosed balconies + windows enlargement; C) expanded polystyrene insulation + redistribution of living area + asymmetric balcony; D) expanded polystyrene insulation + cantilevered separated balconies; and E) expanded polystyrene insulation + redistribution of living area + central balcony. Table 5 summarizes the results from the evaluation of the alternatives.

In this case, alternative B performed the best according to the stakeholders' preferences. It included the largest balcony and the enlargement of the front windows, increasing natural lighting. The materials used in the balcony were selected to reduce the embodied $CO_2$ emissions. Therefore, this alternative had the largest useable area (20.6 $m^2$), it was the second-best option based on *Glazing ratio*

**Table 5**
Second case study, general results.

| Alternative | Energy savings [%] (20.9%) | Embodied Global warming potential [%] (32.5%) | Glazing area ratio [$m^2$] (4.5%) | Useable area [$m^2$] (14.0%) | Settlement [mm] (1.3%) | Existing structure preservation [%] (2.4%) | Renovation time [days] (0.7%) | Investment cost [x$10^3$ €] (23.7%) | Ranking |
|---|---|---|---|---|---|---|---|---|---|
| A | 15.97 | 20.9 | **12.71** | 17.3 | 2.7 | **91** | **13** | 217 | 2 |
| B | 18.96 | 19.1 | 12.66 | **20.6** | 0.6 | 85 | **13** | 190 | 1 |
| C | 5.80 | 19.0 | 12.40 | 11.9 | **0.5** | 88 | **13** | 142 | 4 |
| D | **19.87** | 39.3 | 12.45 | 14.1 | 13.4 | 66 | 30 | 272 | 3 |
| E | −12.33 | **13.2** | 12.20 | 12.4 | 13.6 | 71 | **13** | **141** | 5 |

and *Settlement,* and had a low *Embodied global warming potential* (19.1%). It was the best-second option according to *Energy savings* (18.96%) and had a low renovation time (13 days).

The integration of the criteria weights and the alternatives' performances through the TOPSIS method allowed obtaining the final ranking to facilitate the decision-making process of the stakeholders. In this case, in a preliminary assessment of the renovation alternatives, stakeholders identified alternatives A and B as potential final solutions. Both alternatives performed well on multiple of the eight criteria, but it was not clear which one would be the most suitable option. After integrating the criteria weights and alternatives' performances using TOPSIS, stakeholders identified alternative B as the first one in the ranking. It was easier to notice that alternative B performed better than alternative A according to three of the four most important criteria for the stakeholders, *Embodied global warming potential* (weight 32.5%), *Investment cost* (weight 23.7%), and *Useable area* (weight 14.0%) and it is the most suitable option. Therefore, the stakeholders were able to establish clear arguments to select alternative B as the final solution.

### *4.3. Sensitivity analysis*

#### *4.3.1. Weighting setting I, stakeholders' perspectives*

To study how the final ranking would change due to variations in the criteria weights, we analysed two weighting settings as described in Section 3. In setting I, the ranking was obtained based on the preferences of only one stakeholder at a time to analyze the differences between the stakeholders' perspectives and how the participation of all of them and the integration of their perspectives influence the final ranking. In the first case study, each stakeholder assigned different weights to the criteria according their perspective and experience as presented in Table 6. The baseline scenario corresponds to the ranking obtained when the preferences of all the stakeholders are considered in conjunction. *Total energy demand* was very important for stakeholders 1 (weight 62.5%) and 3 (weight 60.3%), meanwhile, *Internal rate of return* was the most important aspect for stakeholders 2 (weight 60.0%) and 5 (weight 71.4%). For stakeholder 4, *Total energy demand* and *Environmental cost* were important (weights 34.2% for both).

Fig. 10 depicts the final rankings according to each stakeholder in the first case study. Alternative C occupied the first position for all the scenarios. It performed the best in terms of *Internal rate of return* and *Additional dead load,* and had a good performance on all the other criteria. The ranking for stakeholders 2 and 5 was the same than the one in the baseline scenario. For stakeholders 1, 3, and 4, the last three positions differed due to their perspectives regarding the importance of *Environmental cost*, *Internal rate of return*, and *Additional dead load*.

Alternatives B, D and E performed similarly as shown in Fig. 11. The main differences occurred in terms of *Environmental cost*. The distance between alternatives D and E and the Ideal solution was the largest of the set, this made these two alternatives score low in the final ranking. For stakeholders 1, 3 and 4, this criterion was relevant (weight 12.5%, 12.1%, and 34.32%, respectively), making this difference impact the final score, leading alternatives D and E to rank in the last positions. For stakeholders 2 and 5, this distance lost relevance, since for them *Environmental cost* had a low level of importance (weights 5.0% and 2.4%, respectively, see Table 6). Even though in the baseline the weight of this criterion was similar to other scenarios (12.5%), alternatives D and E did not occupy the last positions due to the weights for *Additional dead load* (10.3%) and *Internal rate of return* (33.8%) that amplified the distance between alternative B and the Ideal solution, making it to rank at the last position.

Table 7 summarizes the results for the second case study. In this case, stakeholders 1, 2, and 3 found *Embodied global warming potential* highly important (weight 54.3%, 65.7%, and 45.5%, respectively), while stakeholder 4 prioritized *Useable area* (weight 31.9%) and *Investment cost* (weight 48.0%). For stakeholder 5, *Investment cost*, *Energy savings*, and *Embodied global warming potential* were the most relevant criteria (weights 23.7%, 23.7%, and 47.4%, respectively).

As shown in Fig. 12, for the second case study, the rankings for stakeholders 1 and 3 were equivalent to the ranking obtained for the baseline scenario where the preferences of all the stakeholders were considered in conjunction. Nevertheless, for stakeholders 2, 4, and 5, the rankings differed due to their perspectives. Alternative B ranked as the best possible solution for all the scenarios. Alternative A occupied second place in all the cases except for stakeholder 4. On the other hand, alternative E ranked at the last position for all the cases except for stakeholders 2 and 4, where D occupied the last position. Stakeholder 2 considered Embodied global warming potential to be highly important (65.7%). Since alternative E had the lowest Embodied global warming potential (13.2%) and alternative D the highest (39.3%), the former overcame the latter in the ranking. A similar situation occurred for stakeholder 4, Investment cost had a high weight (48.0%). Since alternative E was the cheapest one (141.000 €) and alternative D the most expensive one (272.000 €), the former overcame the latter in the ranking.

In both case studies, the first position of the ranking was the same in all the scenarios, however, the results show how the perspectives of different stakeholders could influence the final ranking of alternatives. For instance, in the second case study, the second-best option according to stakeholder 4 was different to the baseline results, this could have an influence when making the final decision. Instead of considering B and A as the two most suitable options, for stakeholder 4, alternatives B and C would occupy the first

**Table 6**
Weighting setting I, first case study.

| Criteria | Base line | Stakeholder 1 | Stakeholder 2 | Stakeholder 3 | Stakeholder 4 | Stakeholder 5 |
|---|---|---|---|---|---|---|
| Total energy demand | 37.5% | 62.5% | 15.0% | 60.3% | 34.3% | 11.9% |
| Environmental cost | 12.5% | 12.5% | 5.0% | 12.1% | 34.3% | 2.4% |
| Sound damping | 5.8% | 2.4% | 15.0% | 1.0% | 5.3% | 7.1% |
| Additional dead load | 10.3% | 16.6% | 5.0% | 5.1% | 15.9% | 7.1% |
| Internal rate of return | 33.8% | 6.0% | 60.0% | 21.6% | 10.2% | 71.4% |

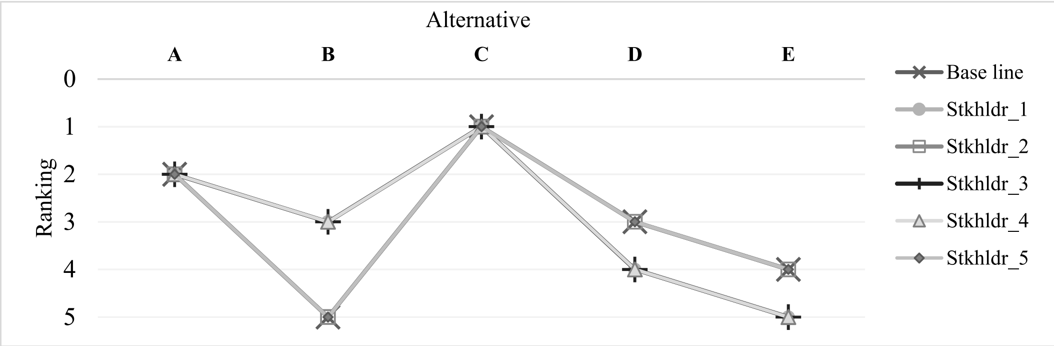


**Fig. 10.** Weighting setting I, evaluating stakeholders' preferences individually, rankings for the first case study.

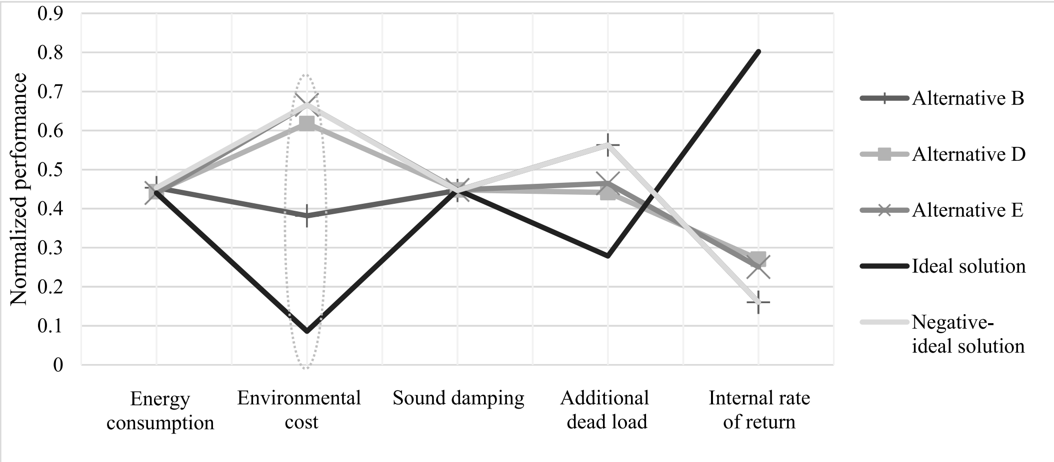


**Fig. 11.** Normalized performance for alternatives B, D, and E for the first case study.

**Table 7**
Weighting setting I, second case study.

| Criteria | Base line | Stakeholder 1 | Stakeholder 2 | Stakeholder 3 | Stakeholder 4 | Stakeholder 5 |
|---|---|---|---|---|---|---|
| Energy savings | 20.9% | 18.1% | 9.4% | 15.2% | 9.6% | 23.7% |
| Embodied global warming potential | 32.5% | 54.3% | 65.7% | 45.5% | 1.9% | 23.7% |
| Glazing area ratio | 4.5% | 3.6% | 2.0% | 12.6% | 3.5% | 1.0% |
| Useable area | 14.0% | 10.9% | 13.8% | 12.6% | 31.9% | 3.0% |
| Settlement | 1.3% | 0.9% | 2.3% | 0.4% | 0.4% | 0.6% |
| Existing structure preservation | 2.4% | 3.5% | 0.6% | 3.7% | 3.3% | 0.6% |
| Renovation time | 0.7% | 0.4% | 0.3% | 1.0% | 1.4% | 0.2% |
| Investment cost | 23.7% | 8.3% | 6.0% | 9.0% | 48.0% | 47.4% |

positions and the focus would be on those options.

### *4.3.2. Weighting setting II, predefined weighting variations*

In the weighting setting II, for the first case study, we analysed six scenarios. In the first scenario, the five criteria were equally weighted (weight 20%). For the other scenarios, all the criteria had weights equal to 10%, meanwhile one of them was the most important at a time (weight 60%). As shown in Fig. 13, Alternative C ranked in the first position for all the scenarios except when *Environmental cost* was the most important criterion. For this case, alternative A moved from the second to the first position in the ranking. Alternative A had the lowest *Environmental cost*, therefore when this criterion gained relevance, the final score of this alternative increased, overcoming alternative C in the ranking. On the other hand, alternative E was ranked at the last position in all the scenarios except when *Additional dead load* and *Internal rate of return* were the most important criteria. In these cases, the distance between alternative B and the best ideal solution in terms of these two criteria gained relevance and affected the final score of alternative B, making it rank at the last position.

For the second case study, nine scenarios were analysed. In the first scenario, the eight criteria were equally weighted (weight

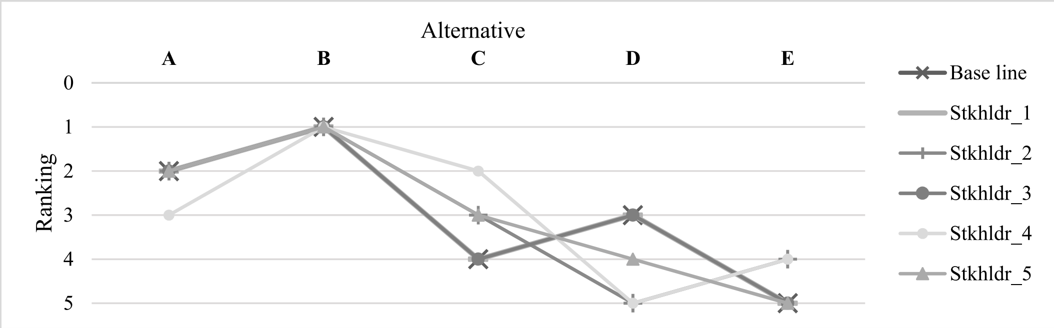


**Fig. 12.** Weighting setting I, evaluating stakeholders' preferences individually, rankings for the second case study.

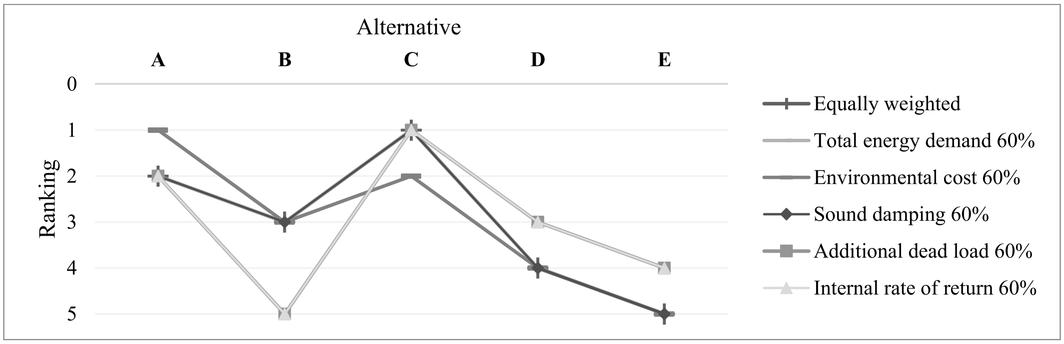


**Fig. 13.** Weighting setting II, one important criterion at a time, rankings for the first case study.

12.5%). In the other scenarios, all the criteria had weights equal to 5.71%, meanwhile one of them was the most important at a time (weight 60%). As presented in Fig. 14, in this case study, the ranking varied more due to the criteria weights' changes. Nevertheless, alternative B was ranked at the first position in most of the scenarios, except when Existing structure preservation and Investment cost were the most important criteria. When Existing structure preservation had 60% weight, alternative A occupied the first position of the ranking. Since it preserved the highest percentage of the existing structure (91%), its final score increased, overcoming alternative B in the ranking. When Investment cost was the most important criterion, alternative C was ranked at the first position. This alternative had a low investment cost (142[x$10^3$ €]) close to the Ideal solution (141[x$10^3$ €]), hence, its final score increased, overcoming alternative B in the ranking. Alternative E had the lowest investment cost, however, it did not overcome alternative C due to its low performance according to criteria such as Global warming potential, Settlement, and Existing structure preservation.

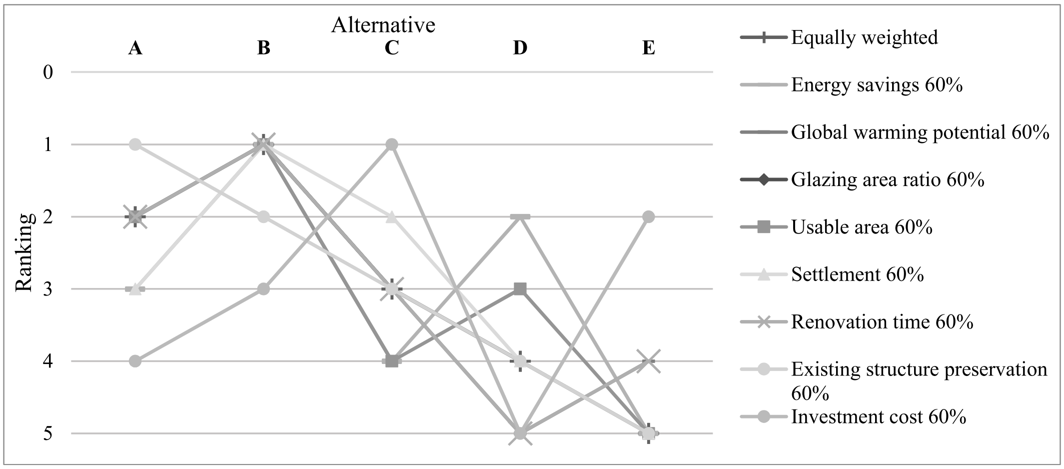


**Fig. 14.** Weighting setting II, one important criterion at a time, rankings for the second case study.

## 5. Discussion

The proposed MCDM framework provides stakeholders with a structured approach to perform the decision-making process of selecting renovation solutions in the context of residential renovation projects. The proposed approach enables the participation of multiple stakeholders, requiring them to perform specific actions at different stages, engaging in the decision-making process. The aggregation of the preferences of stakeholders with different interests through the Pairwise comparison method allows obtaining a gathered perspective of the problem. Following the perspective of only one of them can lead to different results in the ranking of alternatives, which could influence the final decision. Moreover, the integration of the stakeholders' preferences and alternatives' performance through the TOPSIS method shows to be relevant in the decision-making process of renovation projects. For instance, in the second case study, where the complexity of the alternatives and the number of criteria were higher, it contributed to facilitating the analysis of the renovation options to choose the final solution.

Particularly, the two case studies represent the scenario where a group of experts from different domains design and select the renovation solution. From a general perspective, these cases include the participation of multiple stakeholders with different or conflicting interests. Therefore, they can also partially represent other scenarios where multiple owners, investors, tenants, or additional stakeholders with different points of view take part in the decision-making process. Furthermore, in the two case studies, all the stakeholders involved had the same influence on the final decision. However, there are cases where the main decision-maker would be interested in capturing the preferences of other stakeholders without including them directly in the final weighting. In these cases, the framework allows capturing the preferences of additional stakeholders such as tenants (without the right to vote) or a design team (external advisor). Nevertheless, their criteria weights are not integrated, these weights are displayed on the prototype only to support the analysis of the main stakeholder to make a better-informed decision independently. This flexibility plays a key role in engaging specific stakeholders' groups that could not have the right to affect directly the final choice but who are directly affected by the implementation of the renovation solution. Involving the stakeholders in the design could be a starting point to engage in adjusting their behaviour or aligning it with the new conditions of the building to guarantee the benefits of the renovation [25].

One of the limitations of the proposed MCDM framework is associated with the consistency ratio of the pairwise comparison method. For instance, stakeholder 2 from the second case study had to revisit the pairwise comparisons between *Environmental*, *Social*, and *Economic* categories. The initial consistency ratio was 0.9, after three iterations of the comparisons, stakeholder 2 reached a 0.18 consistency ratio for the matrix representing these three elements. According to Saaty [53], human judgment is of necessity inconsistent, and if with new information one can improve inconsistency to near consistency, then that could improve the validity of the priorities of a decision. Even though the final consistency value is higher than the 0.10 threshold proposed in the literature, Saaty [53] highlighted that judgment is much more sensitive and responsive to large rather than to small perturbations. Hence once near consistency is attained, it becomes uncertain which coefficients should be perturbed by small amounts to transform a near consistent matrix to a consistent one. Saaty [53] stated that any forced perturbation could be arbitrary and thus distort the validity of the preferences in representing the underlying decision. Therefore, after stakeholder 2 from the second case study performed three iterations of the comparisons of these three elements, we did not request any additional comparison. It is important to notice, that for stakeholder 2 *Environmental* is more important than *Social*, which is more important than *Economic*, and *Environmental* is more important than *Economic*. The inconsistency, in this case, is related to the scale but not to the basic perspective of the stakeholder. The impact of scales and the consistency ratio has been studied by some authors such as Franek & Kresta [54].

Another limitation of the research is related to the stakeholders involved in the two case studies. The two case studies represented the scenario where a social housing company and its group of experts from different fields make the decision on the renovation. Since the case studies included multiple stakeholders with different and conflicting perspectives, these cases can also partially represent other scenarios where multiple owners, investors, or additional stakeholders with different points of view participate in the process. Nevertheless, all the stakeholders involved in the two cases had a technical background, which may not be the case in all the scenarios encountered in renovation projects. Even though the advantages of the Pairwise comparison to facilitate the capture of stakeholders' preferences and TOPSIS simplicity have been highlighted in the existing literature, stakeholders without a technical background (e.g. tenants) may encounter difficulties interpreting the results from these two stages of the framework.

Therefore, future research activities include conducting an observation group to study in detail how stakeholders use the proposed framework, especially in cases involving tenants or multiple owners. To study how the stakeholders can reach a consensus on the decision tree, the Delphi method can be implemented. The proposed framework was developed to support these cases as well, by allowing the participation of multiple stakeholders, considering their different roles, and providing a prototype to facilitate the participation of any kind of stakeholder. Nevertheless, studying these scenarios can provide insights regarding potential conflicts between stakeholders' perspectives, new relevant criteria, and user comprehension barriers. Which can support the development of additional strategies and adjustments for the prototype in terms of usability. The possibility of having different weighting methods according to the characteristics of the project and stakeholders involved should be studied. Implementing different weighting methods will contribute to determining which are the most suitable strategies to capture the preferences of stakeholders in the context of building renovation projects.

## 6. Conclusion

Residential renovation projects encounter different scenarios and particularities that require a better-structured decision-making approach to select suitable renovation solutions that fulfil the requirements of the project and stakeholders involved. This paper presented an approach that enables the participation of multiple stakeholders through the Pairwise comparison method, supports the objectives and criteria setting based on a predefined comprehensive decision tree and complementary activities, and integrates the criteria weights and alternatives' performance through the TOPSIS method. Firstly, the implementation of the Pairwise comparison allows gathering the preferences of stakeholders with different interests to obtain a gathered perspective of the problem. The first weighting setting showed that following the perspective of only one of the stakeholders can lead to different results in the ranking of the renovation alternatives. Secondly, promoting the setting of objectives and criteria can enable discussions and encourage a broader and more complete analysis of renovation alternatives, including social-related issues. In the two case studies, besides economic and environmental aspects, stakeholders selected social and technical elements to evaluate the renovation alternatives, assigning in total weights around 20% to this category. Since each renovation project encounters specific requirements, the flexibility of the proposed framework to include new goals and criteria in the decision tree proved to be relevant. Stakeholders included new criteria according to their requirements. Thirdly, the inclusion of the TOPSIS method enabled the integration of the stakeholders' perspective and alternatives' performance to make a better-informed decision, especially in complex cases where the effects resulting from the different renovation alternatives are not easy to differentiate. Different weighting settings showed that TOPSIS allows considering the importance of the criteria in combination with the alternatives' performance to differentiate renovation alternatives and rank them accordingly to facilitate the analysis by the stakeholders involved. Finally, even though the proposed approach was implemented in two specific cases, it can be applied in other scenarios including single or multiple stakeholders, playing different roles in the decision-making process.

## CRediT authorship contribution statement

**Jerson Alexis Pinzon Amorocho:** Conceptualization, Validation, Investigation, Software, Formal analysis, Writing – original draft. **Timo Hartmann:** Conceptualization, Writing – review & editing, Supervision

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: This research project is funded under the European Commission's program H2020-EU.2.1.5.2., under Grant Agreement no 820553.

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