

Article

# Development of a Weight Factor Method for Sustainability Decisions in Building Renovation. Case Study Using Renobuild

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Received: 6 July 2020; Accepted: 30 August 2020; Published: 3 September 2020



**Abstract:** Energy efficiency investments have become strategically important for the European Union. In particular, energy efficient renovation and investment in the existing building stock have become major challenges. Renovation of a building should involve a holistic and integrated design process, which considers all aspects of sustainability. The aim of this work is to suggest a mathematical model that weighs economic, social and ecological aspects into a measure that supports housing owners/decision makers to find the optimal renovation alternative from their perspective, taking factors such as budget, energy consumption, etc. into consideration. Multi-criteria decision-making (MCDM) concerns structuring and solving multiple-criteria decision problems. MCDM has become popular in energy planning as it enables the decision maker to pay attention to all the criteria available and make the appropriate decision as per the priority of the criteria. In this study, the concept is introduced based on economic, social and ecological aspects assessed during a renovation project. A pedagogical example illustrates the suggested numerical system for comparing different renovation alternatives. The suggested method will facilitate decision-making processes in renovation projects and will allow decision makers to choose the best renovation alternatives that are in line with their business ideas and principles.

**Keywords:** building renovation; sustainability; multi-criteria decision-making; weighted sum method

## 1. Introduction

“Sustainable development is the bridge, between environmental, economic and social goals, between north and south, between Governments, civil society and business, between science and policy, and between policy and actions” [1]. Today, the world faces challenges in all three main dimensions of sustainable development, i.e., regarding environmental, economic, and social concerns. Achieving sustainable development requires global actions towards further economic and social progress and, at the same time, the strengthening of environmental protection. Strategies need to be ambitious, action-oriented and collaborative, and to adapt to different levels of development [2]. European Union institutions and Member States identify several systemic barriers shared among participants, such as the availability and reliability of data; lack of political will; weak capacity and technical know-how; and inadequate mechanisms and structures for recognizing financial opportunities and accessing available financial resources [3].

Investments for improvements in energy efficiency have become strategically important for the European Union; they are seen as the most effective way to reduce the EU’s dependence on energy

imports [4]. Buildings are central to the EU's energy efficiency policy, as buildings account for nearly 40% of the final energy consumption and 36% of greenhouse gas emissions [5]. Buildings are also long-term assets expected to remain in use for 50 years or more [4]; some 75–90% of the stock of buildings today are expected to exist at least until 2050 [6]. At present, around 35% of the EU's buildings are over 50 years old and about 75% of the building stock is energy inefficient [7]. Demolition rates are low (0.4–1.2% per year, depending on the country) and so too are renovation rates (1.2% per year). Although the growth of the number of new buildings encompasses highly energy-efficient new-build (1% additions per year) [6], the new buildings will increase the stock's absolute use of energy and fuel consumption. It is therefore necessary to reduce the energy use of the existing stock through energy efficient renovations, and the implication of this investment has become a challenge for the EU. Thus, one of the adopted policies for improving energy efficiency in the EU is that member countries should carry out energy efficient renovations on at least 3% of the buildings owned and occupied by governments per year [8]. Renovation of existing buildings can significantly increase energy efficiency and play an essential role in clean energy transition, as it could reduce the EU's total energy consumption by 5–6% and lower CO<sub>2</sub>-emissions by around 5% [7].

“Sustainable Development involves the simultaneous pursuit of economic prosperity, environmental quality, and social equity” [9], thus “sustainable renovation” should correspond to sustainable development principles. According to the European Commission's 2019 recommendations on building renovation, all environmental, economic, and social aspects need to be included in the renovation process to achieve sustainable development [10].

The definition of sustainability mentioned above is commonly used. It is, however, only one of many definitions [11,12]; there are more than three hundred others [13]. One of the present arguments about the concept regards the need for criteria that enable sustainability assessments of systems [14]. However, many definitions consider that sustainability is to be understood as constituted by three general aspects: economical, environmental, and social [15,16]. Some studies stress the importance of adding other aspects to sustainability in renovation assessment, such as a cultural dimension, suggested by Mickaityte [17] and Kohler and Hassler [18]. Lind [19] stresses the importance of including a “technical” aspect as a fourth dimension.

However, regarding sustainability aspects, a literature review concerning building renovation projects by Farsäter in 2017 [20] revealed that energy efficiency measures are those most widely researched. The energy aspect is included in over 70% of the analyzed strategies for refurbishment. Moreover, very few publications evaluate the effects of renovation measures regarding a combination of all three aspects: economical, environmental, and social. Kohler and Hassler [18] highlight the importance of the interrelationships between these aspects in terms of the sustainable management of the building stock.

Several obstacles hindering the creation of sustainable buildings through renovation are identified by Thuvander [21], Cattano [22], and Häkkinen and Belloni [23]. Apart from a fear of high investment costs and problems regarding low profitability, as identified by Olsson [24], the literature particularly emphasizes four obstacles: lack of knowledge about sustainability aspects; lack of simplified evaluation and decision-making tools; inadequate knowledge of the quality of the building stock; weak coordination between the goal of energy-saving and other project goals. Lind et al. [25] conclude that although sustainable renovation is possible, there are various conflicts between the different dimensions of sustainability. As an example of such a conflict, giving more weight to the environmental aspect of sustainability would increase costs and rents, which would create problems from a social perspective. Consequently, very few housing owners manage to address all sustainability aspects throughout a renovation project in a satisfactory manner. Several studies indicate that the focus on economic/financial issues reduces building owners' interest in other sustainability aspects of buildings [26,27]. This suggests that owners/decision makers do not consider the various aspects of sustainability to be equally important.

Considering a multitude of sustainability criteria while undertaking a renovation project naturally adds to its complexity. Several critical decisions are taken throughout the process and certainly during the design stage [28]. Additionally, different actors involved in the renovation process, and specifically decision makers, have diverse priorities and preferences. There is a notable lack of simplified evaluation and decision-making tools [28,29]. An optimal tool should reduce complexity and help the decision makers to carry out renovation projects according to a holistic and integrated design process which considers various aspects of sustainability.

This study mainly concerns sustainability aspects applying so-called “deep renovation” of buildings. To accomplish sustainable deep renovation, different renovation alternatives or packages are evaluated regarding economic, environmental, and social performance. Changing the windows, adding extra insulation, and choosing between different HVAC systems are examples of renovation measures that can be included in possible packages of deep renovation. Different renovation packages/alternatives have different impacts as regards sustainability aspects and different decision makers/owners have different preferences. Accordingly, the research question of this study is the following: How to weigh the decision-making input factors regarding deep sustainable renovation packages? To address this research question, this work develops a method using the Weighted Sum Method (WSM). The reason behind the choice of the WSM is its simplicity and applicability. Moreover, if the assessment of different alternatives is based on three or four criteria and each criteria has one or two metrics, the WSM can be a very suitable method due to its straightforward implementation. To assess the trade-off between different criteria, a new way of weighting is suggested in this study.

#### *Novelty and Aim of the Study*

A way to support decision makers during renovation projects is to find a systematic method—a tool—that evaluates the various aspects of sustainability of different renovation scenarios. Given that there is a tool that assesses various aspects of sustainability, decision makers have difficulty when evaluations of vastly differing aspects have to be made. This paper relates these aspects in terms of quantitative values for different renovations, presents how this can be realized, and shows how this might be applied in a case study.

The aim of this work is thus to suggest a method that considers sustainability aspects in the decision-making process regarding the optimal sustainable renovation alternative for the building/property owner.

One tool for assessing aspects of sustainability, which has gained interest from decision makers in Swedish renovation projects, is Renobuild [30]. This tool is used in the present case study, and the output from Renobuild is used as input to the proposed method of weighting sustainability aspects.

## **2. Decision-Making Processes in the Early Phases of a Renovation Project**

The importance of proper decision making in the early phases of projects has been addressed by Kolltviet and Gronhaug [31], who conclude that these decisions may dramatically affect a project’s value generation. Other studies emphasize that it is important to consider sustainability at an early stage in renovation projects [32,33]. The most important decisions that influence the life-cycle performance of a building are taken in the early phase of the design process [34]. According to Kohler and Moffatt [35], the earlier the assessment, the higher the ability to affect the life-cycle performance of the building.

Various studies address different steps in the early phase of renovation projects to define goals, assessment criteria, and the weighting of these; the steps are defined in different ways in these studies. Some studies [36,37] address sustainable decision models in building renovation; the models consist of steps regarding the choice of possible renovation scenarios and sustainability criteria that can be used for assessments and final decisions. Nielsen [29] performed a literature review concerning the tools that are developed to support decision-making processes in the early phases of renovation projects. Performance estimation of different renovation projects is the most researched area and the evaluation

of design alternatives is the least researched area within the literature that concerns decision-making processes in renovation projects [29].

Multi-criteria decision-making (MCDM) is considered a potential tool for analyzing complex real problems due to its deep-rooted ability to judge different alternatives on various criteria for possible selection of the optimal alternative [38]. In a sustainable renovation process, the decision maker needs to compare the performance of different renovation alternatives/packages as regards aspects of sustainability, which make MCDM a suitable tool for analyzing this complex system.

MCDM methodologies have been developed in order to carry out a sustainable assessment. When it comes to the weighting of sustainability assessment criteria there are two principal approaches brought forward: the first is to consider criteria as having equal weight and the second is to assign weight to the particular criterium [29]. One study [39] investigates the use of two subjective weighting methods in the case of selecting which buildings to renovate within a building portfolio of 56 schools; an important finding of the study was that most of the participants experienced advantages of using a weighting method in the final decision-making process in comparison to not having any weighting method. The weighting methods can be classified into three categories: subjective weighting depending on the preferences of the decision maker, objective weighting based on quantitative measured data, and combination of subjective and quantitative weighting methods [40]. The most used weighting method is the Analytic Hierarchy Process (AHP) according to the review study by Nilsson [29]. Saaty [41] developed the Analytic Hierarchy Process (AHP) in 1980, and it is now a widely-used MCDM approach. With this approach, a scale of priorities is derived from pairwise comparison measurements of decision criteria. One of AHP's limitations is the assumption of independence among various criteria of decision-making [41,42], which is not reasonable considering renovation projects. It is widely recognized that there is a conflict between the economic, environmental and social aspects of sustainability in renovation projects [19]. A study by Pirouz et al. [43] concerned with sustainability in the industrial sector has suggested Triangular Fuzzy Analytic Hierarchy Process (TFAHP) as a method to mitigate this limitation.

The Decision Making Trial and Evaluation Laboratory (DEMATEL) method [44] has been used in several studies to extract the mutual relationships and strength of interdependencies among criteria [45–47]. The DEMATEL method can be used with other techniques such as the Analytic Hierarchy Process (AHP) since it accounts for interdependence among the criteria. As the first step in using DEMATEL, the degree of influence between criteria should be defined based on data from literature reviews, brainstorming, or expert opinions. However, in renovation projects where the relationship between the different aspects of sustainability have not been defined in literature, especially the social aspect is hard to define by other means [20]. Moreover, as stated by many authors, there is a general lack of knowledgeable decision makers/buildings owners as regards the principles of sustainable renovation projects [21–24]. Thus, use of DEMATEL will probably add further complexity to the decision-making process in renovation projects where the aim of this work is to develop a simplified method that could be practical enough to be used by decision makers/buildings owners.

The Weighted Sum Method (WSM) is probably the oldest and most commonly used approach in MCDM, especially in single-dimensional problems [48]. Kumar reviewed [49] various MCDM techniques for making development sustainable in terms of renewable energy. The strength of WSM developed by Fishburn in 1967 is its simplicity; however, it fails to integrate multiple preferences. AHP allows more than one decision maker to be involved; however, it has been found that such wider involvement can make assigning weights to criteria a more complicated and time-consuming problem [39,45]. Kolios [50] compared WSM and AHP in a wind turbine design case study, in which 10 alternatives were assessed based on 10 criteria. WSM was the simpler method and gave similar results as AHP. Tupenaite [51] used different multiple criteria analysis to assess alternatives for built and human environment renovation. Here AHP and WSM also revealed similar results. However, weighting of criteria using AHP was more complicated, requiring experts in the fields to estimate weight.

### 3. Suggested Sub-Criteria to Assess Sustainability of Renovation Projects

To assess sustainability in a renovation project, sustainability performance needs to be quantified, i.e., estimated. The need for a sustainability performance metric and publicity tools brought about the development of certification rating systems by the World Green Building Council (GBC). The World GBC is a union of national councils, which was formed by eight nations in 2002. Its mission is to accelerate the transformation of the built environment towards sustainability [52]. However, these rating systems do not include the three aspects of sustainability, and thus they are not necessarily sustainability metrics and rarely used in academic literature as a means to measure sustainability performance and behavior [53].

Many studies [34,53–55] emphasize that the life cycle analysis (LCA) method is the most popular and comprehensive metric to evaluate environmental sustainability in renovation projects. LCA was developed in the early 1960s in an effort to quantify the environmental impact of various packaging options at a Coca Cola factory. It has now been developed and standardized into an analytical framework in the ISO 14040 series of standards. LCA is the “compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle” [56]. LCA studies were applied in many different sectors and, previously, were widely applied in the construction field [55,57].

For the economic assessment of sustainability in a renovation project, life cycle costing (LCC) is among the most solid and used methodologies [34,54]. LCC comprises an economic approach for assessing the total costs of products or projects during the service life of a system or component. It entails predominant influencing economic factors and discounts future costs to their present values, perceived as particularly relevant for systems with a long life span, such as buildings [58]. Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) are combined by expressing environmental impacts in financial values [59,60].

The social aspect of sustainability in renovation projects is the least researched subject in literature [20,34]. Thermal comfort and indoor air quality are the most used criteria to assess the social aspect of sustainable renovation [29]. However, Attia [61] summarizes the evolution of comfort models in the last 50 years, worldwide, and conclude that these are mainly focused on office buildings, and there are a limited number of surveys in the area of residential buildings.

### 4. Weighted Sum Method in Multi-Criteria Decision Making

MCDM is a well-known abbreviation for multiple-criteria decision-making and multiple-criteria decision analysis. MCDM concerns structuring and solving decision and planning problems involving multiple criteria [62]. It helps a decision maker to quantify a particular criterion based on its importance in the presence of other objectives.

MCDM has become popular in energy planning as it enables the decision maker to give attention to all the criteria available and to make an appropriate decision as regards the priority of criteria [62]. Multi-criteria decision analysis has been widely applied in environmental decision-making. In single-dimensional cases, where all the units are the same, the WSM can be used without difficulty [63]. WSM is the most used of the multi-criteria decision-making methods in projects/studies concerned with renewable energy, planning energy, and building energy management, according to a literature review carried out by Pohekar [64].

In the renovation process, the decision maker will choose between different renovation measures based on the environmental, social, and economic impact of these alternatives. Each renovation alternative has a score reflecting its performance in each sustainability aspect. However, the sustainability aspects are not always equally important from the decision makers' perspective. The present work suggests the WSM to be a suitable method to help decision makers in their final decision regarding the best renovation alternative from their perspective.

There are three steps in utilizing any decision-making technique involving the numerical analysis of alternatives:

1. Determine the relevant alternatives and criteria.

a. If there is set  $A$  with  $n$  alternatives, then

$$A = \{a_1, a_2, a_3 \dots, a_n\} \tag{1}$$

A set  $C$  with  $m$  criteria can be established such that

$$C = \{c_1, c_2, c_3 \dots, c_m\} \tag{2}$$

2. Quantify the elements of matrices  $A$  and  $C$ .

3. Process the numerical values to determine the ranking of each alternative.

This is formulated in matrix form, with normalized elements, as:

$$\begin{matrix}
 & a_1 & \dots & a_n \\
 \begin{matrix} c_1 \\ \vdots \\ c_m \end{matrix} & \begin{bmatrix} \mu_{11} & \dots & \mu_{1n} \\ \vdots & \ddots & \vdots \\ \mu_{m1} & \dots & \mu_{mn} \end{bmatrix}
 \end{matrix} \tag{3}$$

where  $\mu_{ij} \in [0, 1]$ ,  $i = \{1, 2, 3 \dots m\}$ ,  $j = \{1, 2, 3 \dots n\}$  represents the satisfaction of criterion  $c_i$  by alternative  $a_j$ . A higher value of  $\mu_{ij}$  means that alternative  $a_j$  satisfies criterion  $c_i$  in a better way.

If  $w_i$  is the weight of importance associated with each criteria,  $c_i$ , then

$$A_{WSM\_score} = \max \left( a_{WSM\_score\ j} = \sum_{i=1}^m \mu_{ij} \cdot w_i \right) \tag{4}$$

In Equation (4),  $a_{WSM\_score\ j}$  denotes the WSM score of each alternative,  $j$ , and the best alternative is the one with the highest  $A_{WSM\_score}$ .

### 5. Steps of the Suggested Method

The following chart, Figure 1, explains the proposed method in this work.

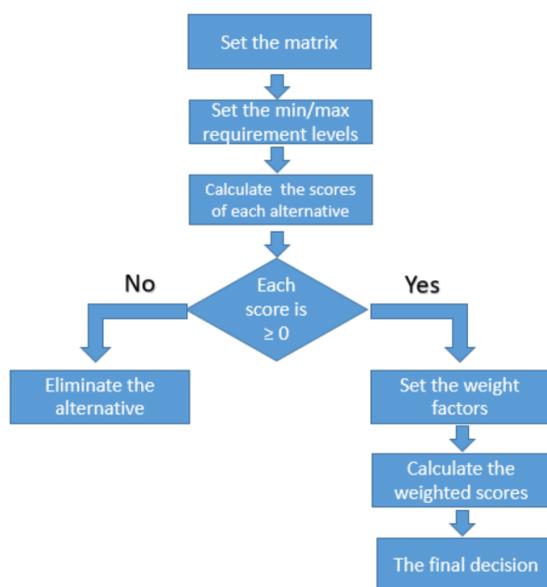


Figure 1. Steps in the suggested method.

1. **Set the matrix:** The decision maker has different renovation scenarios/alternatives, and these scenarios/alternatives should be evaluated with respect to the three sustainability aspects. Life cycle cost analysis (LCCA) is used to calculate the life cycle cost related to the energy efficient renovation measures of each alternative, which helps to assess the economic aspect of sustainability. Life cycle analysis (LCA) to calculate CO<sub>2</sub> emissions and primary energy can be used to evaluate the environmental impact of each renovation alternative. After the preliminary calculations for different criteria (LCC, LCA, and social aspect analysis) for all the renovation scenarios, the matrix in Equation (3) can be formed.
2. **Set the min/max requirement levels:** As has been mentioned before, there are neither specific requirements nor a clear definition of a sustainable system. However, there are usually certain regulations (minimum requirements) to be fulfilled, for example, the energy use of buildings, ventilation requirements, and thermal comfort criteria. Moreover, the decision makers may have a limited budget, which should not be exceeded. This step will allow the decision maker to justify the minimum requirement of each aspect of sustainability. For example, the decision maker can cap acceptable cost or CO<sub>2</sub> emissions or require a certain level of social points.
3. **Calculate the score of each alternative on each criterion:** This step calculates the value of certain alternatives lower or higher than the minimum requirement as a percentage. Any alternative with a negative score will be eliminated to guarantee that the final choice complies with the minimum requirements of sustainability.
4. **Set the weight factors:** Depending on the project, ambitions and company policies, decision maker preferences can, for certain aspects of sustainability, have more weight than other aspects and the weight factors are subjectively quantified. The method in this work suggests that the decision maker should choose the weight factor for each aspect of sustainability between [0, 1] so that the final sum of factors is 1. If a certain aspect has more than one metric to assess, the weight factor of this aspect can be divided between the used metrics.
5. **Calculate weighted scores:** In this step, scores from step 3 for different alternatives regarding certain criteria should be multiplied with the weight factor of this criteria to calculate the weighted scores.
6. **Take the final decision:** Calculate the total score for each alternative by adding the weighted scores for all criteria. The renovation scenario with the highest score is the best alternative from the decision makers' perspective.

## 6. The Renobuild Case Study

The suggested methodology is set up to use any assessment tool that quantifies variables within each sustainability aspect. The SP Technical Research Institute (RISE) of Sweden has developed such a tool: Renobuild [30,65,66]. This tool aims to develop an instrument for evaluating various renovation options for an individual building or an area with several buildings (a neighborhood) regarding economic, environmental, and social aspects. The tool aims to support decision makers when choosing alternatives in renovation projects regarding the three aspects of sustainability, simply and transparently. The goal is to reduce energy use while at the same time maximizing the positive social effects of the measures at a reasonable cost. Renobuild is unique as it mainly concerns renovation projects and provides a framework for quantifying the assessed variables.

To assess the economic value of each renovation scenario, a particular LCC analysis tool [30] is used. For each renovation option, information needs to be generated and specified concerning investment costs, energy costs, discount rates, and annual price increases. For conducting more detailed analysis, the following items should also be included: reinvestment costs, operation/maintenance costs, and rental change. As a result, total life cycle costs are reported in a table and a bar graph, where the various parts are quantified and graphically represented.

Renobuild includes environmental impact in production as well as during the actual usage phase of the building. In the environmental module, the user defines the refurbishment options with quantity

data, including systems energy, insulation, windows and doors, building materials, and the plumbing distribution system. Results are presented as changes in climate impact and primary energy use (resource use) in tables and charts.

In assessing the social aspects, the impact of renovation on people's living conditions is supposed to be analyzed. However, involved parties need to form ideas and definitions as regards the building without renovation and possible future scenarios, for example through discussions with residents and current situation analyses. "Parks and squares", greenery, storage and functions, common places and premises, and indoor environment are examples of items that can be analyzed from a social perspective.

Renobuild has certain limitations due to being in a development phase. An example of these limitations is the problem of finding correct input data. For Renobuild, this becomes a challenge at an early stage of renovation projects, since many uncertain inputs and many estimates/assumptions must be made. Furthermore, to be able to carry out the analysis with accurate results, a relatively extensive database is required, which can mean significant work for a decision maker. However, the analysis can be repeated during later stages when more data is available.

The results of Renobuild assumes that the three aspects of sustainability have equal importance, which is not necessarily true from the owner/decision maker's perspective. This has posed problems for decision makers, since they have difficulties in evaluating which measure is better than the others.

### 6.1. Building Description

The Million Homes Program in Sweden is a common name for a housing project which was undertaken in Sweden between 1965 and 1974. During this program, 1,005,578 dwellings were constructed, both as single-family houses and multi-family buildings [67]. Some 50 years later, many of the technical systems and components in these buildings are reaching the end of their service-lives and need renovation. Almost 300,000 buildings are in urgent need of renovation [68]. Increased insulation of the floor and facades, new windows with lower U-values, and changed ventilation systems are some examples of the renovation measures needed.

The following example, which is a renovation project that was a case study for Renobuild, reflects the principal numerical system. The example is taken from the report that was published by Mjörnell [30]; the building example typifies the buildings of the Million Homes Program.

The chosen case is called Garvaren and is located at Uddevalla Municipality in Västra Götaland County, Sweden, as Figure 2 shows. Over the year, the temperature in Uddevalla typically varies from  $-4\text{ }^{\circ}\text{C}$  to  $20\text{ }^{\circ}\text{C}$  and is rarely below  $-13\text{ }^{\circ}\text{C}$  or above  $25\text{ }^{\circ}\text{C}$  [69]. The building is a U-shaped building constructed in 1955 and is three storeys high. It has 76 apartments and a heated floor area ( $A_{\text{temp}}$ ) of almost  $7227\text{ m}^2$ .



Figure 2. Location of Uddevalla Municipality [70].

Table 1 shows the five renovation alternatives, which were suggested and used as renovation alternatives in the Renobuild calculations:

**Table 1.** Studied renovation alternatives.

Studied Alternatives	Renovation Measures
Alternative 1	Adding more insulation to the attic, facades, and basement walls.
Alternative 2	Adding an extra pane to the existing double-glazed windows.
Alternative 3	Installing exhaust air heat pumps.
Alternative 4	Alternatives 1 and 2.
Alternative 5	Installing mechanical ventilation with heat recovery.
	Alternatives 1 and 4.

## 6.2. Calculation Procedure

### 1. Set the matrix:

The decision maker chose the input data in the calculation of LCC and LCA in this case study. The study period of LCC analysis is 40 years, the discount rate is 3.8%, and price escalation is 2%. The analysis includes investment costs, operation and maintenance costs, and energy costs. The chosen study period of LCA is also 40 years and the greenhouse gas (GHG) emissions with the unit CO<sub>2-eq</sub> were calculated taking into consideration the technical lifespan for renovation material, and the production, transportation, and use phases.

To assess the social aspect, four sub-criteria were chosen assessed on a scale from 1 to 5 regarding each renovation alternative. The studied aspects in the present case are limited to habitat quality and they are:

- The renovation does not cause any significant disturbance to the residents.
- The rate of relocation in the area is low.
- The indoor environment is perceived as good.
- Noise levels in the outdoor environment are low and not disturbing.

Table 1 shows the final results from Renobuild for all the renovation alternatives regarding the life cycle cost, reduction of/increase in GHG emissions with the unit CO<sub>2-eq</sub> and primary energy use compared to the case without any renovation, and the social assessment. Note that the environmental aspect is composed of two indicators to illustrate how more variables/indicators can be introduced under each aspect.

As seen in Table 2, Alternative 2 is the most expensive and Alt5 the cheapest based on an LCC period of 40 years. Alternative 5 displays the largest reduction in GHG emissions; Alt4 the least. In terms of primary energy, only Alt1 shows a reduction, while Alt4 presents the largest increase. In term of social aspect, the Alt3 has the highest points. Diversity in results poses a problem for the decision-maker.

**Table 2.** Results from Renobuild for studied renovation alternatives.

Studied Aspects	Studied Metrics	Studied Alternatives				
		Alt1	Alt2	Alt3	Alt4	Alt5
Economy	Life cycle cost LCC(€)	1,949,000	2,466,000	2,406,000	1,989,000	1,929,000
Environment	GHG emissions (tons of CO <sub>2-eq</sub> ) *	-814	-280	-1093	-702	-1453
	Primary energy use (MWh) *	-95	2037	1942	2072	1530
Social	Habitat quality (points)	15	15	16	12	15

\* The results are presented comparing to the case without any renovation.

### 2. Set the min/max requirement levels:

There are always limits to which values a variable can have. These may be linked to legislation, resource limitations, ambitions, or related to moral limits. Table 3 shows an example of min/max requirement levels: the maximum life cycle cost which the company can afford, the minimum acceptable

value of reduction of CO<sub>2-eq</sub> compared to the case without any renovation, the minimum acceptable value of reduction, the maximum acceptable value of an increase in primary energy compared to the case without any renovation, and the minimum acceptable point for the social questionnaire.

**Table 3.** An example of minimum/maximum requirements.

Studied Aspects	Studied Metrics	Min/Max Requirement
Economy	LCC (€)	2,410,000 (max)
Environment	GHG emissions (tons of CO <sub>2-eq</sub> )	−700 (min)
	Primary energy (MWh)	2000 (max)
Social	Habitat quality (points)	12 (min)

### 3. Calculate the score of each alternative in each criteria:

The amount by which each renovation alternative is higher or lower than the minimum requirement in percent is shown in Table 4. The score is in this case related to how well the quantified variable relates to the maximum/minimum values presented in Table 2. Alt2 and Alt4 have negative scores, which means that they do not comply with the min/max requirement levels of the owner/decision maker, and consequently, they are eliminated as alternatives. Alternative 2 is too expensive for the budget, generates too much CO<sub>2</sub>, and uses more resources than desired. Alternative 4 also consumes more resources than the upper limit and is rejected.

**Table 4.** The scores for the studied renovation alternatives based on min/max requirements.

Studied Aspects	Studied Metrics	Scores				
		Alt1	Alt2	Alt3	Alt4	Alt5
Economy	LCC (€)	19%	−2%	0%	17%	20%
	Environment	GHG emissions (tons of CO <sub>2-eq</sub> )	16%	−60%	56%	0%
		Primary energy (MWh)	105%	−2%	3%	−4%
Social	Habitat quality (points)	25%	25%	33%	0%	25%

### 4. Set the weight factors:

Weight factors are to be pre-determined based on the companies' principles, ethics, etc. These should be decided prior to utilization and should be based on comprehensive and accepted values for the decision makers' companies/institutions. Tables 5 and 6 give two examples/cases of decision makers' weight factors, which are subjectively quantified, depending on each owner/decision maker's perspective. The environmental aspect of sustainability in this example is assessed using two indices, thus the weight factor of this aspect is divided between them according to the owner/decision maker's point of view. Note that the sum of the weight factors is unity (1), thereby making the choice of weight factor quantities a reflection of the companies/institutions/organization's principles. The weight factors of metrics handles the weight of variables within each sustainability aspect.

**Table 5.** Case 1 for weight factors.

Studied Aspects	Weight Factors of Aspects	Studied Metrics	Weight Factors of Metrics
Economy	0.4	LCC	0.4
Environment	0.4	GHG emissions	0.2
		Primary energy	0.2
Social	0.2	Habitat quality	0.2

**Table 6.** Case 2 for weight factors.

Studied Aspects	Weight Factors of Aspects	Studied Metrics	Weight Factors of Metrics
Economy	0.3	LCC	0.4
Environment	0.5	GHG emissions	0.2
Social	0.2	Primary energy	0.3
		Habitat quality	0.2

### 5. Calculate weighted scores:

Tables 7 and 8 show the weighted scores of case 1 and case 2 respectively, according to Equation (4), and the final total scores of the three renovation alternatives that have positive scores from step 3. This illustrates the influence of a slight difference in the weighting factors.

**Table 7.** Case 1—The final scores for the renovation alternatives.

Studied Aspects	Studied Metrics	Weighted Scores		
		Alt1	Alt3	Alt5
Economy	LCC	0.08	0.00	0.08
Environment	GHG emissions	0.03	0.11	0.22
	Primary energy	0.21	0.01	0.05
Social	Habitat quality	0.05	0.07	0.05
Total scores		0.37	0.19	0.39

**Table 8.** Case 2—The final scores for the renovation alternatives.

Studied Aspects	Studied Metrics	Weighted Scores		
		Alt1	Alt3	Alt5
Economy	LCC	0.06	0.00	0.06
Environment	GHG emissions	0.03	0.11	0.22
	Primary energy	0.31	0.01	0.07
Social	Habitat quality	0.05	0.07	0.05
Total scores		0.45	0.19	0.39

As can be observed, Alt 3 renders the lowest final score. Alt 1 and Alt 5 are sensitive to the minor differences in factors as displayed in Tables 4 and 5, giving different maximum scores.

### 6. Take the final decision:

Based on the final scores shown in Table 7, Alt5 is the optimal renovation scenario based on the suggested weight factors shown in Table 5. On the other hand, Alt1, which has the highest total score in Table 8, is the optimal renovation scenario based on the suggested weight factors shown in Table 6. This shows how different weight factors give different results. This example illustrates that a small shift in weight from the economic to environmental aspect, here corresponding to 10%, has an impact on results and shows which alternative is most suitable depending on a company's economical, environmental, and social profile.

### 7. Discussion and Conclusions

The suggested method in this study facilitates the decision-making process in renovation projects and allows the decision makers to choose the most suitable renovation alternatives according to their own preferences—that is, guided by company management principles and values—but also for the fulfillment of minimum requirements set by society and other institutions. The final scores of

renovation alternatives are nonetheless guided by the decision makers' choices of the weight factors. No recommendations are provided for choosing the weight factors; decision makers choose them depending on their companies' business ideas, missions, and policies. The choice of weight factors opens up discussion about prioritizing sustainability aspects, both internally in the company and externally between the companies in the building sector, and about what image each company wishes to convey to customers, partners, and the public in general. The chosen weight factors should be consistent in various timely renovation projects but are likely to change in the transition process to a more sustainable society.

In the case presented in this work, LCA was used to assess associated carbon emissions and primary energy and to quantify the environmental aspect of sustainability; LCC was used for the economic part, and a questionnaire was used for the social part. In the social questionnaire, it is easy to alter the contents and the number of questions. Other criteria could be added or substituted in each category if there are case-specific aspects to which the decision makers prefer to compare the renovation alternatives. Today, the Swedish building regulations (BBR) have requirements regarding primary energy, and in the near future, they will have a requirement regarding carbon emissions related to building projects. Other regulations concerning deep renovation projects include requirements for minimum ventilation flow rates, thermal comfort, accessibility to and within the building, natural lighting, and preservation of historic buildings.

MCDM can be used to reduce complex problems to a singular basis for selection of a preferred alternative. The suggested method in this work is a way to consider sustainability as a whole and not just in terms of only one aspect, such as energy use. The intention of this method is to establish the idea of sustainability as a one-dimensional issue and, at the same time, to encourage decision makers to include all aspects of sustainability in their decision-making, as they can give weight for each criterion depending on the project and their own preferences. A current major drawback with the method is that there is no guidance on weight factor quantities—neither empirical nor theoretical values. Future work could encompass interviews to try to assess the order of magnitude of values expected for the weight factors for different decision makers, e.g., managers of public and private housing companies.

The presented method is flexible and can be compiled with various sustainability definitions or decision maker requirements by adding more criteria to the matrix of decision. As the European Union considers that it is important to accelerate the renovation process, it is possible to add the duration of the renovation process as a criterion in the decision matrix and assign a weight for it.

In future work, the proposed method will be applied in a renovation project to evaluate sustainability aspects of different renovation scenarios. Stora Tunabyggen AB, the public housing company in Borlänge municipality, began a renovation project in the Tjärna Ängar area where three multi-family buildings were renovated with different renovation packages (E2B2 grant No 39628-1). The proposed method in this work will be applied to compare the three buildings from the owner/decision maker's perspective. A qualitative study is also planned to investigate how much weight decision makers in the Swedish building sector give to each aspect of sustainability in renovation projects.

**Author Contributions:** Conceptualization, A.K., M.H., J.A. and J.A.M.; Data curation, A.K.; Formal analysis, A.K.; Funding acquisition, J.A.M.; Investigation, A.K.; Methodology, A.K., M.H., J.A. and J.A.M.; Software/Programming, A.K.; Supervision, M.H., J.A. and J.A.M.; Writing—original draft, A.K.; Writing—review and editing, A.K., M.H., J.A. and J.A.M. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by Swedish Energy Agency grant number [40811-2].

**Acknowledgments:** The research leading to these results has received funding from the Swedish Energy Agency under grant agreement No 40811-2 and from Sustainable Integrated Renovation (SIRen).

**Conflicts of Interest:** The authors declare no conflict of interest

## Nomenclature

MCDM	Multiple-criteria decision-making
WSM	Weighted sum method
HVAC	Heating, ventilation, and air conditioning
AHP	Analytic hierarchy process
TFAHP	Triangular fuzzy analytic hierarchy process
DEMATEL	Decision making trial and evaluation laboratory
GBC	World green building council
LCA	Life cycle analysis
LCC	Life cycle cost
GHG	Greenhouse gases

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