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Article

Application of a Decision Support Tool in Three Renovation Projects

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Abstract: Building owners are encouraged to reduce energy use in order to both contribute to national energy-saving goals and reduce the costs of heating and operation. It is important to choose the most optimal renovation measures available so as to achieve cost-effective energy use while maintaining excellent indoor environments, without sacrificing architectural quality or negatively affecting the environment. Building owners and managers often have neither the time nor the expertise required to properly evaluate the available renovation options before making a final decision. Renovation measures are often calculated to repay investments in a short time, rather than taking into account life-cycle costs (LCC), despite the fact that a thoughtful, comprehensive renovation is often more cost-effective in the long run. This paper presents a systematic approach for evaluating different renovation alternatives based on a number of sustainability criteria. The methodology has been verified using three multi-family apartment buildings in Sweden. The benefit of using the proposed methodology is made clear through a comparison between the different renovation alternatives from a sustainability perspective, and will hopefully serve as encouragement to choose renovation measures which involve marginally increased investments but lead to significant environmental and social benefits in the long-term.

Keywords: case study; sustainable renovation; decision-making; life-cycle cost; life-cycle assessment; social indicators

1. Introduction

1.1. Background

The need to renovate commercial and residential buildings has become increasingly important in recent years, for example in order to comply with the demands of reducing CO_2 emissions. At the same time, renovation projects need to comply with economic, social, and other environmental goals [1]. In Sweden, the renovation of buildings is urgent for several reasons, including the need to repair damage, improve energy efficiency, and upgrade building service systems, which are approaching the end of their service lives [2]. There will be a need in the coming years to increase the pace of renovation. The situation is similar across Europe, where renewal of building stock has been less than 2% per year [3]. All told, this means that the pace of renovation must increase at the same time as other, and sometimes conflicting, demands (economic, environmental, social) are met.

The renovation and modernisation of buildings can be performed for different reasons; expired service-life of components, tenant complaints, and high energy use are common motives. In many cases, the renovation involves extensive measures to the building's envelope or heating and ventilation systems, which are often costly to perform, disturb the tenants during the renovation period, and in some cases cause rent levels to increase. This further adds to the complexity of making decisions regarding which renovation measures to carry out. The increased awareness of climate change which has been evident in recent years, as well as an improved understanding of tenants' needs, has also led to a greater emphasis on choosing sustainable solutions, which puts more focus on social and environmental factors besides economic.

One example of the complexity involved in sustainable renovation is that any changes made may lead to energy savings and general modernisation but could also have a negative impact on the environment; for example, the resultant increase in usage of building materials could contribute to CO_2 emissions through both production and transportation, in turn reducing the net CO_2 savings that result from the improved energy efficiency of the changes themselves. Consequently, there is a need for evaluation methods which can consider the increase in usage of material in relation to potential energy savings, as well as other factors. Another example is the balance between short-term profits and the life-cycle perspective when comparing renovation measures. Short-term economic benefits have often been prioritised over life-cycle cost (LCC), even though this may be less beneficial for building owners who intend to keep and manage their buildings over a long period. We, however, see an increased interest in addressing sustainability from the perspectives of both tenants and society in general and, as a consequence, it is on the agenda of many building owners. While the imminent needs of building renovation must naturally be addressed by choosing appropriate renovation measures, it is our impression that an ever-growing number of building owners are becoming increasingly motivated to choose sustainable solutions.

However, property owners are facing difficult decisions in trying to balance economic, environmental, and social values in deciding on renovation measures. Sufficient time, knowledge, information, or tools are often lacking for those who wish to evaluate renovation with regard to sustainability [4–6]. At the same time, it has been argued that the tools available today have, thus far, gained limited acceptance for renovation [5], and that there is a need for greater integration of conflicting values so as to facilitate comparisons between possible measures in the early stages of a renovation process which balances all aspects of sustainability equally.

1.2. Aim

The objective of this paper is to demonstrate how the decision support methodology developed within the research project Renobuild, which aims to develop a tool to assist in the sustainable renovation of buildings, can be used to evaluate renovation alternatives; this is discussed in relation to three different projects. We will go into detail and further explain and verify how the methodology works through case study exemplification. The paper will show how the methodology can be used for real renovation projects, and discusses the strengths and weaknesses of the methodology as well as further developments required before the tool can be more widely implemented. The Renobuild methodology aims to provide a systematic approach to the evaluation of renovation alternatives based on three aspects of sustainability: Economic, environmental, and social. A detailed description of the development of the methodology was published in Mjörnell *et al.* [7]. Results from one of the case buildings were published in Malmgren *et al.* [8]; however, this paper will present a broader background, as well as provide a more general discussion and conclusions.

2. The Renobuild Framework

2.1. Background to the Development of the Methodology

2.1.1. Existing Tools and Decision Support Methodologies

There are many decision support tools and assessment methods available, and many have previously been described [5,9–11]. Thuvander *et al.* [5] evaluate the functionality of several tools and methods, and show that few of the tools consider all aspects of sustainability or can be accommodated to local conditions. Most of the tools available today focus on single aspects of sustainability or do not have a balanced, integrated approach to the evaluation of sustainability [5,9]. Further, many of the established tools do not address the various complexities surrounding, and integration of, technical, environmental, economic, architectural, cultural, and social values [5]. There are, however, tools which cover several aspects, but these have often been described as being too comprehensive or aggregated, lacking in transparency, or providing insufficient consideration of all necessary aspects [5,9]. Singh *et al.* [9] argue that tools and rating systems which evaluate sustainability are also, to some extent, subjective, in spite of the purported objectivity of the evaluation of each aspect [9]. Thuvander *et al.* [5] identify the need for a simplified decision support framework that focuses on the early stages of renovation projects.

Methods are available with which to evaluate sustainability in the early stages of a renovation project, although these generally take slightly different approaches to those used by the Renobuild project. For example, a similar method uses an existing evaluation tool—Miljöbyggnad—which is an established tool used by property owners and developers—to assess environmental aspects [12] but has a different focus and does not directly address CO_2 and primary energy in explicit terms for materials included in the renovation, nor does it accommodate a life-cycle perspective [13]. As regards comparing different renovation alternatives for the same building, this can be seen as a drawback.

Similarly, a tool has been developed in Denmark based on the idea that there is a lack of simple and holistic tools available to help stakeholders in early stage decision-making [14]—an impetus which is shared by Renobuild [7]. As compared to Renobuild, however, this tool is more simplistic and builds on multiple stakeholders' subjective views, rather than calculations and evaluations. Thus, while it provides quick results, its major drawback is its being based on the subjective, and thus often differing, views of various stakeholders.

The ECBS Retrofit Advisor is another tool to help decision-makers in the process of selecting an appropriate level of building retrofit [15]; currently, however, it is restricted to predefined countries and fixed building types.

The REBO model is a conceptual framework which aims to include central and often overlooked qualities in Swedish housing built between 1941 and 1960 [16]. Social, cultural, and architectural values are evaluated qualitatively, alongside more easily measured values such as technical, environmental, and economic.

The multi-variant design and multiple criteria analysis tools have been developed by Kaklauskas *et al.* [11]. They aim to evaluate many aspects of renovation, such as economic, technical, architectural, aesthetic, and comfort. Based on the needs, weights, and data of buildings, the system can compare up to 100,000 options so as to automatically find the best.

Poel *et al.* [17] have developed a tool which analyses the energy performance of buildings. It can provide building owners with recommendations for cost-effective measures which can improve energy performance. Calculations are made independent of local context, but the interface in the tool must be localised so as to accommodate differences in weather files, construction libraries, *etc*.

Juan *et al.* [10] have developed a hybrid decision support system for the sustainable renovation of office buildings. It is an integrated approach with which to assess the current condition of buildings, and to suggest sustainable renovation actions based on cost, quality, and environmental impact. The system can analyse trade-offs between preferred budget and expected improvement, and compare energy performance for different scenarios.

To summarise, many decision support systems and methods have been developed, and some of these efforts incorporate several aspects of sustainability in an automated process. Too much automation, however, may be a risk if the user is not privy to the logic behind how the tools prioritise and suggest solutions. Further, there is also a risk that these tools are not able to consider all of the specific conditions of a renovation project, which could lead to decisions being made based on incomplete information. These risks need to be considered and borne in mind by the users of decision support systems.

Most tools focus on energy, cost, and the technical aspects of renovation; however, some also consider the social aspects. It is our understanding that social aspects are at present gaining more attention from the perspective of tenants and society, and thus must be an integral part of a decision support system. Based on the above, there is a need to develop easy-to-use, effective tools which can provide results relatively quickly based on actual data and take into account a life-cycle perspective. There is a need for tools which compare all aspects of sustainability equally, which has been a shortcoming in many of the tools that have been surveyed. This is the foundation on which the Renobuild methodology and tools have been developed. Since then, several tools, both competing and complementary, have been developed with a similar scope; none of them, however, have presented quantifiable indicators for environmental, economic and social aspects.

2.1.2. The Decision Process for Swedish Property Owners

The decision process can vary between companies, over time, and even between property managers within the same company [6]. Häkkinen and Belloni [18] state that the implementation of sustainable building can be hindered by a lack of a common understanding of the concept of sustainability. The implementation of tools for assessing sustainability within companies could help to establish a common definition and process, as this process requires an explicit definition of what to evaluate.

Within companies, there can be entirely logical reasons behind a decision to not select the most sustainable renovation alternative proposed by the used methodology or tool, as a result of the fact that companies often have conflicting goals. Our understanding is that it is important for both users and those developing methodologies and tools to understand that there is some degree of subjectivity in the results, as argued by Singh *et al.* [9]. Consequently, and in spite of the input of decision support tools, conflicting opinions can often be legitimate. Therefore, it is particularly important to have a structured and transparent decision-making process, in which alternatives can be evaluated and compared based on several perspectives, including those which focus on economic, environmental, and social consequences, all of which are in line with company policy, while maintaining sufficient openness within the discussion as to allow for the potential challenging and even improvement on current policy.

An investigation of Swedish property owners showed several shortcomings regarding renovation processes [6]; for example, that LCC approaches are seldom used, and that there is a lack of guidelines for data input as relates to economic evaluation, modest sustainability targets, and limited routines for managing sustainability aspects in projects. The shortcomings identified further show the need for structured approaches which include a focus on sustainability aspects in renovation processes.

The need of building owners to quickly remedy technical problems within their buildings can lead to the selection of immediate solutions instead of long-term and sustainable ones, particularly if no rigid decision processes are in place and/or these decisions are made at the discretion of an individual project manager. Additionally, the fact that improving the energy efficiency of a building is primarily performed in conjunction with other renovation measures [19], further demonstrates the need for methodologies or tools for the evaluation of total sustainability so as to provide an overview of different alternatives, rather than just those which can remedy urgent problems.

Based on the above reasoning, the introduction of a decision support tool for the evaluation of renovation alternatives could act as a mechanism for ensuring that the solutions chosen for renovation are sustainable in the long term.

2.2. The Evaluation Process with Renobuild

The background and development of the Renobuild methodology was published in Mjörnell *et al.* [7], which featured detailed descriptions of the tools used to evaluate the three aspects of sustainability (economic, environmental, and social). This chapter will give a brief summary as to how the methodology has been used to evaluate the case study buildings introduced in the next chapter. The evaluation of buildings in this article was performed in order to validate the Renobuild methodology and identify avenues for further development.

The intended users of the methodology are building owners, managers, consultants, and decision makers, all of whom are involved in the evaluation of alternatives in the renovation process. Hence, the methodology is designed to be useful primarily to practitioners. The methodology considers economic, environmental, and social aspects of sustainability. The process consists of two steps, described in Figure 1.

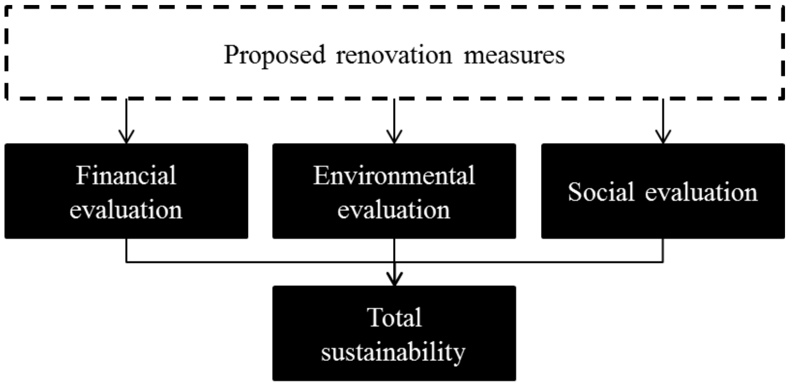

Figure 1. The Renobuild methodology. The process consists of two steps of evaluation, where the first step is performed so as to analyse economic, environmental, and social factors individually. In the second step, the individual analyses are combined into one total sustainability analysis, allowing multiple possibilities to be compared.

To evaluate each of the aspects, different tools are needed. The tools used to evaluate sustainability for the cases presented in this article are described in Table 1. The methodology is sufficiently flexible as to allow users to choose tools similar to those already used within their organisation.

All of the tools need input for all of the renovation alternatives that are to be evaluated with the Renobuild methodology (top row in Figure 1). Although this step is preparatory, it can generate a substantial quantity of work, as it is of central importance to produce a valid sustainability assessment. During the development of Renobuild, it became evident that it can be difficult to find accurate cost estimations, energy consumption data, and/or material quantities for some alternatives at the outset of the process—which, of course, negatively impacts the validity of the sustainability evaluation. In order to address this issue, it may be possible to perform a two-step evaluation, where the first evaluation is based on estimated values and the second is more detailed and performed for the most credible renovation alternatives, based on more accurate data collected over the course of the design process.

Table 1. Tools used for the evaluation of economic, environmental, and social sustainability.

Aspect	Description of the Tool
Economic	Existing tool for LCC developed by Älvstranden Utveckling AB [20]. Simultaneously evaluates LCCs for up to 10 renovation alternatives. Includes investment, maintenance costs, energy costs, changes to rent income, and reinvestments made during the calculation period.
Environmental	A life-cycle assessment (LCA) tool developed by SP within the Renobuild project [7]. An Excel-based tool which can evaluate environmental impact and payback of pre-defined renovation measures in terms of primary energy and CO_2. CO_2 payback is calculated as the time (in years) after the renovation until the accumulated CO_2 savings from the chosen measures are equal to the CO_2 generated as a result of the production and transportation of the materials used. Available renovation measures include change in energy source, ventilation system, building envelope, and water and sewage pipe replacement.
Social	A tool for assessing social sustainability, developed within the Renobuild project [7]. Consists of 25 indicators to evaluate how a renovation would affect tenants (in terms of positive *versus* negative). Indicators range from building to district level, and are divided into 6 groups. Each indicator is assessed and given a score of between 1 (lowest) and 5 (highest) depending on how that indicator is affected by the renovation measure. The assessment can be performed by a user with adequate knowledge, or in a workshop in which multiple stakeholders are represented.

The second row in Figure 1 describes the individual evaluations of economic, environmental, and social aspects with the tools presented in Table 1. All renovation alternatives are evaluated and the results are compared with one another, then arranged on a scale of 0%–100%, where the least favourable alternative is given 0% and the best is given 100%. The remaining alternatives are ranked according to their percentages.

In the final step of the Renobuild process (bottom row in Figure 1), the results of the individual evaluations are summarised manually by the user so as to evaluate total sustainability. Here, all of the renovation alternatives are compared, and the results are plotted on a bubble diagram, facilitating comprehension and comparison of the alternatives for decision-makers, as well as the possibility to communicate this information to other stakeholders. LCC and life-cycle assessment (LCA) are plotted on the x and y axes, respectively. The social aspect is indicated by the size of the bubble, with a larger bubble surface indicating a better solution from a social perspective. The best alternative is taken to be 100% surface, and so the rest of the alternatives are scaled so as to be proportional to their percentage in relation to the best alternative.

3. Sustainability Evaluations with Renobuild in the Case Studies

3.1. Description of Case Study Projects

Case studies were performed using three buildings in Sweden so as to verify the functionality of the Renobuild methodology, as well as to show the practical value to potential users. The buildings represent common residential multi-story house types in Sweden, and the measures represent frequently considered renovations. All of the buildings are owned by municipality-controlled companies.

There was a general need for renovation, as well as an ambition from the owner to improve energy performance, in all of the cases. The proposed renovation alternatives and data used to evaluate and compare with Renobuild were mostly based on real renovation alternatives provided by the building owners. For Building B, the renovation had already been completed when the evaluation took place; Buildings A and C were subject to planning and evaluation at the time of the Renobuild assessment.

Table 2, below, provides a general description of the case study buildings and their main renovation needs.

Table 2. Description of the current status and renovation needs of the case study buildings.

	Building A	**Building B**	**Building C**
Year built:	1948	1971	1955
Layout:	2 buildings, 3 floors	1 building, 4 floors	3 buildings, 3 floors
Area:	4200 m^2	1252 m^2	5018 m^2
No. of apartments:	59, some spaces for business on the first floor	16	76
Heating:	District heating, radiators	District heating, radiators	District heating, radiators
Ventilation:	Natural ventilation	Exhaust ventilation	Natural ventilation
Structure:	Concrete structure with brick façades	Concrete structure	Bricks, lightweight concrete, and wood

3.1.1. Building A

The renovation was initiated based on the need to replace the water and sewage pipes. To gain access to the pipes, it was also necessary to tear down and rebuild all of the bathrooms. When the attention of the property owner was first drawn to the need for renovation, they also pursued the possibility of upgrading the ventilation system from a natural to a supply and exhaust system with heat recovery. Pipe replacement and bathroom renovation is a common renovation measure in Sweden, and therefore relevant to the Renobuild methodology, in spite of it not having a strong focus on improving energy efficiency.

3.1.2. Building B

The property owner felt a general need for renovation of the building. At the same time, they saw the potential to test and evaluate how the building could become a low-energy building through available, affordable renovation measures. A pre-study was performed by the property owner, in which seven different methods of lowering energy consumption were evaluated. The results of this study were used as input for the Renobuild evaluation.

3.1.3. Building C

The building owner was interested in a general renovation, as well as the specific replacement of water and sewage pipes and bathrooms and kitchens. At the same time, they were also interested in measures to improve the energy efficiency of the building, involving changes to both the building envelope and the ventilation system. A limited pre-study was performed, and became the basis for the alternatives evaluated by the Renobuild methodology.

3.2. Renovation Alternatives

Table 3 presents the renovation alternatives of the case study projects used for verifying the Renobuild methodology. The case studies were limited so as to primarily include measures related to energy efficiency, due to the sustainability focus of Renobuild. However, in some cases, other renovation measures were performed at the same time by the property owner. Table 4 describes general calculation prerequisites used in the analysis of the case study buildings.

Table 3. Renovation alternatives used for the Renobuild evaluation of the case study buildings.

	Building A	**Building B**	**Building C**
Alt. 1	Reference, no renovation	Reference, no renovation	Reference, no renovation
Alt. 2	Replacing of water and sewage pipes, new bathrooms, new electrical wiring, conversion to supply and exhaust ventilation system with heat recovery	Conversion to supply and exhaust ventilation system with heat recovery, additional insulation in roof and walls, new windows, new balconies	Additional insulation in roof and walls, additional window pane
Alt. 3	Replacing of water and sewage pipes, new bathrooms, new electrical wiring	Conversion to supply and exhaust ventilation system with heat recovery	Conversion to exhaust ventilation system with heat recovery
Alt. 4	Conversion to supply and exhaust ventilation system with heat recovery	New windows, additional insulation in roof and walls	Additional insulation in roof and walls, additional window pane, conversion to exhaust ventilation system with heat recovery
Alt. 5	-	-	Conversion to supply and exhaust ventilation system with heat recovery
Alt. 6	-	-	Additional insulation in roof and walls, additional window pane, conversion to supply and exhaust ventilation system with heat recovery

Table 4. General calculation prerequisites.

	Building A	**Building B**	**Building C**
Calculation period:	50 years	30 years	40 years
Required rate of return:	5.00%	5.75%	3.80%
Yearly cost increase:	2.00%	2.25%	2.00%

3.3. Data Input and Data Quality for the Renobuild Decision Support Methodology

The data for the Renobuild analysis is based primarily on input from the building owners. All of the case study buildings had real renovation needs, and the input was based on actual renovation possibilities suggested by the owners. In order to be able to complete the LCC and LCA analyses and the evaluation of the social impact, it was necessary to select those renovation measures that were possible to achieve using the tools used for the evaluation. This meant that some renovation measures which were originally considered by the property owners were excluded. In addition, in some cases it was necessary to complement the input of the building owners with additional data, or to make certain assumptions. For example, the quantity of ventilation ducts water and sewage pipes needed to be calculated so as to be able to determine the environmental impact for Building A. The majority of the data used for the LCC analysis was taken from the cost estimations made by building owners. Regarding the social aspects, no analyses had been made by any of the building owners; instead, the results presented in this article build on analyses made by the authors with the support of a sociologist. The cases presented in this article should be seen as examples and, consequently, the results do not necessarily indicate the best solutions for the buildings as they exist in reality.

4. Results

4.1. Building A

The results of the LCC analysis show that alternative 2 had the lowest cost for the calculation period. A strongly contributing factor is that the property owner increased the rent as a result of the bathroom modernisation; see Table 5 (all costs are positive, hence increased rent levels are shown as negative in Table 5). Because alternative 3 would have involved an increase in rent, it also had a relatively low LCC for the property owner. The most expensive alternative was to perform no renovations (Alternative 1) due to the fact that this would have involved failing to make energy savings and a continued high cost of maintenance.

Table 5. Building A: Results for the life-cycle costs (LCC) evaluation, climate impact change compared to the reference case (no renovation), and social evaluation.

	Alternative 1	**Alternative 2**	**Alternative 3**	**Alternative 4**
Investment (€)	-	2,425,615	2,101,093	328,556
Reinvestment (€)	-	12,124	12,124	-
Maintenance (€)	1,901,944	-	-	1,901,944
Energy (€)	413,371	-	413,371	-
Loss of rent income (€)	-	−1,533,808	−1,533,808	-
Total LCC (€)	*2,315,315*	*903,932*	*992,781*	*2,230,500*
Climate impact (*tonne CO_2-equiv.*)	-	−1173	6	−1179
Environmental payback (*years*)	-	1.3	∞	1.0
A cohesive city	4	2	2	4
Social interaction, teamwork, and meetings	1	4	4	3
A well-functioning everyday life	12	8	9	9
Identity and experience	8	8	7	8
Health and green urban environments	-	-	-	-
Safety, security, and openness	-	-	-	-
Total score (social)	*25*	*22*	*22*	*24*

The results of the LCA analysis showed that climate impact in terms of CO_2 reduction decreased most for alternative 4, in which the ventilation system was to be exchanged. The reduction in climate impact is wholly related to the change in ventilation system in this case study, and all other evaluated measures had a negative impact on the climate aspect. Consequently, for alternative 3, the environmental payback period becomes infinite, as the suggested measures would only have increased the impact.

From a social perspective, all renovation alternatives were relatively similar, as shown by Table 5. The results show that the best alternative from a social perspective was not to perform any renovation, which scored high in the "A well-functioning everyday life" category. The reason for this was that the tenants would be disturbed during the renovation process for all of the other alternatives. In general, however, all of the alternatives received similar scores, making it difficult to draw any conclusions. For example, the alternative in which no renovation was to be performed would lead to an increased risk of water-related damage due to the expired service life of the pipes, which in turn would lead to inconvenience for tenants. This risk was, however, not included in the evaluation.

The evaluation of total sustainability shows that the alternatives are scattered across Figure 2, and that no alternative stands out as the most sustainable for all three aspects. Alternative 2 proved to be the most favourable from both cost and environmental perspectives, but was, however, one of the least sustainable from a social perspective. To do nothing was the most socially sustainable option but would also have been the most costly and the least environmentally sustainable. From a practical perspective, the renovation of the buildings must be performed, so doing nothing was not a realistic possibility. From an environmental perspective, the ventilation system change represents the entire difference between the most and least sustainable alternative. For Building A, the need to replace the pipes was the primary renovation requirement and provided the impetus for the project, thus imposing a different focus in terms of choosing alternatives to evaluate; however, this also provided an opportunity to consider improving the energy performance of the building. For Building A, the evaluation showed that the possibility which entailed the highest investment could also be one of the most sustainable from a life-cycle perspective, mostly due to the fact that the investments made it possible for the property owner to increase rent.

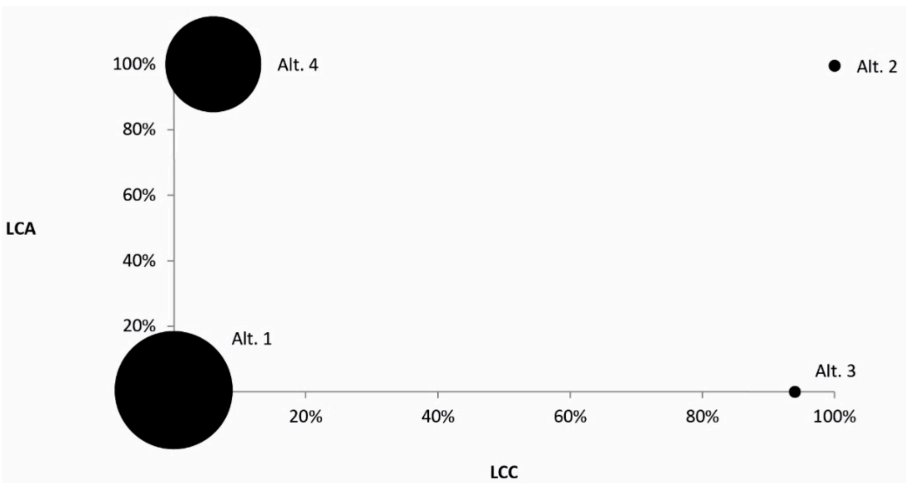

Figure 2. Building A: Combined evaluation. Social aspects are indicated by the size of the bubble; larger means better from a social perspective.

4.2. Building B

The results of the LCC analysis showed that the most costly alternative of the calculation period was alternative 2, which was also the most comprehensive and had the highest initial investment cost. The least expensive alternative s alternative 3, which was to simply modernise the ventilation system. However, undertaking no renovation work was only slightly more expensive, and amongst the least expensive alternatives. The physical state of the building, however, required some kind of intervention on the part of the owner, and so the "no renovation" alternative may not have been a realistic one. See Table 6 for a summary of all alternatives.

Table 6. Building B: Results of the LCC evaluation, climate impact change compared to the reference case (no renovation), and social evaluation.

	Alternative 1	**Alternative 2**	**Alternative 3**	**Alternative 4**
Investment (€)	369,869	996,117	422,377	696,485
Reinvestment (€)	1916	2370	2062	2663
Maintenance (€)	2007	6020	6020	2007
Energy (€)	289,331	54,404	185,129	170,919
Loss of rent income (€)	6646	0	6646	6646
Total LCC (€)	*669,769*	*1,058,912*	*622,235*	*878,720*
Climate impact (*tonne CO_2-equiv.*)	-	−340	−176	−146
Environmental payback (*years*)	-	4.9	1.4	8.5
A cohesive city	-	-	-	-
Social interaction, teamwork, and meetings	-	-	-	-
A well-functioning everyday life	5	1	3	3
Identity and experience	7	13	9	11
Health and green urban environments	6	10	6	8
Safety, security, and openness	-	-	-	-
Total score (social)	*18*	*24*	*18*	*22*

The environmental evaluation was based on quantity takeoffs from construction drawings provided by the building owner. The results showed that alternative 2 gave the largest reduction of CO_2 for the calculation period, although it had a longer environmental payback period than alternative 3. Alternative 3 and 4 were relatively equal in terms of CO_2 emissions, but adding more insulation (alternative 4) resulted in a longer payback period as compared to changing the ventilation system (alternative 3). The results show that more attention to energy efficiency leads to less CO_2 emissions over the calculation period; see Table 6.

The evaluation of the social aspects of each renovation alternative show that each was relatively similar; alternative 2, however, stands out as the most socially sustainable according to the results in Table 6. All of the renovation processes would have resulted in some form of disturbance to the tenants, and would consequently have caused negative social impact during the process. This would, however, have been compensated in the evaluation by the positive effects in terms of the improved indoor environment, modernised apartments, *etc*. It should be noted that many of the indicators in the social evaluation tool were not applicable in this case. None of the renovation alternatives would have had a significant effect on social sustainability, as they are oriented towards building physics and involve little change for tenants (except what is stated above).

The combined evaluation presented in Figure 3 shows that alternative 2 was most favourable from the environmental and social perspectives, but was also the most expensive. Alternatives 2, 3, and 4 could be good choices, but the decision would ultimately be up to the building owner. Which alternative to choose depends on the owner's prioritisation of the sustainability aspects: If cost is more important, 3 might be preferable; otherwise, alternative 2 stands out as the most sustainable from both environmental and social standpoints. In this case, the results of the evaluation do not give a clear indication of a most optimal alternative, which would have been in the top right of Figure 3.

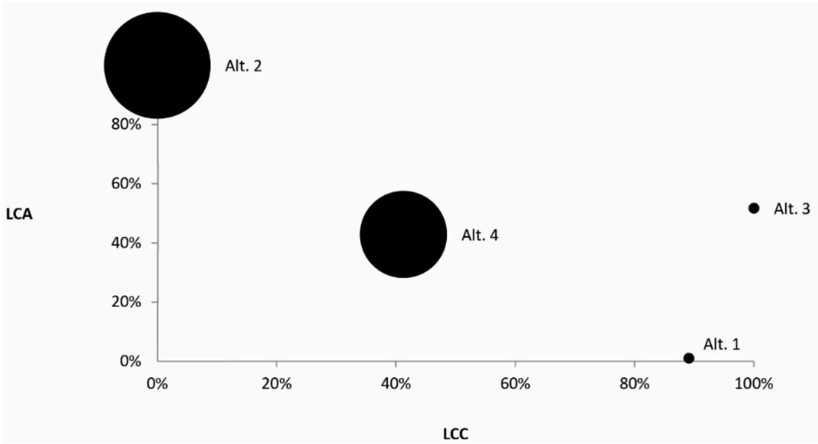

Figure 3. Building B: Combined evaluation. Social aspects are indicated by the size of the bubble; larger means better from a social perspective.

4.3. Building C

The LCC calculation shows that the alternatives were relatively similar; see Table 7. It should, however, be noted that the results were based on preliminary data from the building owner, making any conclusions speculative. Because of the fact that these calculations were made in such an early stage, reinvestments and maintenance costs were not included, which obviously affected the results. Nonetheless, the results show that alternative 6 had the lowest LCC, despite having the highest investment cost. Making no change except to add insulation also proved to be a cost-efficient alternative (Alternative 2).

From a climate perspective, alternative 6 offered the greatest CO_2 reduction, while alternative 3 offered the least (excluding alternative 1—to do no renovation). The environmental payback periods were shorter than the calculation period for all alternatives, alternative 3 stands out with a repayment period of 2.5 years, which was the shortest, although the repayment period of alternative 6 was also relatively short.

Table 7. Building C: Results of the LCC evaluation, climate impact change compared to the reference case (no renovation), and social evaluation.

	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5	Alternative 6
Investment (€)	-	708,576	104,826	813,403	459,800	1,168,376
Reinvestment (€)	-	-	-	-	-	-
Maintenance (€)	-	-	-	-	-	-
Energy (€)	2,664,482	1,434,785	2,607,431	1,832,787	1,728,603	953,959
Loss of rent income (€)	-	-	-	-	-	-
Total LCC (€)	*2,664,482*	*2,143,361*	*2,712,258*	*2,646,190*	*2,188,403*	*2,122,335*
Climate impact (*tonne CO_2-equiv*)	-	−814	−280	−1093	−702	−1463
Environmental payback (*years*)	-	7.7	2.5	6.5	2.8	3.0
A cohesive city	-	-	-	-	-	-
Social interaction, teamwork, and meetings	-	-	-	-	-	-
A well-functioning everyday life	5	3	4	3	2	2
Identity and experience	8	7	8	8	7	8
Health and green urban environments	3	5	3	5	3	5
Safety, security, and openness	-	-	-	-	-	-
Total score (social)	*16*	*15*	*15*	*16*	*12*	*15*

Based on the social aspects applicable to Building C, we found that all alternatives would impact the tenants to roughly the same degree during the course of the renovation project. Consequently, alternative 1 (no renovation) stood out as beneficial, at least from a short-term perspective. We assume that the alternatives which would result in the greatest disturbance to tenants would also be the ones most likely to make the tenant feel the need to move as a consequence of the renovation. The renovation works would, however, have been limited in terms of duration, and most likely not have caused long-term disturbance. Regarding the indoor environment, positive effects were to be achieved through changes to both the building envelope and the ventilation system, although without further investigation it is difficult to quantify these improvements. On the whole, alternative 4 stands out as the most socially sustainable, aside from alternative 1 (no renovation). Most alternatives received similar scores. Alternative 5 stands out as the least sustainable as a result of the fact that it would cause major disturbance during the renovation process.

The combined evaluation showed that alternative 2 and 6 were the most sustainable, although the latter was slightly better from an environmental perspective. From a social perspective, alternative 4 would have been the most optimal, although it involved an increased LCC. The option to not do any renovation also stands out as socially sustainable, but would be less so from economic and environmental perspectives. As previously discussed, performing no renovation may have been perceived as sustainable but would most likely be detrimental from a long-term perspective. Based on the results in Figure 4, alternatives 2 and 6 clearly stand out as the most sustainable, and were potentially positive for all three sustainability aspects. The results from Building C were the most clear in terms of which alternatives that stood out as sustainable, and were thus of interest as regards further investigation. It should, however, be mentioned that the data available was relatively limited, and that it has been necessary to make assumptions so as to be able to complete the evaluation. Further, data regarding maintenance and reinvestments for the duration of the calculation period was not available, impacting the LCC analysis, especially for the possibilities involving small investments at the outset. To summarise, the results from Building C can serve as input as to which solutions to investigate in detail.

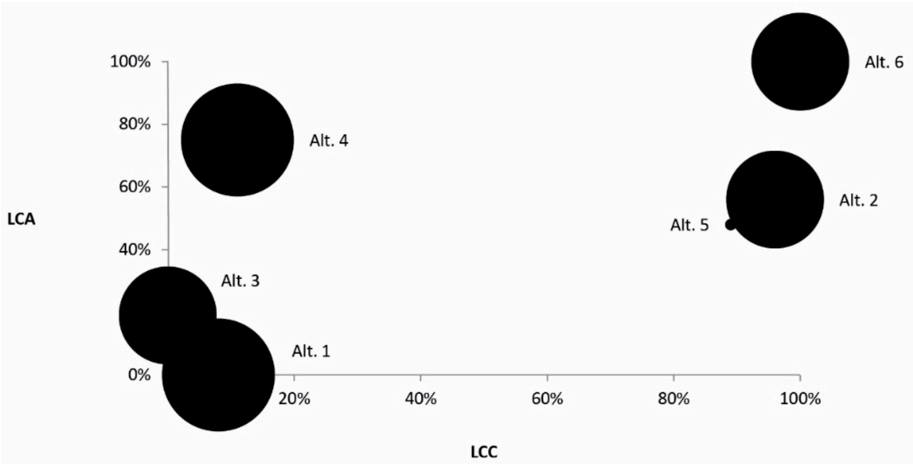

Figure 4. Building C: Combined evaluation. Social sustainability is indicated by the size of the bubble; larger means better from a social perspective.

5. Discussion

The results of the case studies show that the Renobuild methodology can be used to compare the sustainability aspects of renovation alternatives for multi-family houses in Sweden. The methodology has no apparent restrictions which might hinder use for other types of buildings or in other countries, which some other decision support tools have. The tools used to evaluate economy, environmental and social aspects may, however, need to be further developed so as to accommodate new renovation measures and different social contexts, as well as to be applicable to other countries or buildings. As an alternative, prospective users can use other tools to evaluate LCA, LCC, and social impact which better fit the specific needs and circumstances.

As compared to other decision support tools and methods, Renobuild is flexible, as the tools used are adaptable or can be exchanged. However, this requires users to prepare more input data as compared to automated tools which possess complete databases featuring, for example, the costs for specific renovation measures. With that said, this increased flexibility allows for a greater degree of tailoring to the specific conditions and needs of individual building owners and renovation projects, which can improve practical usability as part of a decision process. Further, Renobuild has a stronger emphasis on integrating social sustainability than many other tools, which we see as a benefit, in line with the continuing growth of interest in the integration of social aspects into building renovation. The case studies show that the social impact of building renovation is similar across many of the alternatives. One explanation for this is that renovation on a building level has a limited impact on social factors. The proposed tool with which to evaluate social impact also includes the neighbourhood level, which was not applicable to the cases presented in this article. In addition, significantly improving the social aspects of sustainability may require more comprehensive renovation, as well as additional measures to add to the social qualities of the area such as the creation of new meeting places and areas for recreation.

The sustainability evaluation showed that the danger inherent in using a percentage scale is that to do so—to set up two results as extreme ends of the scale—entails the possibility that the greater context of these results, along with the ability to compare different sets of results, is utterly lost. If all of the alternatives are relatively similar from a cost perspective, the least cost-effective will still be 0% and the most will be 100%. It takes some consideration on the part of the user to fully understand the results.

In this paper, we aimed to show how the methodology can be used at various stages of the decision process; consequently, buildings which represented these various stages were chosen. The stage of the project development process which the building is in naturally decides data availability. Consequently, this also influences the interpretation and usage of the results as in early phases, in which data quality is low, the methodology can be used to select alternatives for further investigation. In later phases of project development, the methodology can be used to compare sustainability on a more detailed level. We have shown using the case studies that the methodology produces credible results based on various levels of input data. For Building B, fairly detailed data was available; for Building C—which was in an early planning phase at the time of the study—only rough estimations were available. Thus, the importance of data availability and quality is stressed, as this can be an issue in any decision process. In the case studies presented in this paper, it has in some cases been difficult to find data on which to base the evaluations, and it can be problematic if additional data gathering is required in order to make a decision regarding which solution to choose, particularly if the user needs to know which solutions to investigate further. In particular, data regarding future maintenance and energy costs for the duration of the calculation period can be difficult to estimate correctly, and underestimating the maintenance costs related to performing no renovation can make this alternative more compelling than it actually is.

In several of the cases, it became evident that cost is often in conflict with social and environmental sustainability. The authors see great potential in visually presenting renovation alternatives to decision-makers so as to bring forward the trade-offs between cost, environmental and social factors. In Building B, for example, the most expensive alternative also proved to be the most sustainable in terms of environmental and social aspects. In this way, the Renobuild methodology can be a means of balancing a discussion which often tends to focus on cost, as well as a way to help decision-makers to visually compare and evaluate alternatives and conduct strategic discussions.

6. Conclusions

In this paper, we have shown that the Renobuild methodology can be used to evaluate sustainability for the renovation of multi-family houses. The main benefit is easy-to-compare results, based on inputs which many property owners already have available, albeit with an often inconsistent level of detail. We value the possibility of including more aspects than cost when evaluating renovation alternatives, as well as facts which might facilitate discussion and communication with owners and other stakeholders in the planning and design process. Data availability and quality of data may, however, be an issue.

We believe that tools for the evaluation of sustainability have great potential as regards showing the practical use of such methodologies. Given the extensive need for renovation and modernisation in the coming years, as well as the need to reduce CO_2 emissions, we believe that the use of Renobuild and similar methodologies can continue to grow, based on the positive responses we have received from building owners during the research process.

The Renobuild methodology will continue to be developed alongside the individual tools which were used to evaluate the different aspects of sustainability. There is a need to further improve the visual presentation of the total sustainability evaluation, as this will add to the ease of interpreting the results for decision-makers. There are also ongoing initiatives to further develop the method of evaluating social sustainability. The inclusion of additional renovation measures, new materials, and solutions in the LCA tool could be made continuously, in collaboration with the construction industry and building material suppliers.

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Author Contributions

Kristina Mjörnell came up with the project idea; to develop a decision support tool for building managers which includes economic, environmental, and social aspects in order to achieve sustainable renovation, and she outlined the methodology. Linus Malmgren performed the verification of the methodology through the renovation projects presented in this article, and further developed the presentation of the results.

Conflicts of Interest

The authors declare no conflict of interest.

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