

Article

A hybrid Decision Support System for Generation of Holistic Renovation Scenarios—Cases of Energy Consumption, Investment Cost, and Thermal Indoor Comfort

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Abstract: Future building renovations must rely on a holistic perspective in relation to sustainability. This paper presents a Decision Support Systems (DSS) that can be used by architects and engineering consultants to generate and evaluate the sustainability of renovation scenarios in a holistic manner during the early design stage of renovation projects. Firstly, this paper discusses both the notion of a sustainable renovation, together with various renovation approaches, towards the appreciation of the developing DSS for the generation of holistic scenarios. Secondly, it provides details about the mechanism and types of Multiple Criteria Decision Making methods to be exploited in the main body of the DSS. As such, a hybrid approach including a search algorithm with the Genetic Algorithm is used to combine and develop countless optimal scenarios. The performance of the generated scenarios is simulated and evaluated in terms criteria for *Energy Consumption*, *Investment Cost*, and *Thermal Indoor Comfort*. The trade-off between the criteria is addressed using the Pareto-front approach, and subsequently, the optimal scenarios are determined and selected using MCDM-based rating methods. The outcome is verified discussing a case study about an actual [recently] renovated dwelling and the top ranked generated scenarios using the DSS in this paper.

Keywords: building renovation; sustainable renovation; decision support systems (DSS); holistic renovation scenarios; multiple criteria decision making (MCDM); genetic algorithms (GA); energy consumption; investment cost; thermal indoor comfort

1. Introduction

The renovation of existing buildings plays a crucial role in reducing energy consumption and greenhouse gas emissions in the building sector and the built environment. Recent investigations into the field of building renovation for energy improvements of existing buildings has received increasing attention in many European countries [1,2]. The primary reason is that about 35% of the EU's buildings are over 50 years old [3], and thus they grow less attractive if they are not maintained thoroughly during life time (for reasons such as insufficient indoor air quality and thermal comfort). According to SBi [4], renovation initiatives can often be more cost-effective than new building projects.

Energy improvement and resource-conscious architecture are known as environmental friendly issues. Considering just them for a renovation project is not sustainable if the result is non-functional, costly, and malformed. The extent of the potential for energy improvements within the building renovation field can be described and made up in several ways [5]. This can happen with a focus on climatic interests, security of supplies, environmental impacts, life-cycle cost, indoor climate, building

functionality, spatial quality, etc. When all of these interventions are summated, they can move the renovation case towards the goal of overall sustainability that demands the development of holistic renovation scenarios.

The improvement of existing buildings can be divided into two major tasks: (1) current condition assessment and (2) formulation of upgrade strategies [6]. Most of the methods focus on the first part of the improvement process, understanding, or exploration of a renovation project (i.e., energy usage), while the latter is about proposing the future upgrade renovation scenarios through the generation of holistic renovation scenarios. This paper is about the latter, i.e., how to propose renovation scenarios via the generation of holistic renovation scenarios. The paper addresses the fact that the development of renovation scenarios rarely takes into consideration interactions between the various objectives of a renovation project [7]. The results are, therefore, suboptimal renovation scenarios that do not reach the full scope of sustainability for refurbished building(s). In addition, in the development of more holistic renovation scenarios, beside embracing and evaluating more objectives and criteria attached to the sustainability, one of the major issues can be addressed through consideration of the interactions or trade-offs of these criteria with each other when the renovation scenarios are being developed.

Holistic Multi-Methodology for Sustainable Retrofitting—HMSR

The paper begins in a Holistic Multi-methodology for Building Renovation—HMSR, previously proposed by the authors [8]—a methodology for addressing interactions and trade-offs between renovation objectives and criteria in a holistic manner when generating and evaluating renovation scenarios. It is an integrated design methodology, based on a mix of Soft Systems Methodologies—SSM [9], and Multiple Criteria Decision Making—MCDM, methods [10–13], which can serve as a means to structure renovation projects in accordance with sustainability to support the decision making and help to develop and select the most optimal and efficient renovation scenarios. The authors in [8] discuss that the HMSR, through a ‘proactive’ approach, can help consultancy companies and housing associations, or even municipalities, to deal with the increased complexity and wicked nature of the problem in building renovation (the phrase wicked problems [14] was originally used to demonstrate problems that are difficult to solve, because they address complex social interdependencies. The two attributes of a wicked problem include (a) difficulty of formulating their solutions due to the complexity of socio-cultural interactions and interdependencies that lead to the inability to foretell the long-term effects of decisions, since the recognition of the source of the problem is highly complicated; (b) the definition of objectives regarding these problems due to various provisional circumstances, and it entails different features, ideas and interests).

The HMSR has been built upon the research study in [15]. The HMSR includes three decision levels within a sequence of 23 activities in which a renovation project can primarily be explored; the problem is structured, the scenarios are generated and improved, and ultimately the decision is made at level 3 about which renovation scenario to pursue at the end of the design process. The HMSR, in the decision level 2, distinguishes between evaluation of hard (quantitative) and soft (qualitative) criteria. It therefore proposes the application of a DSS [6,16,17] that can be used for the generation and evaluation of the holistic renovation scenarios focusing on the hard (quantitative) criteria. The top ranked evaluated scenarios in this stage are further improved concerning the soft (qualitative) criteria. The developing DSS in the present paper is attached to the principles of the proposed DSS in the main body of HMSR for the generation and evaluation of the simulation-based performance of holistic renovation scenarios for an apartment block. As such, a hybrid DSS including a search algorithm with Genetic Algorithms (GA) is introduced and used to combine renovation approaches, as well as simulations and MCDM methods to cope with the selected [hard] criteria and renovation approaches for the development and evaluation of holistic renovation scenarios. The performance of the generated scenarios is simulated and evaluated in terms criteria for *Energy Consumption*, *Investment Cost*, and *Thermal Indoor Comfort*.

The paper is organized in Section 2, which summarizes the material and methods including the key objectives in the generation of holistic renovation scenarios, the criteria that are used for the evaluation of the simulation-based performance of the scenarios, and the renovation approaches considered in this study. Section 3 provides details about the system architecture and mechanism of the developing DSS. In order to verify the outcome, Section 4 presents and discusses a case study, including a renovation scenario about an actual [recently] renovated dwelling and compares the top-ranked generated scenarios using the DSS. Finally, Section 5 provides the conclusion and further research work.

2. Materials and Methods

Building renovation projects is a complex task given their multifaceted value profile and involvement of many different stakeholders. The complex task of identifying sustainable renovation objectives and criteria and available renovation approaches, and how to subsequently deal with the stakeholder complexity when generating holistic renovation scenarios, is ultimately the key motivation for the development of the DSS presented in this paper. To this end, we lean on the conceptual design framework entitled Tectonic Sustainable Building Design (TSBD) from the study by Kamari et al. [18], in which the authors address the TSBD for the development of holistic renovation scenarios. The term ‘holistic scenario’ and ‘sustainable renovation’ in this paper are attached to the TSBD. These terms serve to underline a holistic approach in which various objectives linking to sustainability in its full sense are achieved in a balanced way.

2.1. Sustainability Objectives and Criteria

There are various benefits that can be achieved as the result of a holistic and sustainable renovation to higher energy performance standards. Many are tangible and possible to quantify, while others are less so and may be difficult to allocate a monetary value. These renovation objectives must be identified and targeted early in the design process while renovation scenarios are being developed. Regarding the full scope of this discussion, Kamari et al. [7] attempts to address this through a new holistic sustainability Value Map, which applies Checkland’s Soft Systems Methodologies—SSM [9], together with Keeney’s Value Focused Thinking—VFT [19]. The Value Map consists of the three overall categories *Functionality*, *Accountability*, and *Feasibility* (a total of 18 sustainable value oriented criteria and 118 sub-criteria have been identified within these categories, see Table 1). The major part of the criteria in the Functionality category is quantifiable (hard), while criteria in Accountability are more qualitative (soft). The Feasibility category contains a mix of quantitative (i.e., cost criteria) and qualitative criteria such as advantages in using an efficient renovation process in which it influences the key stakeholders.

Table 1. List of sustainability objectives and criteria for building renovation from [7].

Functionality	Accountability	Feasibility
Indoor comfort	Aesthetic	Investment cost
Energy efficiency	Integrity	Operation & maintenance cost
Material & waste	Identity	Financial structures
Water efficiency	Security & safety	Flexibility & Management
Pollution	Sociality	Innovation
Quality of services	Spatial	Stakeholders engagement & education

Nevertheless, the list can be extended in future research; in the current paper, the focus is to deal with the three criteria *Energy Consumption* (sub-criteria to energy efficiency in Table 1), *Investment Cost*, and *Thermal Indoor Comfort* (sub-criteria to energy efficiency in Table 1). These three sub-criteria are all hard (quantitative) in nature, which enables us to some extent measure them quantitatively. The following paragraphs elaborate on these criteria and how they are evaluated in this study.

2.1.1. Energy Consumption

Reduction of energy consumption is a highly motivating criteria for renovation purposes. Separate standards calculate the energy consumption of services within a building (heating, cooling, hot water, ventilation, and lighting) and produce results that are exploited to demonstrate overall energy use. In this study, energy consumption is referred to as reduction of energy consumption for heating measured in kWh/m²/year. The hourly dynamic simulation tool ICEbear [20] was used to calculate the heating performance.

2.1.2. Investment Cost

Investment cost is often prioritized as one of the most essential criteria, particularly from customers or clients points of view. In this paper, investment cost is referred to as cost of procurement in DKK (Danish Krone (currency))/unit of material.

2.1.3. Thermal Indoor Comfort

It is essential to focus on the indoor climate for renovation projects. Buildings are meant to create a protective environment for people. People spend 90% of their time inside of the buildings, which makes a healthy and comfortable environment for occupants important. DS15251 [21] is a European standard, i.e., “Dansk Standard”, and describes the different indoor environment parameters and presents three Indoor Climate categories (see Figure 1). DS15251 contains more comprehensive guidelines compared to the restrictions from the Danish Building Regulation. The evaluation of the thermal comfort in this paper takes its foundation in this standard.

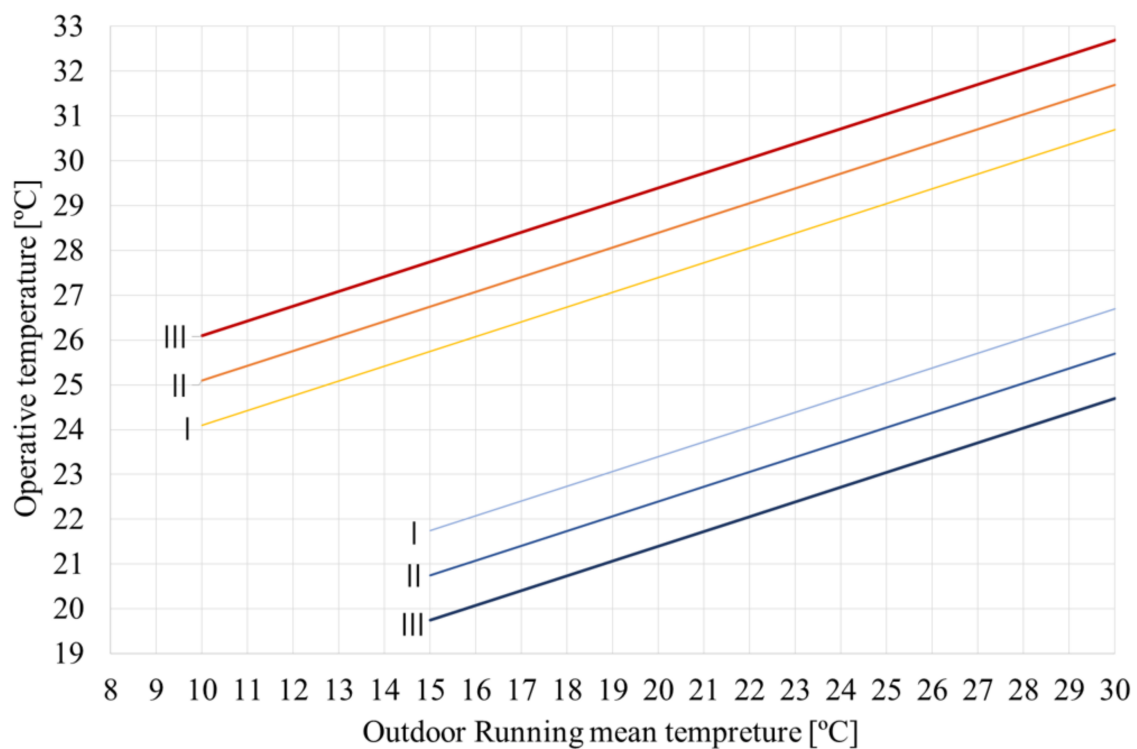


Figure 1. The indoor classification with adaptive occupants [21].

The evaluation is founded in three different classes of the indoor climate. For buildings without mechanical ventilation, which often is the case for dwellings, it is important to take adaption into account. DS15251 provides an interval for optimal indoor temperatures, which are dependent on the outside temperature. This indicates the flexibility in homes, in which it is possible to adapt the amount

of clothing, compared to offices. Accordingly, thermal comfort is evaluated according to class I of the adaptive method in DS15251 [21] (see Figure 1), since it is assumed that people in their home adjust their amount of clothing and vent when necessary. The hourly dynamic simulation tool ICEbear [20] is used to calculate the operative temperature.

2.2. Renovation Approaches and Alternatives

Figure 2 demonstrates the terminology that has been used in this paper to distinguish between a renovation scenario, a renovation approach, and a renovation alternative. The term *renovation scenario* used in this study means a selection and combination of some different renovation approaches (i.e., insulation of the external walls, replacement of windows, etc.) consisting of a specific alternative (i.e., Insulation [Class 37]—30 mm) that, together, build renovation scenarios and subsequently are applied in a renovation project.

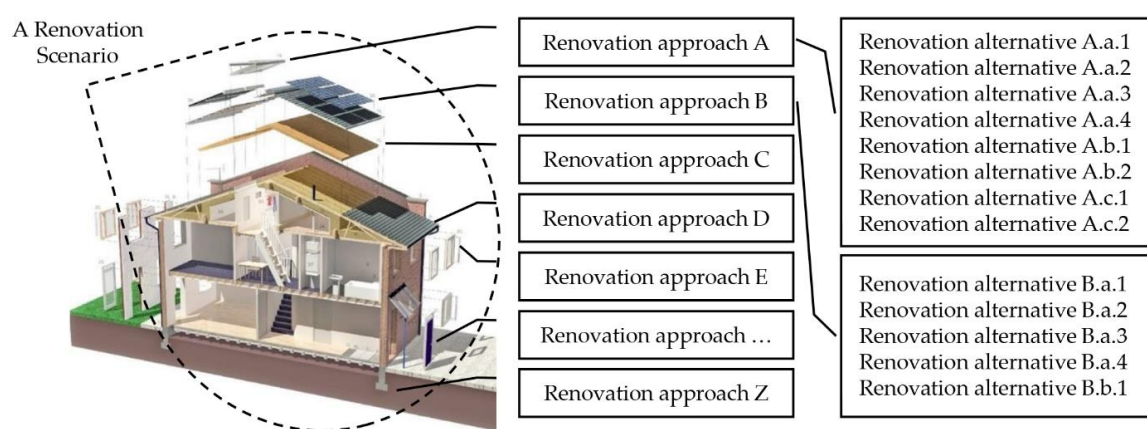


Figure 2. An example of a renovation scenario including various renovation approaches and renovation alternatives.

There is a broad range of renovation approaches that needs to be considered when renovating existing buildings. Kamari et al. [22] based on analysis of a real case study and available literature [23–26] identified a total of 139 renovation alternatives and grouped them into 26 approaches (see Table 2).

Table 2. A–Z renovation approaches from [22].

A. Insulation approaches	J. HVAC system	S. Increasing solar gain
B. Envelope (exterior finishes)	K. Renewable energy sources	T. Avoiding overheating
C. Window (replacement)	L. Energy storage	U. Re-designing of external and internal spaces
D. Doors (replacement)	M. Electrical system	V. Common areas (interior)
E. Airtightness and damp proofing approaches	N. Plumbing system	W. Individual building elements
F. Waste facilities	O. Controls	X. Sanitary appliances
G. Building security approaches	P. Flooring	Y. Fixed furniture [essential]
H. Building site	Q. Interior finishes—Ceiling	Z. Movable furniture [opt.]
I. Structural system	R. Interior finishes—Walls	

The following list displays some of the commonly applied renovation approaches within the categories in Table 2 that specifically are listed and used for generation of renovation scenarios in the present paper:

- External wall insulation, A.a
- External wall finish, A.b
- Internal wall insulation, B.a
- Internal wall finish, B.b
- New wall construction, C.a
- Internal roof insulation, D.a
- Internal roof finish, D.b
- Roof outside, E.a
- New floor construction, F.a
- New windows, I.a

There is a list/database of various renovation alternatives (i.e., A.a.1: Insulation [Class 37]—30 mm) within the above-listed renovation approaches developed for this paper. The data includes detailed properties of the different alternatives such as cost, thickness, thermal conductivity, heat transfer coefficients, and resistance. The database is used for generation of holistic renovation scenarios. It can be found in Figures A1 and A2 in Appendix A.

2.3. Decision Support Systems (DSS) for Sustainable Building Renovation

There is a remarkable number of early stage DSS for sustainable building renovation [27]. They are used by owners and designers mostly to plan energy efficiency renovation. Nielsen et al. [27] state that almost 30% of the DSS (10 out of 43 studied tools) have been developed to generate the design alternatives. Ferreira et al. [28] conclude that these DSS (which are capable of making design alternatives) are mostly focused on technical performance enhancement of renovation approaches and therefore are used by engineers. Application of such a method as a tool in the early design stage of renovation projects leads one to reduce the decision-making period [dramatically], improve the accuracy and quality of decision making, and encouraging stakeholders to accommodate holistic renovation scenarios.

3. Development of the Hybrid DSS for Generation of Holistic Renovation Scenarios

3.1. System Development Process

The DSS in this paper is developed to generate holistic renovation scenarios using a combination of two MCDM methods: Multiple Objective Decision Making—MODM, and Multiple Attribute Decision Making—MADM [29,30]. Figure 3 demonstrates the development process of the hybrid system in three steps. Each step is described below. Visual studio and thus C# programming language is used for scripting.

Step 1: The aim of this step is to specify the project requirements by collecting the information about the renovating project, and identify involving criteria and renovation approaches.

As explained in Section 1, the developing DSS in the present paper is attached to the principles of the use of a proposed DSS in the decision-making level 2 at the HMSR (see 'B' in Figure 4). It hence is used into the main body of HMSR. Following the activities that have been designed for decision-making level 1 at the HMSR (see 'A' in Figure 4), the renovation project is explored, relevant stakeholders are identified, and their demands or their relevant concerns are investigated; then, the design objectives are set up. Thereafter, and by moving into decision-making level 2, the hybrid DSS is used for generation of holistic renovation scenarios, focusing on hard (quantitative) criteria (see 'B' in Figure 4). This means step 1 in Figure 3 is parallel to the performing activities in decision-making level 1 in the HMSR and is instinctively carried out if the developing DSS in this paper is used within HMSR methodology.

Consequently, the outcome of this step influences selection of the criteria, as well as development of the database including detailed properties of the different renovation alternatives.

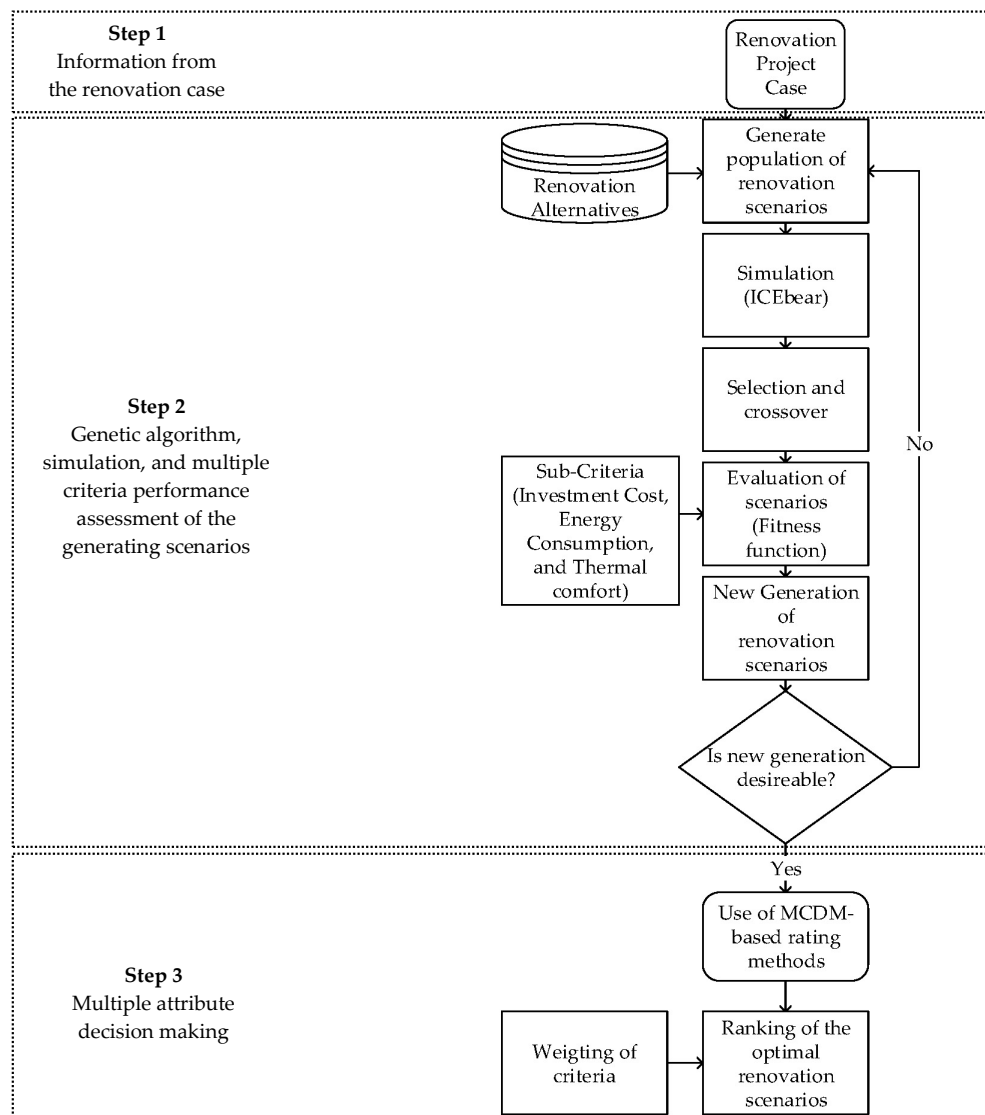


Figure 3. Architecture of the hybrid DSS for generation of holistic renovation scenarios.

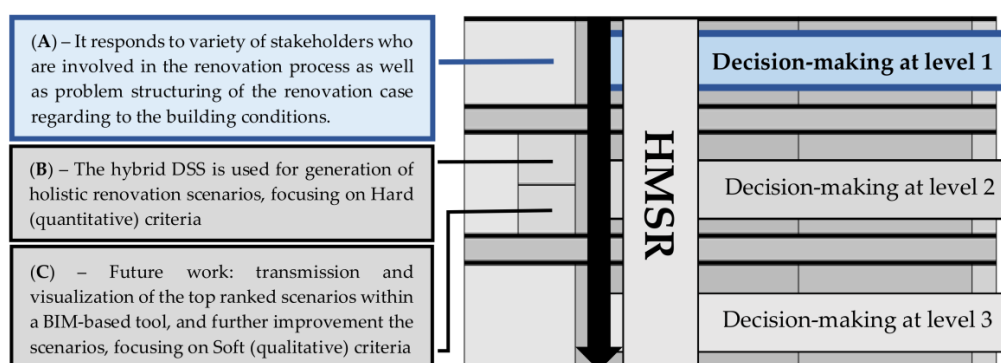


Figure 4. Overview of decision-making level 1 and 2 in HMSR (adopted from [8]).

Step 2: A Genetic Algorithm—GA [31,32] is initially used to combine renovation alternatives so as to generate optimal solutions/scenarios. GA uses a trial and error function for finding a range of solutions with predefined constraints to optimize the criteria in question. The optimization is determined by a combination of Pareto dominance and a diversity measure based on Euclid's distance in the objective space, i.e., NSGA-II [33], SPEA2 [34]. The used GA in this paper is called Hypervolume Estimation Algorithm for multi-objective optimization (HypE), which speeds up the selection process but includes a greater risk of not finding the optimal solution [35–39].

In a building renovation project, knowledge from prior projects may be included along with constraints from the building regulation to limit the solutions to only include criteria that comply with the minimum acceptable solutions. As such, an initial population consisting of scenarios is made from random combinations of renovation alternatives. These scenarios are afterwards selected in a fitness function, in which potential experience can be applied. The “fittest” scenarios survive to reproduce using a crossover scheme, in which a mutation can be applied often by applying a random “gene” or, in this paper, renovation alternatives. The result of the crossover scheme is once again processed in the fitness function, and the process starts over.

The scenarios are generated and sorted by the evaluating criteria. First, a random initial population, which here refers to the renovation alternatives (for generation of a renovation scenarios as demonstrated Figure 2) is taken from the database (see Section 2.2) and analyzed by the GA. For instance, see Appendix 1 (Figures A1 and A2) for the detailed properties of the different renovation alternatives including the data for performance evaluation of the criteria for the case study in the present paper. The best performing scenarios are selected. These are the foundation for the next generation. The GA searches for new scenarios based on the knowledge of the previous generation. With an iterative process, the GA approaches the scenarios with the lowest price. The ICEbear [20] is applied to simulate the *energy consumption* and evaluate the *thermal indoor comfort* (for further information about the evaluating criteria, see Section 2.1). In order to perform a rapid performance evaluation of the generating scenarios, the ICEbear script is combined to the code that we have developed for the DSS. To accommodate the issue of multiple local minima, the optimization is recreated until no new scenarios are found three times in a row. In addition, a mutation rate is used that adds a random scenario alongside the best performing and allows for the possibility of exploring other parts of the solution area. It seeks non-dominated scenarios (through the concept of domination, a solution x_1 is said to dominate solution x_2 , if x_1 outperforms x_2 on all criteria). As such, once again the GA finds a random initial population from the database. The population is evaluated, the non-dominated solutions are found, and from these, the search begins for new population by finding the renovation alternatives crossed from two non-dominated solutions. The scenarios from the first generation are all compared, dominated solutions are discarded, and non-dominated solutions are saved. Likewise, the next generation is compared to the non-dominated solutions and is either saved or discarded. With this iterative process, it is possible to search for superior solutions. The trade-off between the criteria is addressed using a *Pareto-front* approach [40] (also known as multi-objective programming, or Pareto optimization).

Step 3: It is difficult to judge which of the many available rating methods that would be ‘the best’ method [41–43]. To this end, one can use different MADM methods and compare their outcome. In this paper, AHP, TOPSIS, WSM, and ELECTRE are applied. However, these methods are of different nature and belong to different schools of decision-making; they are quite popular due to their mechanism, understandability in theory, and simplicity in application in multi-criteria decision-making problems [8]. They are used to cross validate the ranking, which similar studies also have concluded [41]. Their general principle is summarized in the following.

AHP [12,41,44] uses a pairwise comparison approach to deciding between solutions. The decision maker is then asked to state how much more important a criterion is compared to the other criterion in the pairwise comparison. This is done for all possible comparisons.

TOPSIS [12,41,45] is based on the concept that the ideal alternative has the best level for all criteria, whereas the negative ideal is the one with all the worst criteria values.

WSM [26] is based on an additive utility assumption, which is shown in the sum of products calculation for each alternative.

ELECTRE [41,46,47] constructs the outranking relations and the exploitation of these relations to get the final ranking of the alternative.

Use of these methods includes a weighting of the criteria, reflecting the priorities of the involved stakeholders. The influence of the weighting on the developed ranking is ultimately examined by a sensitivity analysis using a Monte Carlo simulation [48].

3.2. Constraints and Rating Rules

When searching among countless possibilities to combine renovation alternatives in order to generate holistic renovation scenarios, constraints can help to limit the solution space. Various recommendations and regulations exist on building renovations for evaluation of the *energy consumption* and *thermal indoor comfort*, some of which can be included in the GA. In Denmark, the Danish Building Regulation (DBR) [49] issues out the building rules for both commercial and private buildings. For instance, the DBR demands certain U-values for reconstructed or refurbished construction parts, i.e., exterior walls must obtain a U-value of maximum 0.2 W/m²K after a renovation. The regulations for the building elements of interest for this project are presented in Table 3.

Table 3. Minimum requirements of U-value cf. DBR for Renovation.

Building Elements	W/m ² K
Exterior walls	0.20
Ground slab	0.12
Roof	0.15
Doors and windows	1.65

DBR also recommends that the 95% of time that the building is in use should be within thermal category III cf. EN 15251, allowing 5% of the time outside this category, which may correspond to the recommended maximum of 100 h above 27 °C and 25 h above 28 °C. Furthermore, a renovation project may have a budget that perhaps depends on the intended energy savings, which will limit the possibilities on the price. Similarly, unrealistic renovation alternatives may be discarded, i.e., replacement of a bearing wall with a new wall, or combination of existing walls and additional layers of insulation causing unrealistic thick constructions.

4. System demonstration

4.1. Case Study

The selected case study is the renovation of a dwelling apartment block located in Aarhus, Denmark. The apartment block is a part of a dwelling area (see Figure 5) consisting of 27 identical apartment blocks built in 1967–1970. The blocks and common areas went through a renovation in the period of February 2014 to September 2017. The renovation included a refurbishment of all apartment blocks, new terraced houses, and common areas. The blocks were renovated in different styles, so they became a unit of two similar blocks. The façade types are, respectively, concrete/wood combination, and natural slate and zinc/aluminium/wood combination. The budget for the renovation of the blocks was estimated at 880 Mio. DKK.

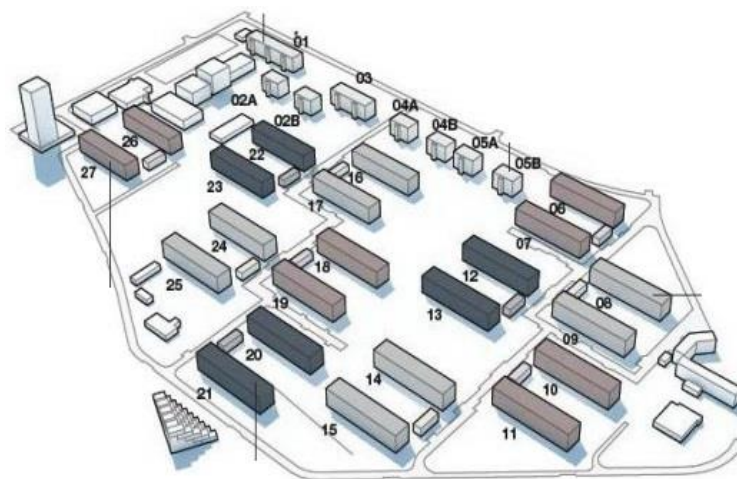


Figure 5. The dwelling area located in Aarhus, Denmark.

The apartment block consists of 32 units with similar layout. Prior to performance simulations of renovation scenarios, the apartment block is separated into six different types of units (as demonstrated in Table 4), as some units are placed at the gables of the block and thereby have a larger exterior wall area.

Table 4. Placement of unit types.

Unit 6	Unit 1	Unit 6
Unit 5	Unit 2	Unit 5
Unit 4	Unit 3	Unit 4

↔

Elevation view →

Table 5 provides the surface area and U-values for walls, floors, and roofs of the existing apartments. These are used as the required input to ICEbear related to the existing condition of the renovation project to simulate the *energy consumption* and evaluate the *thermal indoor comfort*.

Table 5. Six types of unit apartment with coherent areas and u-values.

		Ground	Roof	Windows	Walls
Unit 1	Area	0.00	85.64	21.95	27.54
	U value	0.66	0.41	2.97	0.60
Unit 2	Area	0.00	0.00	21.95	23.20
	U value	0.66	0.41	2.97	0.60
Unit 3	Area	91.72	0.00	21.95	23.20
	U value	0.66	0.41	2.97	0.60
Unit 4	Area	91.72	0.00	21.95	52.20
	U value	0.66	0.41	2.97	0.47
Unit 5	Area	0.00	0.00	21.95	58.28
	U value	0.66	0.41	2.97	0.46
Unit 6	Area	0.00	91.72	21.95	64.32
	U value	0.66	0.41	2.97	0.47

It should be emphasized that the detailed properties of the different renovation alternatives including the data for performance evaluation of the criteria such as cost (per unit), thickness, thermal conductivity, heat transfer coefficients, and resistance have been provided in Appendix A, Figures A1 and A2. These data are evaluated upon the generating scenarios in the next step.

4.2. Constraints and Implementation of the GA

As discussed in Section 3.1 (see step 2 in Figure 3), the GA is used to combine renovation alternatives (the differences between renovation alternatives, approaches, and scenarios was demonstrated in Figure 2) from the developed database (see Appendix A for the database) for generation of countless number of renovation scenarios. In order to decrease the solution space using GA (see step 2 in Figure 3) for the case study in this paper, logical constraints are added, i.e., the possibility of limiting the renovation budget. Although the GA allows addition of insulation and finish on the inside, as well as the outside, of the existing wall construction, the combination may end up with unrealistic thick walls, which will affect the natural daylight. Constraints on the wall thickness are therefore applied. Additionally, if the facade wall is bearing, it is assumed that it cannot be replaced by an entirely new wall construction. To improve the insulation of the bearing walls, insulation must be added to the existing wall.

In order to investigate the solution space for the case study, which may contain a range of local minima, ten repetitions of the GA are conducted. The final generation of each repetition is collected, and 8971 of 10,000 duplicates are removed, indicating similarities in the final generations. The remaining 1039 unique renovation scenarios are then tested for individual dominance. To select superior scenarios from the list of non-dominated scenarios, the HypE based fitness-function scheme is applied to narrow down the population efficiently, as a local minimum is found quickly and no diversity emerges. To accommodate this issue, a rule of zero duplicates as the output of the fitness function is employed; besides, the option of no renovation (reference) is forced into the evaluation. The reference exposes an issue with the crossover scheme, which is changed from always crossing wall and roof with floor and window into a random crossing of three options. A test of ten generations indicated promising results, as a Pareto-front is visible between them (see Figure 6), and the results improve drastically over the generations. The outcome of this process for the case study in this paper is a list of 55 non-dominated renovation scenarios.

4.3. Further Examination of the Non-Dominated Generated Scenarios

With application of Pareto-front approach, a landscape of the 55 remaining non-dominated scenarios is illustrated in a 3D scatter plot within the three evaluation criteria, see Figure 6. A Pareto-front is clearly visible between the cost and the energy consumption in Figure 6A. The cost varies between less than 1 Mio. DKK to above 5 Mio. DKK. Energy consumption varies between 20–30 kWh/m²/year and above 120 kWh/m²/year.

Energy consumption seems to decrease due to increased investment, which indicates that an investment in renovation with the selected renovation alternatives leads to a lowering of the energy consumption.

A less obvious Pareto-front is visible between the cost and the % DHOCI, Figure 6B, as an increased investment improves the % DHOCI from around 2.2% to around 1.8% with an investment of approximately 2.5 Mio. DKK. A further investment appears to worsen the % DHOCI. The same is visible between the energy consumption and the % DHOCI in Figure 6C, in which decreasing in energy consumption appears to have a direct improvement of the thermal comfort level up to about approximately 40 kWh/m²/year. After this point, a decrease in the energy consumption appears to worsen the % DHOCI. In Figure 6C, the improvement in energy consumption may cause fewer hours to be below the temperature limits in category I. However, the lowering energy consumption may cause overheating, which is reflected in the increase of % DHOCI when the energy consumption decreases below approximately 40 kWh/m²/year.

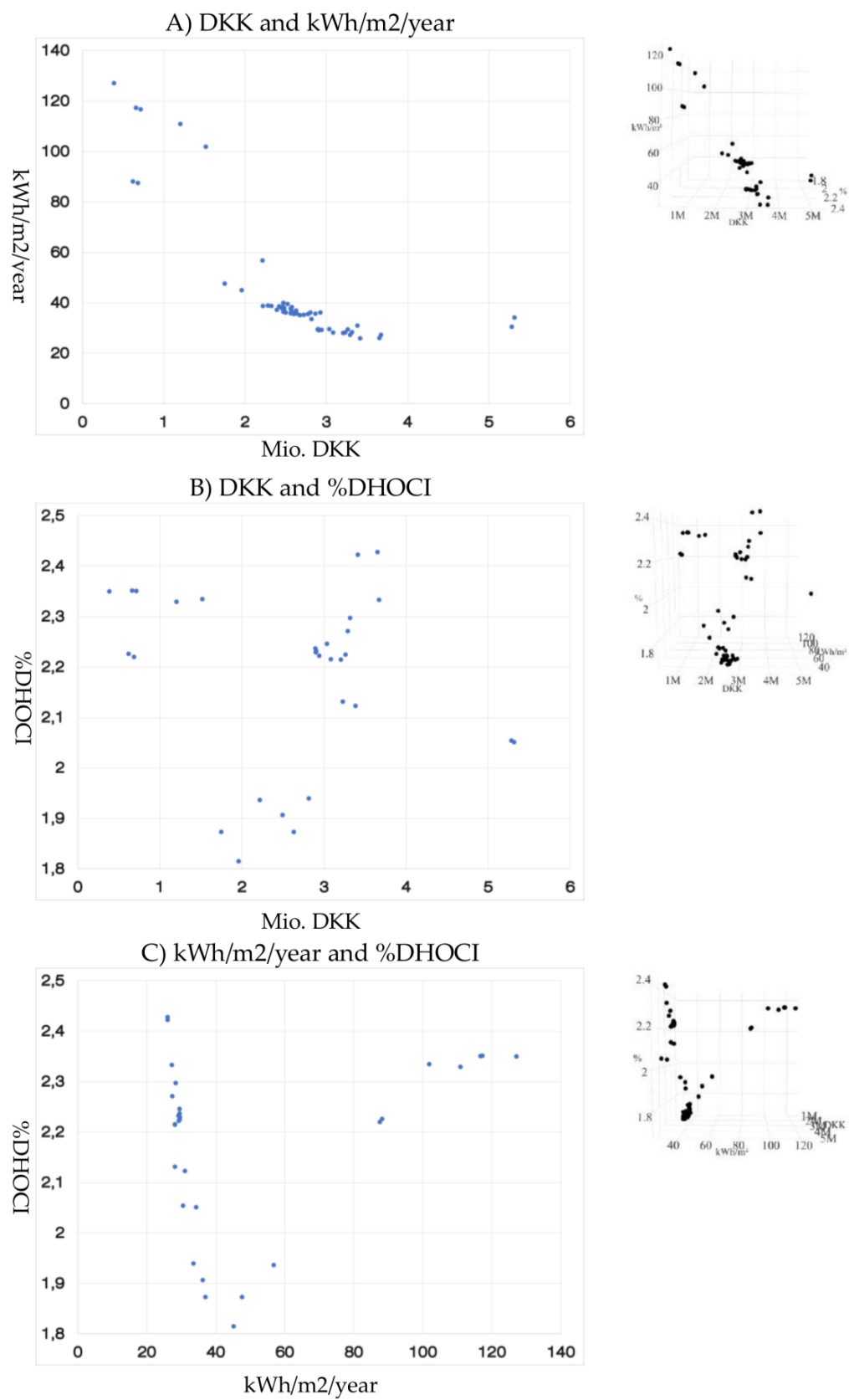


Figure 6. Pareto-front of the 55 non-dominated simulated scenarios upon the evaluated criteria.

For more clarification, Figure 7 represents the 55 non-dominated scenarios with the associated energy consumption and % DHOCI. The scenarios are listed with their reference number as per the database represented in Appendix A. The notation “Ref” before a building component means that this component was not renovated in the scenario. In next step, these are used to develop the ranking of optimal scenarios.

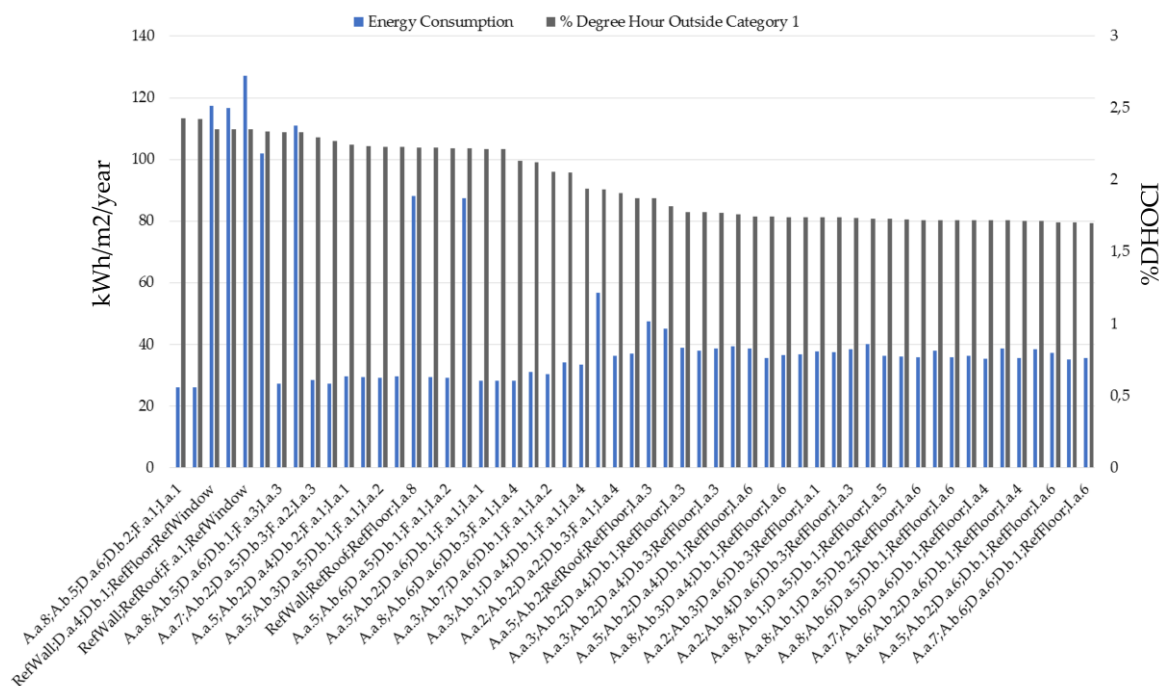


Figure 7. The performance evaluation of the 55 non-dominated simulated renovation scenarios—energy consumption and degree hour outside category I of the scenarios.

4.4. Ranking of the Renovation Scenarios (Step 3 in Figure 3)

In order to make an informed decision upon the performance of the 55 scenarios, the previously described MADM methods including *AHP*, *TOPSIS*, *WSM*, and *ELECTRE* are applied for ranking. The rankings are based on an equal weighting of all criteria, which may not be the case for an actual renovation as stakeholders may have different opinion about the importance of the different evaluation criteria. The results are represented in Figure 8. The ranks differ depending on the used MADM method but their trends are following each other. It is observed that *TOPSIS* and *AHP* methods present exact similar rankings.

The scenarios on the lowest part of the graph in Figure 8 include renovation scenarios for all components except the floor. These scenarios are generally preferable according to the MADM methods. Two scenarios marked with a blue dot:

- “Insulation (Class 37)—150 mm”, “Plaster”, “Insulation (Class 37)—125 mm”, “Plasterboard”, “RefFloor”, “New windows—Hvidbjerg Everluxx Classic”, and
- “Insulation (Class 37)—150 mm”, “Plaster”, “Insulation (Class 37)—200 mm”, “Plasterboard”, “RefFloor”, “New windows—Hvidbjerg Everluxx Classic”

Have a particular low rank by all methods. The only alternative separating these two scenarios is the amount of added internal insulation on the roof.

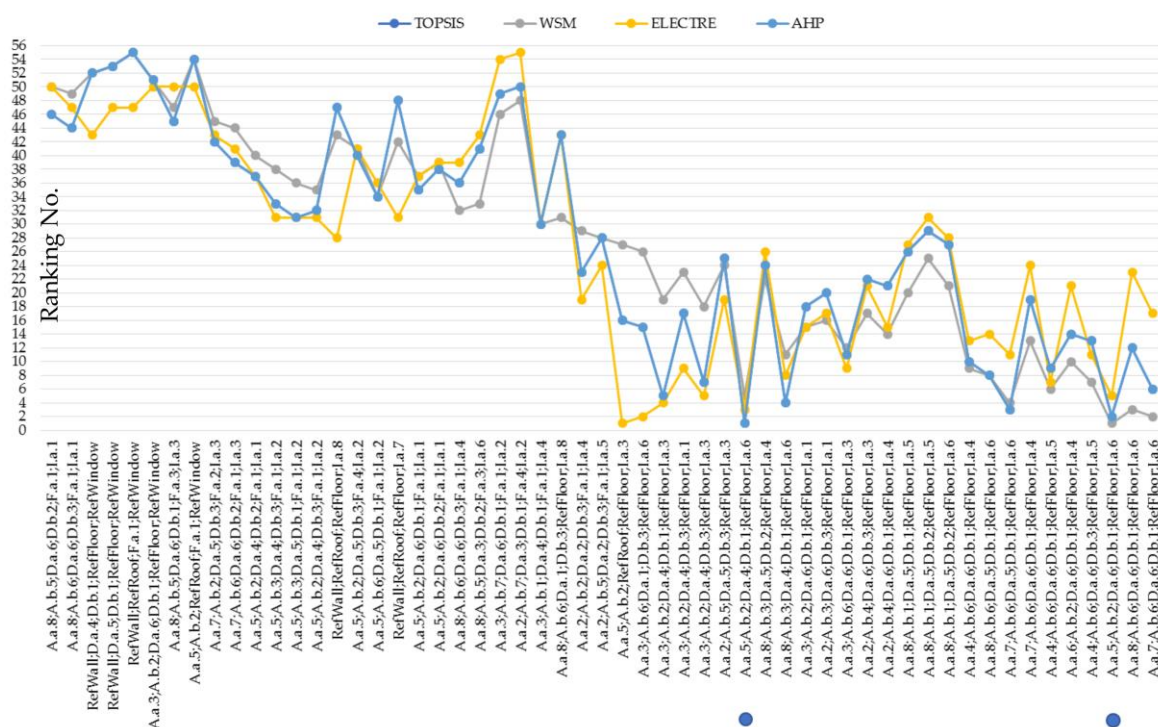


Figure 8. Ranking of the results using four different MADM methods: AHP, ELECTRE, WSM, and TOPSIS.

4.5. Sensitivity Analysis

The MADM methods include a weighting, reflecting the priorities upon the criteria from the involved stakeholders. In this paper, the influence of the weighting on the ranking is examined in a sensitivity analysis. To this end, a Monte Carlo simulation is performed to monitor the robustness of the renovation scenarios by indicating the influence that the different weightings may have on the ranking of the scenarios. As such, a weighting interval between 0.23 and 0.43 is assumed for the investment cost and the energy consumption. The thermal comfort is then assigned the remaining weight to achieve a total weight of 1.

Among the applied MADM methods in previous section, the TOPSIS and AHP methods provided an equal result. In order to test the robustness of the weights, TOPSIS is applied in the Monte Carlo simulation. It is set with random weights in the defined intervals for the three criteria, and the ranking is simulated 100,000 times. The result of the variation of the rank depends on the weighting is illustrated in Figure 9.

The ranking in Figure 8 was made with equal weighting and different MADM methods, and the ranking in Figure 9 was made with weighting intervals. Comparing Figures 8 and 9 indicates similarities. The same two scenarios as marked with a blue dot in Figure 8, are still seen with the lowest rank, and little variations depend on the weighting of the criteria. However, these scenarios have been evaluated for investment cost, energy consumption, and thermal indoor comfort. The weighting of the ranking may indicate which scenarios perform best based on these criteria, but as argued in Section 2.1, a holistic approach for building renovation evaluation is necessary in order to reach sustainability in its full sense. As such, a decision based on these criteria is not sufficient if sustainability is desired. However, the best performing renovation scenarios can be exploited as a foundation for further investigation, including additional criteria and the stakeholders' satisfaction.

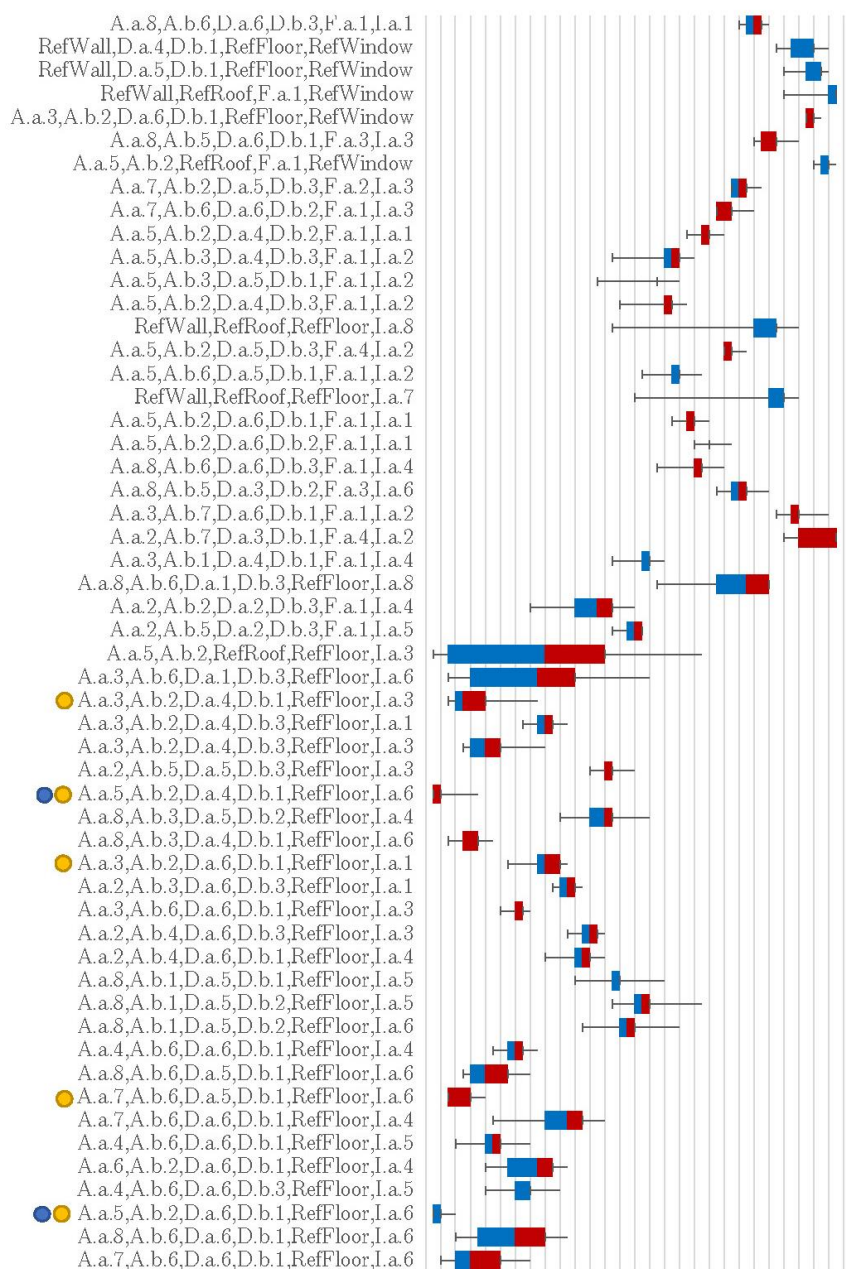


Figure 9. Sensitivity analysis—box plot of Monte Carlo results.

4.6. Comparison of the Top Ranked Generated Scenarios with the Actual Renovation Scenario

To test the effectiveness of the generated and evaluated scenarios, the five renovation scenarios marked with yellow dots on Figure 9 are compared with the actual renovation scenario used by the real project. The five selected optimal scenarios include improvement of building envelope, consisting of renovations of walls, roof, and windows. No renovation of the floor was constructed.

4.6.1. Walls

The existing façade of the apartment before renovation, consists a light wall construction of 60 mm reinforced concrete back wall, 60 mm insulation, and 40 mm reinforced concrete outside as illustrated in Figure 10. The gables consisted of a double brick wall, with 75 mm insulation.

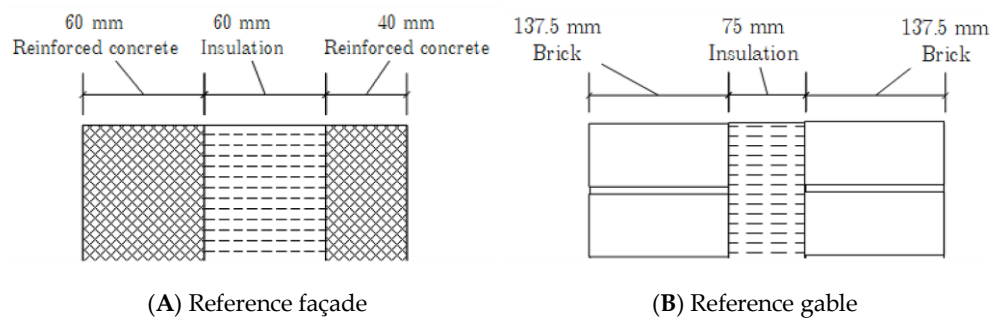


Figure 10. The build-up of the reference facade and gable.

As part of the actual renovation, all walls have been renovated, and 100 mm additional external paper wool insulation has been applied in wooden panels mounted to the existing external walls. A combination of concrete screen tiles and wooden plates has been used as exterior final finish that may not be the cheapest alternative but could improve the impression of the building. The construction detail for renovated wall is illustrated in Figure 11.

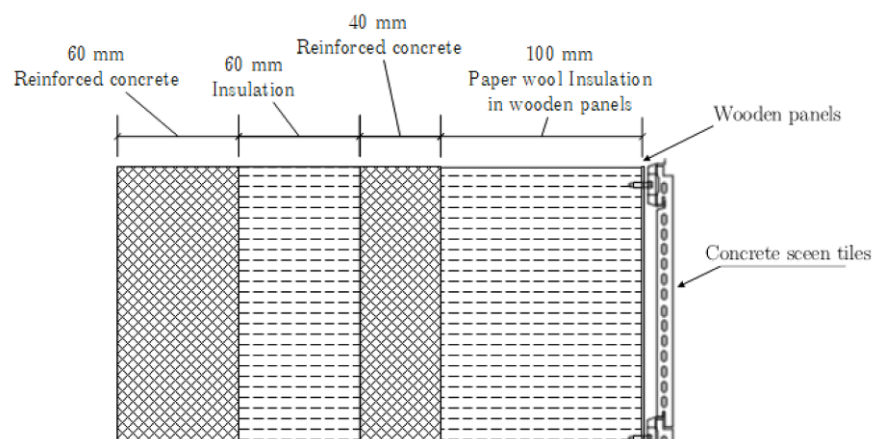


Figure 11. Wall construction after renovation.

Similar to the actual renovation, the five top ranked scenarios found with the DSS all suggest applying exterior insulation on the walls. However, 150 mm insulation with a 15 mm plastering finish is suggested by the two top-ranked scenarios in the DSS (marked with a blue dot in Figure 9). The DSS only evaluate the scenarios based on the three implemented criteria. The finish will, therefore, be evaluated based on the thermal influence affecting the investment cost, energy consumption, and thermal comfort, although the finish may often be chosen based on aesthetics instead of the thermal quality. The DSS has therefore favored the cheap finish which is illustrated in Figure 12.

The top two ranked scenarios (marked blue and yellow dots in Figure 9) both propose the wall renovation presented in Figure 12. The remaining three (marked only yellow dots in Figure 9) considered scenarios all consist of applying additional external insulation on the walls. The amount, however, varies between 100 mm to 220 mm, and the finish consists of plastering, plaster boards, or stainless steel trapeze plates, which are the three cheapest wall finish alternatives in the database.

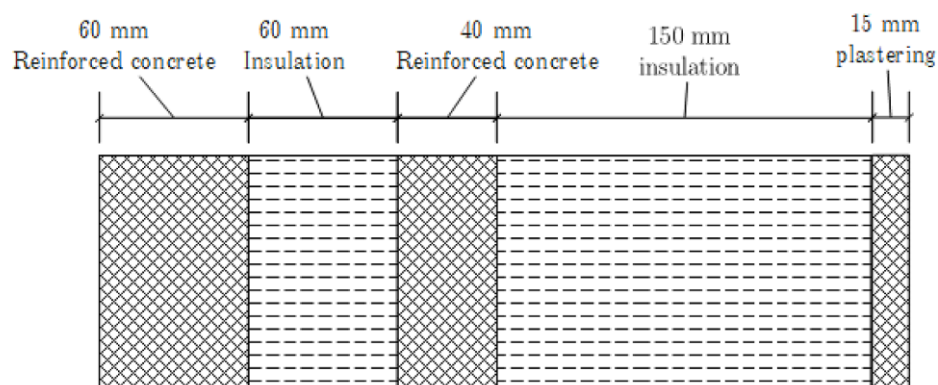


Figure 12. Proposed wall construction for renovation.

4.6.2. Roof

All roofs have been renovated, with additional external insulation. The existing roof before renovation consisted of a 120 mm concrete slab, on top of which a layer of averagely 200 mm puffed clay nuts creating a slope for drainage, and subsequently a 50 mm screed concrete layer finished with 10–20 mm roofing felt, as illustrated in Figure 13. The combined U-value of the reference roof is calculated to 0.41 m²K/W, compared with the maximum allowed U-value of roofs of 0.1 m²K/W today cf. [50]. Perhaps, based on this indication, the renovation description describes that additional, wedge-shaped pressure resistant insulation with a maximum combined U-value of 0.1 m²K/W must be added on the roof as illustrated in Figure 13.

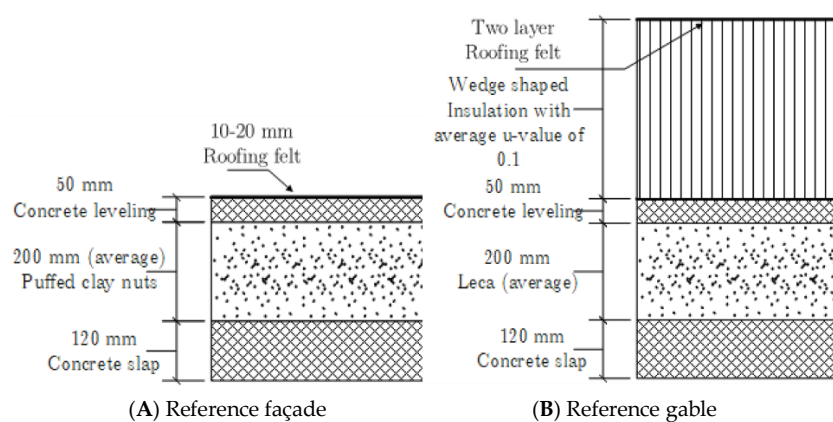


Figure 13. Roof before and after renovation.

Exterior additional insulation is, however, not included in the database, as different roof types may not allow it unless the existing finish is removed, re-attached, and re-placed. This could obviously be implemented in the database, and the corresponding U-value of the new wall constructed could be calculated in the DSS. As exterior roof insulation is not included in the current database, and only renovation alternatives for internal roof insulation with new finishes are considered in the proposed renovation scenarios. The amount of interior insulation varies between 125 and 200 mm for the five top-ranked renovation scenarios. All of them are finished with two layers of plasterboards (as shown in Figure 14), which is the cheapest interior roof finish alternative in the database. The scenarios with the best average rank in the Monto Carlo simulation are presented in Figure 14, with 125 mm. internal insulation and two plasterboards as a finish. However, these scenarios did receive worse ranks with certain criteria weights than the same scenarios only differentiated on applying 200 mm interior roof insulation.

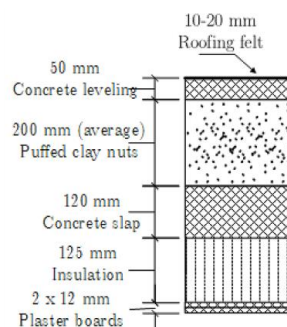


Figure 14. Proposed roof construction for renovation.

4.6.3. Windows

No data on the thermal performance of the existing windows have been obtained for this case study. Therefore, typical values for windows have been collected for apartment buildings built between 1961 and 1972. These windows typically consist of a wooden frame with thermal glazing; the U-value is then approximately 2.7 and G-value is 0.76, according to [51]. However, no thermal data on the light transmittance, line loss, etc., is provided. Therefore, these values are estimated as input in ICEbear, to obtain a combined U-value of approximately 2.7. The renovation of actual project consisted of replacement of the old windows and installing new windows in the gables. In addition, some of the balconies were closed off with new windows, and the living rooms were extended to include the old balcony. Other balconies were just extended out from the facade. These possibilities are not included in the database and were therefore not proposed in the top-ranked scenarios. Four out of five proposed renovation scenarios suggest replacing the existing windows with new three-layer glazed windows with a plastic frame. The fifth proposed scenario also suggests replacing the windows with three layer glazed windows with wood/aluminum frames.

4.6.4. Overall Comparison

Table 6 represents the differences in renovation alternatives between the real project and the scenarios proposed by the DSS. Since no information has been collected on the previous along with the renovated windows, the windows are not included in the comparison table.

Table 6. The comparison of the real and generated scenarios in this paper.

		Actual Scenario	Generated Scenarios
Wall	Additional insulation	100 mm	100–220 mm
	Finish	Concrete screen tiles	Plastering, plaster boards, and stainless-steel trapeze plates
Roof	Additional insulation	~370 mm	125 mm
	Finish	External roofing felt	Internal plaster boards
Floor		-	-
Window		-	-

Some similarities are seen from the comparison. For example, the best performing renovation scenarios all propose not to renovate the floor. However, the amount of insulation varies between the actual renovation and the proposed.

Differences in the finishes are seen, due to the variation in priorities between the actual renovation, in which quality and image might have been in focus, and the DSS aims at producing the cheapest alternatives.

The number of criteria are influencing the results, and by adding more criteria the results will vary. However, even though only three criteria are implemented, it is possible to see how thermal comfort affects the outcomes.

5. Conclusions Further Studies

5.1. Conclusions

The application of methodologies and methods in the early design stages for interdisciplinary collaborations in renovation projects plays a significant role in coping with the multiple criteria, i.e., energy efficiency and indoor comfort, together with the existing interactions and trade-offs between them. The aim of this paper was to further develop and test a hybrid DSS for generation of holistic renovation scenarios that can be used by different stakeholders, particularly architects and consultant corporations in the early design stages of renovation projects. The application of such a tool can help to reduce the decision-making period [significantly], improve the accuracy and quality of the final decision, and encourage stakeholders to accommodate holistic renovation scenarios. To this end, this paper took offset in a multi-methodology for building renovation called HMSR. It provided information about both the notion of a sustainable renovation together with various renovation approaches. As well, it discussed the mechanism and development of the DSS using various MCDMs and GAs. The product is a hybrid DSS that can be used for generation of holistic renovation scenarios, encompassing *Energy Consumption*, *Investment Cost*, and *Thermal Indoor Comfort*.

The major issues in the developed DSS for generation of holistic renovation scenarios were how to combine the renovation alternatives and how to take into account the interactions and trade-offs between different performance criteria, when the scenarios are being generated. The use of GA demonstrated in this paper seems complicated to implement but a useful approach for combining the renovation alternatives to generate the countless number of scenarios that obviously the human brain is incapable of processing. Nevertheless, much attention is still required about the type of the algorithm and the time it needs to generate and extract the scenarios. In addition, the application of the ICEbear for simulations, together with the Pareto-front approach for addressing the trade-offs, was considered a useful approach. It seems like MCDM methods are valuable to rank and address conflicting criteria, but this study indicates that several MADM methods should be used for cross-validating the ranking—which similar studies also have concluded [41].

For further verification of the outcome, the developed hybrid DSS was applied to an actual [recently] renovated dwelling. The studied case demonstrated that a proper renovation of the building envelope could result in reducing the energy consumption. Moreover, it was observed that how renovation effects the improvement of the indoor comfort linking to the occupants' satisfaction and thus can be considered as added-value to the building. Although the DSS has been developed for the renovation of dwellings/residential buildings, the flexible employed database can be used and expanded further to include more renovation approaches and parameters to be applied for other i.e., offices or commercial buildings.

5.2. Further Studies

Future study concerns the embracing of further soft criteria, i.e., the health or aesthetic effectiveness of each renovation scenario, to contribute towards more sustainable development. In addition, there is significant potential to extend and implement the outcome of this paper into the Building Information Modelling—BIM [52,53] (see 'C' in Figure 4). The results that are informed and updated on the BIM model can be used further to visualize alterations and also to identify any potential design issues in the very early design stage of renovation projects.

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Appendix

Figures A1 and A2 represent the database of alternative renovation approaches, which have been used for generations of holistic renovation scenarios.

		Cost	Thickness	Lambda	U-Value	Resistance
		Kr./m2	mm	W/mK	W/m2K	m2K/W
A	Facade (External)					
A.a	Re-Insulation					
A.a.1	Insulation (Class 37) - 30 mm	556	30	0.037	1.233	0.811
A.a.2	Insulation (Class 37) - 80 mm	716	80	0.037	0.463	2.162
A.a.3	Insulation (Class 37) - 100 mm	780	100	0.037	0.370	2.703
A.a.4	Insulation (Class 37) - 125 mm	860	125	0.037	0.296	3.378
A.a.5	Insulation (Class 37) - 150 mm	940	150	0.037	0.247	4.054
A.a.6	Insulation (Class 37) - 200 mm	1100	200	0.037	0.185	5.405
A.a.7	Insulation (Class 37) - 220 mm	1164	220	0.037	0.168	5.946
A.a.8	Insulation (Class 37) - 250 mm	1260	250	0.037	0.148	6.757
A.b	Finish					
A.b.1	Brick	358	108	0.600	5.556	0.180
A.b.2	Plaster	90	15	0.800	53.333	0.019
A.b.3	Plasterboard	85	25	0.250	10.000	0.100
A.b.4	Wood	261	22	0.150	6.818	0.147
A.b.5	Cement Fibre Plates	335	13	2.000	153.846	0.007
A.b.6	Stainless Steel Trapez Plates	130	1	17.000	17.000.000	0.000
A.b.7	Copper Plates	5000	4	380.000	95.000.000	0.000
B	Facade (Internal)					
B.a	Re-Insulation					
B.a.1	Insulation (Class 37) - 30 mm	556	30	0.037	1.233	0.811
B.a.2	Insulation (Class 37) - 80 mm	716	80	0.037	0.463	2.162
B.a.3	Insulation (Class 37) - 100 mm	780	100	0.037	0.370	2.703
B.a.4	Insulation (Class 37) - 125 mm	860	125	0.037	0.296	3.378
B.b	Finish					
B.b.2	Plaster	90	15	0.800	53.333	0.019
B.b.3	Plasterboard	85	25	0.250	10.000	0.100
C	New Wall Construction					
C.a	Complete Walls					
C.a.1	Light concrete wall, 450mm, (LECA thermal blocks)	1160	450	0.06	0.140	7.143
C.a.2	Light concrete wall, 350mm, (LECA thermal blocks)	915	350	0.11	0.310	3.226
C.a.3	Steel wall, steel/facade(80)/plasterboard(31)/ins(245)/plasterboard(15)/ins(95)/plasterboard(15)	2851	482	0.07	0.140	7.143
C.a.4	Concrete facade element, prefabricated, concrete(150)/ins(225)/concrete(80)	2080	455	0.06	0.140	7.143
C.a.5	Concrete facade element, concrete(60)/ins(370)/plaster(10)	2200	370	0.04	0.120	8.333
C.a.6	Brick wall, Brick(108)/insulation(190)/brick(108)/plaster(10)	2319	416	0.07	0.160	6.250
C.a.7	Brick wall, Brick(108)/insulation(250)/brick(108)/plaster(10)	2278	478	0.06	0.130	7.692
C.a.8	Wood wall, plasterboard(13)/wood(25)/iso(95)/iso(95)/wood(25)/wood(22)/wood molding(9)	1780	295	0.06	0.200	5.000
C.a.9	Wood wall, plasterboard(13)/wood(25)/iso(120)/iso(95)/wood(25)/wood(22)/wood molding(9)	1813	320	0.06	0.180	5.556
D	Roof (Inside)					
D.a	Re-Insulation					
D.a.1	Insulation (Class 37) - 30 mm	556	30	0.037	1.233	0.811
D.a.2	Insulation (Class 37) - 80 mm	716	80	0.037	0.463	2.162
D.a.3	Insulation (Class 37) - 100 mm	780	100	0.037	0.370	2.703
D.a.4	Insulation (Class 37) - 125 mm	860	125	0.037	0.296	3.378
D.a.5	Insulation (Class 37) - 150 mm	940	150	0.037	0.247	4.054
D.a.6	Insulation (Class 37) - 200 mm	1100	200	0.037	0.185	5.405
D.b	Finish					
D.b.1	Plasterboard	85	25	0.250	10.000	0.100
D.b.2	Wood	261	22	0.150	6.818	0.147
D.b.3	Cement-Bond Wood Wool Plates	150	26	0.076	2.923	0.342
E	Roof (Outside)					
E.a	Finish					
E.a.1	Concrete tile	493	50	1.5	30.000	0.033
E.a.2	Red tile	608	50	1	20.000	0.050
E.a.3	Steel	473	15	17	1.133.333	0.001
E.a.4	Plywood	196	20	0.15	7.500	0.133
F	Floor (Inside)					
F.a	Finish					
F.a.1	Laminate	525	11	0.11	10.000	0.100
F.a.2	Beech planks on joists, joists(47x50), iso(45), planks(22)	862	69	1.53	22.174	0.045
F.a.3	Untreated slats	883	70	1.56	22.286	0.045
F.a.4	Treated slats	943	70	1.56	22.286	0.045

Figure A1. The database used for generation of renovation scenarios.

	Windows	Cost	Type	d	Ug	gg	LTg	?	Uf
	Glazing Type	Kr./m2		m	m2K/W				
1	I.a.1	1500	VELFAC Classic Træ A	0.093	0.53	0.53	0.74	0.02	1.300.198
2	I.a.2	1412	VELFAC Energy 200	0.054	0.53	0.53	0.74	0.033	1.822.852
3	I.a.3	1324	VELFAC Energy 200 Opt.	0.054	0.55	0.61	0.75	0.033	1.842.852
4	I.a.4	1236	Rolfsted Glas 3 Lags Træ/Alu	0.093	0.61	0.54	0.63	0.037	1.249.649
5	I.a.5	1148	Schüco	0.093	0.63	0.61	0.73	0.01	1.616.129
6	I.a.6	1060	Hvidbjerg Everluxx Classic	0.093	0.64	0.53	0.74	0.01	131.592
7	I.a.7	972	VELFAC Classic Træ B	0.093	1.21	0.73	0.82	0.02	1.359.779
8	I.a.8	884	Futura + I 28	0.054	1.21	0.73	0.82	0.01	2.133.748

Figure A2. The windows database used for renovation scenarios.

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