“Towards a Greener Campus: A Comprehensive Evaluation of Sustainable Building Renovations through Multi-Actor Multi-Criteria Analysis.”

Master Thesis

By

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Abstract

This thesis investigates sustainable renovation alternatives for campus buildings at TU Delft, aiming to contribute to the university's sustainability goals and promote energy-efficient building renovation solutions. The study uses a Multi-Actor Multi Criteria Analysis (MAMCA) framework to evaluate two main alternatives: the implementation of a green roof and an energy efficiency upgrade (EER) project. Stakeholder engagement and analysis is an important aspect of the research, with input gathered from a variety of campus users, including academics, students and Campus Real Estate & Facility Management (CREFM). The criteria considered in the evaluation include environmental, social, economic and technical dimensions, reflecting the multifaceted nature of sustainability. Subsequently, sensitivity analysis are conducted to assess the impact of different stakeholders' preferences on the ranking of alternatives, thus exploring possible trade-offs and aligned views. The results show that green roofs perform favorably on most criteria, particularly in promoting biodiversity, preserving habitats and producing sustainable energy. Despite the challenges posed by limited data availability and stakeholder response rates, this research introduced an effective decision-making framework based on the inclusion of stakeholders and concluded that the multiple interests of different stakeholders can significantly influence the decision making process in sustainable renovations.

Executive Summary

Introduction

Since buildings in the EU contribute to 40% of the total energy consumption and 36% of the overall greenhouse gas emissions, as stated by the European Commission, renovating existing buildings is crucial for reducing energy consumption and greenhouse gas emissions, with studies indicating that this could significantly decrease the EU's overall energy usage and mitigate carbon dioxide emissions.

This research investigates sustainable renovation alternatives for the TU Delft campus buildings through a Multi-Actor Multi Criteria Analysis (MAMCA) framework. The study engages stakeholders from diverse backgrounds, including members from the Campus Real Estate and Facility Management (CREFM) department, Academics & teaching staff and Students, to evaluate and prioritize two renovation options (Green Roofs and Energy Efficiency Retrofit project) based on environmental, social, economic and technical criteria. The research aims to provide insights into the decision-making process for sustainable building renovations and promote inclusive, stakeholder-driven approaches to campus sustainability.

Methodology

The methodology includes a comprehensive literature review, stakeholder analysis and the application of the MAMCA method by engaging the Best-Worst Method (BWM) to assess stakeholder preferences and assigning weights to the criteria, and then the Weighted Sum Model (WSM) method to prioritize renovation alternatives. Stakeholders participate in weighting criteria by giving their unique perspective as campus users given their particular priorities and interests. The criteria include indicators from multiple sustainability dimensions, such as Energy efficiency, CO_2 reduction, Campus User Satisfaction, Cultural Heritage, Innovation and Renovation Costs.

Results

The results highlight the varied preferences of stakeholders and reveal the trade-offs between the different renovation options. Of the alternatives considered, green roofs are emerging as the most preferred alternative, offering environmental benefits such as CO_2 reduction, biodiversity promotion, lower renovation costs and aesthetics. However, the Energy Efficiency Upgrade (EER) project also demonstrates strong performance, particularly in terms of energy efficiency and promoting renewable energy. By performing sensitivity analysis the impact of stakeholder preferences on alternative classifications was further explored, emphasizing the importance of inclusive decision-making processes in complex sustainability contexts.

Conclusions

It was concluded that differences in criteria weightings reflects the diverse interests of stakeholders and highlights the importance of balancing environmental, social, economic but also technical considerations in the decision-making process. In addition to that, the inclusion of stakeholders with multiple perspectives can influence the decision making process in sustainable renovations. Lastly, the MAMCA method provided a structured framework for evaluating alternative renovation strategies, allowing the stakeholders to express their preferences and priorities by ranking the selected criteria.

Limitations & Recommendations

The findings suggest the need for inclusive decision making regarding renovation strategies that align with stakeholder priorities and campus sustainability goals. The limitations of this particular research are mostly related to the limited sample of participants and the lack of a real-life case study within the TU Delft campus to apply this research framework. Recommendations for future research include standardizing and automating the MAMCA framework to facilitate decision-making processes for sustainable building renovations. By incorporating different stakeholder perspectives and including various sustainability criteria, TU Delft can further enhance its commitment to sustainable goals and create a more sustainable campus for its current and future users.

Contents

1. Introduction

According to the European Commission (2020), buildings within the EU are accountable for 40% of the total energy consumption and 36% of the overall greenhouse gas emissions. The construction of energy neutral buildings has become particularly popular in recent years, with various research being conducted into the most energy efficient and circular construction methods. However, constructing a new building would result in three times more CO2-eq emissions compared to renovating an existing, well-functioning building (Blom and Dobbelsteen, 2019). Moreover, renovating current buildings could decrease the EU's overall energy usage by 5-6% and mitigate carbon dioxide emissions by approximately 5% (European Commision, 2020). Consequently, the need to increase renovation projects can be considered imperative.

University institutions are also striving towards sustainability and minimizing CO-2 emissions. According to Dobbelsteen and Gameren (2020), TU Delft is committed to the strategic goal of being completely energy neutral by 2030, investing considerable resources in the renovation and sustainable transformation of the university's existing buildings.

1.1. Problem Statement

Although sustainable renovations are particularly important for achieving the European targets for energy neutral buildings by 2030 and would have a significant impact on the energy performance of buildings, less than 1% of European buildings are renovated annually at a national level (European Commission, 2020). This fact highlights the need for further scientific research on sustainable building renovation practices, as well as the decision making processes surrounding it. Especially in the context of university institutions, scientific research on sustainable renovations is even more limited, despite the significant complexity of these buildings due to their multiple users and increased energy requirements.

Regarding the decision-making methods for sustainable renovations, an emphasis solely on environmental criteria is often observed, sometimes accompanied by an economic evaluation of the proposed solutions (Jensen et al., 2018). Therefore, Jensen et al. (2018) highlighted that there is an imperative need for developing more comprehensive methods of prioritizing and evaluating sustainable building renovations. While methods such as Life-Cycle Assessment (LCA) and Life-Cycle Cost (LCC), which cover environmental and economic aspects respectively have already been established, the social aspects in sustainable building renovations are not widely researched and successfully integrated into the decision making process (Jensen et al., 2018).

1.2. Relevant Literature

In order to investigate relevant research that has been carried out in the field of sustainable renovations and specifically in the respective decision-making methods, a search was carried out on the Google Scholar and Scopus citation databases, with the following keywords: "Sustainable Renovations", "Decision making" and "Multi-Criteria Analysis". As a result, several relevant articles were identified, some of which are summarized below.

Jensen et al. (2018) conducted a literature review on sustainable building renovations, with the goal of identifying key strengths and weaknesses, as well as gaps for future research. His findings primarily focuses on the limited availability of scientific research on developing productive and effective renovation strategies and holistic decision making processes. Moreover, his research pointed out that social sustainability is the least well-defined pillar of sustainability. On the other hand, Estévez et al. (2021), employed a Multi-Criteria Decision Analysis (MCDA) to evaluate renewable energy projects by only focusing on the social aspects and stakeholder participation. In this way, the authors tried to explore MCDA's potential to provide inclusive and transparent results by involving multiple stakeholders' values.

Sánchez-Garrido et al. (2022) outlined a methodology to evaluate the sustainability of four different design options for concrete structures by applying five commonly used MCA techniques. In this case, the MCA aimed at calculating a sustainability score which was derived by the life cycle performance of each of the design options. Dijkstra (2013), performed a comparison analysis of three different renovation concepts for Dutch buildings, by focusing on environmental and economic key performance indicators based on the Life-Cycle Assessment and Life-Cycle Cost methods.

Nielsen et al. (2016) provided an overview of the decision support tools for sustainable building renovations that can be used in early phases (pre-design and design). The findings indicated that environmental criteria were included in 81% of these tools, economic in 72% of them, while 63% of the tools included social criteria. Lastly, sustainability of campus universities specifically, has been assessed by Kesten Erhart et al. (2016), who focused on efficient solutions for ventilation and lightning systems to retrofit the campus buildings of the University of Applied Sciences Stuttgart.

It is clear, therefore, that there is a gap in the current literature regarding the inclusion of multiple criteria and stakeholder inputs in decision making for sustainable renovations. Most articles focus on environmental and economic factors, while articles that include social factors tend to focus primarily or even exclusively on social impacts. Moreover, the sustainable renovations specifically in university campuses is a field of research which, despite its complexity, has not been researched significantly, especially at the level of decision-making.

1.3. Research Question & Sub-questions

Having identified the problem statement and the research gap in this study, the main research question and the subsequent sub-questions can then be formulated. Consequently, the main research question is formulated as follows:

What are the most optimal sustainable building renovation measures for TU Delft campus, taking into account both environmental, economic, social and technical criteria and while also incorporating various stakeholders' perspectives?

To simplify the main research question, the following research sub-questions will also be researched and answered:

1. Which evaluation criteria and Key Performance Indicators are considered the most relevant for sustainable renovation, according to academic literature?
2. What are the current evaluation methods for selecting the optimal sustainable renovation measures that have been proposed or tested in academic literature?
3. Who are the stakeholders involved in the sustainable transition of the TU Delft campus and what are their particular interests?
4. What are the different perceptions among the involved stakeholders, regarding the importance of each criterion?
5. How does the rankings of sustainable building renovations change with variations in the weights assigned to the environmental, economic, social, and technical criteria?

2. Literature Review

2.1. Introduction

In this chapter the relevant research concepts will be explored through a literature review. Upon completion of this chapter, it is expected that the first two research sub-questions will be effectively addressed.

The definition of sustainable building renovations is provided in the first section of the literature review, as well as cited examples from recent research papers. The second part includes an elaboration of the commonly used methods of evaluation and selection of sustainable renovation measures. The Life Cycle Assessment and Life Cycle Costing methods are considered some of the most frequently used and well established assessment methods (Jensen et al., 2018), and therefore they will be analyzed in separate subsections. In addition, the most commonly used evaluation methods based on the results from a search conducted in Scopus will be analyzed. The third and final part of the literature review is an investigation of the most commonly used Key Performance Indicators (KPI's) for sustainable renovations. The KPI's to be used in this study will be derived from a combination of relevant literature findings, TU Delft's already established KPIs for the sustainable transition of the campus, but also the inputs of the stakeholders involved. In this way, comprehensive criteria will be formulated, against which the alternatives will be compared in this proposed MAMCA method.

2.2. Sustainable Building Renovations

By definition, the term sustainable renovations is referred to by Thuvander et al. (2012) as the objective of achieving the environmental, social and economic dimensions of sustainability through the implementation of changes in buildings. According to a European research carried out in three European countries, the reasons for which renovations are usually carried out, mainly concern energy savings in terms of environmental impact, and cost reduction in terms of economics. Beyond these two main pillars, such interventions may also relate to improving the physical condition of the buildings such as moisture, degradation or simply maintenance, but also reasons related to indoor air quality and comfort. Finally, the aesthetic factors were also noteworthy, as well as branding or corporate social responsibility reasons (Jensen et al., 2018(2)).

Since this research examines decision-making around sustainable renovations, the following subsections will outline the most common assessment methods of building renovations, across all the sustainability pillars.

2.3. Evaluation Methods

Based on the findings mentioned in Subchapter 1.2., a particularly important research area around sustainable renovations, but also the main focus of this research is the decision-making methods and evaluation of sustainable renovation practices.

For the optimal interpretation and selection of the most frequently used evaluation methods, which will be analyzed in the following sub-chapters, a search was carried out in the research engine Scopus with the keywords "Decision-Making" and "Sustainable Renovation". The search filters indicated that both terms should be included in the results, but also that the timeframe should only include results from the last decade, i.e. from 2013 to present.

The results of this search showed that there are 50 relevant articles, which, among others, include the following keywords:

- Multi-Criteria Analysis in 12 articles with the keywords varying in Multicriteria Analysis, Multi-criteria Decision Making, and Multiple Criteria Decision Making
- Cost-Benefit Analysis in 6 articles
- Life-Cycle Analysis/Assessment in 5 articles
- Building Information Modeling (BIM) in 3 articles.
- Life-Cycle Thinking in 3 articles, and
- Life-Cycle Cost in 3 articles.

Consequently, the above methods will be extensively defined and analyzed, as some of the most prevalent evaluation and decision-making methods in the field of sustainable renovations, in the last decade.

2.3.1. Multi-Criteria Analysis (MCA)

Multi-Criteria Analysis (MCA) encompasses a variety of methodologies and tools that take into account multiple criteria when addressing problems involving decision-making (Dean, 2020). One of the main advantages of MCA is its ability to incorporate various relevant criteria, even when these criteria are not directly associated with financial implications (Nijkamp and van Delft, 1977). Consequently, as found in the results of the search, MCA is a popular method of comparing and evaluating sustainable renovations, through incorporating multiple criteria, both environmental, economic and social, and providing a multidimensional analysis to the decision-making process.

The MCA methods that can be used are diverse and differ according to each decision-making problem. These methods can be used either individually or in combination for the best utilization of the characteristics of each method towards the most accurate results. A typical example of this is the research conducted by Seddiki and Bennadji (2019), where several multi-criteria methods were combined in their study for the selection of the optimal renewable energy source for generating electricity. The Delphi approach was first used to develop an initial set of alternatives and criteria including economic, environmental, and social considerations, among others. A questionnaire survey is then carried out to assess the perspectives of residential buildings' occupants regarding these renewable energy options, followed by the Fuzzy Analytical Hierarchy Process (FAHP) which was used to determine the weights of the criteria. Lastly, a full ranking of the renewable energy options is obtained, using the Fuzzy Preference Ranking Organization Method for Enrichment Evaluation (FPROMETHEE) ranking method (Seddiki, M., and Bennadji, A., 2019).

In another research study, Serrano-Jiménez et al. (2021) presented a decision support method for the most effective determination of the optimal renovation strategy, through a combination of MCA based on ten renovation factors and a financial feasibility analysis based on the Net Present Value (NPV) index. The difference of this research lies in the emphasis given to the multifaceted impact of the processes of each strategic renovation in different time frames (during, but also after the renovation), and not simply in the evaluation of the renovation proposal (Serrano-Jiménez et al., 2021).

2.3.2. Cost-Benefit Analysis (CBA)

Cost-Benefit Analysis (CBA) is a policy evaluation method used to assign monetary values to a policy's outcomes, considering its overall effects on the individuals within a society as a whole (Boardman et al., 2017). In the field of sustainable renovations, CBA was used by Šuman et al. (2020) who proposed a framework for the sustainable renovation of existing workplaces, employing both a CBA and a green building grading system. The steps in this proposed framework included data gathering, determining the required renovation extent, choosing the green building grading system, identifying the impact categories and criteria, and lastly the final assessment through CBA (Šuman et al., 2020).

In another study carried out by Mahlia et al. (2005), a CBA was performed along with a calculation of electricity savings and reduction of emissions for lighting upgrades in Malaysian residential buildings. The aim of this research was to convince policy makers to adopt this method in the attempt to reduce the residential sector's ever-growing electricity consumptions (Mahlia et al., 2005).

A key limitation of CBA, which was pointed out in another research by Becchio et al. (2021), is the fact that it monetizes all the parameters of the analysis, which might lead to inaccurate conclusions.

For this reason, the authors in their research tried to fill the gap created by CBA, by incorporating an MCA and a CBA in a new, integrated assessment framework called COMpoSIte Modeling Assessment (COSIMA). In this context, they proposed the calculation of the Net Present Value (NPV), Internal Rate of Return (IRR) and Benefit-Cost Ratio indicators as part of CBA, and aggregated values as part of MCA. By merging the results of each analysis, the calculation of the Total Rate of Return (TRR) index is then proposed, according to the COSIMA framework (Becchio et al., 2021).

2.3.3. Life-Cycle Assessment (LCA)

Life cycle assessment (LCA) is defined, according to Finnveden & Potting (2014), as a comprehensive method of evaluating the environmental impact of a product throughout its life cycle. This life cycle can start from the acquisition of the resources for its production or construction, and extend up to the management of the waste generated from it. Specifically for buildings, Jensen et al. (2018) pointed out that LCA is one of the most widely recognized methods for evaluating the environmental performance of buildings, at a research level.

A study conducted by Menna et al., (2021) proposes a method for performing life cycle assessment (LCA) of building renovation projects, but also a comparative assessment of renovation versus new construction. This method has been tested through a case study, which demonstrated that the renovation scenario resulted in environmental impact reductions of 53%-75% in six categories, compared to the new construction scenario.

Many times it has been observed to use the LCA in combination with the Life-Cycle Cost (LCC) method, which will be analyzed below, with the aim of ensuring a more comprehensive evaluation. For example, Moschetti and Brattebø, (2017), combined the LCA and LCC methods to evaluate an energy renovation project in Norway, by using environmental and economic evaluation indicators related to the life cycle of the project. In this particular case, their findings indicated that the environmental impact and the economic impact have an almost inversely proportional course. This means that in the scenarios where the environmental performance was higher, the economic performance would be lower, albeit on a much smaller scale in relation to the environmental benefits of the optimal scenarios.

2.3.4. Life-Cycle Cost (LCC)

Thollander et al., (2020) referred to the Life-Cycle Cost (LCC) method as an investment assessment which takes into consideration all the expenditures incurred over the investment's full life cycle.

Consequently, LCC, like LCA, was considered equally important by many researchers in the evaluation of sustainable renovations.

Sharif and Hammad (2019) investigated several scenarios in an effort to identify the optimal scenario for the renovation of an institutional building, through a combination of LCC and LCA methods. In their research, they pointed out that there is a significant correlation between materials that provide greater energy efficiency, and life-cycle costs, with the researchers highlighting the importance of finding a balance between costs and environmental sustainability.

Xue (2021) carried out a qualitative analysis in which the incremental life-cycle costs of existing buildings related to energy savings in four stages of the buildings were analyzed. Then, the author also analyzed the corresponding additive life-cycle benefits and introduced indicators such as Net Present Value and Payback Period for the application of a cost-benefit analysis. The aim of this research was to educate stakeholders in renovation projects about the relevant influencing elements.

2.3.5. Building Information Modelling (BIM)

According to ISO 29481-1:2010(E), Building Information Modelling (BIM) is defined as a digital model that can capture both the physical and functional aspects of any constructed object and can be used as a reliable reference point for decision-making. According to a Master Thesis carried out by Gökgür (2015), BIM in renovation projects can be effectively utilized for visualization and prototyping purposes, but it can also facilitate energy simulation and collaboration between different stakeholders with varying levels of knowledge and interests. Gholami et al. (2015) pointed out some of the benefits of using BIM for the retrofitting of existing buildings, which are mostly related to the creation of alternative building prototypes that can be compared among themselves in terms of their energy performance but also the cost. Moreover, the clash detection technique enables the identification of interferences between different parts of the buildings, which can minimize the construction cost and facilitate the coordination of all retrofitting processes.

However, according to the research conducted by Gökgür (2015), BIM seems to be used much more in new construction rather than in renovation projects. One of the primary reasons is that in the case of new construction, BIM provides significantly more freedom in creating entirely new designs, as opposed to renovation projects where existing structural elements can be restrictive. Thus, even though the possibilities of using BIM are multiple, it does not seem to be preferred in renovation projects.

Despite this, there are some studies that have focused on the use of BIM in the field of renovations of existing buildings, with the aim of enhancing their sustainability. Kamari et al., (2021) proposed a methodology for the development of the PARADIS system, which is a BIM-based decision support system capable of evaluating as well as generating optimal renovation scenarios. This system can also evaluate these alternatives against a set of sustainable KPIs, as well as visualize them, enhancing transparency in the decision-making process. Furthermore, Stegnar and Cerovšek (2019), presented a progressive BIM methodology which involves the determination of specific information to match the evolving design process of renovations. This methodology has been tested in the renovation of office buildings and has been shown to provide more accurate predictions of energy consumption, reduce both costs and construction times, as well as prevent errors in the planning and design phases.

2.3.6. Life-Cycle Thinking (LCT)

The term "Life Cycle Thinking" (LCT) refers to an approach that considers both financial, environmental, and social effects of a process or product throughout the course of its whole life (Jacob-Lopes et al., 2021). The LCT approach has also been used in the construction sector, but also in the field of sustainable renovations specifically. For instance, Passoni et al. (2021) applied an entire life cycle (LC) framework for the selection of an optimal sustainable building renovation solution, aiming to minimize the financial, environmental, and social consequences in each LC phase. The authors performed a MCDM method for a particular case study building and the possible effects of each solution on the environment, economy, and society were qualitatively evaluated in regard to 14 criteria, which were classified in each phase of the building's life cycle.

In another related research, Passoni et al. (2022) pointed out that although innovative strategies have been developed that address the multifaceted demands of buildings, the principles of LCT are often ignored. Consequently, they propose a Life Cycle Structural Engineering (LCSE) strategy, in line with the principles of Life Cycle Thinking (LCT) with the ultimate goal of promoting a cross-disciplinary approach to building evaluation and retrofitting for building engineers (Passoni et al., 2022).

2.4. Key Performance Indicators & Criteria

According to Kylili et al. (2016), Key Performance Indicators (KPI's) are indicative means of not just reflecting the project's objectives, but also measuring the project's progress towards these objectives, thus facilitating further learning opportunities. This interpretation of the term KPI's differentiates them from the common criteria, which determine that something is good or acceptable, as long as it covers a set of criteria to some extent, and within a specific context (Sadler, 1985).

Various articles in the literature employed either KPI's or criteria for evaluating sustainable renovations, while some others followed a hierarchical approach by formulating broader criteria and then specifying KPI's through these criteria, as a subsequent level of evaluation (Moschetti et al., 2018).

In order to identify the most frequently used evaluation criteria and KPI's in the field of sustainable renovations, a search were carried out on Scopus and Google Scholar with the keywords "Sustainable Renovation", "Key Performance Indicators", "Criteria" and "Decision Making". From the articles that emerged in the results, the criteria related to spatial analysis or real estate indicators were excluded, as the renovations in the present research concern a university campus, where the renovated buildings are not meant to be sold or rented. The criteria identified below were based on 11 articles, one of which is the research conducted by Kylili et al. (2016), whose exclusive objective was the review of the KPI's in sustainable building renovations.

Table 1: Evaluation Criteria for Sustainable Renovation based on a literature review.

Category	Criteria	Reference
Environmental (5)	Energy efficiency/ Non-renewable energy demand/consumption / Energy Savings	Kamari et al. (2017); Moschetti et al. (2018); Kamari & Leslie Schultz (2022); Pinzon Amorocho & Hartmann (2022); Kylili et al. (2016)
	Material cycle & waste management / Reusability & Recyclability	Kamari et al. (2017); Passoni et al. (2021); Kylili et al. (2016)
	Water Efficiency/Consumption/Reuse	Kamari et al. (2017); Pinzon Amorocho & Hartmann (2022); Kylili et al. (2016)
	Pollution / CO_2 reduction / GHG emissions / Embodied Global Warming Potential (EGWP) reduction	Kamari et al. (2017); Seddiki & Bennadji (2019); Moschetti et al. (2018); Pinzon Amorocho & Hartmann (2022); Antonov et al. (2020); Kylili et al. (2016)
	Energy production	Seddiki & Bennadji (2019)
Social (10)	Identity / Architectural/Structure preservation / Cultural heritage	Kamari et al. (2017); Antonov et al. (2020); Pinzon Amorocho & Hartmann (2022); Kylili et al. (2016)
	Aesthetic	Kamari et al. (2017)
	Security / Health & Safety	Kamari et al. (2017); Kamari & Leslie Schultz (2022); Kylili et al. (2016)
	Innovation	Kamari et al. (2017); Kylili et al. (2016)
	Stakeholders Engagement & education	Kamari et al. (2017)
	Quality of Services	Kamari et al. (2017)
	Social acceptability/Perception / Degree of Satisfaction	Seddiki & Bennadji (2019); Kamari & Leslie Schultz (2022); Kylili et al. (2016)
	Inconvenience of the system	Seddiki & Bennadji (2019)
	Indoor Comfort (Thermal, Visual, Acoustic) / Indoor Air Quality /	Kamari et al. (2017); Moschetti et al. (2018); Kamari & Leslie Schultz (2022); Antonov et al.

		(2020); Pinzon Amorocho & Hartmann (2022); Kylili et al. (2016)
	Well-Being	Kamari & Leslie Schultz (2022)
Economic (9)	Investment cost / Price	Kamari et al. (2017); Seddiki & Bennadji (2019); Moschetti et al. (2018); Kamari & Leslie Schultz (2022); Pinzon Amorocho & Hartmann (2022); Antonov et al. (2020); Velykorusova et al. (2023); Passoni et al. (2021); Kylili et al. (2016)
	Operation & maintenance cost / Repair cost	Kamari et al. (2017); Seddiki & Bennadji (2019); Pinzon Amorocho & Hartmann (2022); Passoni et al. (2021)
	Payback Period	Kamari et al. (2017); Seddiki & Bennadji (2019); Antonov et al. (2020); Velykorusova et al. (2023)
	Net Present Value (NPV)	Kamari et al. (2017); Seddiki & Bennadji (2019); Becchio et al. (2021); Kylili et al. (2016)
	Internal rate of return (IRR)	Seddiki & Bennadji (2019); Becchio et al. (2021); Locurcio et al. (2022); Pinzon Amorocho & Hartmann (2022)
	Total life cycle costs	Moschetti et al. (2018); Pinzon Amorocho & Hartmann (2022); Antonov et al. (2020); Kylili et al. (2016)
	Benefit/Cost Ratio	Becchio et al. (2021)
	Return on Investment (ROI)	Locurcio et al. (2022)
	Energy Cost Savings	Pinzon Amorocho & Hartmann (2022)
Technical (7)	Flexibility & Management	Kamari et al. (2017); Kylili et al. (2016)
	Availability	Seddiki & Bennadji (2019)
	Efficiency / Functionality	Seddiki & Bennadji (2019); Kylili et al. (2016)
	Reliability / Durability	Seddiki & Bennadji (2019); Pinzon Amorocho & Hartmann (2022); Velykorusova et al. (2023)
	Renovation Duration	Antonov et al. (2020); Pinzon Amorocho & Hartmann (2022); Velykorusova et al. (2023); Passoni et al. (2021)
	Additional space needed around the building	Passoni et al. (2021)
	Fast Assembling/Disassembling	Passoni et al. (2021)

Table 1 illustrates the most frequently used criteria and KPI's for evaluating sustainable building renovation practices or measures, derived from a literature review. The criteria depicted in this table represent the most relevant ones of each study, taking into account the specifications of this particular research. Moreover, some criteria are clustered together, due to their close correlation or the similar definitions used by the researchers to describe them.

Out of the 31 criteria that were identified, a classification was carried out, based on which 10 criteria are related to social dimensions, 5 to environmental aspects, 9 to economic aspects and the remaining 7 concern technical factors. A remarkable finding is that the environmental criteria related to energy saving and energy efficiency, but also the criteria related to the reduction of CO_2 and GHG emissions, are included in 5 and 6 of the 10 articles studied, respectively. In addition, the economic criterion "Investment Cost" can be considered particularly important, as it was mentioned in 9 out of 10 articles. Among the categories of social and technical criteria, the most frequently addressed criteria are those related to indoor comfort and the duration of renovations, respectively.

2.5. Conclusions

In the literature review chapter, after the concept of sustainable renovations was initially explained, the focus was given to the exploration of the existing and widely used evaluation methods, which thoroughly answers the second sub-question of the present research. By analyzing the literature findings, it is observed that although there is a diverse range of methodologies with multiple areas of focus, there is no adequate research regarding the inclusion of relevant stakeholders in the decision-making process. Conducting a structured stakeholder analysis is particularly important due to the possible existence of conflicting interests among the stakeholders involved, but this is often neglected, and the emphasis is placed on other assessment dimensions, such as environmental and economic.

The next part of the literature review consists of the identification of the most frequently used KPI's and evaluation criteria in the field of sustainable renovations. Through analyzing 11 articles available in online citation databases, a total of 31 relevant KPI's and criteria were identified, which were categorized into 4 categories based on their characteristics. These criteria will be used to be grouped with the already defined KPI's of TU Delft for the renovation of existing campus buildings, but also to cover the aspects that have not been addressed by these KPI's. With the completion of this part of the literature review, the first sub-question of the research will also be successfully answered.

3. Methodology: Multi-Actor Multi-Criteria Analysis (MAMCA)

The present research aims to investigate the effectiveness of various sustainable renovation measures for university campuses, by focusing on buildings located in the TU Delft campus, in which the alternative sustainable renovation measures will be evaluated against several criteria, through a Multi-Actor Multi-Criteria Analysis (MAMCA). In a Multi-Criteria Analysis (MCA) problem, a number of choices are assessed against a variety of criteria to determine the optimal alternative (Rezaei, 2015). In a MAMCA, however, there is also the possibility of creating a framework by integrating the interests of the different stakeholders involved in the decision-making process (Macharis et al., 2012).

In this study a mixed method research approach will be employed to achieve the research objectives. The mixed method research is defined as the application of both qualitative and quantitative research methods in a study (Maxwell et al., 2003). The qualitative part of the research consists of conducting interviews and distributing questionnaires with representatives from each stakeholder group for the sustainable transition of the TU Delft campus. The quantitative part consists of the application of Multi-Actor Multi Criteria Analysis (MAMCA), with the application of the mathematical models of each selected Multi-Criteria methods.

The steps to be taken in order to answer the research questions are listed below and are divided into 5 phases: Identifying Alternatives & Criteria (Literature Review, TU Delft Strategic plan & Interviews), Assigning criteria weights (Application of the Best-Worst Method - Questionnaires), Assigning the scores of each alternative against each criterion (Literature Review), Application of the Multi-Criteria Weighted Sum Method and Sensitivity Analysis. These phases are analyzed and explained in detail below.

3.1. Research Phases

Phase 1: Identifying Alternatives & Criteria (Literature Review & TU Delft Strategic Goals)

The first step involves the identification of sustainable building renovations that will be used as alternatives in the MAMCA. For this purpose, several sustainable building renovation measures will be investigated and the most appropriate ones will be selected for application on the TU Delft campus. Then, a set of selected criteria will be formulated, which will be used to evaluate and therefore rank the alternative solutions. These variables will be determined both based on literature review and the strategic plan of TU Delft for sustainability by 2030.

Phase 2: Weighting (Questionnaires & BWM Method)

In the second stage, weights will be assigned to the evaluation criteria of each sustainable renovation. For this purpose, a hierarchical multi-criteria analysis will be used, which will allow the breakdown of the final objective into categories of criteria (environmental, economic, social, technical), then into criteria and then into pairwise comparisons between these criteria. Among the hierarchical MCA methods, the linear Best-Worst Method (BWM) will be chosen. According to Bafail and Abdulaal (2022), BWM provides more accurate results based on the consistency level, and requires fewer pairwise comparisons than the Analytic Hierarchy Process (AHP), which is also one of the most popular and widely used hierarchical MCA methods. The attribution of weights to the criteria will be done by distributing questionnaires in a BWM excel template format, where the decision makers will be asked to choose the most important and the least important criterion and then they will compare the remaining criteria based on these two. It is important at this stage to have stakeholders with different priorities, in order to formulate a multifaceted, comprehensive problem which will integrate different or even conflicting interests, with the ultimate goal of achieving the sustainable goals of TU Delft. At this stage, the second sub-question will be addressed.

Phase 3: Scoring (Literature Review)

The third phase is also the stage in which the alternatives are introduced. This phase will consist of a literature review to assign scores to both the quantitative and qualitative criteria. The qualitative criteria will mainly focus on assessing the impact of each alternative on social aspects, such as innovation, aesthetics, etc., which cannot easily be quantified or measured in specific units. Regarding the quantitative criteria, different quantitative scales will be used according to the type of each criterion, with the economic criteria being measured in monetary units, while the environmental ones in their corresponding measurement units. As the alternative sustainable renovations are likely to concern different parts of a building, comparisons will be conducted on a “per m^2” basis, for consistency reasons.

Phase 4: MCA Implementation (Weighted Sum Model)

Having formed a complete matrix that will reflect all the alternatives (sustainable building renovations), their evaluation criteria, the weights of the criteria and the performance of each alternative against each criterion, the fourth step involves performing the multi-criteria analysis. For this analysis, the weighted sum method (WSM) will be implemented, one of the most frequently used multi-criteria methods, which calculates the total score of an alternative by summing the performance of each alternative multiplied by their respective weights, which reflect the importance of each criterion (Mateo, 2012).

Phase 5: Sensitivity Analysis, Discussion & Conclusions

A sensitivity analysis in an MCA aims to determine how the ranking of alternatives will be affected when the input data (criteria weights) is altered to new values (Triantaphyllou et al., 1999). For this purpose, four additional MCAs will be carried out, with an emphasis on each group of stakeholders separately: Academics, Students and CREFM and thus four overall conclusions will be drawn. At this stage, the fifth and last research sub-question will be answered.

3.2. Expected Results

Having analyzed all the aspects of the present research at the literature review level, in this chapter the methodology will be developed with which the research goals that were initially set, will be addressed. More specifically, the Multi-Actor Multi-Criteria Analysis (MAMCA) will be used, which will include the identification of the stakeholder groups involved in the sustainable transition of the TU Delft campus, as well as their particular goals and interests.

The present study aims at creating an integrated decision making framework for the selection of the best sustainable renovations in existing buildings of the TU Delft campus. During the formulation of the MCA, different perspectives of the involved stakeholders will be considered, with the active participation of people from diverse departments within TU Delft in the decision-making process. In addition, the criteria identified in the literature review will be combined with the Key Performance Indicators set in the strategic plan of the TU Delft Campus for sustainable renovation of buildings, with the aim of shaping the final criteria that will be used in the MAMCA. Upon the completion of this chapter, the third research sub-question: "Who are the stakeholders involved in the sustainable transition of the TU Delft campus and what are their particular interests?" will have been fully answered.

Regarding the practical application of the research, this analysis will result in an overall ranking of the different strategies for sustainable renovation of buildings, but also four other rankings which will correspond to the cases where emphasis was placed on each stakeholder group separately. It is expected that the results will significantly help the decision-makers in prioritizing the appropriate sustainable renovation measures and proper allocation of the university resources to achieve timely and effective sustainable transformation of the campus buildings.

Lastly, the scientific relevance of the research is related to the integration of multiple criteria in decision-making on issues of sustainability and particularly sustainable renovation practices. The resulting framework will generate greater research interest to further explore integrated decision-making and combinations of existing assessment methods to achieve sustainable goals.

3.3. MAMCA Steps

Multi-Actor Multi-Criteria Analysis (MAMCA) can be considered a useful decision-making tool for assessing several alternatives, in cases where the existence of multiple stakeholders is crucial to the decision making process. In contrast to simple MCA, MAMCA provides the possibility to integrate the different or even conflicting interests of the different stakeholders involved in decision-making (Macharis et al., 2012). Therefore, a more thorough assessment and comparison of the alternatives can be achieved by MAMCA, through including stakeholders and taking into account their preferences and knowledge.

The following steps outline the sequential process in the implementation of this MAMCA method:

1. Stakeholder Analysis: This includes the identification of the stakeholder groups involved, including their particular goals and interests.
2. Formulation of the criteria: It includes the combination of the most frequently used criteria for sustainable renovations from the literature, with the KPI's set in the strategic goals of TU Delft.
3. Assigning weights to the criteria: Participants from each stakeholder group will be asked to assign weights to the criteria, using the Best-Worst Method (BWM) framework that will be given to them.
4. Identification of alternative solutions: In this stage two alternative renovation initiatives will be selected for comparison among themselves, based on the previously selected criteria.
5. Evaluation and Results: The alternatives selected in stage four (4) will be evaluated against each criterion selected in stage two (2), and eventually ranked through the Weighted Sum Model method.
6. Sensitivity Analysis: Following the results presentation, the weights will be changed in favor of each of the selected categories of stakeholders, with the aim of understanding the variability in the ranking of the alternatives, when the weights of the criteria change.

3.4. Stakeholder Analysis

In this chapter, a stakeholder analysis will be carried out, which aims to identify the different categories of campus users, who are either directly or indirectly involved in the decision-making process, but the results of the renovations may have a high impact on them. Stakeholder analysis is a fundamental part of MAMCA and will lay the foundation for a better understanding of the different interests and objectives of each stakeholder group, which will be expressed through the assignment of weights to the criteria. The categories that will be analyzed are all stakeholder groups that contributed to the formation of the sustainable action plan of TU Delft. For the needs of the research, three categories of stakeholders were selected among all the groups and departments that contributed to the development of this plan, which have either been directly involved in the implementation of the sustainable renovations, or constitute the largest share of campus users.

The following sub-chapters will investigate the various objectives and passions of the three primary stakeholder groups of Campus Real Estate & Facility Management (CREFM), Academics, and Students. Each category contributes its distinct viewpoint and focuses on its particular interests, while seeking alignment with the main objectives of sustainable campus development.

3.4.1. Campus Real Estate & Facility Management (CREFM)

The development and management of TU Delft's real estate, including its parks, offices, labs, and lecture halls, is handled by Campus Real Estate & Facility Management (CREFM) (University Corporate Office TU Delft, n.d.). The CRE department focuses on maximizing the use of space, improving the campus environment and maintaining the long-term value of the buildings. Their focus is on implementing improvements to the campus function and appearance, and their interests are consequently aligned with sustainability initiatives that enhance campus energy efficiency, space optimization and overall aesthetics. The questionnaire survey was sent to different members of the CREFM department, thus ensuring diverse perspectives within the same department, even though they represent the same department, due to the different focus of each member.

3.4.2. Academics

The academic staff is an integral part of TU Delft, as they aim to impart knowledge, inspire students and conduct valuable research. For these purposes, they are interested in creating an environment that enables teaching and research and seeking facilities that enhance the teaching as well as the student experience. TU Delft, as an institution, has focused significantly on sustainability in recent years, therefore the exploration and evaluation of sustainable renovations for campus buildings would be a topic of particular interest to academic staff. The questionnaire survey was sent to professors and teaching staff of departments of Civil Engineering & Geosciences, Architecture and the Built Environment, but also Technology, Policy & Management, who have some involvement and interest in sustainability projects.

3.4.3. Students

Students make up the overwhelming majority of campus users, reaching a total of approximately 28,000 students in November 2022, according to data published on the TU Delft website. Consequently, their inclusion in the decision-making process is considered particularly important as they aspire to a welcoming, sustainable and comfortable university environment that enhances their overall educational experience. Regarding the group of students, the survey was sent both to green groups of the university that have an active role in sustainable initiatives, but also to individual students of different departments, such as Civil Engineering & Geosciences and Architecture and the Built Environment, with the aim of drawing out as much diverse results as possible.

3.5. Criteria Formation

As mentioned above, TU Delft is committed to the goal of being energy neutral by 2030. This goal is made up of more specific goals that have been formulated in the university's strategic plans, part of which exclusively concerns the construction and renovation of buildings. More specifically, the goals related to building renovations focus on zero-consumption in at least 50% of campus buildings and the application of circular methods of renovation and maintenance (Dobbelsteen and Gameren, 2022).

This chapter aims to merge criteria from two different sources: the literature criteria identified in subsection 2.4 and the criteria and KPIs set by the TU Delft CREFM department. CREFM, which is responsible for the institution's real estate management, has established a set of KPIs which are tailored to the university's sustainable goals and some of them to its particular ambitions regarding sustainable renovations. Consequently, even though the literature review highlighted the most frequently used criteria for evaluating sustainable renovations based on the research conducted, the present research aims at personalizing these criteria based on the particular strategic goals set by the university.

The goals set by the university are KPI's, and therefore they are measurable and precise goals with a specific timeline. For research purposes, these KPI's will be translated into evaluation criteria, which will reflect their overall importance in the sustainable renovation of the campus. These KPIs are broken down into five categories: carbon neutrality, circularity, climatic adaptability, livability, and demonstration.

3.5.1. Environmental

The environmental element often receives the highest priority, as many organizations focus their efforts on reducing carbon emissions, applying sustainable water and waste management practices, and minimizing several other types of environmental impact (Beattie, 2023). Moreover, it is evident that the environmental criteria are undoubtedly the largest part of the evaluation criteria, both in the literature review and in the goals outlined by TU Delft.

The environmental criteria aligned with each of the TU Delft's KPI's for sustainable campus renovation, are identified as follows:

Table 2: Environmental Criteria from Literature & TU Delft's KPIs.

CO2-Neutral	**Circularity**	**Climate Adaptive**	**Quality of Life**	**Environmental Criteria from Literature Review**
Net Energy Use (kWh/year)	Circular Material Integration	Nature-Based Design Integration	Biodiversity Promotion	Energy efficiency/ Non-renewable energy demand/consumption / Energy Savings
Energy Efficiency Improvements	Building Material Reuse	Climate-Adaptive Building Designs	Buildings Applying Nature-Inclusive Design	Material cycle & waste management / Reusability & Recyclability
Net Zero Energy Performance	Campus Material Recycling	Sustainable Roof Solutions	Green Cool Spots in Heat-Stressed Areas	Water Efficiency/Consumption/Reuse
Greenhouse Gases (tons of CO2-eq/year)	Detachable Materials in Buildings	Sustainable Rainwater Management	Green Shaded Spaces	Pollution / CO_2 reduction / GHG emissions / Embodied Global Warming Potential (EGWP) reduction
Sustainable Production of Heat and Cold	Non-Hazardous Material Selection	Collected Rainwater Usage	Green Pathways	Energy production
Sustainable Production of Electricity	Projects Applying R-Ladder Principle	Rainwater Storage Infrastructure	Biodiversity and Habitat Conservation	
	Projects Applying S-Layer Principle	Wastewater Treatment and Recycling	Animal Habitat Enhancement	

	Registered Materials Used in Projects	Infiltration Pavement around Buildings		
	Circular Maintenance Design			
	High-Quality Waste Processing			
	Water Conservation			

The vast majority of the university's strategic goals for sustainable development are included in the category of the environmental criteria. The ones that are common to those of the literature review are the following: Energy efficiency, water efficiency, water reuse, CO_2 reduction, and sustainable production of electricity, sustainable production of heat and cold, circularity and material reusability. To these, biodiversity promotion & habitat conservation will be added. The Climate Adaptive Designs criterion only applies to major building renovations, and cannot be used as a criterion for evaluating all possible sustainable renovation measures. Therefore, it will not be included in the final list of criteria. Similarly, the rest of the university's KPI's refer to particular sustainable solutions, such as green roofs and rainwater infrastructure. Therefore, they are not applicable as universal criteria for evaluating all sustainable renovation measures.

Table 3: Selected Environmental Criteria.

Environmental Criteria (6)
Energy efficiency
Water efficiency & reuse
CO_2 reduction
Sustainable production of electricity, heat & cold
Circularity and material reusability
Biodiversity promotion & Habitat conservation

3.5.2. Economic

Economic criteria play an equally important role in the overall evaluation of sustainable renovation strategies. This section delves into the economic criteria, which emerged from the combination of the literature review and the goals set by TU Delft. These criteria are presented in the table below:

Table 4: Economic Criteria from Literature & TU Delft's KPIs.

Economic KPI's	**Environmental Criteria from Literature Review**
Inclusion of Total Cost of Ownership (TCO)	Investment cost / Price
Shadow Carbon Pricing	Operation & maintenance cost / Repair cost
Circular Contracts Tested	Payback Period
	Net Present Value (NPV)
	Internal rate of return (IRR)
	Total life cycle costs
	Benefit/Cost Ratio
	Return on Investment (ROI)
	Energy Cost Savings

As mentioned previously, significantly greater weight has been given by the university to the environmental dimension of sustainability. This reiterates once again the university's commitment to become completely energy neutral by 2030. In the case of financial criteria, the criteria "Shadow Carbon Pricing" and "Circular Contracts" are considered more as tools or means by which the goals of the sustainable transition will be achieved, rather than criteria. Consequently, they will be excluded from the MAMCA analysis. The criterion "Total Cost of Ownership" will be included in the final analysis, since it is considered an important indicator for CREFM, because it encompasses the multiple costs and benefits that can be observed throughout the exploitation phase. Moreover, the following criteria from the literature review will also be included in the analysis: "Investment cost", "Operation & maintenance cost", "Payback Period", "Energy Cost Savings" and "Return on Investment (ROI)". The criteria "Internal rate of return (IRR)", "Benefit/Cost Ratio" and "Net Present Value" they are considered more complex financial indicators, and their importance is reflected more easily and almost equally effectively through the criteria chosen above. Therefore, they will not be included in the final list of criteria.

Table 5: Selected Economic Criteria.

Economic Criteria (6)
Total Cost of Ownership (TCO)
Investment Cost
Operation & Maintenance Cost
Payback Period
Energy Cost Savings
Return on Investment

3.5.3. Social

Social impact is a key pillar of sustainability, equally important with environmental and economic considerations. The social criteria in this particular case include a wide range of factors that directly affect the well-being of campus users, but also of the wider society. These factors seem to be embraced by both TU Delft's goals for sustainable development and the corresponding research found in the literature. The criteria from both TU Delft's strategic plan and the bibliography are presented below:

Table 6: Social Criteria from Literature & TU Delft's KPIs.

Social KPI's	**Social Criteria from Literature Review**
Employee Satisfaction	Identity / Architectural/Structure preservation / Cultural heritage
Parking Availability	Aesthetic
Bicycle Accessibility	Security / Health & Safety
Support for Sustainable Transport	Innovation
	Stakeholders Engagement & education
	Quality of Services
	Social acceptability/Perception / Degree of Satisfaction
	Inconvenience of the system
	Indoor Comfort (Thermal, Visual, Acoustic) / Indoor Air Quality

The criteria mentioned in the table above show several similarities between them. The criteria "Bicycle Accessibility" "Support for Sustainable Transport", will be integrated into one criterion: "Accessibility and Support for Sustainable Transport". The "Employee Satisfaction" and "Degree of Satisfaction" criteria will be integrated into the "Campus Users' Satisfaction" criterion. The criteria "Parking Availability" and "Inconvenience of the System" will not be included in the final list of criteria, as these criteria address a very limited range of sustainable renovation practices. In addition, the criteria "Identity / Architectural/Structure preservation / Cultural heritage" and "Aesthetics" can be integrated into a criterion named "Cultural Heritage & Aesthetics", due to their relevance. The "Quality of Services" criterion is considered a generalized criterion to be included in the list of final criteria and will therefore be excluded. Lastly, the criterion "Stakeholder engagement & education" is not considered to significantly influence the process of selecting the most suitable alternative, as it is expected that sustainable renovations that can trigger additional opportunities for education are also the most innovative ones, for which there is already the "Innovation" criterion. The remaining criteria will be integrated into the final analysis as such.

Table 7: Selected Social Criteria.

Social Criteria (6)
Accessibility and Support for Sustainable Transport
Campus Users' Satisfaction
Cultural heritage & Aesthetics
Health & Safety
Innovation
Indoor Comfort (Thermal, Visual, Acoustic) & Indoor Air Quality

3.5.4. Technical

The technical criteria are the main pillar of sustainable renovations, since they express the feasibility of interventions, but also their usability after implementation. In this category of criteria, the literature review and the university's strategic goals focus on a wide range of factors related to the technical nature of sustainable renovations. These criteria are presented in the table below:

Table 8: Technical Criteria from Literature & TU Delft's KPIs.

Technical KPI's	**Technical Criteria from Literature Review**
Regulated Car Parking	Flexibility & Management

Proximity to Waste Collection Points	Availability
	Efficiency / Functionality
	Reliability / Durability
	Renovation Duration
	Additional space needed around the building
	Fast Assembling/Disassembling

From the criteria and KPIs that are included, the criterion "Fast Assembling/Disassembling" can be considered to be reflected in the duration of the renovation, therefore it will not be included separately in the list of criteria. The "Additional space needed around the building" criterion is considered very specific, therefore it is not suitable for evaluating multiple renovation methods, and will not be included either. Similarly, the "Regulated Car Parking" criterion is considered a more general goal and therefore cannot be a criterion for evaluating multiple sustainable renovations. "Flexibility & Management" is a general criterion, which is considered not to significantly influence the selection process of the most suitable sustainable renovations and will therefore be excluded from the final list. The "Proximity to Waste Collection Points" criterion can be combined with the "Availability" criterion regarding materials and resources for the implementation of sustainable renovation measures. The remaining criteria will be used as such in the analysis.

Table 9: Selected Technical Criteria.

Technical Criteria (4)
Availability of Materials
Efficiency & Functionality
Reliability & Durability
Renovation Duration

3.6. Best-Worst Method (BWM)

The Best Worst Method (BWM) is a Multi-Criteria Analysis method, which is based on the pairwise comparison technique (Rezaei, 2020). According to Rezaei (2020), in order to obtain the ideal weights of the criteria, an optimization model is used which is based on the comparison of the "Best" criterion against the rest, but also on the comparison of the rest of the criteria against the "Worst". These best and worst criteria are determined by the decision makers at the beginning of the analysis (Rezaei, 2015). Next, a consistency ratio is suggested to evaluate the validity of the comparisons.

Rezaei (2015) conducted a study in which he carried out a comparison of the BWM method with the Analytical Hierarchy Process (AHP), one of the most widespread MCA methods based on the pairwise comparison technique. In his research, it was found that due to the smaller amount of comparisons required in BWM, but also the increased reliability occurred from more consistent comparisons, BWM seems to yield better results. In this specific research, BWM will be chosen due to the participation of many different stakeholders in the weighting process, therefore it is estimated that the requirement of fewer comparisons will lead to an increased willingness to participate in the survey (Rezaei, 2015).

3.7. Weighted Sum Model (WSM)

According to Triantafyllou (2000), the Weighted Sum Model (WSM) is the most commonly used multi-criteria method. In a WSM, the score of an alternative can be derived from the weighted sum of its ratings, where the weights reflect the importance weights associated with each criterion (Mateo, 2012). This process is called the additive utility assumption, and it is the fundamental assumption on which the WSM method is based (Triantafyllou, 2000).

In the present analysis, the partial score for each selected sustainable renovation of the case study, which constitutes the MAMCA alternatives, will be derived by multiplying the weights of each criterion, by the performance of each alternative, against each criterion. The final score of each alternative will be calculated by adding each partial score, in accordance with the WSM methodology.

3.8. Conclusions

Summing up, the forth chapter provided important information about MAMCA, which is the methodology that will be followed in the present research, and its core principles. The analysis of the stakeholders is an integral part of it and therefore four categories of important stakeholder groups involved in the decision-making process were selected and analyzed: Finance, CREFM, Academics and Students. Moreover, the criteria identified in the literature review were summarized and combined with the KPI's set by the university regarding sustainable renovations, in order to form the final MAMCA criteria, which are expected to fully meet the needs of TU Delft. A total of 30 criteria were selected, of which 8 are environmental, 8 economic, 9 social and 5 technical. Finally, the BWM method was analyzed, which is chosen MCA method to establish the weights of the criteria, as well as the WSM method, which will be used to evaluate the alternatives against each selected criterion, and will form the final ranking of the available options for sustainable renovation measures.

4. Research Implementation

4.1. Weight allocation: BWM Survey

As previously mentioned, the research focus on identifying the key stakeholders categorizing them in order to discern the different priorities and goals of each stakeholder group, by assigning weights to the selected criteria. For this purpose, the Best-Worst-Method (BWM) was employed, by utilizing a BWM excel template that was distributed to the participants. The participants were asked to choose, for each category of criteria, the most important (Best) but also the least important (Worst) criterion and eventually to compare the remaining criteria against these two, on a scale of 1-9.

Among the Campus Real Estate & Facility Management (CREFM) group, there were five stakeholders invited, and two actively participated by providing their inputs. From the Academics stakeholder group, eight individuals were asked to participate, with 1 response given. On the other hand, the Students group, which consisted of ten participants, displayed the most willing attitude to get involved, with half of them filling out the BWM template.

This participatory process, through the Best-Worst-Method, not only provided a quantitative basis for weighting the criteria, but also revealed information about the values and priorities of each stakeholder group. The following chapters will delve into the analysis of these weighted criteria per stakeholder group, resulting in an overall assessment of the sustainable renovation measures for the TU Delft campus buildings.

4.1.1. Stakeholder group 1: CREFM

The results of BWM show that CREFM emphasizes a higher weight in the category of environmental criteria, assigning them an average criterion weight of 0.57. This indicates the importance given by the specific department to the achievement of the sustainable goals of the university by implementing sustainable renovations in the existing buildings of the campus. Specifically, the criteria that gathered the most weight are "Circularity and Material Reusability", "Biodiversity Promotion & Habitat Conservation" and "CO_2 Reduction".

Moreover, in the same analysis, the category of economic criteria gathered a lower weight of criteria, indicating that the specific criteria are not considered equally important in the decision-making process, as far as the CREFM department is concerned. More specifically, the criteria "Investment Cost" and "Payback Period" are the ones that were assigned the smallest weights of all the selected criteria, while

"Total Cost of Ownership" is considered the most important among the economic criteria. The criteria categories "Social" and "Technical" gathered weights equal to 0.18 and 0.21 respectively.

Therefore, it is evident that the priorities of the CREFM department are aligned with the environmental goals of the university, while significant importance is given to the technical nature and feasibility of the renovations but also to their impact on a social level. However, lower weight is attributed to the economic aspects of the upcoming renovations.

4.1.2. Stakeholder group 2: Academics

The academics' scores are based on their evaluations and priorities about several sustainability standards for renovations on campus. Here, it is observed that higher scores were given to "Sustainable production of electricity, heat & cold" and "CO_2 reduction," which showcases a strong focus on environmental factors. Especially for the "Sustainable Production of electricity, heat & cold" criterion, the focus of the Academics stakeholder group on renewable energy and on adopting energy efficient solutions can be explained by the fact that abundant research is related to this scientific field. Also, the third placement of "Campus Users' Satisfaction" highlights the significance attributed to the satisfaction of the campus community.

Similarly to the CREFM department, it is observed that the most important economic criterion for Academics is considered the "Total Cost of Ownership", which highlights the importance of the long-term economic evaluation of renovations, and not simply the emphasis on short-term indicators such as Investment Cost. On the other hand, criteria such as "Renovation Duration" and "Operation & Maintenance Cost" received lower scores, which suggests that they may be of less priority to Academics in regards to sustainable campus renovations.

Regarding the overall evaluation of the criteria categories, the Academics seem to focus more on the environmental benefits of campus renovations, and consequently on the environmental dimension of sustainability. As the second most important category they chose the social criteria, with the economic and technical criteria occupying the third and fourth position respectively.

4.1.3. Stakeholder group 3: Students

Moreover, interesting insights about the students' goals for sustainable campus upgrades may be obtained from the weight allocations carried out by the "Students" category. For the purposes of this research, answers were received from individual students of different faculties within TU Delft, but also from Green Teams of the university. In this case it seems that the social factors, with a score of

0.37, are given the greatest weight by the students, a fact that reflects the importance of the social dimension of sustainability.

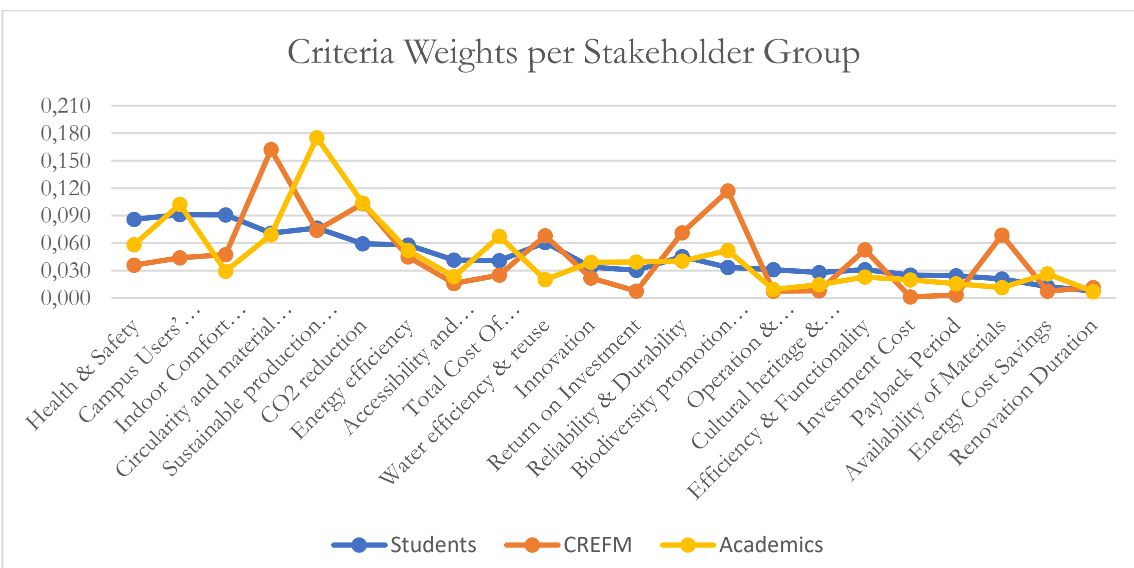
Additionally, “Health and Safety”, “Campus User Satisfaction” and “Indoor Comfort and Indoor Air Quality” are ranked as the top three criteria, indicating that students prioritize factors that affect their experience and well-being while on campus. At a very close distance in the ranking from the social criteria are the environmental criteria with a score of 0.36. This indicates that students perceive the need for taking environmental measures on campus, even if the environmental benefits are obtained long after they have graduated.

On the other hand, students give economic factors a weighting of 0.16 and technical factors 0.10, suggesting that these considerations are not as important compared to the rest of the criteria. The finding that "Energy Cost Savings" and "Renovation Duration" are the least important factors suggests a possible trend toward sustainable renovation practices that would directly benefit society and the environment at the campus level, despite their financial and technical aspects.

4.1.4. Overall Weights

In the above subsections, the individual weights assigned by each stakeholder group to the selected criteria were analyzed and the results were explained in detail. From this analysis, it is possible to obtain the average weights given by all stakeholders regarding the importance of each criterion and consequently to form their overall ranking.

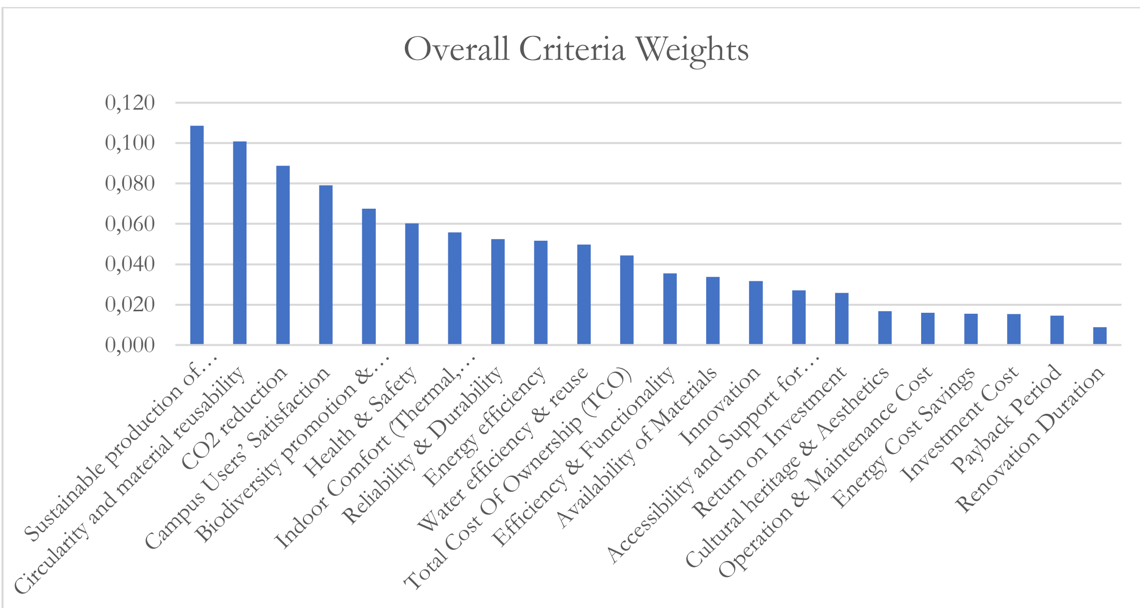
Figure 1: Criteria Weights per Stakeholder Group



The overall weights reveal that the environmental criteria take precedence in the preferences of the stakeholders who participated. This indicates the importance of the environmental dimension of sustainability, which is recognized by multiple campus users, with different functions within the university community. The criteria "Sustainable production of electricity, heat & cold", "Circularity and material reusability" and "CO_2 reduction" emerged as the highest ranked criteria, which indicates that the top three criteria in the ranking are related to environmental concerns.

The significance of the social benefits of sustainable campus renovations and consequently the social dimension of sustainability is also evident, with the two most important social criteria standing out as "Campus Users' Satisfaction" and "Health & Safety" occupying 5th and 7th place in the overall ranking , respectively.

Figure 2: Overall Criteria Weights



4.2. Alternatives Scores

To select the alternatives to be considered in this research, some of the most frequently used and researched sustainable renovations in the literature were examined, forming the table below:

Table 10: Alternative sustainable building renovations found in literature.

Widely researched sustainable renovation measures
Installing a green roof
Upgrading lighting systems to LED
Installing a rainwater harvesting system
Installing double-glazed windows
Energy Efficient Building Retrofit
Installing a geothermal energy system

Subsequently, it was examined how many of the previously identified criteria are relevant and applicable to these alternatives for evaluation, and thus the selection of the two most suitable alternatives was made.

Widely researched sustainable renovation measures	**# Of Selected Criteria Applicable for Evaluation (22 in total)**
Installing a green roof	21
Upgrading lighting systems to LED	17
Installing a rainwater harvesting system	16
Installing double-glazed windows	16
Energy Efficient Building Retrofit	20
Installing a geothermal energy system	17

Consequently, it appears from the above that the green roof and the energy retrofit building projects are the two most suitable alternatives for evaluation in the present research.

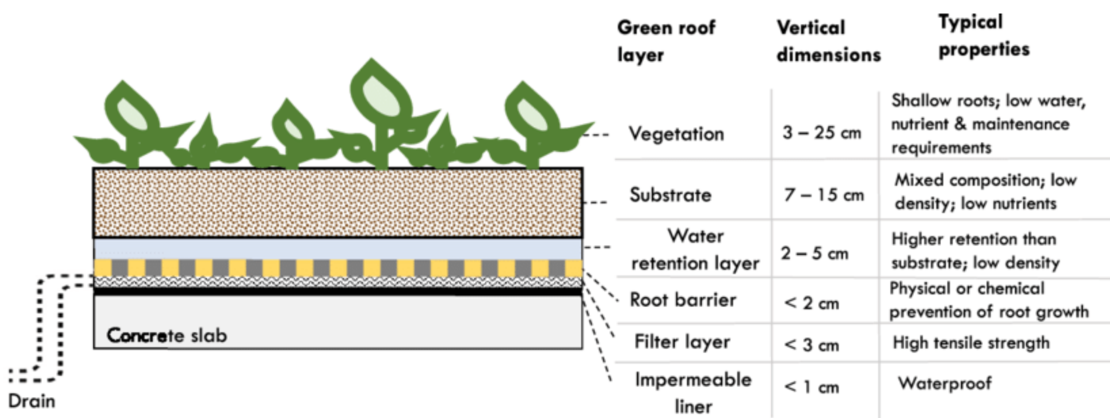
4.2.1. Alternative 1: Green Roofs

Green roofs, sometimes referred to as "vegetated roofs" or "living roofs," are roofs that are covered in vegetation, soil and a waterproofing membrane on top of a conventional roof (GSA, 2011). It is widely acknowledged that green roofs can increase the energy efficiency of buildings. Given that 20–25% of all metropolitan surface surfaces are made up of rooftops, it is highly expected that a green system may provide a long-term solution for reducing energy use (Nguyen Dang et al., 2022).

Specifically at TU Delft, 13,300 m² are roofs with natural covering (grass, sedum, or both) out of a total of 170,000 m² of flat roofs (TU Delft, n.d.). Hence, examining the effectiveness of green roofs against each of the criteria selected in the previous chapter, can be considered of significant importance for the present research.

For this specific research, an extensive green roof will be used as a basis, i.e. a green roof that has a less deep layer of substrate compared to intensive green roofs, which is also considered the most economical solution and requires an easier installation process.

Figure 3: Typical extensive green roof layers (Cook and Larsen (2021)).



Regarding environmental criteria, a report by the United States General Services Administrations (U.S. GSA) outlined multiple benefits that green rooms have on an environmental level. Some of these are the improved water quality due to decreased storm water runoff and less mixing of sewage and storm water overflows, the promotion of biodiversity, lower temperatures in the rooms, reduced energy consumption, improved air quality and improved sound absorption (GSA, 2011).

According to Kuronuma et al. (2018), the yearly CO_2 reduction attributed to energy savings from the implementation of green roofs ranges from 1.703 to 1.889 kg CO_2 / m² / year. For the needs of this particular research, an average of these two estimates will be considered, given that these values are close to each other. Moreover, applying a green roof system can result in an energy saving rate of 4.1%, according to an experimental analysis performed by Zhao et al. (2023). Pirouz et al. (2021) found that during the summer, in humid regions, the average water use for green roofs is approximately 3.7 L/m²/day, while in Mediterranean regions, it is around 4.5 L/m²/day. Lastly, in arid regions, the average water use is about 2.7 $L/m^2/day$. Therefore, the value to be considered in this case will be 3.7$L/m^2/day$, since the Netherlands could fall within a similar range to that of humid regions.

As far as the sustainable production of energy is concerned, green roofs, by providing thermal insulation, reduce the need for air conditioning, lower energy costs, improve the efficiency of AC units, reduce heating costs by insulating against the cold, and maximize the performance of photovoltaic panels, which promotes greater building energy independence (Green Roof Organisation, 2023). Consequently, a score of 4/5 will be assigned to this criterion. Regarding the circularity of materials used, several components of green roofs come from recycled sources, including growth mediums and membranes (Livingroofs, 2016). However, in a research carried out by Bianchini and Hewage (2012), on the lifecycle of green roofs, it was calculated that the average ratio between non-recycled and recycled materials from two different scenarios of green roofs is 2.37 (Bianchini and Hewage, 2012). For this reason, a score of 3/5 will be given for this criterion. Lastly, since they create a healthy habitat, green roofs can improve the wellbeing of wildlife. Although they cannot be used to directly replace terrestrial ecosystems, they are ideal for attracting birds and other fauna as well as for creating a flourishing and environmentally beneficial habitat (Green Roofers, 2016). As a result, this criterion will receive a score of 5 out of 5.

Therefore, the scoring table in regards to the selected environmental criteria can be formed as follows:

Table 11: A1: Environmental Criteria Scores

Environmental Criteria (6)	**Scale**	**Score**
Energy efficiency (saving rate)	Quantitative	4.1%
Water efficiency & reuse	Quantitative	3.7$L/m^2/day$
CO_2 reduction	Quantitative	1.796 kg/m^2 / year
Sustainable production of electricity, heat & cold	Qualitative	4/5
Circularity and material reusability	Qualitative	3/5
Biodiversity promotion & Habitat conservation	Qualitative	5/5

When it comes to the cost of installing a green roof, there are multiple factors that can influence the investment needed, such as the quality and quantity of plants to be used, accessibility of the roof, potential additional support needed for the roof, etc. (Checkatrade, 2023). However, it is estimated that the average investment cost per square meter for the installation of a green roof is between 75

GBP – 130 GBP (Checkatrade, 2023). For the purposes of this research, the median value of these averages will be used, which is 102.5 GBP, or 119.30 Euros based on the January 2024 exchange rate. As previously mentioned, TU Delft campus buildings incorporate green roofs, covering a total area of 13,300 square meters. More specifically, the buildings housed with green roofs are the following: TU Delft Library, Faculty of Technology, Policy and Management, Applied Sciences, Aerospace Engineering, Civil Engineering, Mechanical Engineering and Applied Sciences South (TU Delft, n.d.). For the needs of this research, the average area of these buildings, which equals 1900 square meters, will be considered as an indicative area of the green roof. Therefore, by multiplying this average area by the cost per square meter, an indicative investment cost of 227,050 euros is obtained.

In a Cost Benefit Analysis performed by Konasova (2019), it was found that the average operation & maintenance cost for a green roof is estimated as 0.5 to 11 euros per square meter, per year. On the other hand, in the same research, the annual energy cost savings were estimated to be between 0.14 and 0.52 for cooling and 0.17 for heating (Konasova, 2019). Thus, the average annual energy cost savings for both cooling and heating are estimated as 0.25 euros per square meter. In a research carried out by Alim et al. (2022) on green roofs as a sustainable urban development tool, it has been claimed that a green roof has an average payback period of 16 years. In this case the Total Cost of Ownership (TCO) will be calculated as follows:

TCO = Investment Cost + Operation & Maintenance Cost (20 years) - Remaining Value (20 years)

20 years will be used as a reference timeframe, the same as that used in the CBA carried out by Konasova (2019). The average Remaining Value in this case was calculated as 23.6 euros per sqm. Consequently, the final equation will be as follows: TCO = 119.3 + 5.75 * 20 - 23.6 = 210.7 euros per sqm. Although quantitative data were found in the literature regarding green rooms to calculate TCO, there was no reliable data for the EER project regarding the maintenance cost but also the remaining value after a certain period of time. Consequently, both the TCO and the operations & maintenance cost will be assessed on a qualitative scale for the green roof as well. The maintenance cost is considered much lower than a retrofit project due to smaller scale interventions. Consequently, the TCO is estimated to be also smaller due to the lower investment cost. For the above reasons, a score of 4 out of 5 will be given for both criteria.

According to a research conducted by Green Roofs for Healthy Cities, the return on investment (ROI) for a green roof can vary between 25% and 60% throughout its 50-year lifespan (Fastercapital, n.d.). Consequently, the average value of these will be taken as the ROI to be used in the specific analysis, i.e. 40%.

Table 12: A1: Economic Criteria Scores

Economic Criteria (6)	Scale	Score
Total Cost of Ownership (TCO)	Quantitative	4/5
Investment Cost	Quantitative	227,050 Euros
Operation & Maintenance Cost (Annual)	Quantitative	4/5
Payback Period	Quantitative	16 years
Energy Cost Savings	Quantitative	0.25 Euros/SQM
Return on Investment	Quantitative	40%

The following table depicts the evaluation of green roofs in regards to the social aspects of sustainability and the respective selected criteria. The scores for these criteria are assigned on a qualitative scale from 1-5, since their quantification and measurement in tangible terms is particularly complicated.

Table 13: A1: Social Criteria Scores

Social Criteria (6)	Scale	Score
Accessibility and Support for Sustainable Transport	Qualitative	1/5
Campus Users' Satisfaction	Qualitative	4/5
Cultural heritage & Aesthetics	Qualitative	4/5
Health & Safety	Qualitative	4/5
Innovation	Qualitative	3/5
Indoor Comfort (Thermal, Visual, Acoustic) & Indoor Air Quality	Qualitative	4/5

While green roofs enhance the overall campus sustainability and may promote more eco-friendly options in transportation as well, they do not directly influence sustainable transport and accessibility on campus. Therefore, the score assigned will be 1/5. However, when it comes to campus users' satisfaction, but also health and safety, a research by Nguyen Dang et al. (2023) has shown that green roofs may provide multiple social and recreational benefits, aligned with various Sustainable Development Goals (SDGs). Some of these SDGs are "Good health and wellbeing", "Reduced inequalities" and "Sustainable cities and communities" (Nguyen Dang et al., 2023). As a result, the score assigned to these criteria will be 4 out of 5. As far as the "Cultural Heritage & Aesthetics" criterion is concerned, green roofs can provide an aesthetically pleasant environment by enhancing biodiversity and greenery on campus roofs, while maintaining the architectural landscape of the building. Hence, the score is set as 4 out of 5. From an innovation perspective, while green roofs is a relatively recent trend, their contribution to the overall campus innovative practices can be considered as moderate, and thus the assigned score will be 3 out of 5. Last but not least, green roofs can also impact indoor air quality and comfort by reducing the ceiling temperature and heat absorption, which results in a score of 4 out of 5 for the corresponding criterion (Cirrincione et al., 2021).

Table 14: A1: Technical Criteria Scores

Technical Criteria (4)	Scale	Score
Availability of Materials	Qualitative	3/5
Efficiency & Functionality	Qualitative	4/5
Reliability & Durability	Qualitative	4/5
Renovation Duration	Qualitative	4/5

The technical criteria also play a pivotal role in a comprehensive evaluation of sustainable renovation measures for TU Delft. More specifically, in terms of the availability of materials, current green roofs at TU Delft are covered in either sedum or grass, or the mix of these two. The most commonly used layers for green roofs are decking, water-resistant layer, and insulation, followed by filtration and drainage layers, and finally growth substrate, and vegetation (The University of Chicago Library, 2010). Therefore, most of these materials are considered accessible in the construction industry and hence the score is set as 3 out of 5. Moreover, green roofs are considered as highly functional and effective practices, with multiple benefits related to temperature regulation, stormwater management and insulation, which could lead to a scoring of 4 out of 5. Regarding durability and reliability of green roofs, a study by Richter and Dickhaut (2023), has proved that blue-green infrastructure like Blue-Green-Roofs (BGRs) can yield positive impacts for an extensive period of time. Hence, a 4/5 score will be attributed to this criterion (Richter & Dickhaut, 2023). Lastly, the installation time for a green roof and therefore the total renovation duration can vary depending on the specifications of each project and the extensiveness of the renovation works. However, an approximate duration could be estimated as within a few weeks until the completion of the green roof installation, resulting in a rating of 4/5 in regards to the total duration needed.

4.2.2. Alternative 2: Energy Efficiency Building Retrofit

The second alternative that will be evaluated, involves a comprehensive energy upgrade for the campus buildings, consisting of multiple sustainable renovation measures. The idea behind comparing the installation of green roofs with an extensive building renovation, is intended to identify the optimal solution for varying prioritization of criteria, since these two alternative solutions differ significantly, in terms of both their costs and benefits.

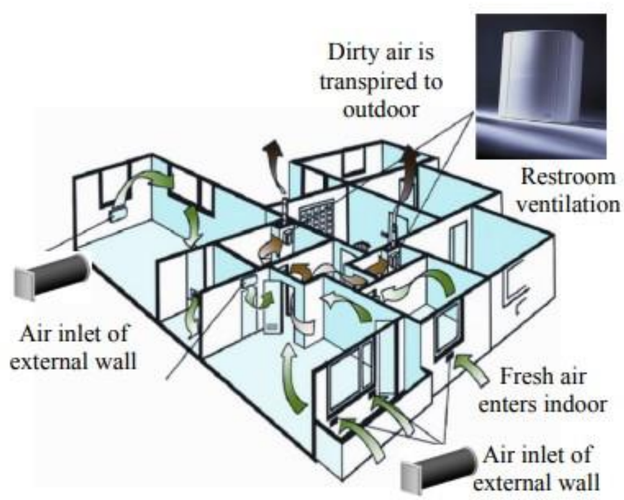
To gather data for this alternative, Energy Efficiency Retrofit (EER), a major initiative for enhancing building energy efficiency of existing structures in China's northern areas, will be used. More specifically, the research of Liu et al. (2018), employed a cost-benefit analysis (CBA) for EER projects based on the assessment of costs and benefits throughout their life-cycle.

The energy efficiency retrofit initiative would include three main activities in regards to the building renovation:

Indoor Heating Pipe Networks Retrofit: This activity refers to the replacement the existing indoor heating pipe network within the building. It included the upgrade of the heating systems, the replacement of radiators, the installation heat meters and flow control valves (Liu et al., 2018).

Installation of Indoor Fresh Air System: This measure aimed at improving the air quality within the building and included the installation of exhaust fans in restrooms and air inlets on each room's external wall (Liu et al., 2018).

Figure 4: Schematic representation of the indoor fresh air system of the selected case study (Liu et al., 2018)



External Thermal Insulation: This process included several modifications, including the installation of a 100mm polystyrene slab system in external walls, the enhancement of internal thermal insulation of basement external walls, the upgrade of materials on external windows and entrances, the insulation of the roof with 60mm polystyrene insulation slab and the addition of another waterproof layer (Liu et al., 2018).

The case study carried out in China revealed an annual CO_2 reduction of 212 tons in a building with a total area of 10,180 square meters, which translates into a CO_2 reduction rate of 20.84 kg per square meter per year. This result seems to be significantly greater than the corresponding reduction in CO_2 emissions from the implementation of green roofs, which is justified due to the significantly larger extent of the renovations involved in this case. Moreover, the Index of Heat Loss (IHL) values for the case study building pre- and post-Energy Efficiency Retrofit (EER), were calculated, and therefore the energy conservation rate can be computed, which equals to a 25.7% reduction (Liu et al., 2018). In the CBA carried out in this research, nothing is mentioned about the effect of sustainable renovations on saving and reusing water. Consequently, in this specific criterion the contribution of the implemented solutions is considered negligible and a 1/5 score will be assigned.

Table 15: A2: Environmental Criteria Scores

Environmental Criteria (6)	**Scale**	**Score**
Energy efficiency (saving rate)	Quantitative	25.7%
Water efficiency & reuse	Quantitative	1/5
CO_2 reduction	Quantitative	20.84 kg/m^2/year
Sustainable production of electricity, heat & cold	Qualitative	3/5
Circularity and material reusability	Qualitative	4/5
Biodiversity promotion & Habitat conservation	Qualitative	1/5

The focus of the retrofit of indoor heating networks is on optimizing existing infrastructure rather than generating renewable energy sources. For the indoor fresh air system the main focus is on air circulation and finally the external thermal insulation mainly targets energy efficiency by minimizing heat transfer. Therefore, these renovation measures although contribute to reducing heating and cooling energy demands, direct sustainable production of electricity, heat, or cold is not a central focus and a score of 3/5 will be assigned. Both the installation, retrofit and insulation interventions involves careful consideration of material choices and can be aligned with the circular economy principles reusable and recyclable materials are prioritized. In that case, choosing materials with a low environmental footprint, can contribute to reducing waste and promoting sustainable material management practices. Therefore, the assigned score will be 4 out of 5. In contrast to the green roof installation, indoor renovations, such as heating system or indoor air system upgrades, have minimal impact on biodiversity or habitat conservation. Thus, in this context, the weight assigned to this criterion is 1 out of 5.

Table 16: A2: Economic Criteria Scores

Economic Criteria (6)	Scale	Score
Total Cost of Ownership (TCO)	Qualitative	3/5
Investment Cost	Quantitative	328,471.82 Euros
Operation & Maintenance Cost (Annual)	Qualitative	3/5
Payback Period	Quantitative	28.2 years
Energy Cost Savings	Quantitative	1.14 (Euros/m^2)
Return on Investment	Qualitative	76.77%

As far as the economic criteria are concerned, based on the data provided from the cost-benefit analysis, the investment cost for the renovation amounted to USD 357,083.10 or 328,471.82 Euros. Moreover, the payback period, which indicates the time required to recover the initial investment through the benefits generated, was calculated as 28.2 years (Liu et al., 2018). The CBA also included an assessment of the potential energy cost savings resulting from the renovation measures implemented. Using residential gas and electricity prices in Beijing, which were found to be $0.374 per cubic meter and $0.082 per kilowatt hour, respectively, the analysis calculated a significant energy cost savings of $1.245 per square meter, or 1.14 euros per m^2 (Liu et al., 2018), based on the exchange rate on 14/03/2024. However, because of challenges in obtaining accurate data, the savings in maintenance and operating costs were not considered in the CBA for this particular case study (Liu et al., 2018). The research states that the EER project is expected to reduce maintenance costs due to the upgrade of the envelope and heating systems (Liu et al., 2018). However, due to the complexity of the renovations compared to the green roof, a score of 3/5 will be given for maintenance costs. According to Amstalden et al. (2007), energy-related retrofits have a technical lifespan lasting between 30 to 50 years, which is the same for green roofs as suggested by an article written by Environmental Quality Resources, LCC (2007). As a result, TCO will be estimated based on the investment cost as the dominant variable of the equation, as it is the variable with the largest difference between the alternatives. For the EER project, a score of 3/5 will be given, one unit above the green rooms due to the high investment cost, and the relatively equal maintenance costs and remaining value. For the ROI calculation, we will need the initial cost, but also the total benefit over a period of 50 years, which are referred to as the maximum useful lifetime for both alternatives:

$$ROI\ (Return\ on\ Investment) = \frac{Total\ Benefits\ (50\ years)}{Initial\ Investment\ Cost} * 100\%$$

Having the total area of the building as well as the energy savings per sqm, the total annual energy savings will be calculated as follows:

$$Total\ Annual\ Energy\ Cost\ Savings = Energy\ Cost\ Savings\ per\ sqm * Total\ Area$$
$$= \frac{1.14}{m^2} * 10{,}180\ sqm = 11{,}611.20\ Euros$$

Therefore, the above equation is formulated as follows:

$$Total\ Benefits\ (50\ years) =$$
$$= Total\ Annual\ Energy\ Cost\ Savings * 50\ years - Initial\ Investment\ Cost =$$
$$= 11{,}611.20\ Euros * 50\ years - 328{,}471.82\ Euros =$$
$$= 255{,}088.18\ Euros$$

And finally the ROI is calculated as follows:

$$ROI\ (Return\ on\ Investment) = \frac{255{,}088.18}{328{,}471.82} * 100\% \cong 76.77\%$$

Table 17: A2: Social Criteria Scores

Social Criteria (6)	**Scale**	**Score**
Accessibility and Support for Sustainable Transport	Qualitative	1/5
Campus Users' Satisfaction	Qualitative	4/5
Cultural heritage & Aesthetics	Qualitative	2/5
Health & Safety	Qualitative	5/5
Innovation	Qualitative	3/5
Indoor Comfort (Thermal, Visual, Acoustic) & Indoor Air Quality	Qualitative	4/5

When it comes to sustainable transportation and accessibility, direct benefits may not be included in this particular renovation plan. Therefore, a score of 1/5 will be given against this criterion. The implementation of renovations such as indoor heating pipe networks, fresh air systems, and external thermal insulation can significantly improve the comfort and satisfaction of campus users. Improved indoor climate conditions and energy efficiency contribute to a more pleasant and functional environment, and for this reason a score of 4/5 will be assigned for the campus users' satisfaction criterion. Moreover, since this particular renovation plan focuses on enhancing energy efficiency and indoor environmental quality, it does not directly impact cultural heritage or aesthetic considerations. However, the renovation design could incorporate architectural elements or materials that provide aesthetic value. For this reason, a score of 2/5 will be assigned.

These renovation measures, can maintain comfortable indoor temperatures and reduce the risk of heat loss by ensuring proper ventilation. Thus, this alternative can provide direct and significant benefits to the health and safety of the campus users, with the assigned score in this case being 5 out of 5. Similar benefits may be observed in regards to the indoor comfort and air quality, however the renovation may not address all potential aspects of indoor comfort such as visual comfort. Therefore, a score of 4 out of 5 will be assigned for this particular criterion. Regarding the innovation criterion, the implementation of indoor heating pipe networks, but also clean air systems and external thermal insulation may be good opportunities for the implementation of advanced and innovative building technology methods. However, the selection of these methods and the subsequent level of innovation can be influenced by multiple factors such as the know-how, speed of implementation and project's budget, therefore a score of 3/5 will be given for the criterion of innovation.

Table 18: A2: Technical Criteria Scores

Technical Criteria (4)	Scale	Score
Availability of Materials	Qualitative	3/5
Efficiency & Functionality	Qualitative	5/5
Reliability & Durability	Qualitative	4/5
Renovation Duration	Qualitative	2/5

Regarding the availability of materials, the materials expected to be used in the specific renovations are typical construction materials such as piping, insulation materials and ventilation components, which are easily accessible in the market. However, it is possible that some specialized materials are required for specific retrofitting works which may have limited availability or longer lead times. Consequently, the rating that will be given here is 3 out of 5. Furthermore, the proposed renovation measures aim to significantly improve the performance and functionality of the campus buildings. The measures contribute to the optimized use of energy, the improved indoor comfort and the overall improvement of the building due to the upgrade of the heating and ventilation systems and the improvement of the thermal efficiency. Therefore, the score that will be awarded for efficiency and functionality is 5/5. Moreover, by upgrading outdated HVAC systems and implementing thermal insulation, the reliability of these systems is expected to improve. However, the long-term performance of these measures may depend on factors such as maintenance and environmental conditions. For this reason, a score of 4 out of 5 will be assigned. As far as the renovation duration is concerned, the timeline can vary based on the building specifications and the complexity of the systems. However, retrofitting external thermal insulation might involve extensive work and can have longer duration depending on the building size. Therefore, the assigned score in this case will be 2 out of 5.

4.3. Score Normalization and Weighted Sums

Having collected the weights of the criteria and assigned a score to each alternative against each criterion, the next step is to normalize the scores of the alternatives and then to perform the Multi-Criteria Analysis, through the simple yet very popular MCA method, Weighted Sum Model. The goal of this normalization is to use a universal and unique scale to measure the performance of the alternatives against each criterion, regardless of the scale previously used for scoring. For this purpose, the Min-max normalization method will be employed, which is also referred to as Feature Scaling and aims to convert all score data into a range between 0 and 1, through the following formula (Ciaburro et al., n.d.):

$$x_{scaled} = \frac{x - x_{min}}{x_{max} - x_{min}}$$

The original data values are retained through this type of normalization. However, restricting the data to this bounded range can result in smaller standard deviations, potentially reducing the effect of outliers (Ciaburro et al., n.d.).

For some of the criteria, their maximization is considered as beneficial for the performance of each alternative, while for others as non-beneficial. Therefore, for the cases where a lower score means a higher performance, the above formula was used the value of the equation subtracted from 1:

$$x_{scaled} = 1 - \frac{x - x_{min}}{x_{max} - x_{min}}$$

The final table for all the selected criteria is the one below, which outlines all the criteria, but also the score of each alternative against these criteria.

Table 19: All criteria scores for both alternatives

Environmental Criteria	Green Roofs	EER
Energy efficiency (saving rate)	4.1%	25.7%
Water efficiency & reuse	3.7L/m²/day	0 L/m²/day
CO_2 reduction	1.796 kg/m² / year	20.84 kg/m²/year
Sustainable production of electricity, heat & cold	4/5	3/5
Circularity and material reusability	3/5	4/5
Biodiversity promotion & Habitat conservation	5/5	1/5
Total Cost of Ownership (TCO)	4/5	3/5
Investment Cost	227,050 Euros	357,083.10 euros
Operation & Maintenance Cost (Annual)	4/5	3/5
Payback Period	16 years	28.2 years
Energy Cost Savings	0.25 (Euros/m²)	1.14 (Euros/m²)
Return on Investment	40%	76.77%
Accessibility and Support for Sustainable Transport	1/5	1/5
Campus Users' Satisfaction	4/5	4/5
Cultural heritage & Aesthetics	4/5	2/5
Health & Safety	4/5	5/5
Innovation	3/5	3/5
Indoor Comfort (Thermal, Visual, Acoustic) & Indoor Air Quality	4/5	4/5
Availability of Materials	3/5	3/5
Efficiency & Functionality	4/5	5/5
Reliability & Durability	4/5	4/5
Renovation Duration	4/5	2/5

With the implementation of min-max normalization, this table will be configured as below:

Table 20: Normalized Scores per alternative (Environmental Criteria).

	Initial Scores		**Normalized Scores**		
Environmental Criteria	**Green Roofs**	**EER**	**Green Roofs**	**EER**	**Desired Outcome**
Energy efficiency (Saving Rate)	0.041	0.257	0.160	1.000	High
Water efficiency & reuse	3.7	0	1.000	0.000	High
CO_2 reduction	1.796	20.84	0.086	1.000	High
Sustainable production of electricity, heat & cold	5	3	1.000	0.500	High
Circularity and material reusability	4	4	0.500	0.750	High
Biodiversity promotion & Habitat conservation	5	1	1.000	0.000	High

Table 21: Normalized Scores per alternative (Economic Criteria).

	Initial Scores		**Normalized Scores**		
Economic Criteria	**Green Roofs**	**EER**	**Green Roofs**	**EER**	**Desired Outcome**
Total Cost of Ownership (TCO)	4/5	3/4	0.750	0.500	High
Investment Cost	227050	357083,1	0.364	0.000	Low
Operation & Maintenance Cost (Annual)	4/5	3/4	0.750	0.500	High
Payback Period	16	28,2	0.433	0.000	Low
Energy Cost Savings	0,25	1,14	0.219	1.000	High
Return on Investment	40%	77%	0.521	1.000	High

Table 22: Normalized Scores per alternative (Social Criteria).

	Initial Scores		Normalized Scores		
Social Criteria	**Green Roofs**	**EER**	**Green Roofs**	**EER**	**Desired Outcome**
Accessibility and Support for Sustainable Transport	1	1	0.000	0.000	High
Campus Users' Satisfaction	4	4	0.750	0.750	High
Cultural heritage & Aesthetics	4	2	0.750	0.250	High
Health & Safety	4	5	0.750	1.000	High
Innovation	3	3	0.500	0.500	High
Indoor Comfort (Thermal, Visual, Acoustic) & Indoor Air Quality	4	4	0.750	0.750	High

Table 23: Normalized Scores per alternative (Technical Criteria).

	Initial Scores		Normalized Scores		
Technical Criteria	**Green Roofs**	**EER**	**Green Roofs**	**EER**	**Desired Outcome**
Availability of Materials	3	3	0.500	0.500	High
Efficiency & Functionality	4	5	0.750	1.000	High
Reliability & Durability	4	4	0.750	0.750	High
Renovation Duration	4	2	0.250	0.750	Low

5. Results & Sensitivity Analysis

5.1. Overall ranking

Having chosen the Weighted Sum Model method as the multi-criteria analysis method in the specific research, the problem will be structured based on the principles of the specific method. WSM assumes that a MCA problem consists of m alternatives and n decision criteria (Wikimedia Foundation, 2022). The equation that calculates the final scores of each alternative is defined as follows:

$A_i^{WSM-score} = \sum_{j=1}^{n} w_j a_{ij}, for\ i = 1,2,3, \ldots, m.$ (Wikimedia Foundation, 2022)

With w_j denoting the weight of each criterion C_j and a_{ij} being the score of alternative A_i against each criterion C_j, while the total score of alternative A_i is denoted as A_i^{WSM} score (Wikimedia Foundation, 2022).

	Normalized Scores		**Weights**	**Normalized Scores**	
Environmental Criteria	**Green Roofs**	**EER**		**Green Roofs**	**EER**
Energy efficiency	0,160	1,000	0,051659	0,008	0,052
Water efficiency & reuse	1,000	0,000	0,049706	0,050	0,000
CO_2 reduction	0,086	1,000	0,088758	0,008	0,089
Sustainable production of electricity, heat & cold	1,000	0,500	0,108599	0,109	0,054
Circularity and material reusability	0,500	0,750	0,100817	0,050	0,076
Biodiversity promotion & Habitat conservation	1,000	0,000	0,067533	0,068	0,000

Table 24: Final Scores per alternative (Technical Criteria).

	Normalized Scores		Weights	Final Scores	
Technical Criteria	**Green Roofs**	**EER**		**Green Roofs**	**EER**
Availability of Materials	0,500	0,500	0,033789	0,017	0,017
Efficiency & Functionality	0,750	1,000	0,035514	0,027	0,036
Reliability & Durability	0,750	0,750	0,052441	0,039	0,039
Renovation Duration	0,250	0,750	0,008791	0,002	0,007

Table 25: Final Scores per alternative (Social Criteria).

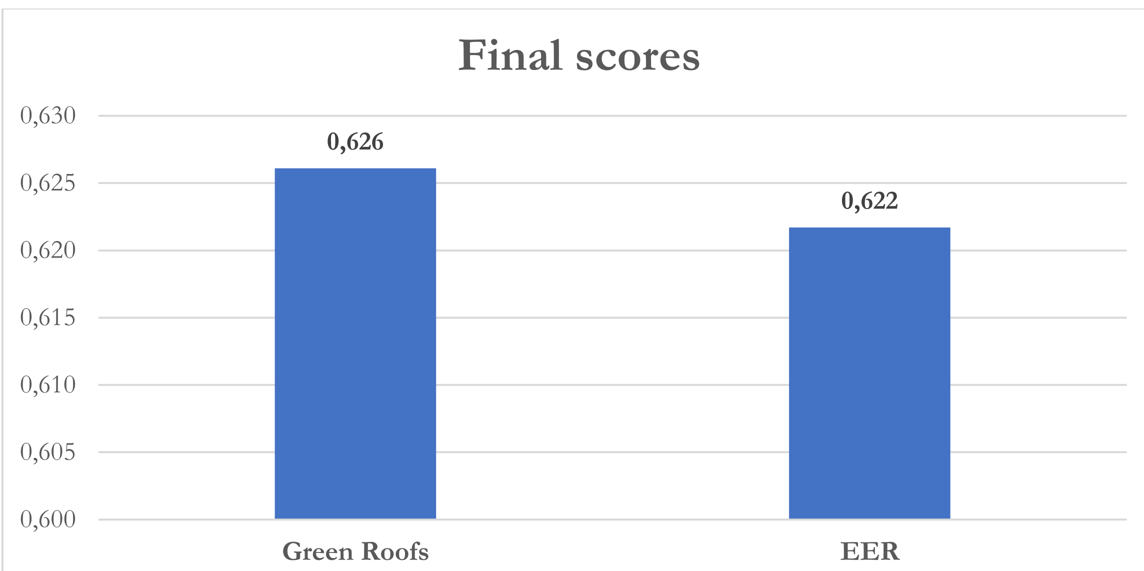
	Normalized Scores		Weights	Final Scores	
Social Criteria	**Green Roofs**	**EER**		**Green Roofs**	**EER**
Accessibility and Support for Sustainable Transport	0.000	0.000	0.027001	0.000	0.000
Campus Users' Satisfaction	0.750	0.750	0.07918	0.059	0.059
Cultural heritage & Aesthetics	0.750	0.250	0.016824	0.013	0.004
Health & Safety	0.750	1.000	0.060186	0.045	0.060
Innovation	0.500	0.500	0.031658	0.016	0.016
Indoor Comfort (Thermal. Visual. Acoustic) & Indoor Air Quality	0.750	0.750	0.055819	0.042	0.042

Table 26: Final Scores per alternative (Economic Criteria).

	Normalized Scores		Weights	Final Scores	
Economic Criteria	**Green Roofs**	**EER**		**Green Roofs**	**EER**
Total Cost of Ownership (TCO)	0.750	0.500	0.044418	0.033	0.022
Investment Cost	0.364	0.000	0.015389	0.006	0.000
Operation & Maintenance Cost	0.750	0.500	0.015939	0.012	0.008
Payback Period	0.433	0.000	0.01459	0.006	0.000
Energy Cost Savings	0.219	1.000	0.015515	0.003	0.016
Return on Investment	0.521	1.000	0.025872	0.013	0.026

Having completed the normalization of the scores of each alternative against each criterion and applied WSM to calculate the final scores, the following scores for each alternative are obtained, as shown below:

Figure 5: Overall Final Scores per alternative.



A remarkable aspect of these results is the close similarity in scores between the two alternatives, despite their significant differences in terms of the scale of renovation needed and their application areas. The EER project has a score of 0,622, with the highest scores concentrated in the criteria of CO_2 reduction, energy efficiency and energy cost savings, indicating the long-term environmental benefits of the specific renovation initiative. On the other hand, the Green roof obtained a slightly higher score of 0.626, with the highest scores being found in the Water efficiency & reuse, Biodiversity promotion & Habitat conservation and Sustainable production of electricity, heat & cold criteria. One of the reasons why EER was judged as a less suitable option compared to Green roof, is the fact that it had no effect on any of the criteria such as the promotion of biodiversity and water efficiency, but also the fact that it requires greater financial investment as it is a larger scale renovation.

In the following subsections, a sensitivity analysis will be carried out, which will determine how different the results (dependent variables) would be if the different weights on the criteria (independent variables) were changed (Kenton, 2023).

5.2. Sensitivity Analysis

5.2.1. Focus on Academics

This analysis aims at determining the extent to which the final ranking of the alternative renovations, and subsequently the decision-making process regarding sustainable renovations on campus, would vary if it was depended solely on the input of one stakeholder group. The first sensitivity analysis will only focus on the stakeholder group of the Academics, thus considering only the criteria weights provided by them.

Consequently, the tables with the final scores of each alternative against each criterion are formed as follows:

Table 27: SA1: Final Scores per alternative (Environmental Criteria).

	Normalized Scores		**Weights**	**Final Scores**	
Environmental Criteria	**Green Roofs**	**EER**		**Green Roofs**	**EER**
Energy efficiency	0.160	1.000	0.052	0.008	0.052
Water efficiency & reuse	1.000	0.000	0.020	0.020	0.000
CO_2 reduction	0.086	1.000	0.104	0.009	0.104
Sustainable production of electricity. heat & cold	1.000	0.500	0.175	0.175	0.088
Circularity and material reusability	0.500	0.750	0.069	0.035	0.052
Biodiversity promotion & Habitat conservation	1.000	0.000	0.052	0.052	0.000

Table 28:SA1: Final Scores per alternative (Technical Criteria).

	Normalized Scores		Weights	Final Scores	
Technical Criteria	**Green Roofs**	**EER**		**Green Roofs**	**EER**
Availability of Materials	0.500	0.500	0.011	0.006	0.006
Efficiency & Functionality	0.750	1.000	0.023	0.017	0.023
Reliability & Durability	0.750	0.750	0.041	0.030	0.030
Renovation Duration	0.250	0.750	0.007	0.002	0.005

Table 29: SA1: Final Scores per alternative (Social Criteria).

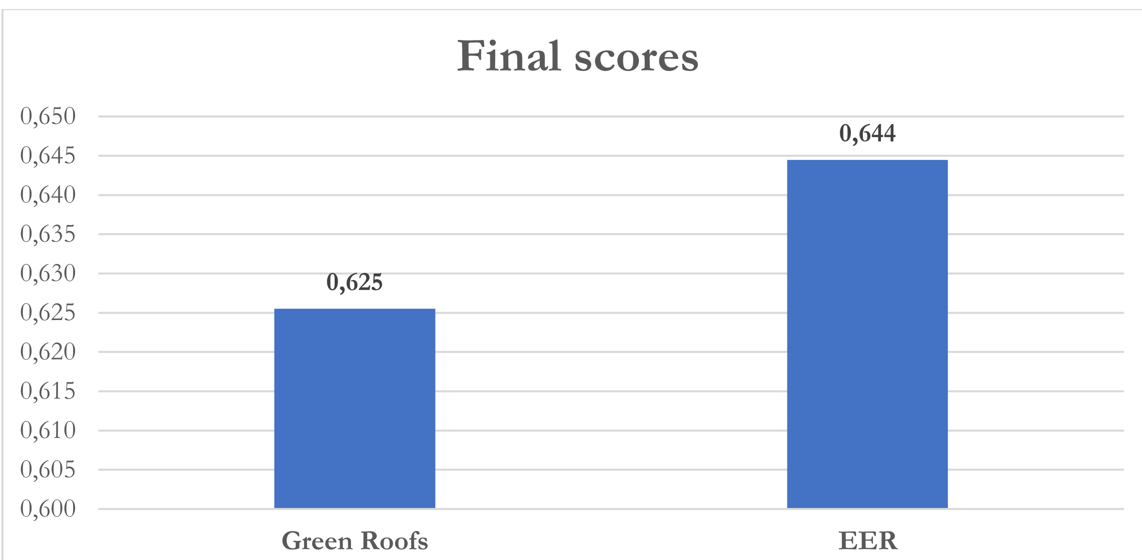
	Normalized Scores		Weights	Final Scores	
Social Criteria	**Green Roofs**	**EER**		**Green Roofs**	**EER**
Accessibility and Support for Sustainable Transport	0.000	0.000	0.023	0.000	0.000
Campus Users' Satisfaction	0.750	0.750	0.102	0.077	0.077
Cultural heritage & Aesthetics	0.750	0.250	0.015	0.011	0.004
Health & Safety	0.750	1.000	0.058	0.044	0.058
Innovation	0.500	0.500	0.039	0.019	0.019
Indoor Comfort (Thermal. Visual. Acoustic) & Indoor Air Quality	0.750	0.750	0.029	0.022	0.022

Table 30: SA1: Final Scores per alternative (Economic Criteria).

	Normalized Scores		Weights	Final Scores	
Economic Criteria	**Green Roofs**	**EER**		**Green Roofs**	**EER**
Total Cost of Ownership (TCO)	0.750	0.500	0.067	0.050	0.034
Investment Cost	0.364	0.000	0.020	0.007	0.000
Operation & Maintenance Cost	0.750	0.500	0.009	0.007	0.005
Payback Period	0.433	0.000	0.016	0.007	0.000
Energy Cost Savings	0.219	1.000	0.026	0.006	0.026
Return on Investment	0.521	1.000	0.040	0.021	0.040

From the above scores, the total final score for each alternative is formed with the application of WSM, which is as follows:

Figure 6: SA1: Overall Final Scores per alternative.



Initially, the overall green roof and EER scores were relatively close, with the green roof slightly ahead at 0.626 versus EER's 0.622. However, by focusing exclusively on the academic group, the EER scored higher at 0.644 compared to the green roof's 0.625. This discrepancy suggests that the criteria weightings provided by academics significantly influence the relative ranking of renovation alternatives.

The criteria to which the academics gave more weight were Sustainable production of electricity, heat & cold, CO_2 reduction, Campus Users' Satisfaction and Circularity and material reusability, in which the EER project had scored highly.

5.2.2. Focus on Students

In the following sensitivity analysis, the focus is placed on the student stakeholder group. Based on the weights assigned by them to each criterion, the scores of the alternatives against each criterion are formed as follows:

Table 31: SA2: Final Scores per alternative (Environmental Criteria).

	Normalized Scores		**Weights**	**Final Scores**	
Environmental Criteria	**Green Roofs**	**EER**		**Green Roofs**	**EER**
Energy efficiency	0.160	1.000	0.058	0.009	0.058
Water efficiency & reuse	1.000	0.000	0.061	0.061	0.000
CO_2 reduction	0.086	1.000	0.059	0.005	0.059
Sustainable production of electricity. heat & cold	1.000	0.500	0.077	0.077	0.038
Circularity and material reusability	0.500	0.750	0.071	0.036	0.053
Biodiversity promotion & Habitat conservation	1.000	0.000	0.034	0.034	0.000

Table 32: SA2: Final Scores per alternative (Economic Criteria).

	Normalized Scores		**Weights**	**Final Scores**	
Economic Criteria	**Green Roofs**	**EER**		**Green Roofs**	**EER**
Total Cost of Ownership (TCO)	0.750	0.500	0.041	0.031	0.020
Investment Cost	0.364	0.000	0.025	0.009	0.000
Operation & Maintenance Cost	0.750	0.500	0.031	0.023	0.015
Payback Period	0.433	0.000	0.024	0.011	0.000

Energy Cost Savings	0.219	1.000	0.013	0.003	0.013
Return on Investment	0.521	1.000	0.030	0.016	0.030

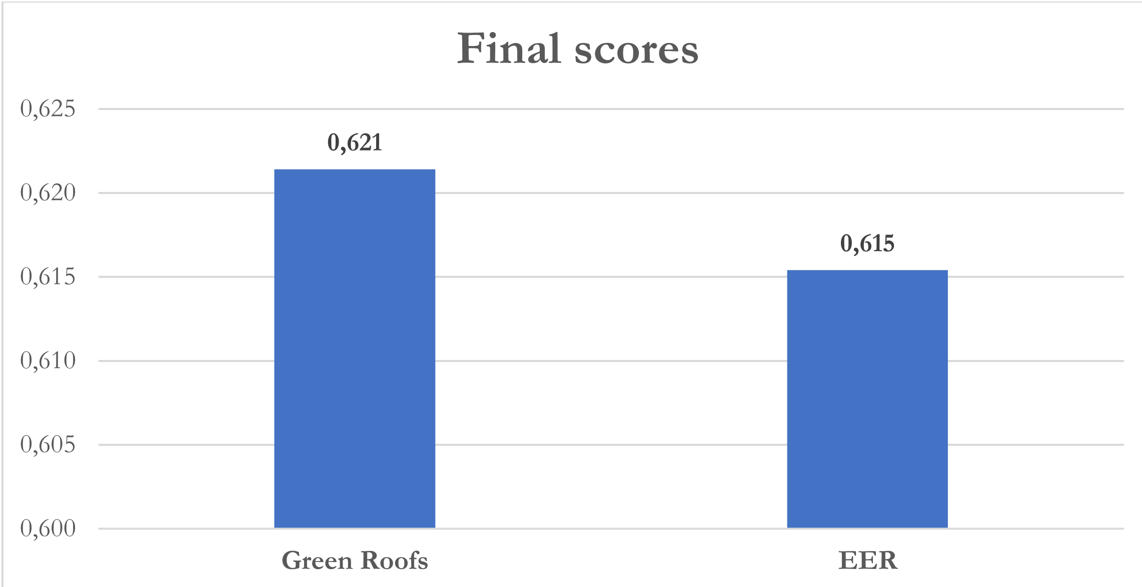
Table 33: SA2: Final Scores per alternative (Social Criteria).

	Normalized Scores		Weights	Final Scores	
Social Criteria	**Green Roofs**	**EER**		**Green Roofs**	**EER**
Accessibility and Support for Sustainable Transport	0.000	0.000	0.042	0.000	0.000
Campus Users' Satisfaction	0.750	0.750	0.091	0.068	0.068
Cultural heritage & Aesthetics	0.750	0.250	0.028	0.021	0.007
Health & Safety	0.750	1.000	0.086	0.064	0.086
Innovation	0.500	0.500	0.034	0.017	0.017
Indoor Comfort (Thermal. Visual. Acoustic) & Indoor Air Quality	0.750	0.750	0.091	0.068	0.068

Table 34: SA2: Final Scores per alternative (Technical Criteria).

	Normalized Scores		Weights	Final Scores	
Technical Criteria	**Green Roofs**	**EER**		**Green Roofs**	**EER**
Availability of Materials	0.500	0.500	0.021	0.011	0.011
Efficiency & Functionality	0.750	1.000	0.031	0.023	0.031
Reliability & Durability	0.750	0.750	0.045	0.034	0.034
Renovation Duration	0.250	0.750	0.008	0.002	0.006

Figure 7: SA2: Overall Final Scores per alternative.



When the sensitivity analysis focused on student preferences, the evaluation of sustainable renovation alternatives also saw changes in ranking. The scores for green roofs and EER were 0.621 and 0.615, respectively, with green roofs maintaining a slightly higher score, as in the original values. The criteria that the students placed the most importance on are Campus Users' Satisfaction, Indoor Comfort (Thermal, Visual, Acoustic) & Indoor Air Quality, Health & Safety emphasizing the social dimension of sustainability, but also the Sustainable production of electricity, heat & cold.

5.2.3. Focus on CREFM

Finally, the last sensitivity analysis concerns the CREFM department of TU Delft and focuses on the weights set by this stakeholder group. This analysis yielded the following results:

Table 35: SA3: Final Scores per alternative (Environmental Criteria).

	Normalized Scores		**Weights**	**Final Scores**	
Environmental Criteria	**Green Roofs**	**EER**		**Green Roofs**	**EER**
Energy efficiency	0.160	1.000	0.045	0.007	0.045
Water efficiency & reuse	1.000	0.000	0.068	0.068	0.000
CO_2 reduction	0.086	1.000	0.103	0.009	0.103
Sustainable production of electricity. heat & cold	1.000	0.500	0.074	0.074	0.037

Circularity and material reusability	0.500	0.750	0.162	0.081	0.122
Biodiversity promotion & Habitat conservation	1.000	0.000	0.117	0.117	0.000

Table 36: SA3: Final Scores per alternative (Economic Criteria).

	Normalized Scores		**Weights**	**Final Scores**	
Economic Criteria	**Green Roofs**	**EER**		**Green Roofs**	**EER**
Total Cost of Ownership (TCO)	0.750	0.500	0.025	0.019	0.013
Investment Cost	0.364	0.000	0.001	0.000	0.000
Operation & Maintenance Cost	0.750	0.500	0.008	0.006	0.004
Payback Period	0.433	0.000	0.003	0.002	0.000
Energy Cost Savings	0.219	1.000	0.008	0.002	0.008
Return on Investment	0.521	1.000	0.008	0.004	0.008

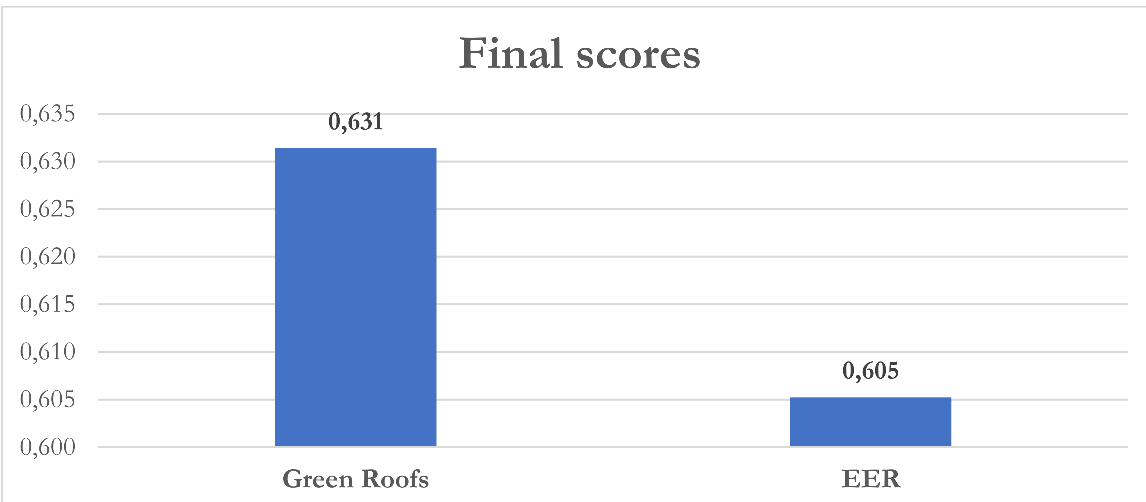
Table 37: SA3: Final Scores per alternative (Social Criteria).

	Normalized Scores		**Weights**	**Final Scores**	
Social Criteria	**Green Roofs**	**EER**		**Green Roofs**	**EER**
Accessibility and Support for Sustainable Transport	0.000	0.000	0.016	0.000	0.000
Campus Users' Satisfaction	0.750	0.750	0.044	0.033	0.033
Cultural heritage & Aesthetics	0.750	0.250	0.008	0.006	0.002
Health & Safety	0.750	1.000	0.036	0.027	0.036
Innovation	0.500	0.500	0.022	0.011	0.011
Indoor Comfort (Thermal. Visual. Acoustic) & Indoor Air Quality	0.750	0.750	0.047	0.035	0.035

Table 38: SA3: Final Scores per alternative (Technical Criteria).

	Normalized Scores		Weights	Final Scores	
Technical Criteria	**Green Roofs**	**EER**		**Green Roofs**	**EER**
Availability of Materials	0.500	0.500	0.069	0.034	0.034
Efficiency & Functionality	0.750	1.000	0.053	0.039	0.053
Reliability & Durability	0.750	0.750	0.071	0.054	0.054
Renovation Duration	0.250	0.750	0.012	0.003	0.009

Figure 8: SA3: Overall Final Scores per alternative.



In the last case where the sensitivity analysis focused on the preferences of the CREFM stakeholder group, the scores for green roofs and EER were 0.631 and 0.605, respectively, indicating a stronger preference for CREFM green roofs. The results result from CREFM's focus on criteria in which green roofs show a higher performance than the EER project, such as Biodiversity promotion & Habitat conservation, Sustainable production of electricity, heat & cold and Water efficiency & reuse.

6. Discussion

In this chapter, a more comprehensive elaboration of the results obtained from the multi-actor multi-criteria analysis (MAMCA) conducted to evaluate sustainable renovation alternatives for TU Delft campus buildings, will be carried out. Moreover, the following sub-chapters will focus on the diverse stakeholder preferences, explore the trade-offs between alternatives, and critically reflect on the efficiency of the MAMCA method in informing decision-making processes within the context of sustainable building renovations for campus buildings.

6.2. Reflection on the Results

The analysis of stakeholder preferences revealed a diverse landscape of views, reflecting the different perspectives and priorities linked with sustainable building renovations. As a result of this analysis, Green roofs emerged as a preferred alternative in the overall ranking, but also in two of the three sensitivity analyses, due to their combination of environmental benefits, aesthetics, potential contribution to promoting biodiversity and natural habitat conservation, as well as lower economic impact. On the other hand, the Energy Efficiency Upgrade (EER) project was highly valued by academics, due to its potential to reduce CO_2 emissions and enhance energy efficiency and promote renewable energy sources. This divergence in preferences reflects the diverse interests of stakeholders and highlights the importance of balancing environmental, social, economic but also technical considerations in the decision-making process. Also, it highlights the trade-offs in the overall results that may arise when one criterion is prioritized over another and the complexity of decision-making in sustainable building renovations. Lastly, these conflicting views reveal the need for a holistic approach that takes into consideration multiple sustainability dimensions and multiple stakeholders in decision-making.

6.3. Reflection on the MAMCA method

The MAMCA method provided a structured framework for evaluating alternative renovation strategies, allowing the stakeholders to express their preferences and priorities by ranking the selected criteria. By facilitating the process of integrating multiple perspectives, MAMCA provided valuable insights into the decision-making process and helped stakeholders make informed choices. However, the analysis also revealed challenges in terms of stakeholder participation, due to participants' lack of knowledge of the specific method, which requires a relatively longer familiarization time with the weighting process compared to a simple questionnaire. Furthermore, regarding the decision-making process, the MAMCA method revealed the need to reconcile conflicting views to balance the different interests of stakeholders. Despite these challenges, MAMCA served as a valuable tool to address the complexity of real-world sustainability assessments, emphasizing the importance of stakeholder engagement and collaborative decision-making to achieve holistic outcomes.

7. Conclusion & Recommendations

7.1. Conclusion

Having completed the analysis, some conclusions can be drawn regarding both the sensitivity analysis and the final results. The overall analysis of stakeholder preferences and criteria weighting revealed that green roofs emerged as a more favorable option than the Energy Efficiency Retrofit (EER) project for TU Delft. While weightings of specific criteria vary among stakeholder groups, green roofs consistently outperform EER work in key areas such as Promoting Biodiversity, Sustainable Energy Production, and Water Efficiency. In addition, green roofs have advantages in addressing criteria prioritized by many stakeholder groups, such as campus user satisfaction, Comfort and Indoor Air Quality, and Health and Safety. This collective assessment leads to the suitability of green roofs as a sustainable renovation solution based on the needs and preferences of TU Delft's different stakeholders.

The exclusive focus on Academics who emphasized criteria such as sustainable energy production, CO_2 reduction, campus user satisfaction and material circularity, resulted in a higher score for EER (0.644) compared to green roofs (0.625). This highlights the significant influence of academic perspectives on alternative rankings.

In contrast, CREFM preferences favored green roofs over EER, with scores of 0.631 and 0.605, respectively. This preference was based on giving greater weight to criteria such as Promoting Biodiversity, Sustainable Energy Production and Water Efficiency, where green roofs demonstrated a stronger performance.

Student preferences also played a key role, as green roofs retained a marginally higher score than EER due to prioritization of criteria such as campus user satisfaction, comfort and indoor air quality, health and safety and sustainable production energy. This highlights the varying priorities of stakeholders and their impact on sustainable renovation assessments.

7.2. Limitations

While this research offers valuable insights into sustainable renovation decision-making for TU Delft campus buildings, some limitations can be acknowledged. First, the limited sample size of respondents from some stakeholder groups may not fully represent the diversity of perspectives within the university community. In addition, the exclusion of certain renovation criteria or options due to data availability or feasibility limitations could affect the completeness of the analysis. Finally, the impossibility of quantifying some criteria due to lack of data and assigning a score to them through a qualitative scale, limits the accuracy and reliability of the findings regarding the preferred sustainable renovation.

7.3. Recommendations

To address these limitations and strengthen the credibility of future research in this area, but also to apply the framework developed on a wider scale, several recommendations can be made. First, efforts should be made to increase the representation of all stakeholders and user groups within the university involved in the decision-making process. Additionally, future analyzes should seek to incorporate a wider range of renovation criteria and options, drawing on both quantitative data and qualitative knowledge. Collaborations with industry partners or external experts as well as research on the more accurate scoring of the alternatives for each criterion will strengthen the credibility of the results. Finally, to enhance the applicability of the findings beyond the context of the case study, future research could investigate sustainable renovations in larger urban settings using the framework developed in the present research. By implementing these recommendations, future research efforts can contribute to more inclusive and accurate approaches to sustainable building renovation.

Standardization of the MAMCA Framework & Development of Decision Support Tools

Future research efforts should focus on standardizing and automating the MAMCA framework to streamline the evaluation process for various sustainable renovation or construction projects. This could include the development of in-house software tools or decision support systems that facilitate the collection, analysis and visualization of stakeholder preferences and criteria weights. By automating the MAMCA framework, researchers and practitioners can accelerate the decision-making process with the least possible effort and enhance the reproducibility and scalability of the framework constructed in this research. This potential tool would combine and automate BWM & WSM methods with the goal of selecting whichever criteria fit each future project, assigning weights to the criteria by selected stakeholder-users, and comparing and evaluating alternatives against these criteria. Consequently, the stages of data collection, analysis and evaluation could belong to a single tool-software instead of addressing them in different stages of the process.

Incorporation of Stakeholder Feedback Mechanisms

To enhance the effectiveness of the MAMCA framework, future research should explore the incorporation of feedback mechanisms from all potential stakeholders regarding criteria evaluation and weighting. This could include implementing online survey platforms or interactive workshops that allow stakeholders to provide input throughout the decision-making process. By incorporating stakeholder feedback into the MAMCA framework, researchers can ensure the validity of their research findings and selections of evaluation criteria, but also promote greater stakeholder involvement and acceptance of the final results.

Actively informing Campus Users - Stakeholders

Based on the MAMCA framework, future research should focus on initiatives that provide stakeholders with useful information and recommendations for sustainable renovation projects, workshops on the potential costs and benefits of each project being discussed but and the importance of taking sustainable building renovation measures. This would enhance the interest of campus users and consequently increase the number of stakeholders in the decision-making process and participation in future MAMCA research.

7.4. Scientific Relevance

From a scientific point of view, this research contributes to the projection of an inclusive process of multi-criteria analysis regarding sustainable building renovations, which does not seem to be often encountered in the existing literature. By applying multi-actor multi-criteria analysis (MAMCA) and the best-worst method (BWM), the study demonstrates a framework for assessing the preferences and priorities of different stakeholder groups within a campus. Furthermore, by conducting sensitivity analyzes to assess the impact of different stakeholder views on the overall ranking of alternatives, this study promotes the inclusion of multiple stakeholders in decision-making processes in complex sustainability contexts. Through this research, the scientific community can leverage the findings to further improve methodologies for assessing sustainable buildings by including multiple stakeholders more effectively in decision-making processes.

7.5. Societal Relevance

The societal value of this research lies in its contribution to promoting sustainable practices within academic institutions. By recognizing stakeholder preferences and evaluating sustainable renovation alternatives for TU Delft campus buildings, this study offers practical value regarding inclusive decision-making processes aimed at enhancing environmental performance by taking into account the interests of multiple stakeholders and campus users. Through collaborative research and collaboration with all stakeholders within the campus, this study promotes a holistic and inclusive approach to sustainability that takes into account environmental, social and economic as well as technical factors, in an effort to create more sustainable university campuses.

References

Alim, M. A., Rahman, A., Tao, Z., Garner, B., Griffith, R., & Liebman, M. (2022). Green roof as an effective tool for Sustainable Urban Development: An Australian perspective in relation to stormwater and Building Energy Management. *Journal of Cleaner Production*, *362*, 132561. https://doi.org/10.1016/j.jclepro.2022.132561

Amstalden, R. W., Kost, M., Nathani, C., & Imboden, D. M. (2007). Economic potential of energy-efficient retrofitting in the Swiss residential building sector: The effects of policy instruments and Energy Price Expectations. *Energy Policy*, *35*(3), 1819–1829. https://doi.org/10.1016/j.enpol.2006.05.018

Antonov, Y., Heiselberg, P., Flourentzou, F., & Pomianowski, M. (2020). Methodology for evaluation and development of refurbishment scenarios for multi-story apartment buildings, applied to two buildings in Denmark and Switzerland. Buildings, 10(6), 102. https://doi.org/10.3390/buildings10060102

Bafail, O. A., & Abdulaal, R. M. S. (2022). A combined BWM-topsis approach versus AHP-Topsis Approach: An application to solid waste management. *2022 The 3rd International Conference on Industrial Engineering and Industrial Management*. https://doi.org/10.1145/3524338.3524343

Beattie, A. (2023). The 3 pillars of Corporate Sustainability. Investopedia. https://www.investopedia.com/articles/investing/100515/three-pillars-corporate-sustainability.asp

Becchio, C., Bottero, M. C., Corgnati, S. P., Dell'Anna, F., Pederiva, G., & Vergerio, G. (2021). Proposal for an integrated approach to support urban sustainability: The cosima method applied to eco-districts. *Smart and Sustainable Planning for Cities and Regions*, 37–47. https://doi.org/10.1007/978-3-030-57332-4_3

Becchio, C., Bottero, M.C., Corgnati, S.P., Dell'Anna, F., Pederiva, G., Vergerio, G. (2021). Proposal for an Integrated Approach to Support Urban Sustainability: The COSIMA Method Applied to Eco-Districts. In: Bisello, A., Vettorato, D., Haarstad, H., Borsboom-van Beurden, J. (eds) Smart and Sustainable Planning for Cities and Regions. SSPCR 2019. Green Energy and Technology. Springer, Cham. https://doi.org/10.1007/978-3-030-57332-4_3

Bianchini, F., & Hewage, K. (2012). How "green" are the green roofs? Lifecycle analysis of green roof materials. *Building and Environment*, *48*, 57–65. https://doi.org/10.1016/j.buildenv.2011.08.019

Blom, T., & Dobbelsteen, A. van den. (2019). CO2-roadmap TU Delft. TU Delft. https://d1rkab7tlqy5f1.cloudfront.net/Websections/Sustainability/CO2-roadmap%20TU%20Delft.pdf

Boardman, A. E., Greenberg, D. H., Vining, A. R., & Weimer, D. L. (2017). Cost-benefit analysis: concepts and practice. Cambridge University Press.

Checkatrade. (2023). How much does a green roof cost in 2024? | https://www.checkatrade.com/blog/cost-guides/green-roof-cost/

Ciaburro, G., Ayyadevara, V. K., & Perrier, A. (n.d.). *Hands-on machine learning on Google Cloud Platform*. O'Reilly Online Learning. https://www.oreilly.com/library/view/hands-on-machine-learning/9781788393485/fd5b8a44-e9d3-4c19-bebb-c2fa5a5ebfee.xhtml

Cirrincione, L., Marvuglia, A., & Scaccianoce, G. (2021). Assessing the effectiveness of green roofs in enhancing the energy and Indoor Comfort Resilience of urban buildings to climate change: Methodology proposal and application. *Building and Environment*, *205*, 108198. https://doi.org/10.1016/j.buildenv.2021.108198

Cook, L. & Larsen, T. (2021). Towards a performance-based approach for multifunctional green roofs: An interdisciplinary review. Building and Environment. 188. 107489. 10.1016/j.buildenv.2020.107489.

Dean, M. (2020). Multi-criteria analysis. In *Advances in Transport Policy and Planning* (Vol. 6, pp. 165-224). Academic Press.

Dijkstra, L. P. J. (2013). An environmental and economic impact comparison of renovation concepts for Dutch residential buildings (Master's thesis).

Dobbelsteen A. van den, Gameren D., van (2022). Sustainable TU Delft: Vision, ambition and action plan for a climate university (Version 5.3).

Estévez RA, Espinoza V, Ponce Oliva RD, Vásquez-Lavín F, Gelcich S. Multi-Criteria Decision Analysis for Renewable Energies: Research Trends, Gaps and the Challenge of Improving Participation. Sustainability. 2021; 13(6):3515. https://doi.org/10.3390/su13063515

European Commission. (2020). Focus on energy efficiency in buildings. Retrieved from https://commission.europa.eu/news/focus-energy-efficiency-buildings-2020-02-17_en.

Fastercapital. (n.d.). Challenges in green building https://fastercapital.com/topics/challenges-in-green-building.html

Finnveden, G., & Potting, J. (2014). Life cycle assessment. *Encyclopedia of Toxicology*, 74–77. https://doi.org/10.1016/b978-0-12-386454-3.00627-8

Gholami, Elaheh & Kiviniemi, Arto. (2015). Implementing Building Information Modelling (BIM) in Energy- Efficient Domestic Retrofit: Quality Checking of BIM Model.

Gökgür, A. (2015). Current and future use of BIM in renovation projects. Chalmers University of Technology.

Green Roof Organisation (2023). How do green roofs save energy?. https://www.greenrooforganisation.org/2023/01/12/how-do-green-roofs-save-energy/

Green Roofers. (2016) *Advantages and disadvantages of green roofs*. https://www.greenroofers.co.uk/green-roofing-guides/advantages-disadvantages-green-roofs/

GSA. (2011). Green roofs. https://www.gsa.gov/governmentwide-initiatives/federal-highperformance-green-buildings/resource-library/integrative-strategies/green-roofs

ISO 29481-1:2010(E): Building Information Modeling — Information Delivery Manual — Part 1: Methodology and Format

Jacob-Lopes, E., Zepka, L. Q., & Deprá, M. C. (2021). Assistant's tools toward Life Cycle Assessment. *Sustainability Metrics and Indicators of Environmental Impact*, 77–90. https://doi.org/10.1016/b978-0-12-823411-2.00006-2

Jensen, P. A., Maslesa, E., Berg, J. B., & Thuesen, C. (2018). 10 questions concerning sustainable building renovation. *Building and Environment*, *143*, 130–137. https://doi.org/10.1016/j.buildenv.2018.06.051

Jensen, P., Maslesa, E., & Brinkø Berg, J. (2018). Sustainable building renovation: Proposals for a research agenda. *Sustainability*, *10*(12), 4677. https://doi.org/10.3390/su10124677

Kamari, A., &; Peter Leslie Schultz, C. (2022). A combined principal component analysis and Clustering Approach for exploring enormous renovation design spaces. Journal of Building Engineering, 48, 103971. https://doi.org/10.1016/j.jobe.2021.103971

Kamari, A., Corrao, R., & Kirkegaard, P. H. (2017). Sustainability focused decision-making in building renovation. International Journal of Sustainable Built Environment, 6(2), 330–350. https://doi.org/10.1016/j.ijsbe.2017.05.001

Kamari, A., Kirkegaard, P. H., & Leslie Schultz, C. P. (2021). Paradis - A process integrating tool for rapid generation and evaluation of holistic renovation scenarios. *Journal of Building Engineering*, *34*, 101944. https://doi.org/10.1016/j.jobe.2020.101944

Kenton, W. (2023). *Sensitivity analysis definition*. Investopedia. https://www.investopedia.com/terms/s/sensitivityanalysis.asp

Kesten Erhart, D., Haag, M. & Schmitt, A., Strasser, D., Bonomolo, M. & Eicker, U. (2016). Retrofitting Existing University Campus Buildings to Improve Sustainability and Energy performance.

Konasova, S. (2019). Cost-benefit analysis of green roofs in densely built-up areas. Proceedings of the 12th Economics & Finance Conference, Dubrovnik. https://doi.org/10.20472/efc.2019.012.013

Kuronuma, T., Watanabe, H., Ishihara, T., Kou, D., Toushima, K., Ando, M., & Shindo, S. (2018). CO2 payoff of extensive green roofs with different vegetation species. Sustainability, 10(7), 2256. https://doi.org/10.3390/su10072256

Kylili, A., Fokaides, P. A., & Lopez Jimenez, P. A. (2016). Key performance indicators (kpis) approach in buildings renovation for the sustainability of the built environment: A Review. *Renewable and Sustainable Energy Reviews*, *56*, 906–915. https://doi.org/10.1016/j.rser.2015.11.096

Liu, Y., Liu, T., Ye, S., & Liu, Y. (2018). Cost-benefit analysis for energy efficiency retrofit of existing buildings: A case study in China. *Journal of Cleaner Production*, *177*, 493–506. https://doi.org/10.1016/j.jclepro.2017.12.225

Livingroofs. (2016). *Recycled materials*. https://livingroofs.org/recycled-materials/

Locurcio, M., Tajani, F., Morano, P., Liddo, F. D., & Anelli, D. (2022). To rebuild or to refurbish? an analysis of the financial convenience of interventions on urban consolidated contexts. WSEAS TRANSACTIONS ON ENVIRONMENT AND DEVELOPMENT, 18, 226–231. https://doi.org/10.37394/232015.2022.18.24

Macharis, C., Turcksin, L., & Lebeau, K. (2012). Multi Actor Multi Criteria Analysis (MAMCA) as a tool to support sustainable decisions: STATE OF USE. *Decision Support Systems*, *54*(1), 610–620. https://doi.org/10.1016/j.dss.2012.08.008

Mahlia, T. M. I., Said, M. F. M., Masjuki, H. H., & Tamjis, M. R. (2005). Cost-benefit analysis and emission reduction of lighting retrofits in residential sector. *Energy and Buildings*, *37*(6), 573–578. https://doi.org/10.1016/j.enbuild.2004.08.009

Mateo, J.R.S.C. (2012). Weighted Sum Method and Weighted Product Method. In: Multi Criteria Analysis in the Renewable Energy Industry. Green Energy and Technology. Springer, London. https://doi.org/10.1007/978-1-4471-2346-0_4

Maxwell, J. A., & Loomis, D. M. (2003). Mixed methods design: An alternative approach. Handbook of mixed methods in social and behavioral research, 1(2003), 241-272.

Menna, C., Felicioni, L., Negro, P., Lupíšek, A., Romano, E., Prota, A., & Hájek, P. (2022). Review of methods for the combined assessment of seismic resilience and energy efficiency towards sustainable retrofitting of existing European buildings. *Sustainable Cities and Society*, *77*, 103556. https://doi.org/10.1016/j.scs.2021.103556

Moments, W. (2017). *The benefits of green roofs part 6: Life span of roofing membrane*. EQR, LLC. https://www.eqrllc.com/post/the-benefits-of-green-roofs-part-6-life-span-of-roofing-membrane

Moschetti, R., & Brattebø, H. (2017). Combining life cycle environmental and economic assessments in building energy renovation projects. *Energies*, *10*(11), 1851. https://doi.org/10.3390/en10111851

Moschetti, R., Brattebø, H., Skeie, K. S., & Lien, A. G. (2018). Performing quantitative analyses towards sustainable business models in building energy renovation projects: Analytic Process and Case Study. Journal of Cleaner Production, 199, 1092–1106. https://doi.org/10.1016/j.jclepro.2018.06.091

Moschetti, R., Brattebø, H., Skeie, K. S., & Lien, A. G. (2018). Performing quantitative analyses towards sustainable business models in building energy renovation projects: Analytic Process and Case Study. Journal of Cleaner Production, 199, 1092–1106. https://doi.org/10.1016/j.jclepro.2018.06.091

Nguyen Dang, H.-A., Legg, R., Khan, A., Wilkinson, S., Ibbett, N., & Doan, A.-T. (2022). Social impact of green roofs. Frontiers in Built Environment, 8. https://doi.org/10.3389/fbuil.2022.1047335

Nguyen Dang, H.-A., Legg, R., Khan, A., Wilkinson, S., Ibbett, N., & Doan, A.-T. (2023). Users' perceptions of the contribution of a university green roof to sustainable development. *Sustainability*, *15*(8), 6772. https://doi.org/10.3390/su15086772

Nielsen, A. N., Jensen, R. L., Larsen, T. S., & Nissen, S. B. (2016). Early stage decision support for sustainable building renovation – A Review. *Building and Environment*, *103*, 165–181. https://doi.org/10.1016/j.buildenv.2016.04.009

Nijkamp, P., & van Delft, A. (1977). *Multi-criteria analysis and regional decision-making* (Vol. 8). Springer Science & Business Media.

Passoni, C., Caruso, M., Marini, A., Pinho, R., & Landolfo, R. (2022). The role of life cycle structural engineering in the transition towards a sustainable building renovation: Available tools and Research Needs. *Buildings*, *12*(8), 1107. https://doi.org/10.3390/buildings12081107

Passoni, C., Marini, A., Belleri, A., & Menna, C. (2021). Redefining the concept of sustainable renovation of buildings: State of the art and an LCT-based design framework. *Sustainable Cities and Society*, *64*, 102519. https://doi.org/10.1016/j.scs.2020.102519

Pinzon Amorocho, J. A., & Hartmann, T. (2022). A multi-criteria decision-making framework for residential building renovation using pairwise comparison and Topsis Methods. Journal of Building Engineering, 53, 104596. https://doi.org/10.1016/j.jobe.2022.104596

Pirouz, B., Palermo, S. A., & Turco, M. (2021). Improving the efficiency of green roofs using atmospheric water harvesting systems (an innovative design). *Water*, *13*(4), 546. https://doi.org/10.3390/w13040546

Rezaei, J. (2015). Best-worst multi-criteria decision-making method. Omega, 53, 49–57. https://doi.org/10.1016/j.omega.2014.11.009

Rezaei, J. (2020). A concentration ratio for nonlinear best worst method. International Journal of Information Technology & Decision Making, 19(03), 891–907. https://doi.org/10.1142/s0219622020500170

Richter, M., & Dickhaut, W. (2023). Long-term performance of blue-green roof systems—results of a building-scale monitoring study in Hamburg, Germany. *Water*, *15*(15), 2806. https://doi.org/10.3390/w15152806

Sadler, D. R. (1985). The origins and functions of evaluative criteria. *Educational Theory*, *35*(3), 285-297.

Sánchez-Garrido, A. J., Navarro, I. J., & Yepes, V. (2022). Multi-criteria decision-making applied to the sustainability of building structures based on modern methods of construction. *Journal of Cleaner Production*, *330*, 129724. https://doi.org/10.1016/j.jclepro.2021.129724

Seddiki, M., & Bennadji, A. (2019). Multi-criteria evaluation of renewable energy alternatives for electricity generation in a residential building. *Renewable and sustainable energy reviews*, *110*, 101-117.

Seddiki, M., & Bennadji, A. (2019). Multi-criteria evaluation of renewable energy alternatives for electricity generation in a residential building. Renewable and sustainable energy reviews, 110, 101-117.

Serrano-Jiménez, A., Femenías, P., Thuvander, L., & Barrios-Padura, Á. (2021). A multi-criteria decision support method towards selecting feasible and sustainable housing renovation strategies. *Journal of cleaner production*, *278*, 123588.

Seyedabadi, M. R., Eicker, U., & Karimi, S. (2021). Plant selection for green roofs and their impact on carbon sequestration and the building carbon footprint. *Environmental Challenges*, *4*, 100119. https://doi.org/10.1016/j.envc.2021.100119

Sharif, S. A., & Hammad, A. (2019). Simulation-based multi-objective optimization of institutional building renovation considering energy consumption, life-cycle cost and life-cycle assessment. *Journal of Building Engineering*, *21*, 429–445. https://doi.org/10.1016/j.jobe.2018.11.006

Stegnar, G., & Cerovšek, T. (2019). Information needs for progressive BIM methodology supporting the holistic energy renovation of office buildings. *Energy*, *173*, 317–331. https://doi.org/10.1016/j.energy.2019.02.087

Šuman, N., Marinič, M., & Kuhta, M. (2020). A methodological framework for sustainable office building renovation using Green Building Rating Systems and cost-benefit analysis. *Sustainability*, *12*(15), 6156. https://doi.org/10.3390/su12156156

The University of Chicago Library. (2010). The Science of Sustainability. https://www.lib.uchicago.edu/collex/exhibits/science-sustainability/green-roofs/construction-components-green-roofs/

Thollander, P., Karlsson, M., Rohdin, P., Wollin, J., & Rosenqvist, J. (2020). Investments, nonenergy benefits, and conservation. *Introduction to Industrial Energy Efficiency*, 147–158. https://doi.org/10.1016/b978-0-12-817247-6.00007-9

Thuvander, L., Femenías, P., Mjörnell, K., & Meiling, P. (2012). Unveiling the process of sustainable renovation. Sustainability, 4(6), 1188-1213. https://doi.org/10.3390/su4061188

Triantaphyllou, E. (2000). Multi-Criteria Decision Making Methods. In: Multi-criteria Decision Making Methods: A Comparative Study. Applied Optimization, vol 44. Springer, Boston, MA. https://doi.org/10.1007/978-1-4757-3157-6_2

Triantaphyllou, E., Shu, B., Sanchez, S. N., & Ray, T. (1999). Operations research decision making. *Wiley Encyclopedia of Electrical and Electronics Engineering*. https://doi.org/10.1002/047134608x.w3338

TU Delft. (n.d.). A roof that changes colour with the season. https://www.tudelft.nl/en/sustainability/operations/green-roofs

University Corporate Office. TU Delft. (n.d.). https://www.tudelft.nl/en/about-tu-delft/organisation/university-corporate-office

Velykorusova, A., Zavadskas, E. K., Tupenaite, L., Kanapeckiene, L., Migilinskas, D., Kutut, V., Ubarte, I., Abaravicius, Z., & Kaklauskas, A. (2023). Intelligent multi-criteria decision support for renovation solutions for a building based on emotion recognition by applying the COPRAS method and BIM integration. Applied Sciences, 13(9), 5453. https://doi.org/10.3390/app13095453

Wikimedia Foundation. (2022). *Weighted sum model*. Wikipedia. https://en.wikipedia.org/wiki/Weighted_sum_model

Xue, H. (2021). Economic Analysis and evaluation of energy-efficient renovation of existing buildings based on the whole life cycle. *E3S Web of Conferences*, *251*, 02093. https://doi.org/10.1051/e3sconf/202125102093

Zhao, S., Hai, G., Ma, H., & Zhang, X. (2023). Experimental analysis of energy consumption of building roof energy-saving technologies based on time difference comparison test. Frontiers in Energy Research, 11. https://doi.org/10.3389/fenrg.2023.1291213